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Expressway Single-lane Work Zone Capacities with Commercial Vehicle Impacts

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ABSTRACT

Like other government transportation agencies, the Ontario Ministry of Transportation performs regular maintenance and reconstruction of freeways across the province. If lane closures are required for this maintenance, they have to occur during a window of time in which travel demand is below the capacity of the remaining open lanes. To date, the estimates of capacity for single-lane work zones have been based on relatively simplistic planning assumptions. The impact of heavy vehicles has not generally been considered and it has been observed that overnight construction windows defined on the basis of these assumptions are often subject to significant queuing and delays. In an attempt to understand work zone capacity, data was collected at seven work zones in the Greater Toronto Area during the fall of 2008. Analysis of this data indicated a wide and unexplained variation in the capacities achieved at the surveyed locations. It was hypothesized that the orderliness of the merging behaviour may be an important factor in the explanation of this variation, particularly the distance upstream from the lane drop location at which the vehicles in the dropping lane merge into the through lane. Using micro-simulation, the effects of different merging processes were evaluated and simulation outputs corresponding to the observed data were achieved. It was observed that there are two operational regimes, one with higher throughputs corresponding to early merging and relatively smooth operation in the remaining open lane. The second, with lower throughputs, involved late merging and interrupted flow in the open lane. These results are preliminary and would benefit from additional data collection and analysis oriented to the evaluation of this particular phenomenon.

Keywords: Work zone, freeway capacity, heavy vehicles

INTRODUCTION

The Ontario Ministry of Transportation operates and maintains an extensive system of freeways and lesser highways across the province. Due to climatic considerations, rehabilitation and improvement activities are concentrated during the non-winter months, meaning that at any given time there may be a number of work zones active on the freeway system in the Greater Toronto Area.

Typical construction staging may call for one of several possible work zone schedules, ranging from nominal lane reductions on a 24-hour basis, to more extensive lane reductions overnight and even to complete closures of either the express or collector lanes for a weekend at a time. At present, timing restrictions are placed on lane closures based on a relatively rudimentary evaluation of hour-by-hour traffic volumes. However, not all of these calculations account for the impact of heavy commercial vehicles, which often travel in the evening or overnight to avoid congestion during commuting peak periods. On a number of occasions, lack of consideration of heavy vehicle or related grade effects, or of other factors, have resulted in significant queuing and delay and, of course, complaints from the driving public.

The objectives of this study were to:

1. Evaluate the capacity of single-lane work zones on three-lane cross section on Toronto-area highways with specific consideration of conditions with queues present; and,
2. Evaluate the impact of heavy vehicles on work zone capacity.

Observations were made at overnight work zones on several freeways in the Toronto area, namely Highway 401 and the Queen Elizabeth Way, during the fall of 2008. Data was collected during those periods where two of three lanes were closed and queuing was prevalent.

Several complementary aspects were incorporated into the analytical approach, including straight volume measurements, assessment of headways for different following combinations (e.g. car following a truck) and micro-simulation analysis using VISSIM. The results from these various approaches are compared and synthesized.

LITERATURE REVIEW

The Highway Capacity Manual 2000 (1) provides a manual method for estimating work zone capacity, which identifies the reduced capacity of a work-zone lane in comparison to a normal freeway lane, but assumes that the passenger car equivalent (PCE) of heavy vehicles is the same as in normal freeway operation. The methodology is based primarily on a study performed by Krammes and Lopez (2) of 33 work zones in Texas prior to 1991.

Other models have accounted for the presence of heavy vehicles in work zones, such as the one derived by Sun, Lv and Paul (3) from observations in Illinois, or Sarasua et. al. (4) from lane closures in South Carolina. Sun, Lv and Paul used a set of PCE values as a function of work-zone speed and heavy vehicle percentage using a multiple-regression method and a closed loop calibration. Sarasua, et. al. derived a model based on a speed-flow relationship from observations of lane closures in South Carolina. The model adjusted for work zone intensity, lane configuration (1 of 2 lane closure, 2 of 3 lane closure, etc.), and heavy vehicle proportion using a variable PCE value depending on work zone speed.

