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Measuring Work Zone Capacity

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Executive Summary

This project had two major objectives:

1) To determine traffic throughput on highways at work zones in Southern Ontario during forced flow conditions.
2) Based on the estimates of different throughput values, refine model output for evaluation of user delay costs at work zones.

Over the course of two construction seasons in 2007 and 2008, usable data were successfully collected at 11 sites over 23 days producing 70 hours of throughput data. Although a model could not be developed for rural, 2-lane highways that employed flagging operations, the analysis allowed for comparison of throughput between different sites and the design values. All of the observed values were lower than the design throughput used, not necessarily because the design throughput should be lowered but because forced flow probably did not occur. Existing models for freeways were used to predict work zone capacities at sites visited, resulting in only 15 of the 120 opportunities being within one standard deviation of the mean.

A paradox was uncovered in that many sites did not experience forced flow conditions although they were expected, implying that the work zone hours could be extended. However, when forced flow conditions did occur, the throughput was significantly less than the standard values used by MTO, implying that the work zone hours should be reduced. One solution to the paradox is to consider highway specific throughput models rather than expect that one model can be an accurate predictor for an entire province.

For sites where queuing did occur, improvement to the predictive capability of existing throughput models found in the literature was made through the creation of a generic model fit to Southern Ontario data. In addition to mean throughput, the 95% confidence intervals were provided in table format. This additive model that employs a base throughput with reduced values when certain site characteristics are present:

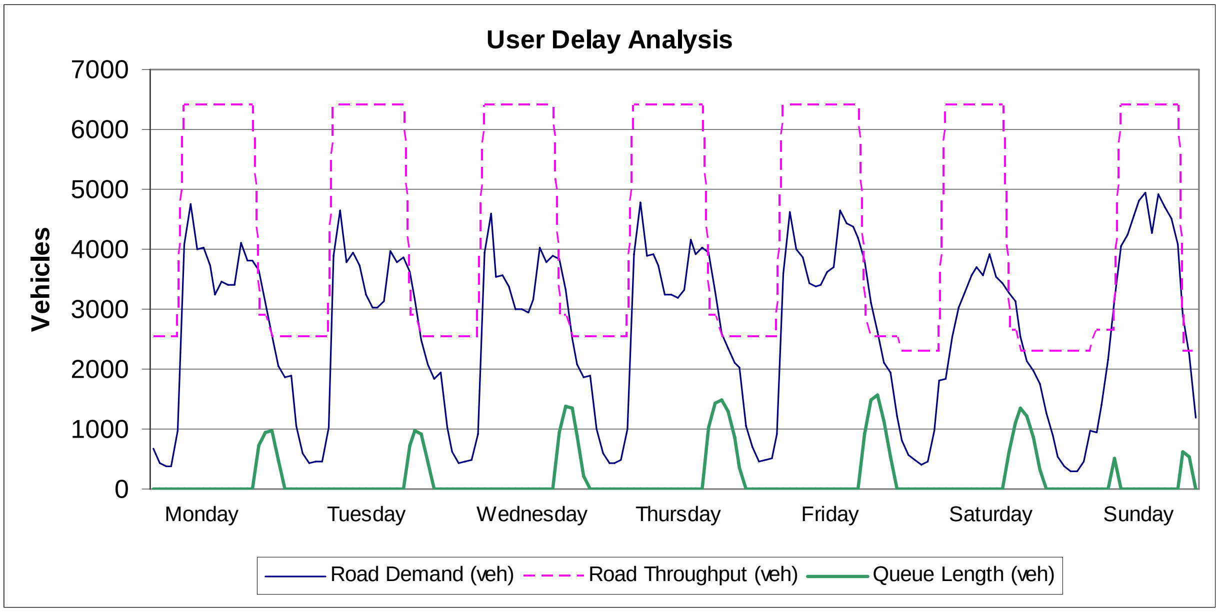
Construction Lane Throughput = 1666
– 179 * (1 if night; 0 if day)
– 216 * (1 if using barrels; 0 if using barriers)
– 126 * (1 if weekend; 0 if weekday)
– 184 * (1 if 2 or more lanes closed; 0 if 1 lane closed)

A highway specific model was also developed for highways 427, 400/401, and QEW.

Construction Lane Throughput = 1702
– 0 * (1 if Hwy 427; 0 otherwise)
– 137 * (1 if Hwy 400/401; 0 otherwise)
– 430 * (1 if QEW; 0 otherwise)
– 107 * (1 if weekend; 0 if weekday)
– 373 * (1 if 2 or more lanes closed; 0 if 1 lane closed)

Objectives related to user delay costs were achieved through the development of SZUDA (Simplified work Zone User Delay Analysis). Using this simple and interactive tool, decision makers can estimate the impacts of lane closure strategies on traffic delays and their associated user delay costs. This model helps to address the paradox uncovered in this study by providing a better understanding of the relationship between throughput, location, and work zone characteristics.

SZUDA output is a graph that plots in a solid blue line the normal hourly traffic flow (one of the inputs), in a pink dashed line the work zone throughput depicting when lanes are closed or fully open (using generic or highway specific models), and in a heavy green line the resulting queues. Also provided are the daily and weekly user delays in vehicle-hours and user delay costs.



User Delay (veh*hr)								
	Mon	**Tue**	**Wed**	**Thu**	**Fri**	**Sat**	**Sun**	**Week Total**
Modified lane closures	3141	3101	4784	6452	5628	5513	1681	37918

The SZUDA model could be used by MTO or by consultants or contractors wishing to examine the impact of various lane closure strategies. Further, this model could be used to customize lane closure strategies for different freeway sections, potentially allowing greater opportunity for contractors to reduce the negative impacts of short work shifts on productivity and quality by increasing lane closure times as appropriate and reducing overall project durations.

1 Introduction

With a greater amount of attention and funding going towards rehabilitating Ontario's highways, it has becoming increasingly important to understand the impact of these activities. Making repairs and performing maintenance often requires lane closures, causing reduced traffic throughput and often resulting in traffic backups and queuing. Due to the number of vehicles and amount of "wasted" time spent in traffic, these delays cause significant costs to the general public. To avoid these costs, construction contractors are forced to keep lanes open during peak hours and work only at night. Having a limited work schedule can not only extend a project, but can decrease both productivity and quality of work. Finding the right balance between keeping the lane open for users and closing it for extended work hours is very important and requires an accurate prediction of the site capacity to do so.

The aim of this project was to study a number of MTO's work zone sites to gain a better understanding of the amount of traffic that can travel through a work zone and the site characteristics that affect that flow. Known as work zone throughput, this value can be compared to the demand for a given section of road, allowing predictions for whether or not vehicles will experience delays due to the construction.

1.1 RESEARCH OBJECTIVES

This project had two major objectives:

1) To determine traffic throughput on highways at work zones in Southern Ontario during forced flow conditions.
2) Based on the estimates of different throughput values, refine model output for evaluation of user delay costs at work zones.

2 Background

Dating back to the mid 1980s, academics have been trying to determine what causes the wide range of values for work zone capacity. Previous studies ranged in scope and depth but highlighted a number of similarities and differences. The topics included in this section are background information, general work zone studies, work zone capacity models, design values, contract strategies and impacts of research.

2.1 BACKGROUND INFORMATION

2.1.1 EARLY ANALYSIS

Early analysis addressed general issues related to construction lane closures. Three problems relating to highway work zones were identified [Levine 1984]: determining the optimum time to perform work, the manner in which the public is warned about the work, and alternative means to protect workers from errant motorists. Additionally, the roads could be categorized into three types of permissible lane closure times: [Levine 1984]

1) Certain time constraints, preferably work during off-peak hours
2) Highways where only night and weekend work is allowed
3) Highways where there are no lane-closure time restrictions

Further, three guidelines for determining lane-closure times were identified. While two of these guidelines are related to performance (public delay of less than 30 minutes and using traffic control plan request forms), the third is more flexible, stating that "the number of lanes closed is site specific and depends on flow rates, capacities, shoulder availability and geometry" [Levine 1984]. Work zone evaluation studies help to understand the dynamics of the different elements in the construction zone.

2.1.2 BASIC TERMS

Standardizing common terms is important to any area of study, and over 50 terms in 6 different categories have been defined as being important to work zone capacity [Lewis 1989].

The Provincial Highway system can generally be grouped into the following classes. Complex and Simple Freeways are designed for 120 km/h and the maximum posted speed is 100 km/h. In construction zones the posted speed is generally maintained at 100 km/h unless specific site characteristics justify a speed limit reduction. In such cases, the posted speed is reduced to 80 km/h.

In addition to the standard highways described in this section, there is a group of highways known as "Special Controlled Access Highways". These roads have similar design standards and posted speeds.

Major Highways are normally designed for 100 km/h with a maximum posted speed of 80 km/h. In construction zones, the posted speed is maintained unless specific site characteristics justify a speed limit reduction. In such cases, the posted speed is reduced to 60 km/h.

The design speed for Minor Highways varies from 70-100 km/h depending upon traffic volume and the percentage of commercial traffic. The posted speed also varies from 50 to 80 km/h. In construction zones the posted speed varies depending upon the geometric conditions.

HCM defines “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 vehicles per hour, passenger cars per hour, or persons per hour” [HCM 2000].

In this report, the term capacity will not be used as we have not sought to find the maximum flow rate. Instead, highway work zone throughput will represent the number of vehicles per hour that could pass a specific point in the work zone during forced flow conditions. Forced flow conditions occur when traffic slows to a speed of less than 20km/hr, causing a queue since more vehicles are arriving at the site than can pass through the zone.

With regard to the unit of measurement, capacity is often measured using passenger car per hour per lane (pcphpl) but it can also be simplified and evaluated in terms of vehicles per hour per lane (vphpl). MTO currently uses vphpl for highway work zones; however, vphpl is not often used in academic studies or in highway design as it does not account for the effect that larger vehicles have on traffic flows. Larger, heavy vehicles affect traffic flow because they take up extra space on the road, and they have lower accelerating and decelerating rates, allowing fewer vehicles to pass through. A heavy vehicle is “any vehicle with more than four tires touching the pavement” [HCM 2004]. Using passenger car equivalents is the accepted way to account for the difference in vehicle size, with common ratios ranging from 1.5 to 3.0 PCE for each heavy vehicle [Al-Kaisey 2003]. However, in this study, throughput will be measured in vphpl to follow current practices within the traffic branch.

2.1.3 CONSTRUCTION AND TRAFFIC MANAGEMENT TECHNIQUES

There are many construction site layout geometries for highway projects, including lane shifts (Figure 2-1), tapering (Figure 2-2), multiple work areas (numerous individual closures along one section of road), complete closures (closing an entire roadway or segment of lanes [i.e. express lanes]), and flagging operations (Figure 2-3).

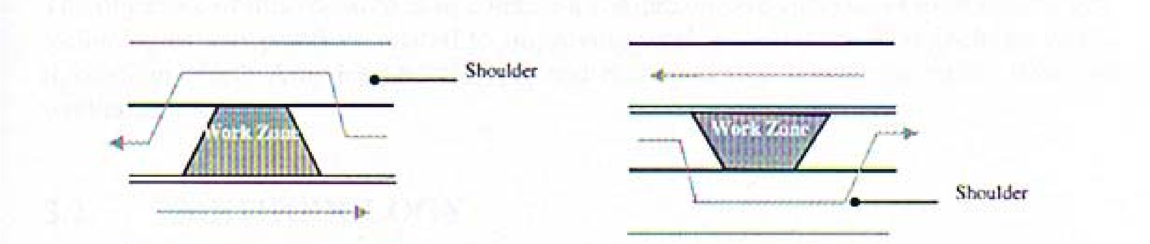


Figure 2-1 - Example of a Lane Shift using the road shoulder [Tighe 2006]

Figure 2-2 - Example of a tapered lane closure of 2 lanes reduced to 1 [Tighe 2006]

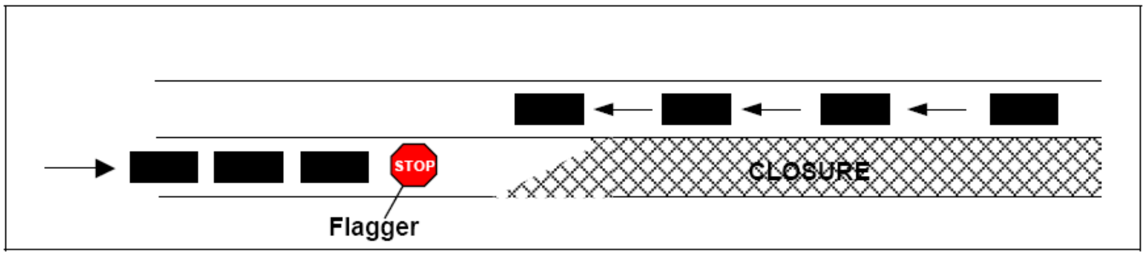


Figure 2-3 - Example of a flagging construction zone [Adapted from IBI 2007]

Highway construction zones can also be evaluated according to their construction window, with three major types of closures [Tighe 2006; Levine 1984]:

- Night Closures
  - 10 hour shift – 8pm to 6am
  - 8 hour shift – 10pm to 6am
- Weekend Closures
  - Friday at 10pm to Monday at 5am (providing 55 hours of work)
- Continuous Closures
  - Continuous operation – 3 shifts continuously work day and night
  - Daytime operation – 1 or 2 shifts work during mandated daytime hours

2.2 GENERAL WORK ZONE STUDIES

Many studies focused on different elements of the work zone, such as traffic control tactics, speed, safety, and flow characteristics.

2.2.1 TRAFFIC CONTROL TACTICS

In a review of traffic management systems in eight projects, three components of a corridor traffic management plan were identified and evaluated: (1) traffic handling strategy; (2) impact-mitigation strategies for alternative routes and modes in the affected corridor; and (3) public information program. The eight projects saw little if any impact from these components to reduce the total corridor daily traffic volumes [Krammes 1989].

Although their impact on daily traffic volumes is debated, public information programs are important since they reduce negative opinions of the work zone [Krammes 1989]. Additionally, the effectiveness of signage varies with what the sign reads [Dudek 1989]. Of three wording options, the most effective to least effective were "Lane Blocked", "Lane Closed", and "Road Work Ahead". The sign reading "Road Work Ahead" was found to cause the most erratic driver manoeuvres [Dudek 1989].

2.2.2 SPEED

Early computer simulations examined the effect of speed reduction in work zones. No disturbance in traffic flow was observed, but it was generally concluded that decreased speeds are safer for workers in the work zone as they reduce the frequency and intensity of accidents [Nemeth 1985]. It has been found that drivers reduce their speed in work zones by approximately 7 km/hr even if limit signs are not posted and by 14.5 km/hr if speed limit signs indicating a speed reduction of 16km/hr are posted [Migletz 1999].

2.2.3 SAFETY

In Indiana, a strategy to choose the appropriate lane closure strategy was developed based on work zone length, traffic volume, duration of project, accident information and estimated project cost. From this, user travel time, vehicle operating cost, traffic control cost, and the expected number of crashes can be estimated [Pal 1996]. Regression models to predict the number of crashes at work zones on rural highways have shown that increased crashes are related to the general disruptions of closed lanes, improper lane merging, presence of heavy construction equipment, inappropriate use of traffic control devices, and poor traffic management [Venugopal 2000]. Work zone length and duration of work were found to be statistically significant factors, and one long work zone was safer than two short work zones [Venugopal 2000].

2.2.4 FLOW CHARACTERISTICS

Flow characteristics change significantly from one location to another even under similar conditions. Predicting flows is difficult but important as delays due to traffic congestion cause hazardous speed change, lost time, and unsafe risk taking [Maze 2000]. Having a police car visible to drivers reduces the variability of headways, thereby stabilizing the fluctuations in traffic flow and improving work zone safety [Polus 1999]. Late merging can reduce queue lengths by 50% and reduce driver frustration [Pesti 1999]. To encourage late merging, warning systems work well until congested conditions occur. Additional signs such as "Use Both Lanes to Merge Point" several kilometres before the lane closure and "Merge Here - Take Your Turn" at the beginning of the taper help to increase late merging in congested conditions [Pesti 1999].

2.3 FREEWAY WORK ZONE CAPACITY MODELS

Many models have been created using data from across North America to estimate work zone capacity. Models for predicting work zone capacity can employ a number of different tactics to arrive at their estimate. These models can generally be classified as mathematical (M), simulation (S) or artificial intelligence (AI) models. Simulation models require many variable inputs to run. The AI models involve more complicated systems such as neural networks and fuzzy logic and tend to be black boxes. Mathematical models tend to use fewer variables, be more transparent, and easier to understand. Table 2-1 summarizes the characteristics included in 9 models.

The most common model type is the mathematical model, a few of which are reviewed next. Simulation and artificial intelligence models are difficult to adapt and reproduce and as such will not be discussed in detail.

	Models								
	Rouphail and Tiwari 1985	Sarasua et al 2004	Krammes and Lopez 1994	Kim et al. 2000	Al-Kaisey and Hall 2003	Karim and Adeli 2003a	Adeli and Jiang 2003	Zhang et al. 1996	Karim and Adeli 2003b
Model Type	M	M	M	M	AI	AI	AI	S	S
Non Flagging Site	x	x	x	x	x	x	x	x	x
Work Activity	x	x	x	x	x	x	x	x	x
Heavy Vehicle	x	x	x	x	x	x	x		x
No. of Open Lanes	x	x	x	x		x	x	x	x
Light Conditions					x	x	x	x	
Lane Width					x	x	x		x
Total No. of Lanes						x	x	x	x
Lateral Distance				x					
Length of Closure				x		x	x		x
Driver Population					x		x		x
Side of Closure				x	x	x			x
Ramps			x		x	x	x		
Work Zone Speed						x	x		x
Work Duration							x		x
Weather					x		x		
Crossover					x		x		
Grade				x		x	x		
Traffic Management				x					x
Work Zone Location							x		
Pavement Condition							x		
Site ID (on database)									x
Start Time									x
Construction Cost									x
Maintenance Cost									x
Flow Rate									x

M – Mathematical
AI – Artificial Intelligence
S - Simulation

Table 2-1 - Summary of Previous Work Zone Capacity Models

2.3.1 KRAMMES AND LOPEZ (1994)

The Krammes and Lopez model starts with a base capacity and then makes adjustments for work intensity, heavy vehicles and ramps within or near to the work zone [Eq. 2-1]. This model is based on 45 hours of data collected from 33 work zones in Texas between 1987 and 1991.

$$C = (C_b + I - R) * f_{hv} * N \qquad \text{Equation 2-1}$$

Where: C = Capacity (in passenger cars per hour per lane [pcphpl])
C_b = Base Capacity = 1600
I = Work Intensity Factor= $\pm 0.10 * C_b$
R = Ramps within 150m (500ft) of the Work Zone $\leq 0.5 * C_b$
f_{hv} = Heavy Vehicle Factor
N = Number of Lanes

The work intensity factor represents an addition or subtraction of 10% of the base capacity depending on the amount of activity occurring in the work zone. The model does not provide guidelines for values for R except that R should not exceed 50% of the determined capacity of the lane. The heavy vehicle factor (f_{hv}) is defined by the Highway Capacity Manual (HCM). As heavy vehicles not only take up more space on a road, but also accelerate at slower rates, and need more space for braking. As such, a passenger car equivalent (PCE) is employed as in Equation 2-2.

$$f_{hv} = 1/[1 + [HV*(PCE - 1)]] \qquad \text{Equation 2-2}$$

Where: HV = Percentage of heavy vehicles on the road
PCE = Passenger Car Equivalent

2.3.2 KIM, LOVELL AND PARACHA (2000)

The Kim et al. model includes a wider range of site characteristics. Using data collected from 12 work zone sites in Maryland, the model is geared towards lane closures on highways that normally have 4 lanes open in one direction. This model starts with a base capacity and adjusts for seven different site characteristics [Eq 2-3].

$$C = 1857 - 168.1*(NUMCL) - 37.0*(LOCCL) - 9.0*(HV) + 92.7*(LD) - 34.3*(WL) - 106.1*(WI_H) - 2.3*(WG*HV) \qquad \text{Equation 2-3}$$

Where: C = Capacity in vehicles per hour per lane [vphpl]
NUMCL = Number of closed lanes
LOCCL = Location of closed lanes (right = 1, left = 0)
HV = Percentage of heavy vehicles on the road
LD = Lateral distance to the open lanes (m)
WL = Work zone length (km)
WI = Work intensity (heavy = 1)
WG = Work zone grade (%)

Although the model includes many site characteristics, some have little effect on the overall capacity and/or low level of statistical significance. In reality, the only elements with a p-value less than 5% (which represents a 95% probability that the variable should be included in the equation) were the base value (1857), number of closed lanes (NUMCL) and work grade times heavy vehicles (WG*HV).

