Guidelines for Estimating Freeway Capacity at Long-Term Reconstruction Zones

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ABSTRACT

This paper reports findings from recent investigations into freeway capacity at several long-term reconstruction zones in Ontario, Canada. The aim is to provide guidelines for estimating freeway capacity at reconstruction sites. Findings are presented in two parts. The first involved results of individual investigations to estimate a base (ideal) capacity at freeway reconstruction sites and the individual effect of several important factors that are believed to affect this capacity, namely; the effect of heavy vehicles, driver population, rain, site configuration, work activity at site, and light condition. In the second part, attempts to model work zone capacity are presented. Initially, two types of "site-specific" capacity models were developed using different analytical techniques and data from sites that have the most extensive and comprehensive capacity observations. Finally, a "generic" capacity model for freeway reconstruction sites is proposed based on results from the individual investigations and the site-specific models. The proposed model suggests a base capacity value of 2000 pcphpl for reconstruction sites under favorable conditions. Heavy vehicles and driver population were found to have the most significant effect on capacity. The information presented in this paper can provide valuable guidance to capacity analysis users in estimating freeway capacity at long-term reconstruction sites.

Keywords: freeways, work zones, capacity, bottlenecks, highway construction

1. GENERAL OVERVIEW

Maintenance and reconstruction zones on freeways have become commonplace due to aging infrastructure and the upgrading of existing freeway systems to accommodate the continuous growth in vehicular traffic. These construction activities usually cause serious disruptions to traffic and result in significant delays, increased fuel consumption, and negative impacts on air quality and traffic safety. Estimation of these disruptions is needed to devise traffic control plans at the affected facilities. Accurate estimation of the freeway capacity during reconstruction is critical to the success of traffic management and control plans at work zones.

Work zones on freeways are typically classified into short-term maintenance sites and long-term reconstruction sites. While many similarities exist between the two types of work zones, capacity of long-term freeway reconstruction zones is typically higher than that of short-term maintenance zones. Two factors are believed to contribute to this difference in capacity. First, the use of portable concrete barriers at reconstruction sites provides a better physical separation between the work activity area and the traveled lanes when compared to plastic barrels and cones commonly used at maintenance sites. The second factor is that regular drivers gain familiarity over time with long-term reconstruction sites, a matter that is quite unlikely at short-term maintenance sites.

The literature search conducted for this research showed that the majority of previous studies on freeway work zones have dealt with traffic control and work zone safety *(e.g. 1, 2, 3, 4, 5, 6, 7 to name but a few)* and that only a little information is found on freeway capacity within work zones. Several studies have investigated freeway capacity at short-term maintenance sites *(8, 9, 10, 11, 12)* but only limited

research has been done to investigate the capacity of long-term reconstruction sites *(13, 14).*

This lack of information in the literature is reflected in the limitations in the state of practice for estimating capacity at freeway reconstruction zones. The Highway Capacity Manual (HCM) procedures provide generic estimates for two types of lane closures only, with no guidance as to how these estimates are affected by traffic, geometric and environmental conditions. These estimates, first introduced in the 1985 HCM *(15),* are based on empirical data collected more than two decades ago in the State of Texas at a limited number of sites and range of circumstances *(13).* The treatment of freeway reconstruction zones by the HCM procedures, as represented by these generic estimates, has not been changed in the subsequent versions of the HCM including the HCM 2000 *(16, 17, 18)*.

This paper reports the results of recent investigations into freeway capacity at several long-term reconstruction sites in Ontario, Canada. These empirical results provide valuable information for estimating freeway capacity at reconstruction sites. From that information, we draw some guidelines that can help make such estimates more reasonably and accurately.

2. STUDY SITES

Six long-term freeway reconstruction sites and one normal freeway site with a recurrent bottleneck were investigated:

Site 1: Gardiner Expressway-Westbound (WB) / Toronto

Site 2: Gardiner Expressway-Eastbound (EB) / Toronto

Site 3: HWY 403-Westbound / Hamilton

Site 4: Queen Elizabeth Way (QEW)-Westbound / Burlington

Site 5: QEW / Burlington Bay Skyway (BBS), Toronto-bound

Site 6: QEW / Burlington Bay Skyway (BBS), Niagara-bound

Site 7: QEW at Burloak – EB / Burlington

Site 7 which is a normal freeway site (not a work zone) was investigated as site geometrics, and traffic patterns were suitable for investigating the effect of heavy vehicles on freeways during congestion. A brief description of configuration and data collected at the study sites is provided in Table 1.