Al-Kaisy and Hall (5) completed an interesting study of a series of long-term lane closures in Ontario. They proposed a model using multiplicative capacity reduction factors, as opposed to additive, to better account for the interactive nature of these factors. Of course many other studies have been conducted to estimate work zone capacity - this is by no means a

complete listing. The interested reader should refer to Edara and Cottrell (6), or to the extensive literature review undertaken by the Transportation Research Centre at the University of Florida (7).

Of particular relevance to the current work is a binomial model developed in a study by Enberg and Mannan (8) to estimate the capacity of a work zone on a freeway in Finland. The model uses headways, differentiated by vehicle following combination, and an estimate of the probability of each headway occurrence from the heavy vehicle proportion. This model was of particular interest as it coincided with the authors' belief that one possible estimate of work zone capacity might be derived from average headways of different types in combination with the proportion of these headway types in the traffic stream. Enberg and Mannan also mention that the binomial method tended to overestimate the directly observed capacity by between 1 and 3 per cent. However, as daily traffic variations from 5 to 10 per cent are common, and during overnight construction periods, variations can be even greater, this overestimate is of little practical significance.

TYPICAL EXPRESSWAY WORK ZONE CONFIGURATIONS IN ONTARIO

To provide context and facilitate comparisons with other sources, it is necessary to describe the prescribed layout for the work zones addressed in this study. The Ontario Traffic Manual establishes typical work zone configurations for use on Ontario highways. The layout for the situation being studied here, that of a freeway being reduced from three lanes to a single lane, is shown in Figure 1 for a normal regulatory speed limit of 100 km/hr. Normally, buffer vehicles, in conjunction with flexible drums or construction markers, would be used to delineate short-term work zones unless moveable concrete barriers could be used effectively. Often, these work zones are signed for a reduced speed of 80 km/hr. and drivers are advised that fines are doubled when workers are present. Depending on the temporal distribution of traffic, lane closures may be introduced in a staged fashion, first closing a single lane and later closing a second lane.

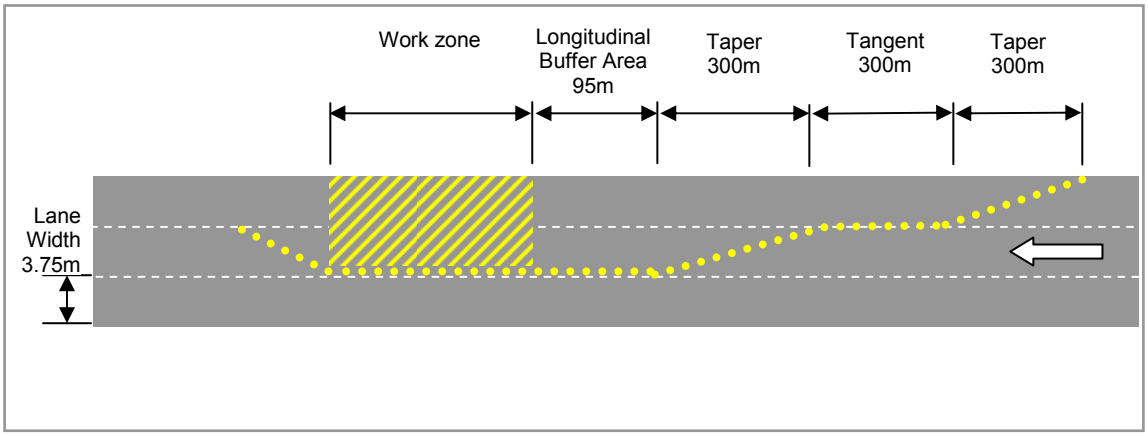

Figure 1: Standard Freeway Work Zone Layout for Reduction to a Single Lane

VARIABLES AFFECTING WORK ZONE CAPACITY

Based on the literature, the capacity of a work zone in vehicles/hour may be affected by a number of variables, including:

(i) proportion of heavy vehicles;
(ii) grade through the work zone;

(iii) configuration of the work zone, including lane width, shoulder width, taper length and angle, and entry and exit ramps upstream of the work zone;
(iv) intensity of construction activity;
(v) weather, lighting, and road conditions; and
(vi) driver population.