2.3.3 AL-KAISEY AND HALL (2003)

Based on data from a long term closure in close proximity to the downtown core of Toronto, Ontario, Al-Kaisey and Hall developed one additive and one multiplicative model, shown in Equation 2-4 and Equation 2-5, respectively.

$$C = C_b + I_1 + I_2 + I_3 + ... + I_n \qquad \text{Equation 2-4}$$

Where: C = Capacity (in passenger cars per hour per lane [pcphpl])
C_b = Base Capacity = 1600
I_i = Impact from various factors

$$C = C_b * f_1 * f_2 * f_3 * f_4 * ... * f_n \qquad \text{Equation 2-5}$$

Where: f_i = Adjustment factors

Starting with a base capacity, the additive model specifies five significant characteristics that affect capacity and adjusts for interactions between these variables, as shown in Table 2-2.

Characteristic	Value/Adjustment (pcphpl)
Base Capacity	1964
Heavy Vehicle	-20.7*(HV)
Weekday	-82
Weekend	-352
Left Lane Closed	-121
Rain	-71
Work Activity Present	-172
Interactions	
Left Lane Closed and Weekday	+55
Weekend and Work Activity	+185
Left Lane Closed and Rain	+58
Weekend and Rain	+107

Table 2-2 - Impacts from factors in Al-Kaisey and Hall 2003 additive model

Similarly, the multiplicative model includes these same characteristics, but instead of altering the capacity value with a lump sum adjustment, it alters the value as a percentage of its original. Adjusting the base capacity of 2000pcphpl, Table 2-3 shows the factors applied in Equation 2-5 to determine the work zone capacity.

Element	Characteristic	Value (pcphpl)
Capacity	Base Capacity	2000
Heavy Vehicle	Heavy Vehicle - Uses f_{HV} formula with different PCE values Level Ground 3% Grade or more	 PCE = 2.4 PCE = 3.0
Driver Population	Weekday Peak Hours Weekday Off-peak Hours Weekend	1.00 0.961 0.825
Light Condition	Daytime Night time with Illumination	1.00 0.96
Work Zone Configuration	Right Lane Closed Left Lane Closed	1.00 0.94
Weather	No Rain Light to Moderate Rain Heavy Rain	1.00 0.95 0.90
Work Activity	No Work Activity Work Activity	1.00 0.943
Variable Interactions	No Interactions Left Lane & Weekday Off-peak Weekend & Work Activity Left Lane & Rain Weekend & Rain	1.00 1.03 1.08 1.02 1.05

Table 2-3 - Impacts from factors in Al-Kaisey and Hall 2003 multiplicative model

2.3.4 SARASUA, DAVIS, CLARKE, KOTTAPALLY AND MULUKTLA (2004)

Based on data from South Carolina, the Sarasua et al. model is almost identical to the Krammes and Lopez model, except that it alters the base capacity instead of including a variable to account for ramps [Eq 2-6].

$C = (C_b + I)*f_{hv}*N$ Equation 2-6

Where: C = Capacity (in passenger cars per hour per lane [pcphpl])

C_b = Base Capacity = 1460

I = Work Intensity Factor

f_{hv} = Heavy Vehicle Factor

N = Number of Lanes

2.4 DESIGN STANDARDS

2.4.1 HIGHWAY CAPACITY MANUAL

The most commonly accepted method of determining work zone capacity is outlined in Equation 2-7 from the Transportation Research Board's Highway Capacity Manual (HCM) [HCM 2000].

$C = (C_b)*(N)*(I) – (R)$ Equation 2-7

Where: C_b = 1600vphpl (for a short term work zone)
N = Number of lanes
I = Work intensity (± 10%)
R = Addition or Subtraction of vehicles due to ramp in work zone

2.4.2 MTO DESIGN VALUES

In addition to HCM, MTO maintains a list of suggested work zone capacities in the Generic Lane Closure Times manual [TPISS 2003] and design values for each type of highway. According to the number of open lanes, this report shows different capacity values, as shown in Table 2-4 [NCHRP].

Type of Roadway	**Capacity (vphpl)**	
	TPISS	**NCHRP**
Two Lane Highway (Alternating Flow)	850	850
Multi-Lane Highway	1400	1405-1570
Freeway	1800 (1600 on weekends)	1405-1610

Table 2-4 - MTO Design Capacity Values

2.5 CONTRACT STRATEGIES

Currently there are three contractual strategies commonly used by agencies for encouraging the early completion of work, thereby reducing the negative impacts of work zones on user delay costs.

1) Incentive/disincentive (I/D) methods have legal implications when the penalties are imposed on contractors for delay and therefore 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]. Although quite popular, the I/D method was found to be the least effective and most expensive overall strategy [Ellis and Herbsman 1998] because in most cases, contractors can easily save some time and be eligible for the incentive payment.

2) Cost/Time (C/T) bid strategies invite the bidding contractors to provide in their bid the project cost and duration. The combination of lowest bid and earliest completion time wins the contract. This method was found to be most economical and generally received more support [Ellis and Herbsman 1998]. Combined with I/D, the enforceability of the completion date can be improved [Gillespie 1998].

3) Lane rental is comparatively a new strategy that charges the contractor for the time that the lane is closed to traffic based on predetermined fees [Ellis and Herbsman 1998]. The time interval can be weeks, days, hours, or even smaller intervals. The fees are normally determined taking into account the day of the week, time of day, annual average daily traffic (AADT), percentage of trucks, and other relevant parameters. This strategy can be combined with I/D by paying an incentive if the actual lane closures are less than the specified amount. If the contractor exceeds the allowable lane closure duration, a disincentive payment applies [Benekohal 2003]. However, there was no consensus on the I/D or lane rental dollar amount to be used.

2.6 IMPACTS OF RESEARCH

2.6.1 USER DELAY COSTS

One of the aims of this research is to reduce the amount of queuing in work zones. By doing so, the amount of wasted time spent in congested traffic is diminished, also reducing their associated cost. These costs are known as user delay costs and they exist only when traffic backup (queuing) is present. User delay costs are more thoroughly discussed in Section 3.

2.6.2 QUALITY OF CONSTRUCTION

The inability for the contractor to perform continuous work in a highway construction zone affects both the productivity and quality of the work being performed relative to new construction. Using concrete slab replacement as an example, the most productive schedule is continuous daytime lane closure; the second most productive is continuous daytime closures during weekends only. Slab replacement work restricted to weekends was found to take 45% more time. Restricting the contractor to night work caused a concrete slab replacement to take on average 2.23 times longer than doing the same work in a continuous daytime closure [Lee 2000, 2004].

Two related factors that decrease quality are the timing of lane closure and discontinuity of work. Sites are often restricted to night lane closures to ensure highways are open during peak travel periods. This means that work is being performed under less favourable lighting conditions making it more difficult to perform and check work. Further, by having to stop work each morning to open a lane, increased cold joints are created where water can enter the pavement structure. This can cause debonding of surface layers, mixture of stripping, and aging of asphalt resulting in accelerated pavement failure. [Tighe 2006]

3 User Delay Costs

3.1 INTRODUCTION

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].

Reduction of speed through a work zone will cause slowing and queuing delays. 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. Early merges reduce the throughput of vehicles in the work zone, whereas late merging will increase road capacity by 18% and lead to 75% fewer merging conflicts [Stidger 2003; Fontaine 2005].

The position of the work activity with respect to the through lanes affects the speed of vehicles. A shift of the work zone one metre towards traffic can reduce vehicle speeds by two miles per hour [Rister 2002]. Also reduced throughput of 9% and 14% were observed when lane widths were reduced to 3.75 metres and 3 metres respectively.

3.2 ROAD USER DELAY COSTS

User delay costs are those additional costs incurred by drivers, industries, businesses and economies as a whole that result from delays caused by work zones. These costs can impact the economy by increasing the cost of goods and services; however, limiting scheduled maintenance activities to off-peak periods may lengthen project duration, reduce quality of work, and increase maintenance costs. Importantly, reducing user delays by encouraging contractors to develop innovative techniques for early completion of construction work can promote economic growth by enhancing the effectiveness of the transport network and reducing congestion.

With the recent focus on user delay costs, it is acknowledged that user costs may outweigh the initial construction and agency costs over the life of a facility [Salem 2008]. Many US agencies are considering various strategies to either directly or indirectly account for user delay costs. For example, traffic control plans for freeway reconstruction projects may require queue analysis to determine the anticipated traffic backups so that 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 [Benekohal 2003]. In a direct approach, user costs can be integrated into pavement type selection processes [Chitturi 2007]. However, incorporating user costs in the analysis of transportation projects is challenging because of the difficulty in determining the real economic value of user costs and the absence of a standard method for quantification of user costs.

Although there is no standard, there are many methods to quantify user delays and their associated costs. One commonly applied measure involves dividing the total delay by the volume of traffic to determine the average amount of delay encountered by a vehicle traveling through a work zone. These methods however, disregard vehicle occupancy, time values and environmental impacts.

In general, user delay costs can be divided into 4 categories. There can be an opportunity cost associated with the cost components but due to difficulty in estimating the opportunity costs in work zone scenarios, it is mostly ignored in practice.

1) Additional Travel Time Costs - are due to a vehicle spending more than normal time traveling between two points due to work zone delays including [Carr 2000]:
    - Speed delay : Due to slower speed of vehicles in the work zone
    - Backup delay : Delay due to queues formed at the upstream of work zone
    - Diversion delay: Delay due to traveling on detour route around the work zone

2) Vehicle Operating Costs (VOC) - may include the fuel, tires, maintenance, depreciation and other costs resulted from the additional time that a vehicle has spent in the work zone. VOC has 3 sub components [FHWA 1998]
    - Speed Change: Due to drop in speed from normal to work zone speed
    - Stopping: Due to stop position and acceleration again to approach speed
    - Idling: Due to stop and go situation traveling through queue

3) Accidents Costs - associated with work zone related accidents

4) Environmental Costs – due to the difficulty in accurately quantifying environmental costs, most agencies ignore it.

3.3 ROAD USER DELAY ANALYSIS

MTO GDM Chapter-B 2002 provides the nine step procedure for calculating the queue and delay for each hour of analysis period [MTO 2002]. Some values used in the analysis are:

- Base capacity of short term work zone = 1600 veh/h/lane
- Delay Cost

  - Passenger Car = $10/h/veh
  - Heavy Vehicle = $50/h/veh
  - Mixed Traffic = $15/h/veh

Details are shown in Appendix C. This model is very useful in that it provides a means to quantify user delays costs, but requires quite a few input variables.

Recently a 12 step method for predicting delays and user costs in highway work zones was developed based on the relationship between speed and capacity [Chitturi 2007]. It requires adjustment of speed to account for the various work zone factors such as work intensity, lane width, and lateral clearance. The method is quite complex and requires significant input of variables. See Appendix D for details.

These models tend to be complex and require a significant number of input variables. Further, it is difficult to quickly see the impact of changes in work strategies, closure hours, and traffic throughputs. For this reason, a simplified work zone user delay analysis model (SZUDA) was developed. SZUDA is presented in full in Section 6.7 of this report.

4 Project Methodology

4.1 DATA COLLECTION METHODOLOGY

After a thorough review of MTO's clearly defined work zone policies and MTO Book 7, data were collected from a number of sites. The following sections explain in detail the method for collecting data from different types of sites.

4.1.1 HIGHWAY WORK ZONES (4 OR MORE LANES)

For this study, data must be collected when the work zone is under queuing conditions. A list of sites was initially provided by MTO. The respective liaisons were first contacted to determine their suitability and data collection started immediately thereafter. The three desired characteristics were as follows:

1) Extended lane closure: Longer than just for periodical movement of machinery
2) Partial lane closure: Reduction of traffic lanes available (i.e. 2-to-1, 3-to-2 or 3-to-1)
3) Adequate amount of traffic demand: Determined based on site contact's observations. If there were any elements of slowed or queued traffic, data were collected from the site.

Once a site was deemed suitable for data collection, a site visit was made. At all work zones visited, site characteristics were recorded. This allowed for each characteristic to be considered in the throughput model created. The proper identification of these characteristics was important to make site comparisons uniform. When each site was visited, a Site Characteristics Form, shown in Table 4-1, was completed.

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

Table 4-1 – Blank Site Characteristics Form

Each work zone was further evaluated to determine if it met the needs of this research project (e.g. queuing). Data collection was performed in a similar manner to the study performed by the IBI Group in 2007 [IBI 2007]. On fifteen minute intervals, the number of vehicles passing through the site was recorded. The vehicles were split into two categories, passenger vehicles, and heavy vehicles. A heavy vehicle was defined using the HCM specification “any vehicle with more than 4 tires touching the pavement” [HCM 2000]. Figure 4-1 shows the ideal location in the work zone to collect data. This location was used as often as was possible based on site layout and safety.

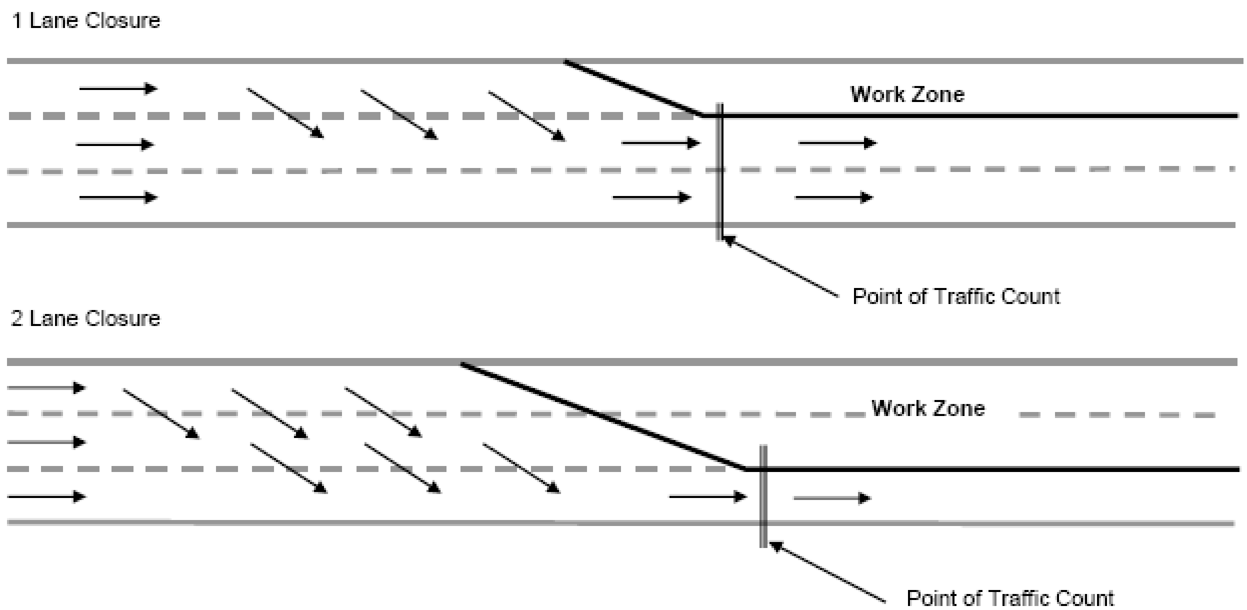


Figure 4-1 - Location of Data Collection on Site

4.1.2 FLAGGING WORK ZONES (2 LANES ONLY)

As outlined in the project scope, the analysis of two lane highways was also completed. Two lane highways must be treated differently, as flag operations are used to manage the traffic flow in alternating directions using the one remaining open lane. In these cases, site characteristics were recorded as previously outlined, but the method of performing throughput counts was different.

Instead of taking 15-minute measurements of the vehicles traveling through the work zone, the measurements were broken into two categories. First was the time for the vehicles to travel past a pre-determined point along the road and second was the down time between groups of cars travelling in each direction. When these times are combined and cars are counted coming from each direction (2 down times and 2 travel times) this is identified as a “round”. Travelling characteristics understood through these data are the number of vehicles allowed through the site in one direction, the approximate speed of the vehicles travelling (since the length of the work zone is known) and the variation of down time of different vehicle convoys.

By recording data in this manner, the capacity of the open lane can be evaluated by the times of both the cars travelling through and time between intervals. This allows for a more thorough understanding of the traffic flows.

4.2 SITE CHARACTERISTICS RECORDED

Following collection of site characteristics, more specific identifiers were determined, as shown in Table 4-2. These help to provide insight into the factors that impact traffic throughput in work zones. Each characteristic was assigned a binary identifier indicating its state.

Presence of Police	1 – Ontario Provincial Police (OPP) present on site during lane closure 0 – OPP were not present
Weekend/Weekday	1 – Data was collected on a weekend (Saturday or Sunday) 0 – Data was collected on a weekday
Time of Closure Night/Day	1 – Data was collected after dark (when headlights were required) 0 – Data was collected during the day
Number of Lanes Closed	1 – Two or more lanes closed, narrowing down to one lane open during construction 0 – One lane closed, leaving one lane open during construction
Lane Closure Right/Left	1 – Right side of freeway was closed 0 – Left side of freeway was closed
Lane Closure Marker Barrels/Barrier Wall	1 – Barrels were used as the method of lane closure 0 – Concrete barrier wall were used as the method of lane closure
Grade of Road 3% or more/0-3%	1 – The grade of the road was more than 3% 0 – The grade of the road was between 0 and 3%

Table 4-2 - List and Description of Site Characteristics Collected

5 Data and Illustrations

Data for this project were collected over the course of two construction years, namely summer and fall of 2007 and summer of 2008. Finding the suitable and appropriate conditions on site as outlined earlier proved challenging. Communications with many of the contacts provided by MTO were inconsistent, resulting in much lost time both on and off site. Due to the weak communications and the difficulty in finding sites with the necessary characteristics, the data collection portion of the project was extended into a second season (Summer 2008). This was done to ensure sufficient data were available for the analysis.