3. CAPACITY MEASUREMENT AND UNITS

Freeway capacity at work zones in this research was treated as equivalent to the mean queue discharge flow rate. This approach is considered the most suitable to measure freeway capacity at bottleneck locations as it reasonably represents the maximum sustainable flow *(19, 20).*

Historically, vehicles per hour per lane (vphpl) and passenger cars per hour per lane (pcphpl) have both been used in measuring capacity. However, base capacity values for freeways and other highway facilities, as provided by the HCM, are expressed in pcphpl. It was deemed necessary for this research to measure capacity using standard uniform units. The use of uniform units (passenger cars) allows valid comparisons to be made in investigating the impact of various traffic, weather and geometric factors or in performing comparisons across different sites.

4. COMPONENTS OF A MODEL

Given that the aim of this paper is to produce a model for the estimation of freeway capacity in a reconstruction site, it is appropriate to start by looking at the probable elements of such a model. Other aspects of the HCM procedures for freeways depend upon a base (formerly ideal) capacity, which is then modified by several factors. We follow the same approach in the models in section 5. To that end, in this section we consider each of those elements individually: base capacity, and possible factors, each taken in isolation.

4.1. Base Capacity Estimates

Base (ideal) capacity is to be estimated under a well-defined set of geometric, traffic, and environmental conditions. Under these "base" conditions (same terminology used by the current HCM procedures), the full (base) capacity of a freeway reconstruction zone can reasonably be expected. If any of these conditions fails to exist, capacity will be reduced.

In this study, conditions that were used to derive base capacity estimate are:

1. Traffic predominantly consists of commuter drivers
2. Traffic is entirely composed of passenger cars
3. Daytime light conditions
4. No work activity on site
5. Clear weather conditions (no rain, no snow or extreme winds)
6. Right-side lane closure
7. Level terrain with grades no greater than 2 percent
8. Lane width of at least 12 ft.

Table 2 shows the mean (queue discharge flow) capacity for each of the sites during periods when these conditions were met, as well as the type of lane/shoulder closure and the amount of data used at each site to calculate the mean. Deriving a base capacity estimate using capacity observations from study sites is not an easy task, as these sites have different configurations and may involve slight deviations from "base" conditions. Also, data collected from these sites vary in their extent and comprehensiveness. At the first two sites, capacity was measured using vehicles per hour per lane without any information on the percentage of heavy vehicles in the traffic stream. Further, these same sites lack information on work activity. For those reasons, it was felt that mean capacity estimates at these two sites might not give a reasonable indication of base capacity value.

Also, it is clear that the mean capacity at HWY 403-WB is significantly higher than that at the remaining three sites. One possible reason is that this site does not involve a lane closure (only the right shoulder was closed) thus causing minimal disruption to traffic. Other possible reasons may involve the slight downgrade and the presence of a wide paved left shoulder that provided ample lateral space to traffic. As such, mean capacity at this site may well be above the base capacity of a typical freeway reconstruction site.

The fourth reconstruction site, QEW at Burlington-WB, which is located on a local upgrade, did not involve a lane closure but instead the right and left shoulders were closed providing more restrictive site geometrics. Also, most data was collected while there was ongoing construction activity at site. These factors may explain the much lower mean capacity observed at this site. Therefore, it is logical to expect that base capacity is higher than the mean capacity at this site.

The last two sites, on the Burlington Bay Skyway, have the most extensive and comprehensive data among the sites investigated by this research. Therefore, it was easier to control factors that are not consistent with "base conditions." Mean capacity observations at these sites are in the proximity of 2000 pcphpl. The only factor that may deviate from base conditions is the fact that both sites are located on a 3%, one-kilometer upgrade. However, this effect was accounted for by using the HCM PCE factors for heavy vehicles on specific grades. Hence a reasonable estimate of base capacity at long-term freeway reconstruction zones is 2000 pcphpl.