The work zone configurations studied were all generally in accordance with the configuration guidelines described previously. Construction activity at each site was of a similar nature, involving one or more of asphalt grinding, resurfacing, median barrier replacement, and striping. All observations were made at night in well-lit locations and there were no particular issues with road or weather conditions, and no grade through the work zones. It is possible that the driver population might vary from location to location at that time of night but it is noted that all survey locations were on inter-regional freeways with connections to the United States border and in a generally semi-rural to suburban environment. It was believed that variations in capacity at the sites observed would primarily derive from the effect of commercial vehicles or from operational differences.

DATA COLLECTION

Headway data was collected manually at 7 sites between September and November 2008. headways were measured front bumper to front bumper In all cases, the work zone involved the overnight closure of two lanes of a three-lane cross-section. Data collection was begun approximately 15 minutes after the lanes were closed, which was typically between 11:15 and 11:45 p.m., and continued until queuing was no longer present, typically between 1:15 and 1:45 a.m. The traffic flow was considered queued when traffic speeds generally below 10 kilometres per hour to 20 kilometres per hour and short headways associated with low speeds were observed upstream of the primary bottleneck.

Observations were made immediately downstream of the beginning of the single-lane section of the work zone and secondary observations were made at the downstream end of the single-lane section. Data recorded included the time at which the vehicle entered the study section, the type of vehicle, and whether or not a queue was present. Vehicles were classified according to whether they were an auto-type vehicle (including light trucks) or a heavy vehicle (large single-unit trucks and trucks with semi-trailers or trailers). There is a tendency for the proportion of heavy vehicles to be higher during the evening hours as drivers try to avoid congestion during peak commuting periods. Table 1 summarizes the data collection activity. Further analysis used only those observations during periods of continuous queuing.

Table 1 Overview of data collection

Location	Date (2008)	Start Time	End Time	Percent of study period with queue	Number of total vehicles observed	Percentage of heavy vehicles
Queen Elizabeth Way between Dorval Drive. and 3rd Line Oakville, Ontario	Sept. 12	23:15	1:15	85%	2,646	4.4%
	Sept. 17	23:42	12:11	79%	1,459	10.4%
	Sept. 18	23:20	1:23	77%	2,018	7.9%
	Sept. 19	23:40	1:20	50%	2,565	3.7%
Highway 401 near Trafalgar Road Milton, Ontario	Sept. 24	23:21	1:36	32%	1,983	23.0%
	Sept. 25	23:46	1:38	73%	1,700	18.7%
Highway 401 near Bennett Road Clarington, Ontario	Nov. 27	22:08	23:10	63%	1,030	25.6%

ESTIMATING WORK ZONE CAPACITY AND THE IMPACT OF HEAVY VEHICLES

Several different approaches were taken towards the estimation of work zone capacity and the effects of differing proportions of heavy vehicles on that capacity. The capacity of interest was the throughput for a single-lane work zone under saturated conditions when a queue is present, as it is this situation that is normally associated with the definition of the allowable time window for overnight work zones.

Direct Estimate of Capacity

To obtain direct estimates of capacity, the observations made while queuing was present were divided into time-slices of five minutes duration. The observed capacities were then plotted against the heavy vehicle proportions as seen in Figure 2. This graph shows a relatively wide range in terms of observed capacity, even among points where the heavy vehicle proportions were similar and, to a certain extent, among points at the same site and time period. In fact, there appears to be two concentrations among the points with less than ten per cent of heavy vehicles, one lying between 900 and 1,150 vehicles/hour and another lying between 1,300 and 1,500 vehicles per hour. This suggests that there may be variations in capacity related to some other factor, although it is not obvious what that factor might be. There is also evidence that capacity tends to decrease with increasing heavy vehicle percentage.

It was concluded that capacity estimates based on these direct observations may not be as reliable, at least on the basis of the current data set, as those derived from the headway or micro-simulation analyses discussed below.