5.1 SITES CONTACTED

MTO provided contact information on 15 short term, 15 long term, and 7 additional locations in 2007. Additionally, data were collected in the summer of 2008, where 6 locations were provided. Table 5-1 shows all of these locations and the resulting data. These 43 locations can be categorized in 5 groups. At 13 of the locations, construction was already completed (NCC), three locations were not visited due to lack of response from contacts (NLR), six locations were not visited due to reports of no queuing (NNQ), seven locations were visited but were not acceptable for data collection (VNQ) and 14 locations were visited and data were collected on at least one of the days visited (VDC). This breakdown is represented in Figure 5-1. Further details on locations and results of visits can be found in Appendix A.

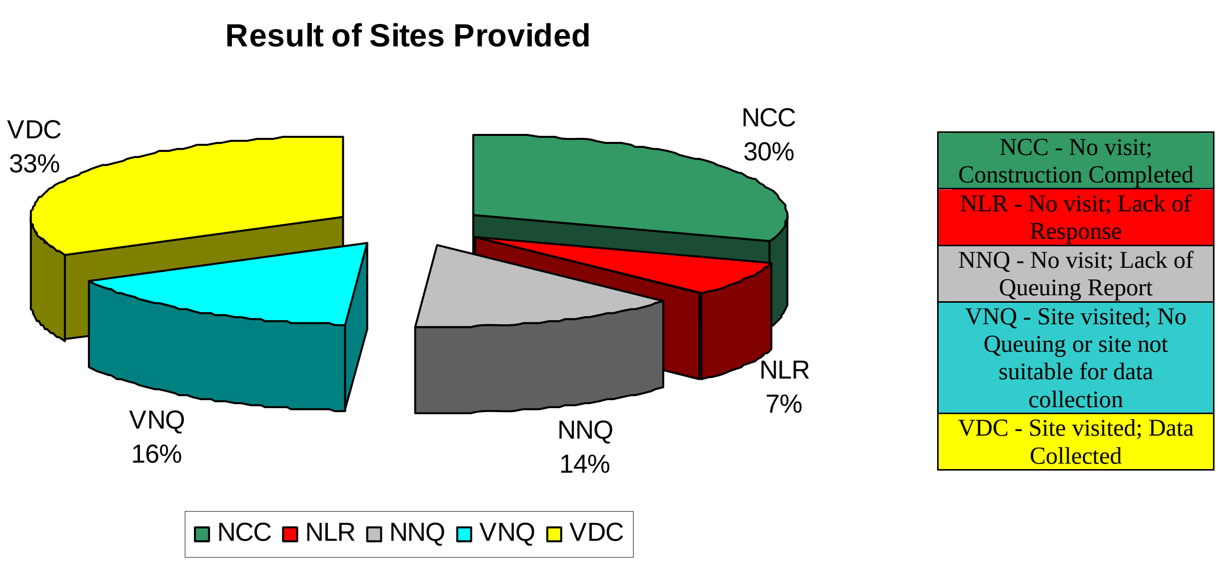


Figure 5-1 - Result of Sites Provided

	Site ID/ Contract No.	Hwy	Cross Road	Direction	Result	Site Visit	Data (hrs)
Short Term	NV1	9	Simcoe Rd. 10	EB	NCC	No	0
	NV2	400	Hwy 407	NB	NCC	No	0
	NV3	400	Hwy 7	NB	NCC	No	0
	NV4	400	Hwy 9	SB	NCC	No	0
	NV5	400	Lower Big Chute	NB	NCC	No	0
	NV6	400	Quarry Rd.	NB	NCC	No	0
	NV7	401	Whites Rd.	WB	NCC	No	0
	NV8	401	Hwy 2A	WB	NCC	No	0
	NV9	401	Markham Rd.	EB	NCC	No	0
	VN10	401	Birchmount Rd.	WB	NCC	No	0
	NV11	401	Hwy 404	WB	NCC	No	0
	2007-2253	401	Guelph Line	EB	VNQ	Yes	0
	NV12	404	Major Mackenzie	NB	NCC	No	0
	2007-2252	QEW	Mountain Rd.	SB	VDC	Yes	4.25
	2007-2252	QEW	Mountain Rd.	NB	VDC	Yes	3.75
Long Term	NV13	6	Hwy 6	NB	NLR	No	0
	NV14	10	RR2	SB	NNQ	No	0
	2007-2128	12	Beaver River	SB	VDC	Yes	5.5
	2007-2128	12	Whites Creek	NB	VDC	Yes	2.5
	2005-2014	401	Park Rd.	EB, WB	VDC	Yes	5.75
	NV15	401	Avenue Rd.	EB	NNQ	No	0
	NV16	401	Westney Rd.	EB	NNQ	No	0
	NV17	403	Wilson Rd.	N/A	NCC	No	0
	2007-2028	427	QEW	SB	VDC	Yes	14.25
	NV18	QEW	Glendale Rd.	SB	NNQ	No	0
	NV19	QEW	Red Hill Creek	N/A	NNQ	No	0
	2007-2031	QEW	Hurontario Rd.	WB	VDC	Yes	2.75
	NV20	12	Price Corners	N/A	NLR	No	0
	2005-3045	8	Grand River	NB	VNQ	Yes	0
	2006-3099	7	Waterloo Rd.	EB, WB	VNQ	Yes	4.75
Additional	2007-2027	QEW	Lake St.	EB, WB	VDC	Yes	2
	2007-2127	26	Horseshoe Valley Rd.	All ways	VDC	Yes	5
	2007-2125	QEW	3rd Line	WB	VNQ	Yes	0
	2007-2030	400	CPR Overpass - Barrie	NB	VNQ	Yes	0
	2006-2024	400	Hwy 89	NB	VDC	Yes	6
	2006-2024	400	Hwy 89	SB	VNQ	Yes	0
	2007-2130	401	Meadowvale	EB	VNQ	Yes	0
Summer 2008	2007-2125	QEW	3rd Line	WB	VDC	Yes	1
	2008-2003	427	QEW	SB	VDC	Yes	5
	2005-2014	401	Park Rd.	EB	VDC	Yes	5
	NV21	401	Hwy 6	N/A	NLR	No	0
	2007-2263	12	Lower Big Chute	EB, WB	VDC	Yes	3
	NV22	401	Guelph Line	N/A	NNQ	No	0

(Site ID) NV# - No Visit
NCC - No visit; Construction Completed
NLR - No visit; Lack of Response
NNQ - No visit; Lack of Queuing Report
VNQ - Site visited; No Queuing or site not suitable for data collection
VDC - Site visited; Data Collected

Table 5-1 - All Work Zone Sites Identified by MTO for Project Use

5.2 SITES VISITED

In total, 16 locations were visited on 39 days. In some cases, data could not be collected due to a lack of queuing, full lane closure or unfavourable site layout. As a result, 23 of the 39 visit days saw data collected, producing 70 hours of data for flagging and freeway sites as shown in Table 5-2. Please note that sites with the same date listed twice represent construction sites in both directions of travel.

Contract No.	Highway	Direction	Nearest Intersection/Interchange	Type of Work	Visit Dates	Data (Hours)
2007-2253	Hwy 401	EB	Guelph Line (Campbellville)	Selective resurfacing	27-Aug-07 29-Aug-07	0 0
2007-2130	Hwy 401	EB	Meadowvale (Ajax)	Road resurfacing	26-Sep-07	0
2005-2014	Hwy 401	EB &WB	Stephenson to Park Rd. (Oshawa)	Road resurfacing and construction of interchange	27-Sep-07 9-Oct-07 12-Oct-07 10-Jul-08 13-Jul-08	3.5 1.25 1 1.75 3.25
2007-2030	Hwy 400	NB	Horseshoe Valley Rd (North of Barrie)	Widening of the structure	22-Oct-07 23-Oct-07	0 0
2006-2024	Hwy 400	NB SB	Hwy 89 (South of Barrie)	Catch basin repairs in the median	2-Nov-07 3-Nov-07 2-Nov-07 3-Nov-07	2.5 3.5 0 0
2007-2252	QEW	SB	Thorold Stone Rd. (Niagara Falls)	Shave and pave	20-Sep-07 21-Sep-07 22-Sep-07 23-Sep-07	0 2 6 2.75
2007-2027	QEW	WB EB	Ontario to Lake St. (St. Catharines)	Road surfacing and widening	2-Oct-07 2-Oct-07 13-Mar-08	0 2 1.25
2007-2031	QEW	WB	Hurontario (Mississauga)	Selective resurfacing	10-Oct-07 11-Oct-07	1.25 1.5
2007-2125	QEW	EB WB WB WB WB	Trafalgar Road (Oakville)	Road widening for HOV lane	13-Nov-07 14-Nov-07 26-Jun-08 2-Jul-08 7-Jul-08	0 0 0 0 1
2008-2003	Hwy 427	EB to NB	EB QEW ramp onto NB Hwy 427 (Etobicoke)	Rehabilitation of ramp	26-Jun-08 2-Jul-08	5 0
2007-2028	Hwy 427	SB to EB	SB Hwy 427 ramp onto EB Gardiner (Etobicoke)	Rehabilitation of ramp	20-Sep-07 21-Sep-07 24-Sep-07	3.75 6 4.5
2006-3099	Hwy 7/8	EB	Waterloo Rd.1 to Waterloo Rd.5 (New Hamburg)	Structure Rehabilitation, paving and New Traffic Signals	18-Sep-07 19-Sep-07 20-Sep-07	0 0 0

Contract No.	Highway	Direction	Nearest Intersection/Interchange	Type of Work	Visit Dates	Data (Hours)
2005-3045	Hwy 8	SB	Grand River to Fergus Ave. (Kitchener)	Selective resurfacing	26-Sep-07 28-Sep-07	0 0
2007-2263	Hwy 12	EB & WB	East of Lower Big Chute Rd. (West of Orillia)	Flagging Site: Road resurfacing and drainage	4-Jul-08	3
2007-2128	Hwy 48/12	NB & SB	Glenarm Rd. (Beaverton)	Flagging Site: Road resurfacing	13-Sep-07 17-Sep-07	3 5
2007-2127	Hwy 26	NB & SB	Horseshoe Valley Rd (Minesing)	Flagging Site: Road resurfacing	3-Oct-07	5

Table 5-2 – List of All Sites Visited

5.3 PART 1 OF A PARADOX

The difficulty in finding appropriate work zones for data collection presented an interesting paradox. Part one of this paradox is that numerous sites identified as work zones expecting queuing did not exhibit forced flow conditions. This shows that the times allotted for lane closures are confined to times when the capacity exceeds the demand. At all of these sites, allowing a longer road closure would not be a detriment to users and could potentially allow the contractor to improve both quality and speed of construction work by working a longer shift.

The second part of the paradox will be presented in Section 6.4.

5.4 DATA COLLECTION

The collected data fall into three categories: site characteristics; capacity measurements; and, photos and video. Part-II of this report contains all the data organized by site. The following is a summary of the site visits.

5.4.1 SITE CHARACTERISTICS

Site characteristics varied drastically from location to location and were recorded in the site characteristics form, outlined in Section 4.2. Table 5-3 summarizes the site characteristics and includes the number of hours of data collected at each site.

Contract Number	Highway	Visit Dates	Data (Hours)	Day of Week	Time of Closure	Speed Limit (km/hr)	Length of WZ (km)	OPP	Weekday	Daylight	2 or more Lanes closed	WZ on Right	Barrels	Low Grade
2007-2253	401	27-Aug-07	0	Mo	22:00-6:00	100	1.1	0	1	0	1	0	1	1
		29-Aug-07	0	We	22:00-6:00	100	1.1	0	1	0	1	0	1	1
2007-2130	401	25-Sep-07	0	Tu	Not closed	100	N/A	NA	NA	NA	NA	NA	NA	NA
		26-Sep-07	0	We	21:00-6:00	100	2.0	0	1	0	1	1	1	1
2005-2014	401	27-Sep-07	3.5	Th	19:00-6:00	100	1.4	0	1	0	1	1	1	1
		9-Oct-07	1.25	Tu	20:00-6:00	100	1.0	0	1	0	1	0	1	1
		12-Oct-07	1.5	Fr	22:00-6:00	100	2.7	1	1	0	1	1	1	1
		10-Jul-08	1.75	Th	22:00-6:00	100	1.5	0	1	0	1	1	1	1
		13-Jul-08	2	Su	18:00-6:00	100	2.9	0	0	1	1	0	1	1
		13-Jul-08	1.25	Su	18:00-6:00	100	2.9	0	0	0	1	0	1	1
2007-2030	400	22-Oct-07	0	Mo	6:00-16:00	100	3.4	0	1	1	0	0	1	1
		23-Oct-07	0	Tu	6:00-16:00	100	3.4	0	1	1	0	0	1	1
2006-2024	400	2-Nov-07	2.5	Fr	Continuous	100	6.8	0	1	0	1	0	1	1
		3-Nov-07	3.5	Sa	Continuous	100	6.8	0	0	1	1	0	1	1
		2-Nov-07	0	Fr	Continuous	100	6.8	0	1	0	1	0	1	1
		3-Nov-07	0	Sa	Continuous	100	6.8	0	0	1	1	0	1	1
2007-2252	QEW	20-Sep-07	0	Th	20:00-6:00	100	1.15	0	1	0	1	1	1	1
		21-Sep-07	2	Fr	22:00-6:00	100	1.15	1	1	0	1	0	1	1
		22-Sep-07	6	Sa	20:00-6:00	100	1.15	1	0	0	1	0	1	1
		23-Sep-07	2.75	Su	19:00-6:00	100	1.15	1	0	0	1	0	1	1
2007-2027	QEW	2-Oct-07	0	Tu	20:30-6:00	100	1.3	0	1	0	0	0	1	1
		2-Oct-07	2	Tu	21:30-6:00	100	1.3	0	1	0	0	0	1	1
		13-Mar-08	1.25	Th	21:00-6:00	100	1.3	0	1	0	0	0	1	1
2007-2031	QEW	10-Oct-07	1.25	We	22:00-6:00	100	2.2	0	1	0	1	1	1	1
		11-Oct-07	1.5	Th	22:00-6:00	100	2.2	0	1	0	1	1	1	1
2007-2125	QEW	13-Nov-07	0	Tu	23:00-5:00	100	6.8	0	1	0	1	1	1	1
		14-Nov-07	0	We	22:30-1:30	100	6.8	0	1	0	1	0	1	1
		26-Jun-08	0	Th	23:00-5:00	100	1.8	NA	NA	NA	NA	NA	NA	NA
		2-Jul-08	0	We	23:00-5:00	100	1.8	NA	NA	NA	NA	NA	NA	NA
		7-Jul-08	1	Mo	22:00-5:00	100	3.6	0	1	0	1	1	1	1
2008-2003	427	26-Jun-08	5	Th	Continuous	100	3.5	0	1	1	0	0	0	1
		2-Jul-08	0	We	Continuous	100	3.5	0	1	0	0	0	0	1
2007-2028	427	20-Sep-07	4	Th	Continuous	100	3.5	0	1	1	0	0	0	1
		21-Sep-07	6.5	Fr	Continuous	100	3.5	0	1	1	0	0	0	1
		24-Sep-07	4.5	Mo	Continuous	100	3.5	0	1	1	0	0	0	1
2006-3099	7/8	18-Sep-07	0	Tu	7:00-19:00	80	5.7	1	1	1	0	0	1	1
		19-Sep-07	0	We	7:00-19:00	80	5.7	1	1	1	0	1	1	1
		19-Sep-07	0	Th	7:00-19:00	80	5.7	1	1	1	0	0	1	1
2005-3045	8	26-Sep-07	0	We	22:00-6:00	80	2.9	0	1	0	0	1	1	0
		28-Sep-07	0	Fr	22:00-8:00	80	2.9	0	1	0	0	0	1	1
2007-2263	12	4-Jul-08	3	Fr	7:30-14:00	80	0.9	0	1	1	F	F	1	1
2007-2128	12	13-Sep-07	3	Th	7:00-18:00	80	1.5	0	1	1	F	F	1	1
		17-Sep-07	8	Mo	7:00-18:00	80	1.0	0	1	1	F	F	1	1
2007-2127	26	3-Oct-07	5	We	7:00-16:00	80	0.5	1	1	1	F	F	1	1

Table 5-3 - Summary of Site Characteristics from All Sites Visited

5.4.2 THROUGHPUT MEASUREMENTS

Table 5-4 shows the average throughput value (vphpl – vehicle per hour per lane) and standard deviations for each visit. Although there was significant variation between sites, within each site the values were relatively steady, indicating that there may be a need for a location specific model. Having a location specific model would mean that traffic characteristics specific to a road or region could be accounted for. This proves to be a fruitful form of analysis and is further discussed in Section 6.5.

Please note that the site code found in the far left column of Table 5-4 will be used throughout the document hereon in to reference that site.

Site Code	Site ID	Visit Dates	Data (Hours)	Throughput (vphpl)	
				Mean	St. Dev
h401s1	2005-2014	27-Sep-07	3.5	1,190	143
h401s2		9-Oct-07	1.25	1,298	76
h401s3		12-Oct-07	1.5	1,233	84
h401s4		10-Jul-08	1.75	1,134	99
h401s5		13-Jul-08	2	1,141	168
h401s6		13-Jul-08	1.25	1,155	146
h400s1	2006-2024	2-Nov-07	2.5	1,182	115
h400s2		3-Nov-07	3.5	1,011	185
hQEWs1	2007-2252	21-Sep-07	2	828	142
hQEWs2		22-Sep-07	6	1,098	141
hQEWs3		23-Sep-07	2.75	810	203
hQEWs4	2007-2027	2-Oct-07	2	1,168	86
hQEWs5		27-Mar-08	1.25	1,353	38
hQEWs6	2007-2031	10-Oct-07	1.25	830	78
hQEWs7		11-Oct-07	1.5	954	177
hQEWs8	2007-2125	7-Jul-08	1	1,019	51
h427s1	2008-2003	26-Jun-08	5	1,564	82
h427s2	2007-2028	20-Sep-07	4	1,755	97
h427s3		21-Sep-07	6.5	1,726	83
h427s4		24-Sep-07	4.5	1,625	138
h12s1	2007-2263 (F)	4-Jul-08	3	351	114
h12s2	2007-2128 (F)	13-Sep-07	3	462	61
h12s3		17-Sep-07	5	542	90
h12s4		17-Sep-07	3	571	83
h26s1	2007-2127 (F)	3-Oct-07	5	592	87

Table 5-4 - Mean and Standard Deviation vphpl Values of Sites Visited

Figure 5-2 shows the 15-minute interval counts (denoted by a horizontal dash '-') for each freeway site visit along with the range of values that fall within one standard deviation of the mean (denoted by the bold vertical line). Following this, Figure 5-3 shows recorded throughput values for each flagging site. These are shown as vphpl for each round of cars passing through the lane.