4.2. Factors Affecting Freeway Capacity at Long-Term Reconstruction Zones

A number of factors have been suggested as important for construction capacity. In previous papers, we have reported on the results of investigations for four such factors:

- Heavy vehicles *(21)*
- Driver population *(22)*
- Light condition (day versus night) *(23)*
- Inclement weather *(24)*

The conclusions from those earlier papers are summarized here to assist in evaluating the factors in the model. Three additional factors have also been investigated for this paper:

- Work activity on site
- Lane closure configuration, and
- Rain

Other factors that might affect work zone capacity, but for which insufficient data are available for analysis are discussed in the final part of this section.

4.2.1. Heavy Vehicles

Extensive capacity data for oversaturated conditions were used to develop PCE factors that were reported in a previous study *(21)*, based on data from sites 5, 6, and 7. An optimization approach was used to develop PCE factors for heavy vehicles by minimizing the variation in capacity (queue discharge flow rate) measured in passenger cars. The results suggest that the effect of heavy vehicles is greater in queue discharge (capacity) flow than during free-flow operation. On level terrain, the study found a mean PCE value of 2.36 for trucks and buses versus 1.5 as provided by Exhibit 23-8 of the HCM 2000 *(18).* On the Skyway, where trucks encounter a 3% one-kilometer upgrade when they start to accelerate at the bottleneck, the mean PCE factor was 3.2 Toronto-bound and 2.7 Niagara bound. The corresponding HCM PCE factor for a 1-km long, 3 percent upgrade is 2.0 *(18).*

In light of these results, a PCE factor (for trucks and buses) of 2.4 is considered reasonable and realistic for use at freeway reconstruction sites on level terrain. For reconstruction sites on specific grades, the equivalency factors developed by this research (level terrain & 1 km 3% upgrade) and the current HCM PCE's can be used to interpolate an approximate equivalency factor. Note that the use of higher PCE factors at freeway reconstruction sites would result in a higher base capacity than the value determined above from the use of the HCM PCE factors.

4.2.2. Driver Population

This factor was investigated using extensive data from sites 5 and 6 *(22),* and limited data from sites 1 and 2 *(24).* Results from these studies were consistent: the reconstruction zone capacity was highest during peak hours, i.e. when traffic consists mainly of commuter drivers. The two studies suggest a capacity reduction of around 7 % during off-peak hours when compared with that during peak hours. Sites 5 and 6 suggest that the reduction is even higher during weekends, and is around 16% compared to weekdays peak-hours.

4.2.3. Light Condition (Day versus Night)

This factor is important as freeway reconstruction projects are increasingly performed during nighttime to mitigate the impacts of construction activities on the traveling public. An investigation into the effect of darkness on freeway reconstruction zones was conducted using data from sites 3 & 4 in fall 1999 *(23).* Study results suggest that freeway capacity at reconstruction sites significantly decreases in the nighttime and that it would be appropriate to expect roughly a 5 % reduction in capacity during nighttime hours, for a facility with good illumination. In this regard, a previous study *(25)* reported a much higher reduction in the capacity of normal freeways (13%-25%) during nighttime in the absence of illumination.

4.2.4. Work Zone Configuration

For the purpose of this research, work zone configuration refers to 1) lane closure configuration, i.e. the number of normal lanes and the number of open lanes within the activity area of the reconstruction site, and 2) location of lanes closed, i.e. closure of

rightmost lanes versus closure of leftmost lanes. When only shoulders are affected by the reconstruction work, closure could involve the right, left, or both shoulders.

Despite the fact that study sites involved a 4-to-2 lane closure, a 3-to-2 lane closure, right-shoulder closure, and both-shoulders closure, the data did not allow investigation of the effect of lane closure configuration on work zone capacity. One of the limitations in the data is that the capacity measured on the Gardiner Expressway sites (3-to-2 lane closures) is expressed in vphpl without information on vehicle classification. This did not allow a valid comparison between these and other study sites with different configurations. A study by Krammes and Lopez *(9)* on short-term freeway maintenance sites investigated capacity at five different lane closure configurations. They concluded that, after adjusting for the percentage of heavy vehicles, there were no statistically significant differences among the capacities of the five configurations investigated.