Capacity Estimation from Analysis of Headway Types and Proportions

Analysis of Mean Headways by Headway Type

It was hypothesized, as in the analysis of Enberg and Mannan, that headways vary with the type of headway, the four types or "following combinations" being:

(i) car followed by another car (car-car);
(ii) truck followed by a car (truck-car);
(iii) car followed by a truck (car-truck); and
(iv) truck followed another truck (truck-truck).

Table 2 summarizes the mean headways for each headway type based on the combined set of observations. As might be expected from the differences in vehicle acceleration performance, the combinations with a following truck exhibited larger headways. Analysis confirmed that the means for the various combinations were statistically different at the 95% confidence level. Note that Table 2 includes only headway observations during periods of continuous queuing.

Analysis of Frequencies of Different Headway Types

The analysis reported by Enberg and Mannan assumed that the proportion of different headway types in the traffic stream was based on a binomial distribution for the given heavy vehicle percentage. For this study, based on personal observation, it was hypothesized that the proportion of truck-truck headways may be higher than would be found with random arrivals, based on the proportion of heavy vehicles, due to a tendency for truck-drivers to travel in platoons. The observed frequencies of the various headway types during periods of continuous

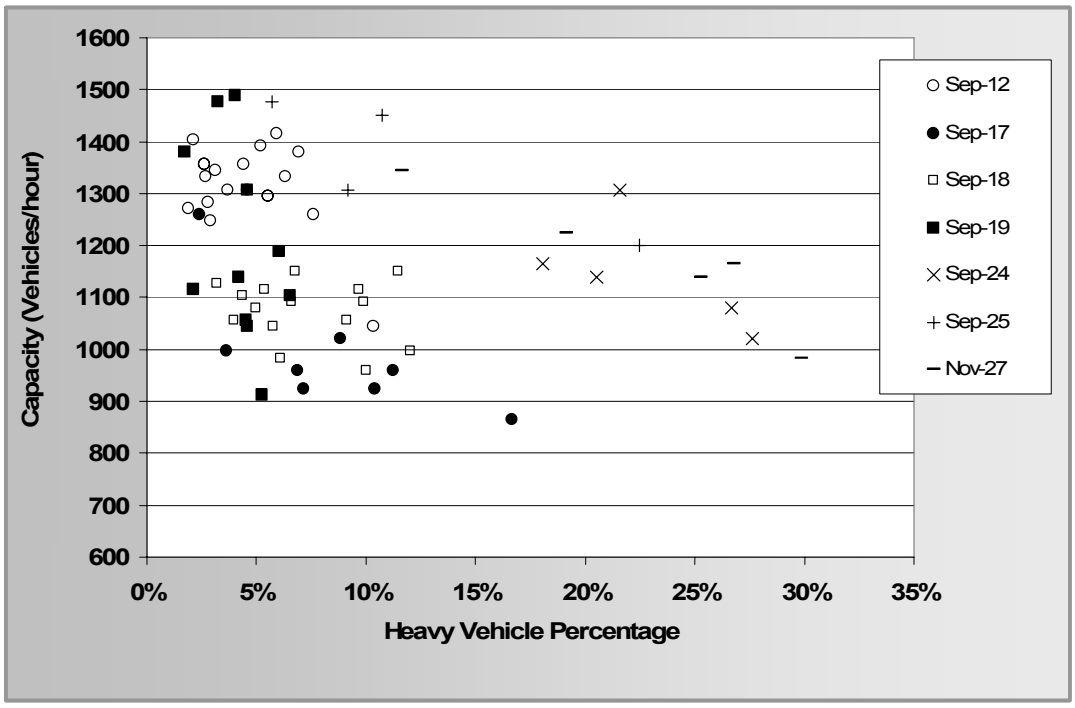

Figure 2 Capacity vs. heavy vehicle percentage based on direct observations

Table 2 Mean headways for different following combinations

Headways (seconds)	Car-Car	Car-Truck	Truck-Car	Truck-Truck
Mean	3.0	4.5	3.5	5.4
Standard deviation	1.7	2.5	2.0	2.7
15^{th} percentile	2.5	3.1	2.9	3.3
85^{th} percentile	3.4	6.4	4.6	8.0
Observations	5,347	498	492	147