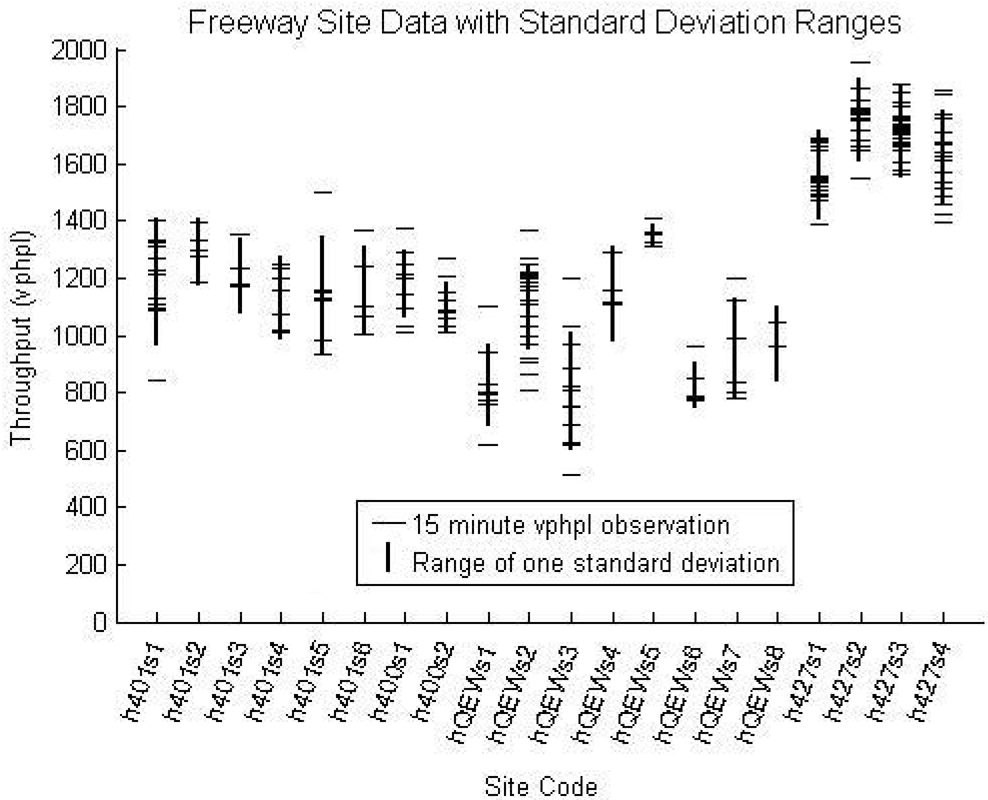


Figure 5-2 - Graph of Freeway Data and the Range of One Standard Deviation

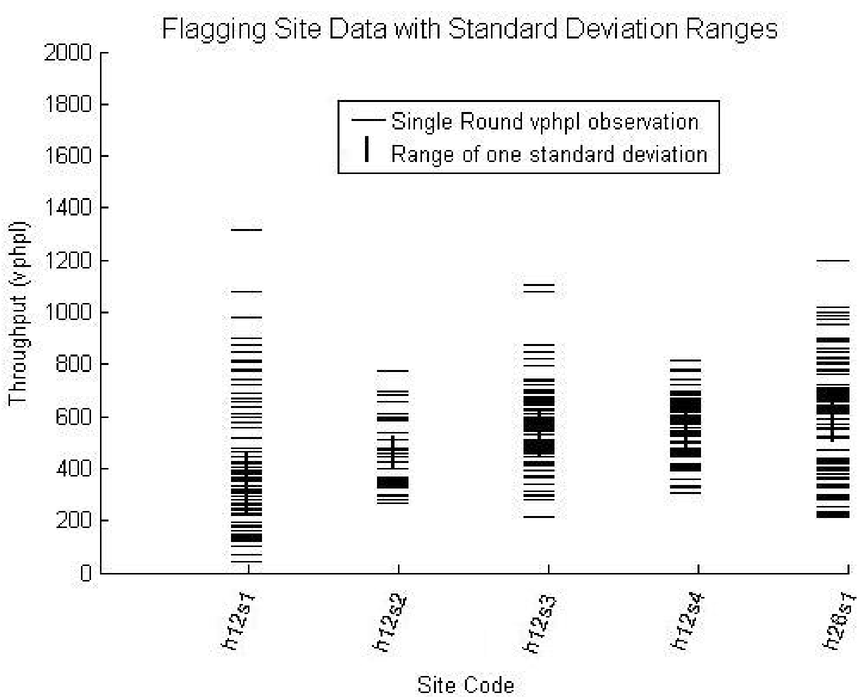


Figure 5-3 - Graph of Flagging Data and the Range of One Standard Deviation

A model's applicability to locales other than the one upon which it was based is variable. Given flow variability, having information about the range of capacity values for a work zone may be more appropriate than a single value.

Part-II of this report contains the raw data collected on each site, in addition to some preliminary calculations for each data set. For each 15-minute interval, the number of Passenger Vehicles per hour and the number of Heavy Vehicles per hour were recorded. These values were combined to make the total vehicles per hour per lane (vphpl). A graph was then created showing the travel through the construction zone over time. On this graph, a linear fit was deemed to be most appropriate with the Total Volume data, providing an equation and R^2 value.

5.4.3 PHOTOS AND VIDEO IMAGES

Whenever possible, photos and videos were taken at sites where data collection took place. These are intended to provide for additional analysis and a better understanding of what the site was like, as well as providing a record of lane closure layout. Additionally, in some situations, this information can give a general understanding of the type of vehicles (e.g. number of axels on heavy vehicles) traveling through the zone.

5.5 BARRIERS TO RESEARCH

While the research team was able to collect data at a number of sites, a number of challenges were encountered. These are outlined to assist in improving data collection practices.

The first challenge encountered by the team related to making contact with the site. Site Contract Control Officers (CCO) were generally not accessible by e-mail and when contacted by phone were often too busy to respond promptly (which resulted in missing a number of sites). The researchers found that contacting the Contract Administrators (CA) proved more effective, as these individuals were more familiar with the site. To facilitate a change in first contact protocols, it is recommended that the CAs be aware of future data collection efforts and their responsibility to provide researchers access to the site. It would be useful for the MTO Regional Contract Coordinator to facilitate this by also contacting the CA (not just CCO).

Once in the work zone, the next challenge was finding a suitable location for data collection. It was not always possible to be located at the end of the taper as desired due to construction traffic or safety reasons. However, it was reasoned that since all of the vehicles entering a construction zone would leave the zone at a comparable rate, data could be collected within the construction zone without disrupting traffic, construction or impacting safety on site.

The final challenge was related to equipment. Both a beacon light and a radar gun were vital to gaining access and collecting speed data, respectively. The radar guns that were first provided did not function properly, as the fuse broke easily. Additionally, since the proximity to the traffic was not always guaranteed (due to site characteristics and safety issues) even the working radar guns did not always provide useful data. Alternate means of collecting speed data would be helpful.

Notwithstanding these challenges, the research team was able to collect data and analyze it. The intent of the aforementioned is to provide positive feedback so that these barriers can be avoided or minimized in the future.

6 Results and Discussion

The data collected during this research was analyzed using both traditional models and as well used to develop new models based on specifications. In short, a comparison of existing models to fit the data was initially performed. Following this, the data were used to develop models for the two types of roadways that were visited in this research. This analysis saw the development of a model for freeways and evaluation of a model for flagging construction sites using the MTO data. Finally, an additional model was created to reflect highway specific driving characteristics.

6.1 HEAVY VEHICLE ANALYSIS

Although calculations were carried out using the unit vphpl to denote capacity, some work was also done to touch on the impact of heavy vehicles on throughput. Previous studies have shown that when the percentage of heavy vehicles on the road increases, the number of vehicles that can travel through a site decreases [IBI 2007]. However, although this is a sound theory, this trend is not supported by data collected for this project. Figure 6-1 shows that there is little correlation between heavy vehicles and throughput.

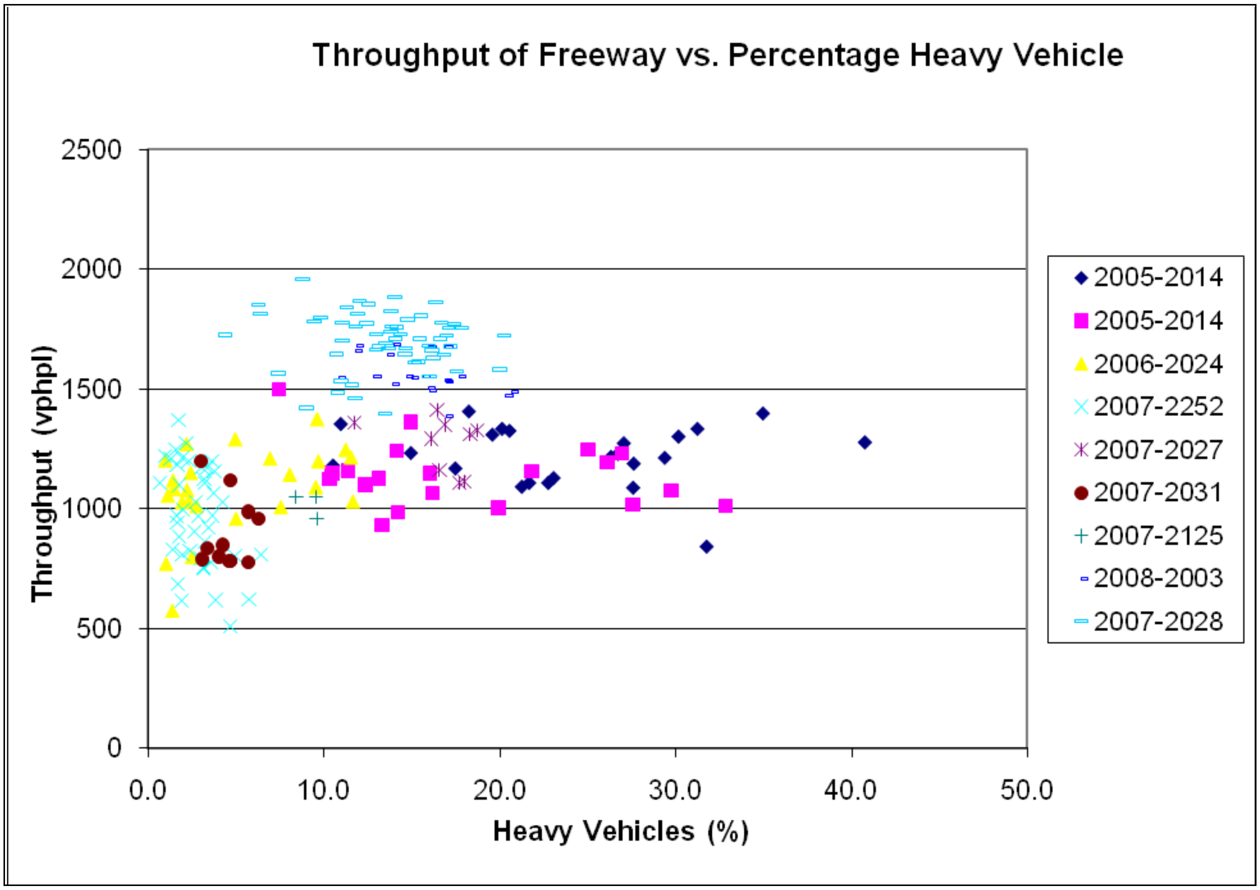


Figure 6-1 - Capacity of Freeway vs. Percentage Heavy Vehicles

6.2 EXISTING FREEWAY MODEL EVALUATIONS

As a precursor to developing an Ontario specific model, a comparison of the existing freeway models was performed for two reasons. First it was important to check if one of the models was particularly well suited to our conditions. The second objective was to gain an understanding of the model structures and characteristic impacts.

The predicted capacity for each roadway was calculated using five existing mathematical models and compared to the observed throughput (vphpl). Table 6-1 shows each of the calculated values and the highlighted entries represent those that fall within one standard deviation of the mean (15 of 120 occasions). The majority of the models did not fit within the range.

Site Code	Recorded Average (vphpl)	St. Dev	1 StDev Range		Models					
			Low	High	Krammes & Lopez	Kim et al.	Al-Kaisy & Hall – Add.	Al-Kaisy & Hall – Mult.	Sarasua et al.	MTO Design Values
h401s1	1,190	143	1048	1333	1450	1374	1706	1339	1339	1800
h401s2	1,298	76	1222	1375	1415	1425	1639	1256	1309	1800
h401s3	1,233	84	1149	1317	1458	1330	1706	1349	1347	1800
h401s4	1,134	99	1034	1233	1386	1319	1704	1263	1284	1800
h401s5	1,141	168	972	1309	1574	1361	1502	1356	1447	1600
h401s6	1,155	146	1009	1302	1525	1360	1501	1248	1405	1600
h400s1	1,182	115	1067	1297	1615	1358	1763	1557	1482	1800
h400s2	1,011	185	826	1195	1731	1359	1495	1479	1581	1800
hQEWs1	828	142	686	970	1713	1589	1773	1619	1567	1800
hQEWs2	1,098	141	957	1238	1719	1589	1373	1462	1571	1800
hQEWs3	810	203	607	1013	1714	1589	1503	1456	1568	1800
hQEWs4	1,168	86	1082	1254	1507	1583	1640	1364	1389	1800
hQEWs5	1,353	38	1315	1391	1507	1583	1640	1364	1389	1800
hQEWs6	830	78	752	909	1685	1516	1894	1630	1543	1800
hQEWs7	954	177	777	1131	1696	1516	1709	1643	1552	1800
hQEWs8	1,019	51	968	1069	1574	1230	1642	1445	1447	1800
h427s1	1,564	82	1482	1646	1525	1590	1586	1459	1405	1800
h427s2	1,755	97	1658	1851	1624	1508	1587	1587	1490	1800
h427s3	1,726	83	1643	1809	1624	1508	1587	1587	1490	1800
h427s4	1,625	138	1487	1764	1624	1508	1587	1587	1490	1800

Table 6-1 – Recorded Site Averages Compared to Calculated Model Values

The lack of consistency in the models achieving an appropriate value to describe throughput shows a need for a model that can more accurately describe the roads in Southern Ontario.

6.3 FREEWAY ANALYSIS

Having identified the need for a model specific to our highways, the next step was to use the Southern Ontario data to form a new model. The following section outlines the amalgamation of data, the analysis performed, the resulting model and this model's impacts.

6.3.1 DATA USED

This study makes the assumption that all freeways in Southern Ontario can be treated in the same manner, allowing for direct comparison between sites with similar characteristics. Table 6-2 provides the average site capacity and site characteristics for all locations used to develop the model. For full 15-minute data counts, please refer to Part II of this document which contains the raw data.

Site Code	Average Throughput (vphpl)	Weekend	Nighttime with Illumination	2 or More Lanes Closed	Left Lane(s) Closed	Barrels	>3% Grade
h401s1	1,190	0	1	1	0	1	0
h401s2	1,298	0	1	1	1	1	0
h401s3	1,233	0	1	1	0	1	0
h401s4	1,134	0	1	1	0	1	0
h401s5	1,141	1	0	1	1	1	0
h401s6	1,155	1	1	1	1	1	0
h400s1	1,182	0	1	1	1	1	0
h400s2	1,011	1	1	1	1	1	0
hQEWs1	828	0	1	1	1	1	0
hQEWs2	1,098	1	1	1	1	1	0
hQEWs3	810	1	1	1	1	1	0
hQEWs4	1,168	0	1	0	1	1	0
hQEWs5	1,353	0	1	0	1	1	0
hQEWs6	830	0	1	1	0	1	0
hQEWs7	954	0	1	1	0	1	0
hQEWs8	1,019	0	1	1	0	1	0
h427s1	1,564	0	0	0	1	0	0
h427s2	1,755	0	0	0	1	0	0
h427s3	1,726	0	0	0	1	0	0
h427s4	1,625	0	0	0	1	0	0

Table 6-2 – Site Characteristics and Throughput Counts

6.3.2 ANALYSIS

Using the fifteen minute vehicle counts and the site characteristics, multiple linear regression was performed to determine which characteristics were statistically significant. For a variable (site characteristic) to remain in the model it had to exhibit P-values less than 5%, otherwise it was removed from the model. The data from September 22, 2007 for site 2007-2252 was found to be an outlier in that it limited the regression to fewer characteristics. Excluding this site maintains the same total error as including all data collected, but provides greater flexibility as it doesn't eliminate site characteristics as extensively.

6.3.3 GENERIC MODEL

The result of this analysis is a mathematical model that includes a base capacity of 1666 vphpl, with reductions for nights, weekends, the use of barrels instead of jersey barriers, and 2 or more lanes closed. The equation produced through this analysis is shown in Equation 6-1.

Construction Lane Throughput = 1666 Equation 6-1
– 179(if night)
– 216(if using Barrels)
– 126(if weekend)
– 184(if 2 or more lanes closed)

It is not possible to predict the exact capacity, so 95% confidence intervals for the base capacity and impact factors are provided. Ranges were calculated by combining extremes of capacity at the 95% confidence level with the amount of reduction associated with the variable. For example, the lowest value of capacity that is within a 95% confidence level (1628 vphpl) and the amount reduction required for a weekend site provides a lower 95% confident value of 1465 vphpl. Table 6-3 shows the ranges of values for the base capacity, each characteristic and the interactions between the characteristics.

		95% Confidence Interval	
Element	**Expected**	**Lower**	**Upper**
Base Capacity	1666	1628	1704
Weekend (W)	1540	1465	1615
Nighttime with Illumination (N)	1487	1353	1621
More than 2 Lanes Closed (M)	1483	1362	1603
Barrels (B)	1450	1271	1629
W&N	1361	1227	1495
W&M	1356	1236	1477
W&B	1324	1145	1503
N&M	1303	1011	1595
N&B	1271	920	1622
M&B	1267	929	1604
W&N&M	1177	810	1544
W&N&B	1145	719	1571
N&M&B	1087	616	1558
W&N&M&B	961	415	1507

Table 6-3 - Range of vphpl Values Provided by Model

According to this analysis, two factors (the presence of police and whether the left or right side of freeway was closed) were not found to be statistically significant and were therefore not included in the model.

6.3.4 IMPACT OF GENERIC MODEL

This model differs from previous ones both in the characteristics included and the vphpl values associated with each element. When comparing the predicted to the actual values, a greater number of the sites fit into the range of within one standard deviation from the mean. Table 6-4 shows that 25 of 35 sites have values within one standard deviation of the mean (shaded yellow).