Table 3 Statistical comparison of frequencies of following combinations (type of headway) during intervals of continuous queuing

Date	Location	Heavy Vehicle Percentage	Relative Frequency								Capacity calculated from headways	
			Car-Car		Car-Truck		Truck-Car		Truck-Truck			
			Observed	Binomial	Observed	Binomial	Observed	Binomial	Observed	Binomial	Observed Headways	Binomial Headways
12-Sep	QEW	4.4%	92%	91%	4%	4%	4%	4%	0.5%	0.2%	1,133	1,134
17-Sep	QEW	9.5%	82%	82%	8%	9%	8%	9%	1.4%	0.9%	1,091	1,093
18-Sep	QEW	7.9%	85%	85%	7%	7%	7%	7%	0.9%	0.6%	1,105	1,106
19-Sep	QEW	3.8%	93%	92%	4%	4%	4%	4%	0.2%	0.1%	1,138	1,139
24-Sep	Hwy 401	23.1%	61%	59%	16%	18%	16%	18%	7.2%	5.3%	1,144	1,144
25-Sep	Hwy 401	18.7%	68%	66%	13%	15%	13%	15%	5.7%	3.5%	1,186	1,187
27-Nov	Hwy 401	25.8%	57%	55%	17%	19%	17%	19%	8.3%	6.6%	1,119	1,119
Chi-Square Test	Chi-Square statistic (reject hypothesis if > 14.1)		3.1		11.7		12.5		62.4			
	Reject binomial process?		No.		No.		No.		Yes.			

queuing, were compared with the probabilistic frequencies from the binomial distribution, as shown in Table 3, and the Chi-square test applied. It was found that the proportions for all headways types, except for the truck-truck headways, were statistically no different from that predicted based on the binomial distribution at the 95 per cent confidence level. The proportion of truck-truck headways was statistically different; however, the net impact of this difference on the calculated capacity, as shown in Table 3, is insignificant and binomially-distributed headways can be substituted with minimal loss of accuracy. The capacity was calculated using mean headways by type and the frequency of each type of headway.

Analysis of Capacity based on Headways

When the mean headways summarized in Table 2 are combined with the probabilities of occurrence of the different following combinations in the traffic stream, a relationship can be derived between the work zone capacity and the proportion of heavy vehicles. Binomially-distributed headways have been assumed as per the previous discussion. The following equation defines this relationship:

$$Q = \frac{3600}{(1-P_t)^2 t_{cc} + (1-P_t)(P_t)t_{ct} + (P_t)(1-P_t)t_{tc} + (P_t)^2 t_{tt}}$$

Substituting the values for the mean headways, the average capacity estimate is:

$$Q_{avg} = \frac{3600}{0.4P_t^2 + 2.1P_t + 3.0}$$

where: Q = capacity in vehicles/hour
P_t = proportion of heavy vehicles
t_{xx} = mean headway for following combination x-x
c = car, t = truck or heavy vehicle