Site Code	Average Throughput	St. Dev	St. Dev. Range		Generic Model
			Low	High	
h401s1	1,190	143	1048	1333	1087
h401s2	1,298	76	1222	1375	1087
h401s3	1,233	84	1149	1317	1087
h401s4	1,134	99	1034	1233	1087
h401s5	1,141	168	972	1309	1140
h401s6	1,155	146	1009	1302	961
h400s1	1,182	115	1067	1297	1087
h400s2	1,011	185	826	1195	1140
hQEWs1	828	142	686	970	1087
hQEWs2	1,098	141	957	1238	961
hQEWs3	810	203	607	1013	961
hQEWs4	1,168	86	1082	1254	1145
hQEWs5	1,353	38	1315	1391	1145
hQEWs6	830	78	752	909	1087
hQEWs7	954	177	777	1131	1087
hQEWs8	1,019	51	968	1069	1087
h427s1	1,564	82	1482	1646	1666
h427s2	1,755	97	1658	1851	1666
h427s3	1,726	83	1643	1809	1666
h427s4	1,625	138	1487	1764	1666
IBIh6d1	1802	249	1553	2051	1450
IBIh6d2	1603	231	1372	1834	1450
IBIh6d3	1544	249	1295	1793	1450
IBIh6d4	1394	288	1106	1682	1450
IBIh6d5	1490	211	1279	1701	1450
IBIh6d6	1476	214	1262	1690	1450
IBIh6d7	1512	160	1352	1672	1450
IBIh6d8	1445	134	1311	1579	1450
IBIhQEWd1	1367	285	1082	1652	1087
IBIhQEWd2	1613	78	1535	1691	1087
IBIhQEWd3	1180	183	939	1305	1087
IBIhQEWd4	1498	228	910	2086	1087
IBIhQEWd5	1218	242	976	1460	1087
IBIhQEWd6	1581	260	697	2465	1087
IBIhQEWd7	1394	434	960	1828	1087

Table 6-4 – Throughput values: Southern Ontario Model vs. Actual Values.

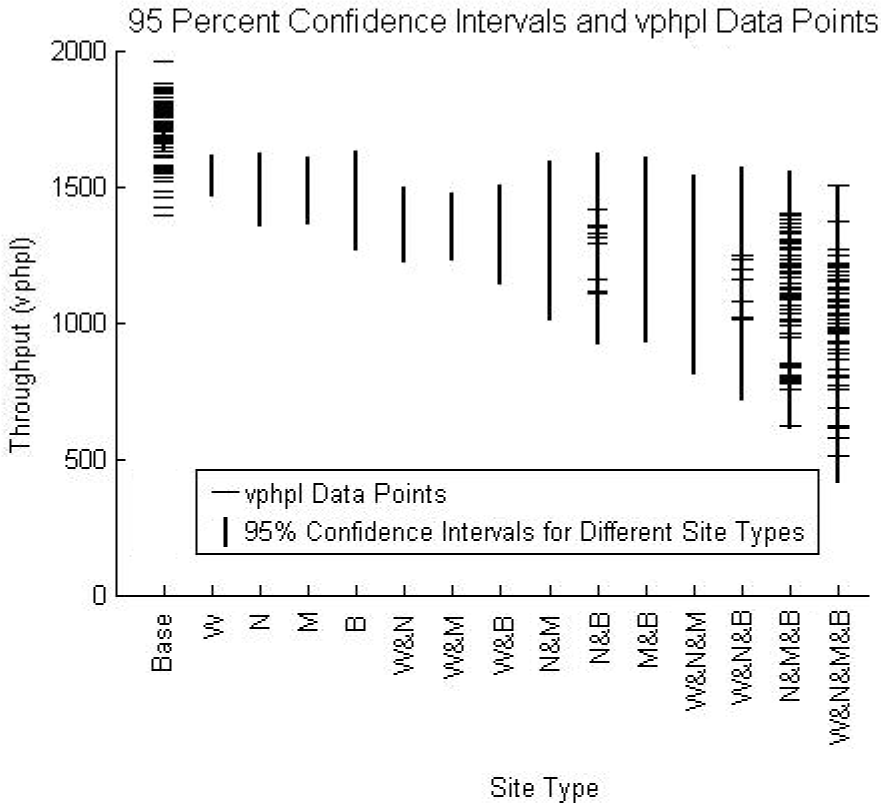


Figure 6-2 – Graph of Different Site Types Determined by Generic Model and where the Data Collected falls within these Ranges

Figure 6-2 shows the 95% Confidence Intervals for the different types of sites as described in Table 6-4. It also shows where the collected data fit into each range.

6.3.5 LANE CLOSURE CALCULATION EXAMPLES

The generic model developed in this research provides throughput values that can be compared to the anticipated demand for a section of road. By never allowing the number of expected vehicles to exceed the estimated throughput, a set of lane closure times can be determined. These lane closure times can then be compared to the times outlined by MTO for that work zone. This comparison was done for two sites, Site 2007-2028 at the point where South Bound traffic on Highway 427 exits onto East Bound Gardiner Parkway and Site 2005-2014 on highway 401 in Oshawa near Stevenson road.

Queuing at site 2007-2028 occurred during daylight on a weekday. One left lane was closed and a permanent concrete barrier was used. According to Equation 6-1, the calculated throughput for this zone is 1666 vphpl during the weekday, 1487 vphpl on weeknights, 1540 vphpl on weekends and 1361vphpl on weekend nights. When compared to the hourly traffic volumes [iTRANS 2006], the times at which a lane closure would not impede traffic were determined. Table 6-5 and Figure 6-3 show the times at which MTO suggested allowing a one lane closure (darker blue) and the times at which the model estimates that the lane could be closed (lighter turquoise). The closures recommended through the model are longer than those allowed by MTO for this site.

	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
Calculated start and end times							
Night	21:00	22:00	23:00	22:00	21:00	21:00	22:00
Next Morning	6:00	6:00	6:00	7:00	6:00	6:00	7:00
MTO actual start and end times							
Night	24:00	24:00	24:00	24:00	24:00	24:00	24:00
Next Morning	6:00	6:00	6:00	6:00	6:00	6:00	9:00

Table 6-5 - Table of Calculated Values and MTO Values for Lane Closure at 2007-2028

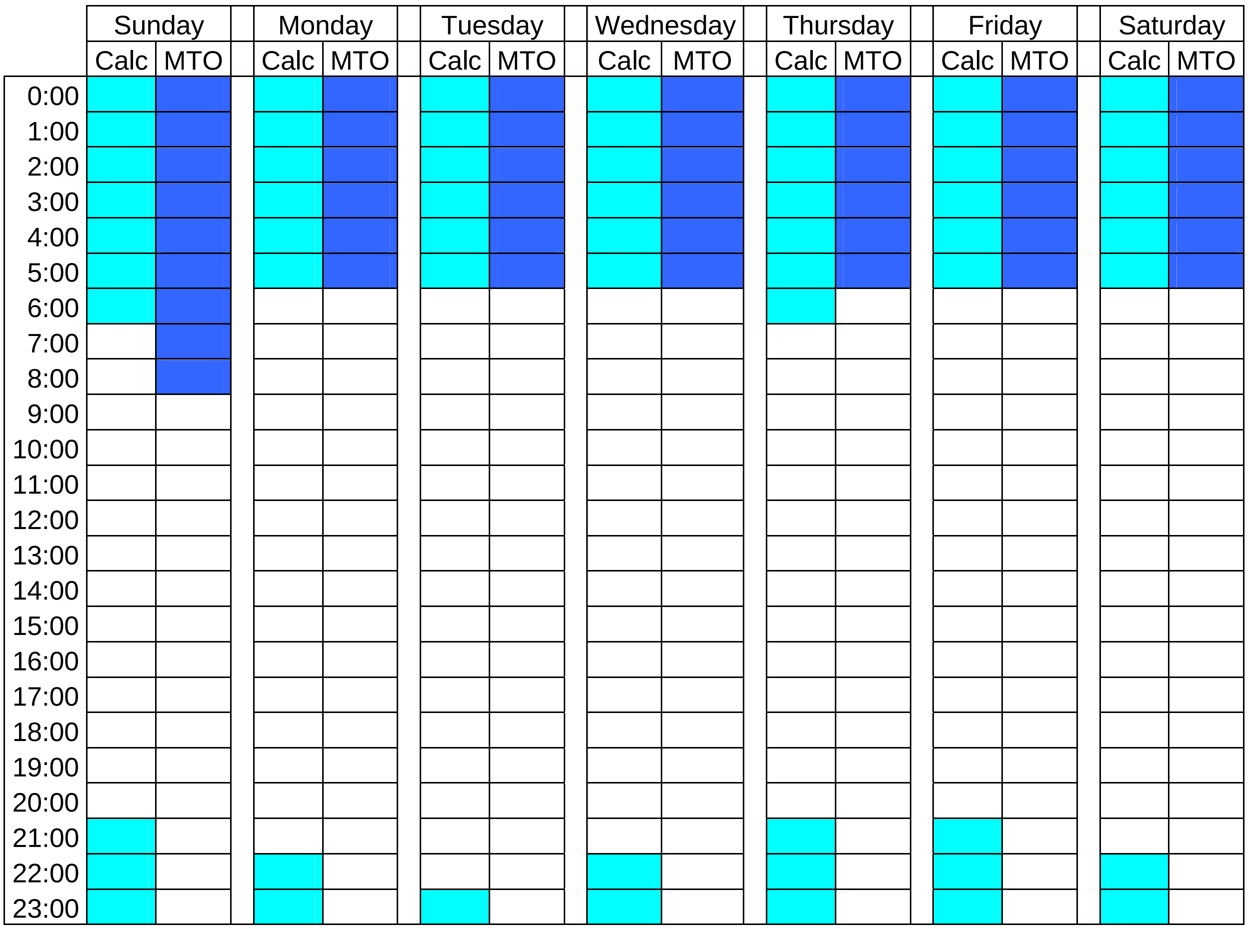


Figure 6-3 - Diagram of Lane Closure Times for 2007-2028

A similar type of analysis was done for Site 2005-2014, where most of the data were collected at evening closures on weeknights. This site used barrels to close the lane and although at times more than two lanes were closed, for the purpose of this analysis, it is assumed that the closure involves any two of the three lanes available (as this would allow for better construction work to occur). Calculated capacities for this type of closure are 1450 vphpl during the weekday, 1271 vphpl on weeknights, 1324 vphpl on weekends and 1145 vphpl on weekend nights. Table 6-6 and Figure 6-4 compare the windows of acceptable lane closure times for east bound traffic.

	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
Calculated start and end times							
Night	23:00	24:00	24:00	24:00	24:00	24:00	24:00
Next Morning	7:00	6:00	6:00	6:00	6:00	6:00	8:00
MTO actual start and end times							
Night	24:00	19:00	19:00	19:00	19:00	20:00	15:00
Next Morning	14:00	14:00	14:00	14:00	6:00	9:00	24:00

Table 6-6 - Table of Calculated Values and MTO Values for Lane Closure at EB 2005-2014

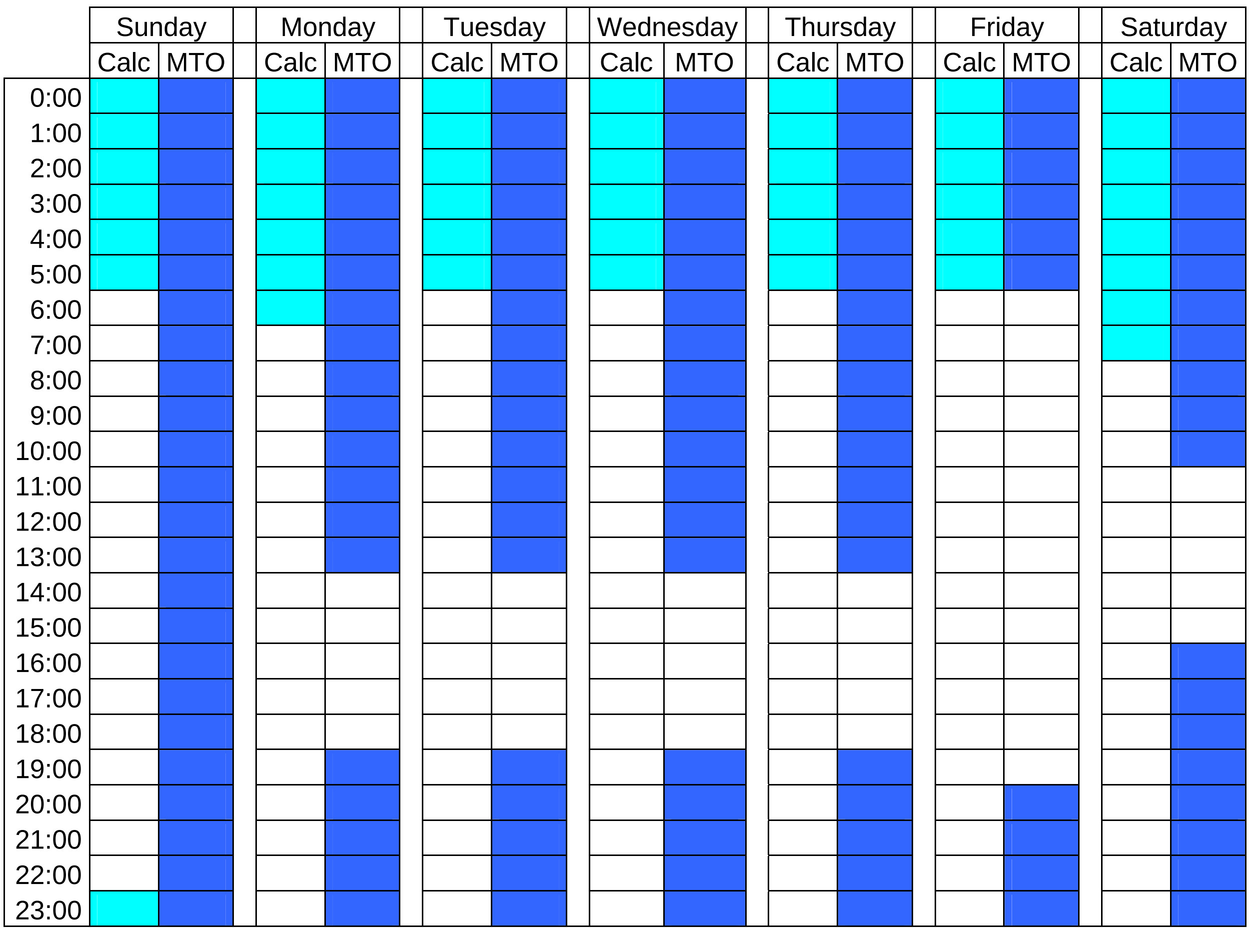


Figure 6-4 - Diagram of Lane Closure Times for EB 2005-2014

Similarly, Table 6-7 and Figure 6-4 show the west bound values for lane closure times.

	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
Calculated start and end times							
Night	24:00	23:00	23:00	23:00	23:00	23:00	24:00
Next Morning	8:00	5:00	5:00	5:00	5:00	5:00	6:00
MTO actual start and end times							
Night	23:00	20:00	20:00	20:00	20:00	21:00	20:00
Next Morning	5:00	5:00	5:00	5:00	5:00	9:00	10:00

Table 6-7 - Table of Calculated values and MTO values for lane closure at WB 2005-2014

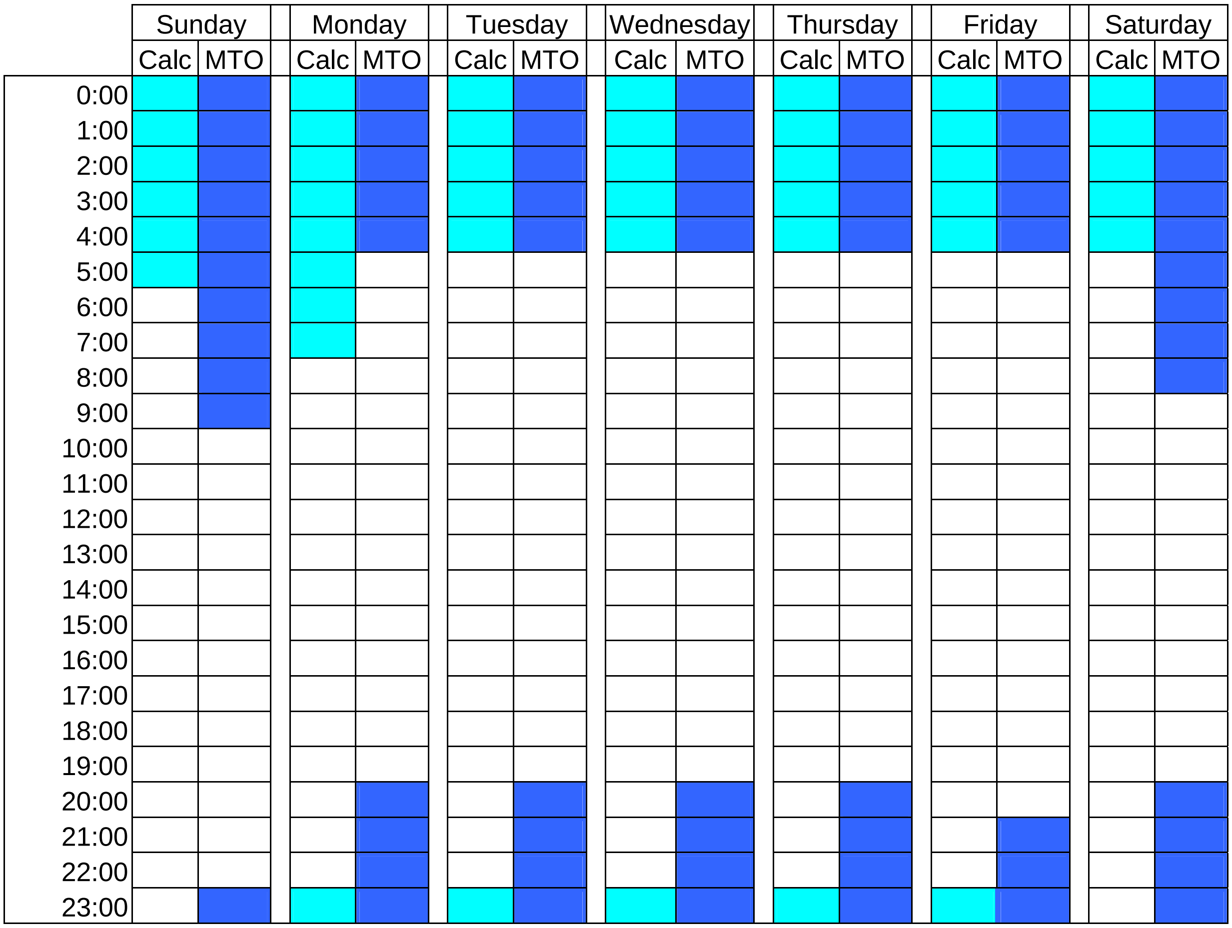


Figure 6-5 - Diagram of Lane Closure times for WB 2005-2014

6.4 THE PARADOX PART 2

Having introduced the first component of the paradox in Section 4.3, the second part can now be presented. The data collected in this research and the resulting throughput prediction model show that fewer vehicles pass through a construction work zone than previously thought. This lower throughput would normally result in a reduction in allowable lane closure times to reduce traffic delays. However, as previously stated, a number of construction sites did not display queuing at all, even though their closure times were based on the same assumptions, practices, and policies. These two contradicting results thus present a paradox.