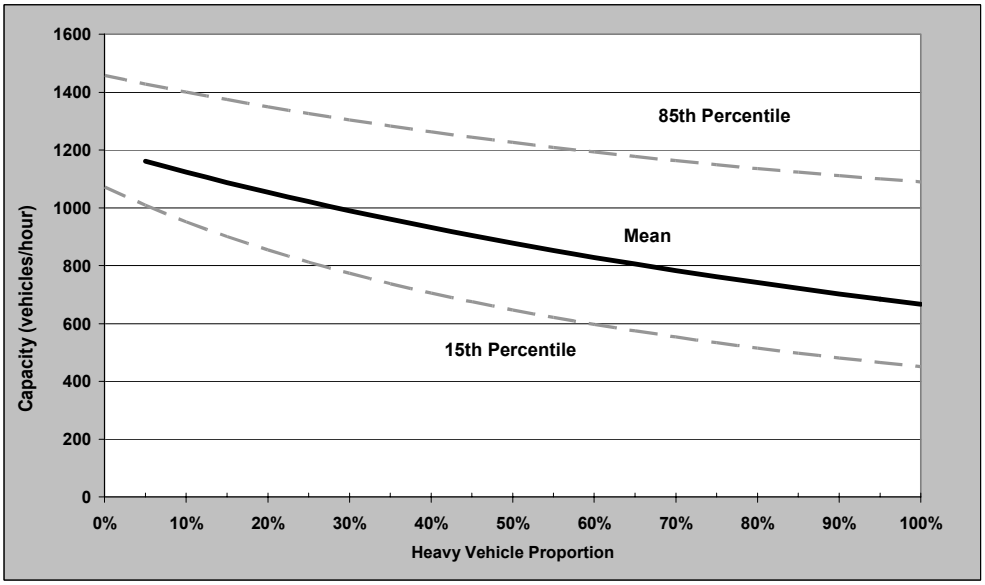

Figure 3 Variation in capacity vs. heavy vehicle percentage based on headway analysis

This relationship is also shown in Figure 3 and reasonable error bounds have also been shown based on the 15th and 85th percentiles for each headway type. However, considering this estimate of capacity based on mean headways in the context of the wide variation in the direct capacity observations discussed previously, it is obvious that a simple mean does not adequately cover all possible traffic situations. It is also noted that the estimated maximum capacity based on "mean" headways and no heavy vehicles, of approximately 1,200 vehicles/hour, is much less than the commonly used value of approximately 1,750 to 1,800 vehicles/hour. This obviously reflects the wide variation in directly-observed capacities from Figure 2.

It is also possible to derive PCE values for heavy vehicles based on these headway and capacity estimates. It was found that the PCE for heavy vehicles ranged between 1.7 and 1.8, depending upon the proportion of heavy vehicles and therefore the relative proportions of different headway types (following combinations). Again, naïve application of these values is not recommended.

The variations in capacity evident in Figure 2 among the various work zone sites and among data points at the same site, given that the sites themselves were quite similar and the conditions under which data was collected were similar, suggests that there is another significant factor influencing work zone operations. One possibility, based on anecdotal evidence and personal observation, is that the capacity of a given work zone might vary depending on the nature of the merging process upstream of the lane drops. If vehicles are able to merge smoothly ahead of the lane drops without causing traffic in the open lane(s) to come to a complete or virtual stop, one would expect to achieve a higher capacity than if vehicles in the open lane(s) came to a complete or virtual stop to allow vehicles from the dropped lane to merge. There could be a number of factors involved in determining which "regime" a given work zone would operate under. Traffic demand and queue length and duration could be factors as could the effectiveness of advanced warning information, and the level of courtesy/aggression among the drivers. The proportion of heavy vehicles could also influence this behaviour since auto drivers may attempt to get past as many heavy vehicles as possible before being funneled into the work zone.

Capacity Estimation from Micro-simulation

To further understand the factors affecting capacity at the level of the individual vehicle, it was decided to use micro-simulation (VISSIM) to model a generic work zone to assess the impacts of different merging mechanisms and possible operating "regimes" as discussed in the previous section. A VISSIM model was constructed of a generic work zone with a lane reduction from three lanes to a single lane using the standard physical configuration from Figure 1. This model was calibrated to match the observed mean headways through relatively minor adjustments to the various acceleration and headway parameters available in VISSIM. A nominal proportion of 7 per cent heavy vehicles was used for most scenarios tested although several scenarios were assigned higher proportions. The demand was varied dynamically, beginning at 1,200 vehicles/hour and increasing in increments of 25 vehicles/hour every five minutes.

To examine the impact of different merging protocols, different combinations of routing decisions and associated lane-changing distances were evaluated. Lane-changing distance is the distance upstream of a required lane change that drivers will begin to attempt to change lanes. When higher percentages of the traffic stream are assigned an increased lane-changing distance (700 meters), this has the effect of promoting early lane changes and smoother flow through the work zone. When more of the traffic is assigned a reduced lane-changing distance (150 or 75

meters, there is a reduced probability that vehicles will be able to merge before the lane drop, often resulting in the formation of a queue in the dropped lane. When this situation is prevalent, vehicles tend to alternate from the open and dropped lanes when entering the work-zone and vehicles in the open lane may either stop or slow down to allow a vehicle from the dropped lane to proceed in accordance with this informal but often-observed protocol. Table 4 summarizes the various combinations of parameters tested.

Table 4 Lane-changing assumptions by scenario

	Percentage of traffic at given lane-changing distance			Heavy vehicle percentage
Scenario	700 metres	150 metres	75 metres	
1	100	0	0	7
2	0	100	0	7
3	95	5	0	7
4	90	10	0	7
5	80	20	0	7
6	0	0	100	7
7	88	12	0	7
8	0	0	100	20
9	0	0	100	10

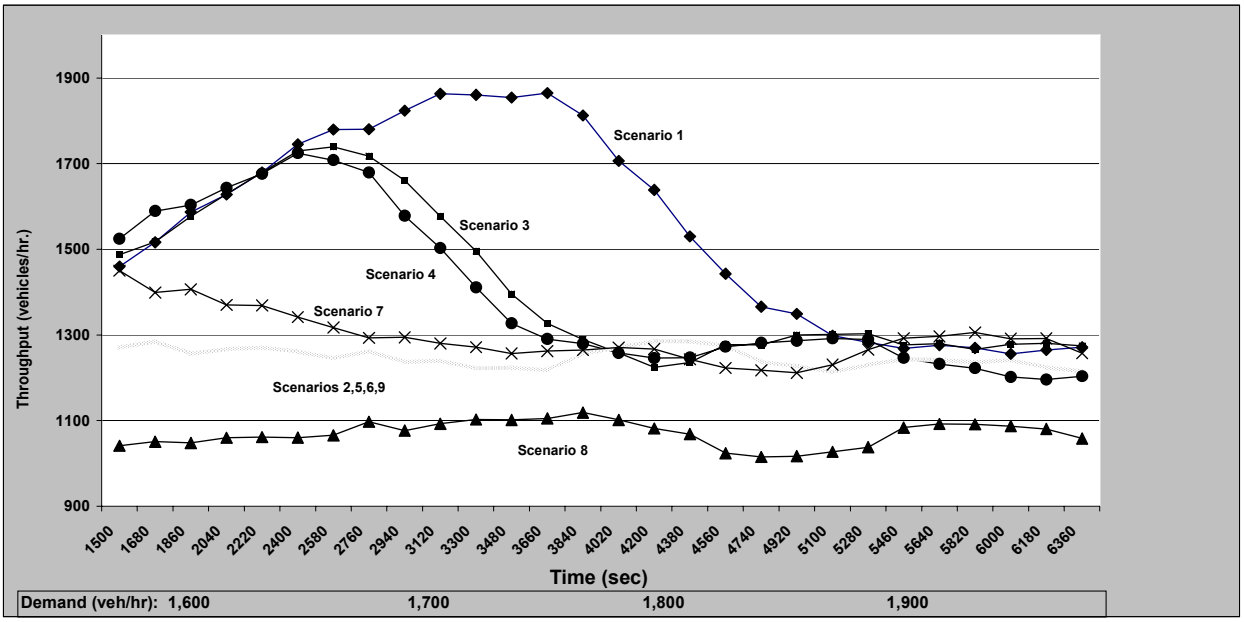

Figure 4 Simulated work zone throughput under different lane-changing assumptions

For scenarios 1,3, and 4, where the proportion of traffic assigned to change lanes early was at least 90 per cent, throughput increased with demand up to a maximum in the range of 1,700 to 1,850 vehicles/hour before further increases in demand brought the throughput down to approximately 1,200 to 1,300 vehicles/hour. At the higher throughputs, vehicles tend to merge smoothly without requiring vehicles in the open lane to stop or slow drastically. Scenario 1, with 100 per cent of vehicles assigned to change lanes early, achieved a throughput at the top end of

this range. When conditions require vehicles in the open lane to stop or slow drastically, the throughputs drop significantly. Scenarios 2,5,6, and 9, with anywhere from 20 to 80 per cent of vehicles assigned to a lane-changing distance of 75 or 150 meters, exhibit a relatively consistent throughput of approximately 1,200 to 1,300 vehicles/hour. Scenario 8, with a higher percentage of heavy vehicles, operated at an even lower throughput of 1,000 to 1,100 vehicles per hour. Scenario 7 represents perhaps an approximate threshold between the "high throughput" and "low throughput" groups, with approximately 12 per cent of vehicles assigned to the shorter lane-changing distances.