On the one hand, lane closures times should be extended as no queuing is occurring on certain sites. On the other, actual throughput data show that fewer vehicles move through a work zone than originally though, leading one to conclude that more restrictive closure times are needed.

This suggests that one model for all of Ontario may not be the optimal means of determining throughput. For this reason, the data were re-examined to see how site location affected throughput.

Another possible explanation for lower than expected throughput is that there is unused lane capacity due to early merges or other factors; however, this is outside the scope of this project.

6.5 HIGHWAY SPECIFIC MODEL

When looking at the throughput values for each site, it is possible to see an additional trend based on the highway where the data were collected. Figure 5-2 shows three general grouping of values, one for highway 401 or 400, one for the QEW and another for highway 427. Further analysis shows that when this identifier is included in a linear regression analysis (in addition to the site characteristics), the highway identifier is statistically significant. While this is only a small sample of highways, the result of this indicates that the throughput of a highway work zone is sensitive to the road travelled upon.

Equation 6-2 shows the impact of the different highways when included with the impact of site characteristics. The sites used to produce the throughput model of Equation 6-1 are the same ones used in this analysis. It is important to note for this equation that the highway 427 sites are assumed to use concrete barriers, whereas the other highways assume the use of barrels to close the lane(s). The levels seen in Figure 5-2 of each type of highway is also reflected in this equation, as the graph shows highway 427 as the highest throughput group, highway 400/401 as the second highest and the QEW as the highway with lowest values. With more data, this could be extended to other regions in Ontario.

Construction Lane Throughput = 1702 Equation 6-2
– 0 (if Hwy 427)
– 137 (if Hwy 400/401)
– 430 (if QEW)
–107 (if weekend)
– 373 (if 2 or more lanes closed)

6.5.1 HIGHWAY SPECIFIC VERSUS GENERIC MODEL

Using the data collected for this project, two models were developed to estimate the throughput of work zone sites. The generic model is based on standard site characteristics and the highway specific model includes the highway the work zone is on in addition to those characteristics. When comparing the throughput estimates to what was actually observed on site it can be seen that the highway specific model performs better. Table 6-8 shows that in the highway specific model outperformed the generic model by predicting the actual mean throughput within 100 vphpl 18 times out of 27 whereas the generic model was within 100 vphpl only 12 times out of 27, as shown in yellow shading.

Site Code	Observed Throughput (vphpl)	Generic Model (vphpl)	Generic Error (Abs Avg = 116)	Highway Specific Model (vphpl)	Hwy Specific Error (Abs Avg = 84)
h401s1	1,190	1087	-103	1,192	2
h401s2	1,298	1087	-211	1,192	-106
h401s3	1,233	1087	-146	1,192	-41
h401s4	1,134	1087	-47	1,192	58
h401s5	1,141	1140	-1	1,085	-56
h401s6	1,155	961	-194	1,085	-70
h400s1	1,182	1087	-95	1,192	10
h400s2	1,011	961	-50	1,085	74
hQEWs1	828	1087	259	899	71
hQEWs2	1,098	961	-137	792	-306
hQEWs3	810	961	151	792	-18
hQEWs4	1,168	1271	103	1,272	104
hQEWs5	1,353	1271	-82	1,272	-81
hQEWs6	830	1087	257	899	69
hQEWs7	954	1087	133	899	-55
hQEWs8	1,019	1087	68	899	-120
h427s1	1,564	1666	102	1,272	-292
h427s2	1,755	1666	-89	1,702	-53
h427s3	1,726	1666	-60	1,702	-24
h427s4	1,625	1666	41	1,702	77
IBIh6d1	1802	1450	-352		
IBIh6d2	1603	1450	-153		
IBIh6d3	1544	1450	-94		
IBIh6d4	1394	1450	56		
IBIh6d5	1490	1450	-40		
IBIh6d7	1476	1450	-26		
IBIh6d8	1512	1450	-62		
IBIh6d9	1445	1450	5		
IBIhQEWd1	1367	1271	-96	1,272	-95
IBIhQEWd2	1613	1271	-342	1,272	-341
IBIhQEWd3	1180	1271	91	1,272	92
IBIhQEWd4	1498	1271	-227	1,272	-226
IBIhQEWd5	1218	1271	53	1,272	54
IBIhQEWd6	1581	1271	-310	1,272	-309
IBIhQEWd7	1394	1271	-123	1,272	-122

Table 6-8 – Comparison of Generic to Highway Specific Model

6.6 FLAGGING ANALYSIS

6.6.1 DATA

Of the 12 sites visited, 3 of them were on rural, 2 lane highways where the closure required a flagging person to alternate the traffic through the work zone. On these sites, the method of collecting data differed slightly from the method used on the freeway/highway sites. While the site characteristics recorded were the same, the capacity was not measured in the same manner since traffic was flowing in both directions and on intervals. This methodology is outlined in Section 4.1.2.

The three flagging sites were visited on 4 separate days, with 16 hours of data collected. Table 6-9 shows an example of how the capacity data were recorded. In this data table "PV" represents the number of passenger vehicles that travelled through the work zone in that time and "HV" represents the heavy vehicles during the same time.

	South Bound					North Bound			
Down Time	Start Time	Finish Time	Passenger Vehicles	Heavy Vehicles	Down Time	Start Time	Finish Time	Passenger Vehicles	Heavy Vehicles
							10:06:20		
00:01:50	10:08:10	10:10:10	16	11	00:02:10	10:12:20	10:17:25	43	15
00:02:25	10:19:50	10:23:40	23	11	00:00:20	10:24:00	10:27:45	38	15
00:03:00	10:30:45	10:32:40	16	8	00:01:30	10:34:10	10:37:50	43	16
00:02:50	10:40:40	10:44:45	34	17	00:00:30	10:45:15	10:48:12	25	15
00:02:23	10:50:35	10:54:25	20	11	00:01:10	10:55:35	10:59:45	38	16
00:02:35	11:02:20	11:05:00	18	13	00:01:20	11:06:20	11:10:00	42	15
00:04:35	11:14:35	11:15:55	22	11	00:01:40	11:17:35	11:20:20	33	11

Table 6-9 – Example of Flagging Data Recorded from Site 2007-2128 (h12s2)

6.6.2 ANALYSIS

The "down time" represents the amount of time for one car to travel from one end of the construction zone to the other. In theory, this should be calculated using an average speed and the work zone length, where downtime = work zone length/average speed. "Travel time" varies according to the number of vehicles that the flagger allows in the convoy. As the number of vehicles in the convoy increases, the vphpl increases. A regression analysis was performed to best understand how the vphpl value varied according to the number of cars driving through the zone.

6.6.3 FLAGGING RESULTS

It was very difficult to fit a model to the data for a couple of reasons. First, since these sites are on rural highways, there was a wide variance in the number of cars that arrived at the site. Second, since there was no pace vehicle the cars would travel at a different speed for each round, depending on the comfort of the first driver through the site. Finally, the vphpl varied greatly according to driver habits and vehicle type. Therefore, a statistically significant model was not found. Instead, the throughputs were compared using the actual vphpl values. Table 6-10 shows the variation in the values observed at each site. Also included in this table is the standard value for throughput used by MTO.

Site	Mean Throughput (vphpl)	Standard Deviation (vphpl)
MTO Standards	850	-
h12s1	351	114
h12s2	462	61
h12s3	541	90
h12s4	571	83
h26s1	592	87
IBI Study	667	134

Table 6-10 – vphpl Values for Flagging Sites

6.6.4 FLAGGING RESULTS IMPACTS

Although the observed capacities are significantly lower than those used by MTO for design, this does not imply that work zones should have shorter closure times. At a number of sites, all the vehicles that arrived to the flagging position were able to travel through the work zone without the flagging individual having to stop cars mid-stream. The observed throughputs, therefore, represented the traffic demand rather than the maximum capacity.

6.7 SZUDA MODEL FOR USER DELAY ANALYSIS

To meet the second objective of this research, methods for determining user delay costs were examined and compared. The methods that exist tend to be complex and require many inputs that may be difficult to determine.

SZUDA (Simplified work Zone User Delay Analysis) is easy to use and requires limited input. It can provide agency decision makers with quick feedback on the impacts of changes in closure schedules or work zone strategies. It may also be used by contractors to prepare lane closure proposals. SZUDA is a spreadsheet-based model that requires the normal hourly traffic flow and predicted average work zone throughput (using the models developed in Section 6.3.3 and Section 6.5). The percentage of heavy vehicles can be accounted for if it is known; otherwise, it is assumed that the road supports a general mix of vehicle types. This impacts hourly user delay costs used in the model (values were discussed in Section 3.3).

SZUDA output is a graph (Figure 6-6) that plots in a solid blue line the normal hourly traffic flow (one of the inputs), in a pink dashed line the work zone throughput (using models developed in Section 6.3.3 and Section 6.5), and in a heavy green line the resulting *number of vehicles delayed at some point during the hour* (not that the vehicles were delayed the entire hour). *For this reason, user delay costs are over-estimated in SZUDA.* Also provided are the daily and weekly user delays in vehicles. The case depicted is a 3 lane freeway with a 1 lane closure work zone using barrels. The data used for the normal hourly traffic is from a west bound section of highway 401 in Oshawa.

On examination of the model output, one dominant feature is the significant queue that forms Friday evening. By delaying the start of the lane closure just one hour in Table 6-12 from 5PM to 6PM, the queuing is reduced by 60% (Table 6-11).

One of the observations of the research team was that in some cases, the lane closure times can be extended to expedite construction activity. In this case, adding 2 hours of lane closure time to Sunday morning shows very little impact on delays but provides the contractor with a longer work shift in which to complete continuous work. The results of these two changes are shown in Figure 6-7.

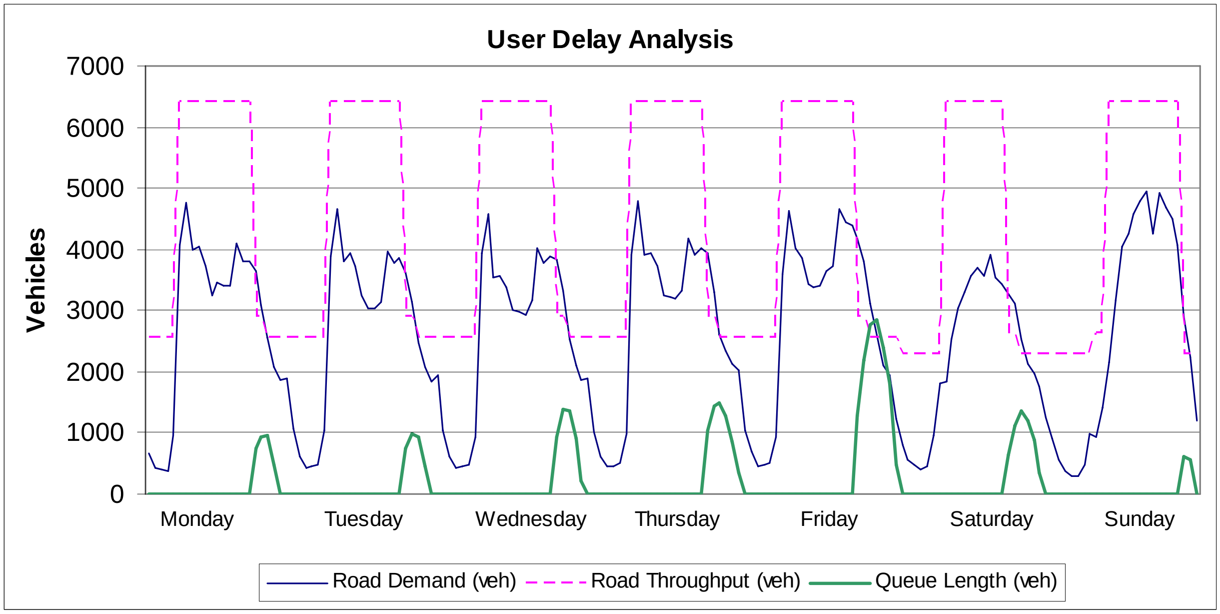


Figure 6-6 - SZUDA Result of Original Lane Closure Schedule

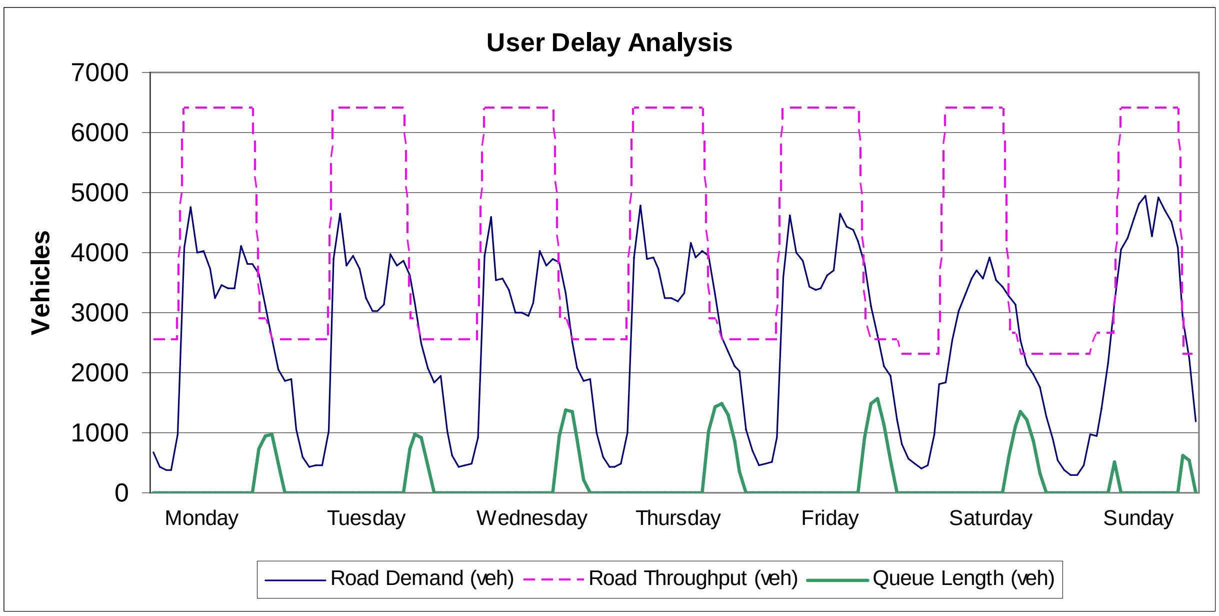


Figure 6-7: SZUDA Result of Changes to Lane Closure Schedule

User Delay (veh)								
	Mon	**Tue**	**Wed**	**Thu**	**Fri**	**Sat**	**Sun**	**Week Total**
Original lane closures	3141	3101	4784	6452	13767	5513	1160	37918
Friday closing delayed 1 hr to 6PM	3141	3101	4784	6452	**5628**	5513	1160	29779
Sunday morning opening delayed	3141	3101	4784	6452	**5628**	5513	**1681**	30300

Table 6-11 - SZUDA Result of Various Lane Closure Scenarios

Lane Closure Hours (1=Lane closed, 0=Lane open)							
Hour	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
0:00	1	1	1	1	1	1	1
1:00	1	1	1	1	1	1	1
2:00	1	1	1	1	1	1	1
3:00	1	1	1	1	1	1	1
4:00	1	1	1	1	1	1	1
5:00	0	0	0	0	0	1	1
6:00	0	0	0	0	0	1	1
7:00	0	0	0	0	0	0	1
8:00	0	0	0	0	0	0	1
9:00	0	0	0	0	0	0	0>>1
10:00	0	0	0	0	0	0	0>>1
11:00	0	0	0	0	0	0	0
12:00	0	0	0	0	0	0	0
13:00	0	0	0	0	0	0	0
14:00	0	0	0	0	0	0	0
15:00	0	0	0	0	0	0	0
16:00	0	0	0	0	0	0	0
17:00	1	1	1	1	1>>0	1	0
18:00	1	1	1	1	1	1	0
19:00	1	1	1	1	1	1	0
20:00	1	1	1	1	1	1	0
21:00	1	1	1	1	1	1	1
22:00	1	1	1	1	1	1	1
23:00	1	1	1	1	1	1	1

Table 6-12: Table Showing Lane Closure Times Through the Week

As long as the hourly traffic data are available for the area in which the road closures are to take place, this model can provide MTO decision makers with a means to customize lane closure schedules to both maximize contractor opportunities and minimize user delays. MTO will have to correlate the vehicle delays depicted in this model to tolerances acceptable to the road users. As long term closures can cause a certain proportion of drivers to take alternate routes, SZUDA accepts percentages of reduced traffic demand to approximate the impact of these drivers without having to re-establish traffic demands.

7 Conclusions

Over the course of two construction seasons in 2007 and 2008, data were successfully collected at 16 sites on 39 days. Due to reasons such as lack of forced flow, weather and inadequate site lines these visits resulted in 11 sites of usable data with 23 days of visits producing 70 hours of throughput data. Existing models were used to predict work zone capacities at sites visited, resulting in only 15 of the 120 opportunities being within one standard deviation of the mean. This supports the hypothesis that a region specific model is needed.

An important conclusion from this research is presented in the paradox (Section 6.4) discussed in this paper. Although it was concluded that, on average, fewer vehicles travel though a work zone than originally anticipated, it was also observed that a number of sites where queuing was expected did not display forced flow. This presents a paradox related to determining when lane closure times should occur. It is suggested that MTO consider highway specific throughput models to better predict the impacts of lane closures. This will benefit both the road users and work contractors.

For sites where queuing did occur, improvement to the existing capacity models was made through the creation of a model fit to Southern Ontario data, which provides better predictions than capacity models found in the literature. The model is an additive model that employs a base throughput with reduced values when certain site characteristics are present.

Construction Lane Throughput = 1666
– 179 * (1 if night; 0 if day)
– 216 * (1 if using Barrels; 0 if using barriers)
– 126 * (1 if weekend; 0 if weekday)
– 184 * (1 if 2 or more lanes closed; 0 if 1 lane closed)

This equation results in estimates for work zones with varying site characteristics. In addition to variation due to characteristics, the 95% confidence intervals for each site provide a range of values that are statistically acceptable. These values and ranges are also provided.

In addition to this generic model, a highway specific model was also developed. It can be used if the site in question is on highway 427, 400/401, or QEW, and has been found to be very suitable for the data collected on this project and the IBI project.

Construction Lane Throughput = 1702
– 0 * (1 if Hwy 427; 0 otherwise)
– 137 * (1 if Hwy 400/401; 0 otherwise)
– 430 * (1 if QEW; 0 otherwise)
– 107 * (1 if weekend; 0 if weekday)
– 373 * (1 if 2 or more lanes closed; 0 if 1 lane closed)

As well as analysis on freeway lane closures, this report includes closures that occurred on rural, 2-lane highways that employed a flagging operation. Although a model could not be developed that accurately reflected the variation in throughput, the analysis allowed for comparison of throughput between different sites and the design values. All of the observed values were lower than the design throughput used, not necessarily because the design throughput should be lowered but because full lane capacity was not used.