Although the throughputs achieved in simulation were generally higher than those observed, the two regimes observed in the simulated results appear to correspond to the two groupings evident in the observed data shown on Figure 2. Differences probably result from factors not considered or from behavioral aspects not included in the simulation model. In addition, the data points shown on Figure 2 are themselves averages which may include stretches of time in both regimes. However, we believe it is reasonable to conclude that the variation in throughput achieved during the site surveys is, in large part, due to the variation in merging protocol at the entrance to the work zone. This cannot be confirmed since the site observations did not include information on merging behaviour. Further surveys, possibly including video-recording, would be beneficial in this regard.

CONCLUSIONS

Observed throughputs at overnight, single-lane work zones on Toronto-area expressways were not consistent with commonly used work zone capacities and varied substantially between sites and between observations at the same site. An analysis of mean headways and capacities derived from these headways found varying headways depending on the following combination of vehicle types but these means do not reflect the wide variation observed. A micro-simulation model was used to analyze the impacts of varying lane-changing behaviour as a possible reason for the wide variation in capacities observed. The simulation results provided evidence of two operating regimes. The first, with throughputs in the range of 1,750 to 1,850 vehicles per hour, corresponded to early lane changing and more-or-less continuous flow in the open lane. The second, with throughputs in the range of 1,000 to 1,300 vehicles per hour, corresponded to late lane changing and alternating vehicle discharge into the work zone from the open and dropped lanes. This study suggests that there is a risk associated with operational planning on the basis of currently-used assumptions concerning work zone capacity. However, additional data collection and analysis are required to confirm the preliminary findings reported here and to develop a methodology for more general application.

References

1. *Highway Capacity Manual*. TRB, National Research Council, Washington D.C., 2000.

2. Krammes, R., and G. Lopez. Updated Capacity Values for Short-Term Freeway Work Zone Closures. In *Transportation Research Record No. 1442*. Transportation Research Board, Washington, D.C., 1994, pp. 49-56.

3. Sun, D., J. Lv, and L. Paul. Calibrating Passenger Car Equivalent (PCE) for Highway Work Zones using Speed and Percentage of Trucks. Presented at 87th Annual Meeting of the Transportation Research Board, Washington, D.C., 2008.

4. Sarasua, W., W. Davis, and M. Chowdhury, J. Ogle. Estimating Interstate Highway Capacity for Short-Term Work Zone Lane Closures. In *Transportation Research Record No. 1948.* Transportation Research Board, Washington, D.C., 2006, pp. 45-57.

5. Al-Kaisy, A., and F. Hall. Guidelines for Estimating Capacity at Freeway Reconstruction Zones. *Journal of Transportation Engineering*, Vol. 129, No. 5 2003, pp. 572-577.

6. Edara, P., B. Cottrell. Estimation of Trafic Mobility Impacts at Work Zones: State of the Practice. Presented at TRB 86th Annual Meeting of the Transportation Research Board, Washington, D.C., 2007.

7. Impact of Trucks on Arterial LOS and Freeway Work Zone Capacity – Part B: Freeway Work Zone Capacity - Lily Elefteriadou, Diego Arguea, Alexandra Kondyli, Kevin Heaslip, Florida Department of Transportation – July 2007.

8. Enberg, A., and M. Mannan. Capacity and Traffic Characteristics at a Freeway Work Zone in Finland. Presented at the Third International Symposium on Highway Capacity, Copenhagen, Denmark, 1998.

9. Ontario Traffic Manual – Book 7, Queen's Printer for Ontario, 2001.