Objectives related to user delay costs were achieved through the development of SZUDA (Simplified work Zone User Delay Analysis). Using this tool, users can estimate the impacts of lane closure strategies on traffic delays measured as number of vehicles delayed at some point during the hour and their associated user delay costs. This model helps to address the paradox uncovered in this study by providing a better understanding of the relationship between throughput, location, and work zone characteristics.

8 Recommendations

One of the major results of this study can be found in the paradox presented. Although two new models are presented to represent work zone throughput, it is recommended that they not be used without regard to the conditions under which they were developed; some sites may require site specific evaluation.

Having said this, it is recommended that MTO include the new throughput models in the process that determines when lane closures can occur. The new model has lower throughput values than were previously used but reflect the data collected over numerous site visits.

It is recommended that MTO continue to collect data from work zone sites with differing conditions and locations. Increased amount of data will allow models to be refined providing for a more accurate throughput estimate. For a long term project, construction sites should collect information on the queuing length when the lane(s) is (are) closed. On a site where free flow continues through the site at all times, this may be an opportunity for an extension in the closure time. However, queuing would indicate that the outlined times for closing the lanes are too liberal. Collecting this information from long term sites would be a useful measure to be taken over the next two or three years.

Consequently, collecting this information at numerous sites is also an opportunity to change the way work zone throughput measurements are acquired. Due to the difficulty in gaining contact and access to appropriate sites, requiring each site to monitor the traffic flow on site could be possible; however, consistency in data collection practices is critical to the ability of a model to predict throughput. For this reason, it would be beneficial to have only a few people involved in data collection, or to have an automated system to provide consistency in practice.

It was found that conveying information to road users was lacking at a number of sites. Signs that indicated when and where closures were to occur were not always up to date and researchers generally found that they could not be relied upon. In one instance when a site had special permission to close a lane on a Sunday evening in the summer, drivers were not warned and could not therefore change their travel routes. As such, having a reliable information database for road closures could not only help divert traffic, but could also manage the expectations of drivers who use roads under construction on a regular basis.

Although this project produced results in the form of vehicles per hour per lane (vphpl), evaluating roads in passenger cars per hour per lane (pcphpl) is more widely accepted. To convert vphpl to pcphpl, a passenger car equivalent (PCE) generally between 1.5 and 3.0 must be used to transform a heavy vehicle to a passenger vehicle. Using PCEs is something that MTO should consider for the future as heavy vehicles have different impacts than passenger cars. Some benefits that may result from switching to this vehicle representation are the ability to consider its inclusion in throughput models and having a better estimate of when roadways will next require maintenance.

An analysis of flagged rural highway work zones yielded a wide range of throughput measurements. While it was possible to determine an average throughput, it is recommended that further analysis be done to understand why the vehicle flows vary so drastically. It is suggested that the range is partially due to driver behaviour; however more research is needed to better understand this phenomena.

Finally, it is recommended that the SZUDA model be used to help determine suitable times for road closures by both MTO and contractors. The combination of the new throughput models developed in this research along with the road demand should provide a much better indication of the costs incurred due to user delay. SZUDA is easy to use and allows for the user to specify characteristics specific to the site they are working on. Adopting the SZUDA model will help to make more informed decisions with regards to lane closure times. The SZUDA model can also be further developed by refining the model based on additional data and adding sensitivity to the evaluation through interpolation of the hourly normal traffic volumes.

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10 Appendices

The complete set of data collected for this project can be found in the “Data” document (Part II) of this report.

APPENDIX A – FURTHER DETAILS ON ALL SITES CONTACTED

Please Note: In the table provided below all known Contract Numbers are included in the site IDs. Sites where the contract number is not knows are listed as NV (Not Visited).

	Site ID	Location	Hwy	Direction	Result	Description/Status of Site
Short Term	NV1	20 m east of Simcoe Rd. 10	9	EB	NCC	Construction already completed
	NV2	Bullnose at 407 to 407 structure. At Steels Av.	400	NB	NCC	Construction already completed
	NV3	407 Structure to just North of Hwy 7 (Core)	400	NB	NCC	Construction already completed
	NV4	1.3 Km South of Hwy 9 for 1.0 Km	400	SB	NCC	Construction already completed
	NV5	Deceleration lane. Lower Big Chute to N of flyover	400	NB	NCC	Construction already completed
	NV6	Quarry Rd. Bt Taylor Docks from end of last patch N.	400	NB	NCC	Construction already completed
	NV7	100 m E of Whites Rd. bridge structure. Express	401	WB	NCC	Construction already completed
	NV8	Bullnose Westerly on Hwy 2A to W of 401-Collector	401	WB	NCC	Construction already completed
	NV9	Markham Rd. to 1st bridge joint of Markham Rd.Br.	401	EB	NCC	Construction already completed
	VN10	Birchmount to Victoria Park Br. Express	401	WB	NCC	Construction already completed
	NV11	404/DVP to 1st Br. Joint at Leslie St. Collectors	401	WB	NCC	Construction already completed
	2007-2253	Lane 1 & 2 from 3 to 4.1 Kms East of Guelph Line	401	EB	VNQ	No forced flow condition
	NV12	Rouge River St. to Maj. Mackenzie. S of M.Mack & 404	404	NB	NCC	Construction already completed
	2007-2252	Niagara Region from Mountain Road to Hwy 420	QEW	SB	VDC	Data collected on Sept 21, 23
	2007-2252	QEW from Thorold Stone Rd. to Mountain Rd.	QEW	NB	VDC	Data collected on Sept 22
Long Term	NV13	Hwy 6/York Rd I/C. Hwy 403 to Hwy 5 (Hamilton)	6	NB	NLR	CCO contacted on Sept 10, 2007. Lack of response meant no site visit.
	NV14	1 Km N of RR 24 N’ly to 1Km S of H9(Orangville)	10	SB	NNQ	CCO indicated no forced flow
	2007-2128	S.Jct of H48 to S of Beaver River Br (Beaverton)	12	SB	VDC	Site visited for two days
	2007-2128	From N of Whites Creek Br. To N. Jct. Hwy 48	12	NB	VDC	Site visited for two days
	2005-2014	Park Rd. to H 35/115 and Stevenson Rd. (Oshawa)	401	EB, WB	VDC	Data collected from 5 sections
	NV15	Avenue to Leslie St. transfer EB	401	EB	NNQ	No traffic impact (MTO)

		Collectors				
	NV16	Westney to Salem Rd- 410 EB & WB (Ajax)	401	EB	NNQ	Only temporary closure
	NV17	From Wilson to King St. (Oakville)	403	N/A	NCC	Construction completed
	2007-2028	Hwy 427 to QEW SB Exp. Lanes, Toronto	427	SB	VDC	Site visited for three days
	NV18	Glendale Rd. to Mountain Rd. (Hamilton)	QEW	SB	NNQ	No forced flow on Oct 03, 2007 visit
	NV19	Red Hill Creek I/C (Hamilton)	QEW	N/A	NNQ	No forced flow on Oct 03, 2007 visit
	2007-2031	QEW/Hurontario I/C (Mississauga)	QEW	WB	VDC	Site visited for two days
	NV20	Price Corners to Coldwater, Simcoe Country	12	N/A	NLR	CCO contacted on Oct 01, 2007
	2005-3045	Grand River to Fergus Avenue, Kitchener	8	NB	VNQ	No forced flow on 2-day visit
	2006-3099	Waterloo Rd. 1 to Waterloo Rd. 5, New Hamburg	7	EB, WB	VNQ	Data collected from 3 sections - Couldn't be used due to interchanges in zone
Additional	2007-2027	St. Catharine's Toronto Bound from Lake St.	QEW	EB, WB	VDC	Condition do not completely qualifies as forced flow
	2007-2127	Hwy 26 at Horseshoe Valley Road	26	All ways	VDC	Site visited for one day and data collected
	2007-2125	3rd line to 1.0 Km East of Trafalgar Rd.	QEW	WB	VNQ	Site visited for two days. No forced flow condition in fall
	2007-2030	CPR Overpass, North of Barrie	400	NB	VNQ	Site visited for two days. No forced flow condition
	2006-2024	At Hwy 89 interchange (Simcoe Country)	400	NB	VDC	Forced flow observed for 6 hrs on NB traffic
	2006-2024	At Hwy 89 interchange (Simcoe Country)	400	SB	VNQ	Site visited for two days. No forced flow condition
	2007-2130	East of Meadowvale in Ajax	401	EB	VNQ	Site visited for one day. No forced flow condition
Summer 2008	2007-2125	3rd line to 1.0 Km East of Trafalgar Rd.	QEW	WB	VDC	Forced flow observed for 1 hr on WB traffic
	2008-2003	QEW EB to Hwy 427 NB Lanes, Toronto	427	SB	VDC	Forced flow observed for 5 hrs
	2005-2014	Park Rd. to H 35/115 and Stevenson Rd. (Oshawa)	401	EB	VDC	Forced flow observed for 5 hrs on EB traffic
	NV21	Hwy 6 to Hwy 25 (Hamilton)	401	N/A	NLR	CCO and CA contacted. Lack of response meant no site visit
	2007-2263	Hwy 12 East of Lower Big Chute Rd.	12	EB, WB	VDC	Flagging site. Traffic observed for 3 hours.
	NV22	Guelph Line Interchange (Campbelville)	401	N/A	NNQ	Site contacted. CA reported no sustained queuing

APPENDIX B – PROGRESS REPORT

Measuring Work Zone Capacity
Progress Report #1 – January, 2008

It is generally accepted that increasing traffic volumes are not being accommodated by equal growth in lane kilometres, particularly in urban areas [FHWA 2005]. Instead, the focus is on better management of existing roads to optimize throughput. To maximize throughput, the road network must be kept open and in good condition. At the same time, our highways are approaching middle age and require increased rehabilitation and reconstruction.

To keep the roads in good condition, road closures are required for maintenance and repair; however, this reduces the throughput of the road. To minimize the impact of work zones on throughput, contractors are required to open the road during heavy traffic periods and work during non-congested hours, such as work nights and weekends. This interrupts the work flow and reduces productivity, often resulting in requests for an extended schedule for the contractor to complete the work, which in turn causes more delays. Work interruptions also increase pavement cold joints, which are often weak points in the surface.

The current guidelines for work schedule requirements of contractors are based on estimates of road capacity at work zones. If these estimates are conservative (low) relative to the actual traffic flow, then the contractor is closing the work zone earlier and for a longer time than is necessary to maintain the required road capacity, thereby causing longer construction windows than necessary.

The purpose of this progress report is to provide an update of activities that have been performed to date and to provide a brief outline of the next steps.

Research Objectives

The objectives are:

1. To determine traffic throughput on highways at work zones in the Ontario Central Region during congested conditions.

2. Based on the estimates of different capacity values, refine model output for evaluation of user delay costs at work zones. This objective is additional to the MTO RFP.

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 Central Region.

- Support research assistants who are working to achieve a higher education in engineering. These students will gain a keen understanding of the transportation field from many perspectives including management, design, construction, user impacts, safety, life cycle analysis, and stakeholder issues.

BACKGROUND: Work Zones

Highway configuration factors that may impact both work strategies and the resulting traffic congestion include the number of lanes, the presence of shoulders and medians, and whether the highway is divided or undivided. Some work strategies that may be included in the traffic data collection as viable situations are:

- **Advancing Limited Closure in One Lane**. In this strategy, a single lane closure is deployed and then lengthened or shortened according to traffic or construction. It is usually employed in hot-mix resurfacing and whitetopping treatments. The work area is flexible for traffic, but the traffic control devices have to be moved whenever the lane closure expands or contracts.

- **Lane Shift onto the Shoulder or Median**. The aim of this strategy is to keep the same number of lanes open by directing traffic onto the shoulder or median.

- **Full-Length Single Lane Closure**. A single lane over the entire length of the project is closed to facilitate construction. This enables increased flexibility for contractors in their operations. Reduced throughput capacity at peak traffic volumes are an issue.

- **Multiple Work Areas**. This strategy places the work at several isolated spots. It resolves the problems of full-length closure, but the motorists could be disrupted due to several work areas in a short distance. Construction flexibility is reduced, as well as productivity.

- **Alternating Lane Closures Multiple Work Areas**. This strategy consists of closing one lane from point A to point B, and then closing the other lane from point B to point A. Typically, the work proceeds down one lane in the morning, and back the other lane in the afternoon. Drawbacks of this strategy include increased construction joints, confusion caused by frequent changes to the construction area, and the proximity of traffic to the construction workers.

- **Single-Lane Closure**. This work zone closure is employed on two or four lane highways, divided or undivided. For two lane facilities, the opposing traffic will be disrupted, while on four lane facilities, the traffic in the work zone direction will have to merge to one lane.

- **Crossover**. One direction of a four lane highway is closed and a single lane of traffic is diverted through the median into the opposing lane. The traffic in the opposite direction is consolidated into a single lane. The result is a section of highway with one side closed to traffic entirely while the other side accommodates a two-lane scenario.

Lane closure tactics should weigh the impacts of construction duration and inconvenience to the road users. The pavement research centre at University of California at Berkeley found that closing four lanes instead of just two lanes increased productivity 70% with just an 18% increase in inconvenience to the general public. However, this assessment did not recognize the impact of various traffic volumes in different areas. In the Toronto area, some closure strategies may not be practical at certain times of the day.

Work strategies may significantly impact the time it takes to complete 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 & demobilization, caused by a short construction window.

Table10-1: Productivity Factors for Concrete Slab Replacement [Lee 2000; 2004]

Description	Productivity Factor	
Continuous Closure, Continuous Operation, 3 Shifts	1.00*	
Continuous Closure, Daytime, Weekday Operation	2.80	
Weekend Closure, 55 Hours Continuous Operation	1.45	
Nightly Closure, 10 Hours Operation	1.91	2.23 (Average)
Nightly Closure, 7 Hours Operation	2.55	

*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 the actual decreased 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.

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 et al. 2000; Tighe & McCabe 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 and Graves [2002] analyzed the cost of construction delays and studied various factors. They 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 and Graves 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 [Heidemann 2001] 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. 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 [Heidemann 2001] are more realistic in most situations for partial lane closures. Munoz and Daganzo [2003] 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.

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 et al. 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 [e.g. Fontaine et al. 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.

Methodology

1. Working closely with MTO, identify work zones that meet the conditions of this research i.e. are on a major highway and experience congestion regularly.

2. Gain permission to access each site. Safety protocols are established for each site.

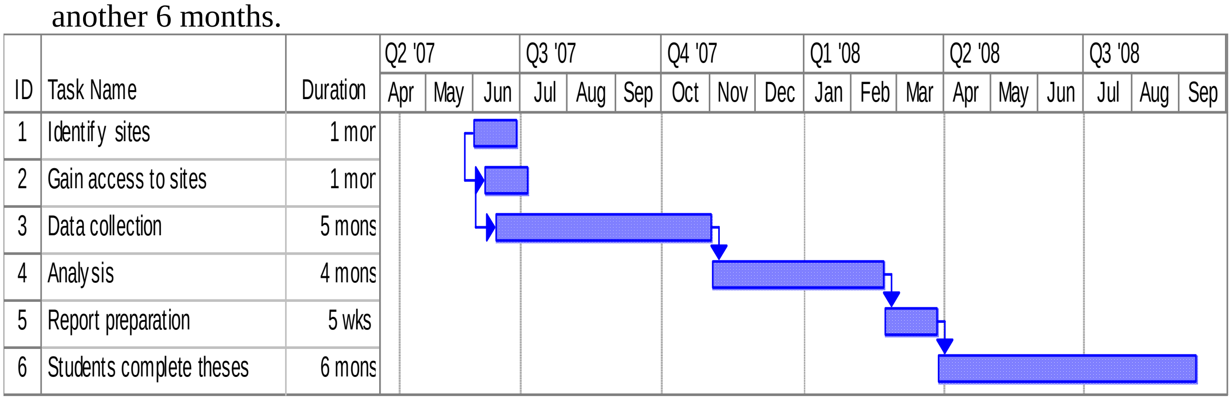
3. Data collection. Research Assistants are involved in attending sites and collecting data. Manual methods were used, using 15 minute interval counts during congestion periods.

4. Data analysis, including the development of adjustment factors using established methods and a refined user delay model [Huen et al. 2006]. Capacity analysis will include establishing mean traffic density values at peak times with standard deviation and confidence intervals [IBI 2007], and the evaluation of adjustment factors using multiplicative and additive capacity modeling [Al-Kaisy and Hall 2003].

SCHEDULE

The following schedule represents the originally proposed time line. Due to a late start, current project status foresees completion three months after planned.

- Identify sites and gain access permission: June 07
- Data collection: June 07-October 07
- Analysis and determination of adjustment factors: November 07-February 08
- Report preparation: March 08
- The two Master's students will continue with the fulfillment of their program requirements for another 6 months.



Work Completed To Date

Work on this project began in August of 2007 with contacting and arranging visits to highway construction sites, as provided by MTO. With the cooperation of individuals on site, a number of work zones across Southern Ontario were visited. Based on the site characteristics and highway demand, data was collected at 10 different locations. It should be noted 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 wasted hours both on and off site. However, regardless of these experiences several hours of data were collected and this is described herein.

SITES CONTACTED

All of the sites suggested by MTO were either contacted or evaluated based on the information provided. Table 3 contains the details of all the Short Term sites (Shave & Pave Projects) suggested by MTO for our project, whereas Table 4 provides details of all the Long Term sites suggested by MTO for the project. Table 5 contains the list of some additional sites suggested by MTO through weekly updates and emergency work sites. While all of the sites suggested by MTO were evaluated, only some of them were deemed appropriate for a site visit. This was either based on the construction schedule, timing, availability and/or whether queuing was present. In total 29 days were spent on sites and 58 hours of data were collected.

Table 3: SHORT-TERM SITES (Shave & Pave Projects)

S.N	Location	Hwy	Dir.	Site Visit	Data (Hrs)	Description
1	20 m east of Simcoe Rd. 10	9	E/B	No	0	Construction already completed
2	Bullnose at 407 to 407 structure. At Steels Av.	400	N/B	No	0	Construction already completed
3	407 Structure to just North of Hwy 7 (Core)	400	N/B	No	0	Construction already completed
4	1.3 Km South of Hwy 9 for 1.0 Km	400	S/B	No	0	Construction already completed
5	Deceleration lane. Lower Big Chute to N of flyover	400	N/B	No	0	Construction already completed
6	Quarry Rd. Bt Taylor Docks from end of last patch N.	400	N/B	No	0	Construction already completed
7	100 m E of Whites Rd. bridge structure. Express	401	WB	No	0	Construction already completed
8	Bullnose Westerly on Hwy 2A to W of 401-Collector	401	WB	No	0	Construction already completed
9	Markham Rd. to 1st bridge joint of Markham Rd.Br.	401	EB	No	0	Construction already completed
10	Birchmount to Victoria Park Br. Express	401	WB	No	0	Construction already completed
11	404/DVP to 1st Br. Joint at Leslie St. Collectors	401	WB	No	0	Construction already completed
12	Lane 1 & 2 from 3 to 4.1 Kms East of Guelph Line	401	EB	No	0	No forced flow condition
13	Rouge River St. to Maj. Mackenzie. S of M.Mack & 404	404	NB	No	0	Construction already completed
14	Niagara Region from Mountain Road to Hwy 420	QEW	SB	Yes	6	Data collected
15	QEW from Thorold Stone Rd. to Mountain Rd.	QEW	NB	Yes	1.25	Data collected

Table 4: LONG-TERM SITES

S.N	Location	Hwy	Dir.	Site Visit	Data (Hrs)	Description
1	Hwy 6/York Rd I/C. Hwy 403 to Hwy 5 (Hamilton)	6	N	No	0	CCO contacted on Sept 10
2	1 Km N of RR 24 N'ly to 1Km S of H9(Orangville)	10	S	No	0	CCO indicated no forced flow
3	S.Jct of H48 to S of Beaver River Br (Beaverton)	12	S	Yes	8.5	Site visited for two days
4	From N of Whites Creek Br. To N. Jct. Hwy 48	12	N	Yes	2.5	Site visited for two days
5	Park Rd. to H 35/115 and Stevenson Rd. (Oshawa)	401	E,W	Yes	8	Data collected from 3 sections
6	Avenue to Leslie St. transfer EB Collectors	401	E	No	0	No traffic impact (MTO)
7	Westney to Salem Rd- 410 EB & WB (Ajax)	401	E	No	0	Only temporary closure
8	From Wilson to King St. (Oakville)	403		No	0	Construction completed
9	Hwy 401 to QEW SB Exp. Lanes, Toronto	427	S	Yes	15	Site visited for three days
10	Glendale Rd. to Mountain Rd. (Hamilton)	QEW	S	No	0	No forced flow on Oct 03 visit
11	Red Hill Creek I/C (Hamilton)	QEW		No	0	No forced flow on Oct 03 visit
12	QEW/Hurontario I/C (Mississauga)	QEW	W	Yes	2.75	Site visited for two days
13	Price Corners to Coldwater, Simcoe Country	12		No	0	CCO contacted on Oct01
14	Grand River to Fergus Avenue, Kitchener	8	N	Yes	0	No forced flow on 2-day visit
15	Waterloo Rd. 1 to Waterloo Rd. 5, New Hamburg	7	E,W	Yes	4.75	Data collected from 3 sections

Table 5: ADDITIONAL SITES VISITED:

S.N	Location	Hwy	Dir.	Data (Hrs)	Description
1	St. Catharine's Toronto Bound from Lake St.	QEW	EB&WB	2	Condition do not completely qualifies as forced flow
2	Hwy 26 at Horseshoe Valley Road	26	All ways	5	Site visited for one day and data colleted
3	3rd line to 1.0 Km East of Trafalgar Rd.	QEW	WB	0	Site visited for two days. No forced flow
4	CPR Overpass, North of Barrie	400	NB	0	Site visited for two days. No forced flow
5	At Hwy 89 interchange (Simcoe Country)	400	NB	2.5	Forced flow observed for 2.5 hrs on NB traffic
6	At Hwy 89 interchange (Simcoe Country)	400	SB	0	Site visited for two days. No forced flow condition
7	East of Meadowvale in Ajax	401	EB	0	Site visited for one day. No forced flow condition

**remaining sites suggested by the weekly updates reported little or no traffic impact

SITES VISITED

When contacting a construction work zone, a number of characteristics were used to determine if the site warranted to be visited in hopes of collecting data. The characteristics are as follows:

1. Extended lane closure: Longer than just for periodical movement of machinery

2. Partial lane closure: Reduction of traffic lanes available (i.e 2-to-1, 3-to-2 or 3-to-1)

3. Adequate amount of traffic demand: Determined based on site contact's observations. If there were any elements of slowed or queued traffic the site was visited.

At all work zones visited, Traffic, Weather and Geometric characteristics of the sites were recorded in a site characteristics form. Table 6 is a sample Site Characteristics form that was used to record the information.

Table 6: Site Characteristics Form

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

Once on site, each work zone was further evaluated to determine if it met the needs of this research project. More specifically, if there was adequate slowing or queuing of vehicles then data were recorded. Table 7 is a list of total sites visited and the result of the visit.

DATA COLLECTED

The data that were collected fall into three categories. First, as previously stated, site characteristics were recorded at each location. Secondly, capacity measurements were taken in zones that exhibited forced flow. Finally, at some sites photos and video were taken to provide useful information to study.

Table 7: Total Sites Visited

S.N	Location	Hwy	Dir.	Cat.	Days Visited	Data (Hrs)
1	Lane 1 & 2 from 3 to 4.1 Kms E of Guelph Line	401	EB	ST	2	0
2	Waterloo Rd.1 to Waterloo Rd.5, N. Hamburg	7	EB-WB	LT	3	4.75
3	Niagara Region from Mountain Rd to Hwy 420	QEW	SB	ST	2	6
4	Thorold Stone Rd. to Mountain Rd.	QEW	NB	ST	2	1.25
5	Grand River to Fergus Avenue, Kitchener	8	NB	LT	2	0
6	Cawthra to Hurontario I/C	QEW	WB	LT	2	2.75
7	Hwy 400 NBL/CPR Overpass, North of Barrie	400	NB	LT	2	0
8	1 Km East of Trafalgar Road on QEW	QEW	EB	LT	2	0
9	Hwy 400 NBL/Hwy 89 (Simcoe County)	400	NB	ST	2	2.5
10	Hwy 400 SBL/Hwy 89 (Simcoe County)	400	SB	ST	2	0
11	S. Jct of Hwy48 to South of Beaver River Bridge	12	SB	LT	2	8.5
12	N of Whites Creek Br. to N. Jct. Hwy 48	12	NB	LT	1	2.5
13	Park Rd. to Hwy 35/115 and Stevenson Rd. Oshawa	401	EB-WB	LT	3	8
14	H 401 to QEW SB, Exp. lanes-SB Access Ramp	427	SB	LT	3	15
15	St. Catharine’s, Toronto bound from Lake St.	QEW	EB-WB	LT	1	2
16	Hwy 26 at Horseshoe Valley Road	26	All	LT	1	5
17	Hwy 401 in Ajax - East of Meadowvale	401	EB	LT	1	0

ST: Short term LT: Long term

SITE CHARACTERISTICS

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 and in flagging operations where two directions of traffic had to share one open lane.

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 Part-II of the progress report.

CAPACITY MEASUREMENTS

At each site that exhibited the desired characteristics, the volume of vehicles traveling through the zone was recorded. These vehicles were categorized into Passenger Vehicle and Heavy Vehicles. In addition to this information, other raw data such as speed and other notes were taken.

Part-II of the progress report contains the raw data collected on each site, in addition to some preliminary calculations for each data set. For each unit of time, the number of Passenger Vehicles per hour and the number of Heavy Vehicles per hour were calculated. By giving heavy vehicles a PCE (Passenger Car Equivalent) of 2.0, the total volume was calculated. A PCE of 2.0 was used as a preliminary value and will be further evaluated in the data analysis stage of the project. The calculated information was then used to create a graph showing the travel through the construction zone over the time evaluated. On this graph, a linear fit was given to the Total Volume data, providing an equation and R^2 value.

PHOTOS AND VIDEO IMAGES

Whenever possible, photos and videos were taken at sites where data collection took place. These are intended to give a general understanding of what the site was like, as well as providing a record of lane closure layout. Additionally, in some situations, the media can give a general understanding of the type of vehicles (e.g. number of axels on heavy vehicles) traveling through the zone.

BARRIERS

While this project was able to move forward and collect data at a number of different sites, which exhibited varying characteristics, there were some barriers encountered during the process. These challenges are outlined in this document in order to facilitate smoother project work in the future.

The main barrier that was encountered was making contact with the site. Site Contract Control Officers (CCOs) were generally not accessible by e-mail and when contacted by phones were too busy to return information promptly (which resulted in missing a number of sites since construction had been completed). Researchers found that contacting the site Contract Administrators (CAs) proved to be much more fruitful since they were more intimately involved with the site. Having said this, it was very important for the CAs to have been contacted by the CCOs outlining the scope of the project and their ability to allow researchers access to the site.

Once in the work zone, one of the challenges that were faced was finding a suitable location for data collection. It was not always possible to be located directly at the end of the taper due to construction vehicles, or other safety reasons. This was overcome through the understanding of input and output of the construction zone. Since all of the vehicles entering a construction zone will be leaving the zone at a comparable pace, data could be collected at a range of points within the construction zone without disrupting traffic, construction or the safety on site.

The final challenge was related to equipment. Both a beacon light and a radar gun were vital to gaining access and gaining data, respectively. The radar guns that were first provided did not function properly, as the fuse broke easily. Additionally, since the proximity to the vehicles was not always guaranteed (due to site characteristics) even the working radar guns did not always provide useful data.

WORK ZONE CAPACITY MODELLING RESEARCH

Given that there have been a number of studies aimed at understanding work zone capacity, it is important to learn and build upon this research. Journal articles have been read and summarized to help lead to the creation of an Ontario specific model that can be used. The models that have been suggested involve a number of different characteristics and vary slightly from study to study. These models will be analyzed to determine their suitability for this research project.

Next Steps

Having acquired a wide range of data from a diverse number of sites, the next steps of the project involve analysis, model creation and model validation as outlined in the original proposal. A general overview of this process can be seen in Figure 8, which had been adapted from Meyer and Millers book, “Urban Transportation Planning”.

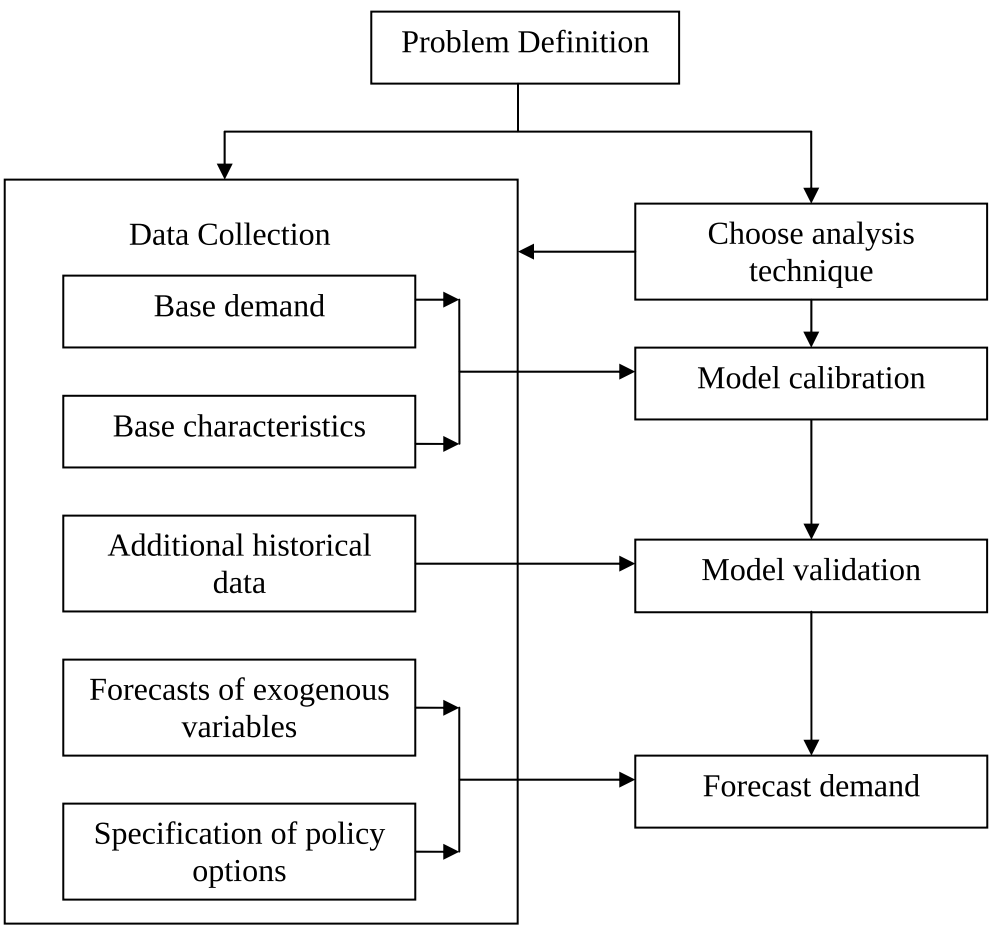


Figure 8: The Demand Analysis Process [Meyer and Miller (2001), p.250]

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 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 and queuing in workzones, the costs associated with user delay can be evaluated.

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APPENDIX C – MTO GDM CHAPTER B 2002

Throughput (veh/hr) = Throughput (vphpl)* #lanes * I
$f_{HV} = 1 / \{1+P_T(E_T-1)+ P_R(E_R-1)\}$
$V_{arrival} = (V_{truck} / f_{HV}) + V_{car}$
$Q_t = V_{arrival}$ - CapacityWZ + Q_{t-1}
Hourly Delay = $(Q_t - Q_{t-1})/2$
Last in Queue = $[(Q_{t-1} + V_{arrival\ for\ period\ t}) (V_{arrival\ for\ period\ t})]/ Capacity_{WZ}$
Total Delay = Σ (Hourly $Delay_t$)
Total Affected Vehicles = Σ ($V_{arrival}$) + Last in Queue
Average Vehicle Delay = {(Total Delay) (60)}/Total Affected Vehicles
Queue Length = $(Q_t)(L)/ (1000)(N)$
Delay Cost = (Total Delay)[(%Truck)($Cost_t$)+(1-%Truck)($Cost_{pc}$)]
Delay Cost = (Total Delay) ($Cost_{mixed}$)

$Capacity_{WZ}$ = Work zone capacity (veh) for t hour
$Cost_{mixed}$ = Delay cost for mixed traffic ($/hr)
$Cost_{pc}$ = Delay cost for passenger car ($/hr)
$Cost_t$ = Delay cost for trucks ($/hr)
E_R = Passenger-car equivalent for RVs
E_T = Passenger-car equivalent for Trucks
f_{HV} = Heavy Vehicle adjustment factor
Hourly Delay = Vehicle delay (veh/h) while in queue in t hour
I = Intensity of work activity (+/- 10%); (+/- 50% of lane capacity for ramp within 450m of closure)
L = Vehicle length (m) = 7.5 m
Last in Queue = Final veh. experiencing queue in the last period when Q=0 for t hour (veh)
N = Number of lanes upstream of work zone
P_R = Proportion of RVs, expressed as a decimal
P_T = Proportion of Trucks, expressed as a decimal
Q_t = Queue (veh) for t hour
Q_{t-1} = Queue (veh) for the previous hour (If Q value is negative, set 0)
Queue Length = (Km) for t hour
Total Affected Vehicles = All vehicles experiencing queue (veh)
Total Delay = Total hours vehicles delayed for analysis period (veh-h)
Varrival = Arrival rate with PCE for truck volume (veh/h) when Q>0
Varrival for period t = Arrival rate with PCE for truck volume (veh/h) for t hour
Vcar = Passenger Car Volume
Vtruck = Truck Volume (veh/h)

APPENDIX D – CHITTURI 2007 MODEL

Inputs required for model: $w, e, ,p\ FFS, R_O, R_{LW}, R_{LC}, P_T, P_{CE}, C_{Uo}, V_i, N_{op}, l_T, P_C, l_C,$ *Buffer space*, L, C_T, C_C, N_{occ}
$WI_r = (w + e)/ p$
$SR_S = 11.918+2.676 \ln (WI_r)$
$SR_L = 2.6625+1.2056 \ln (WI_r)$
$R_{WI} = \{SR_S, SR_L\}$
$U_o = FFS - R_{LW} - R_{LC} - R_{WI} - R_O$
$f_{HV} = 1/ 1+ P_T(PCE-1)$
$C_{adj} = C_{Uo} * f_{HV}$
$n_{i+1} = n_i + V_{i+1} - C_{adj} * N_{op}$ applied at end of every hour if demand is greater than adjusted capacity-at-operating-speed
$l_{eff} = (P_T * l_T + P_C * l_C)$ + buffer space
$Q_{Si} = n_i * l_{eff}$
If $D > Q_{Si} / N_{op}$, queue will not extend past work zone; queue at end of i_{th} hour: $Q_i = Q_{Si} / N_{op}$
If $D < Q_{Si} / N_{op}$, queue will extend past work zone; queue at end of i_{th} hour: $Q_i = D + (Q_{Si} – D*N_{op})/ N_{nr}$
$d_q = \sum_{i=0}^{t-1} \frac{n_i + n_{i+1}}{2}$
$d_{spd} = \sum_{i=0} V_i * \left(\frac{L}{U_o} - \frac{L}{U_{\lim}} \right)$
$d_{total} = d_{spd} + d_q$
$UC = d_{total} ((P_T * C_T) + (P_C * C_C * N_{occ}))$

Buffer space = Distance between vehicles when both are stopped (10 feet)
C_{adj} = Adjusted capacity-at-operating-speed (vphpl)
C_C = Hourly delay costs for each passenger in a car ($/hr/passenger)
C_T = Hourly delay costs for trucks ($/hr)
C_{Uo} = Capacity-at-operating-speed U_o from the speed flow curve (pcphpl)
D = Distance from the work activity area to the beginning of the taper (ft)
d_q = Delay due to queuing (veh-hours)
d_{spd} = Delay due to slower speed (veh-hours)
d_{total} = Total delay experienced by the users (veh-hours)
e = Number of large construction equipment in work space near workers (from 0- 5)
FFS = Free flow speed
f_{HV} = Heavy vehicle factor
L = Length of the work zone (miles)
l_C = Length of passenger cars (feet)
l_{eff} = Effective spacing between vehicles (feet)
l_T = Length of heavy vehicles (feet)
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

N_{nr} = Number of lanes open before the work zone
N_{occ} = Average number of occupants in cars (passengers/car)
N_{op} = Number of lanes open in the work zone
p = Lateral distance between the work space and the travel lane (varies from 0.3 to 2.7 m)
P_C = Percentage of passenger cars
PCE = Passenger car equivalents (HCM recommended values)
P_T = Percentage of heavy vehicles
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)
R_{LC} = Reduction in speed due to lateral clearance (mph)
R_{LW} = Reduction in speed due to lane width (mph)
R_O = Reduction in speed due to all other factors that may reduce speed (mph)
R_{WI} = Reduction in speed due to work intensity (mph)
SR_L = Speed reduction in long-term work zone (mph)
SR_S = Speed reduction in short-term work zone (mph)
t = Number of hours of queuing
UC = Total user costs ($)
$U_{\lim}$ = Posted speed limit inside the work zone (mph)
U_o = Operating Speed (mph)
V_i = Demand in hour i (vph)
V_{i+1} = Total demand in $(i+1)_{th}$ hour (vph)
w = Number of workers working in a group in the work space (Value varies 0-10)
WI_r = Work intensity ratio