Location (side) of lane closure was investigated by this research using the Burlington Bay Skyway data. The 4-to-2 lane closure (in both directions of travel) was performed on the right and left sides to allow expansion joint replacement on the Skyway. Table 3 shows work zone capacity for the two types of lane closure, % difference, and t-test results. In general, the percentage difference in work zone capacity between closure of right and left lanes is noticeably higher Niagara-bound than Toronto-bound. A reason for this difference is not obvious. Also, this percentage is higher for total observations and decreases as other variables are controlled (day of week, weather, and work activity). Comparison of the aggregate data (both directions of travel) suggests that this factor could be responsible for a capacity difference of around 6%.

In talking about which side the lane closures occur on, it is important to specify Ontario's policy of forcing the right-hand lanes to do the merging, regardless of the side of the road on which the lanes are closed. If the closure is on the left side, the two higher-speed lanes are guided around to the right after the point at which the two right-hand lanes have already merged into them. This implies that the difference in work zone capacity could be higher should vehicles on left lanes be forced to merge into right lanes.

4.2.5. Weather Conditions

Inclement weather such as heavy rain, snow, and strong winds can have a significant impact on work zone capacity. The 1997 Highway Capacity Manual *(17)* states that rain typically leads to a 10%-20% capacity reduction on normal freeways and that higher reductions are possible.

Two analyses examined the effect of weather conditions. The first was conducted at site 1 and confirmed that wet snow and freezing rain was partly responsible for a significant drop in capacity *(24).* However, observations were made during a Saturday and it was not possible to disentangle the effect of inclement weather and driver population due to limited field data. More extensive and better quality data from sites 5 and 6 was also used to investigate the effect of rain on work zone capacity. The precipitation data collected at the study sites indicates that no heavy rain took place during the period of data collection. A drop in work zone capacity of 4.4% at site 5 and 7.8% at site 6 were observed during rain while controlling other factors such as day of week, location of lane closure, and work activity at site. Both capacity reductions were

found significant at the 95% confidence level. A recent study on the capacity of short-term maintenance sites reported an approximate 10% capacity reduction due to rain at the sites investigated *(12).* Obviously, more extreme weather conditions could have a greater effect on capacity.

4.2.6. Work Activity

The presence of work activity on site and the intensity of this activity are factors that are believed to affect work zone capacity. The intensity of work activity may involve factors such as type of task performed, number of workers on site, size and amount of equipment on site, closeness of equipment and workers to the traveled lanes, type of barriers between the activity area and the traveled lanes, etc. At present, there is no systematic scheme that is used to assess the intensity of work activity at maintenance and reconstruction zones. Most previous studies *(8, 10)* have dealt with work zone intensity in a qualitative and subjective manner due to the complexity of factors involved in assessing the intensity of work activity.

Work zone capacity data with ongoing construction activity was collected at three sites; QEW-WB at Burlington, BBS Niagara-bound, and BBS Toronto-bound. However, the data collected at the first two sites is too limited to allow an adequate investigation of this factor. An investigation of this factor using the BBS - Toronto-bound data was conducted and the results are provided in Table 4. As shown in this table, capacity drop due to the impact of work activity varied in a wide range with values as low as 1.85% and as high as 12.5%. Also, t-test results showed that the capacity drops in only two of the four comparisons were significant at the 95% confidence level. The limited data used for weekends could be behind the relatively small drop in work zone capacity in

the last comparison, but it is hard to explain why commuters would show a 12.7% drop in one comparison and only a 1.85% drop in another one.

4.2.7. Other Factors

Besides the factors discussed in the previous sections, other factors may also contribute to capacity reduction at work zones. The effect of ramps near work zones, especially entrance ramps that are located at the transition area or within the activity area of the work zone, is important in determining work zone capacity. Also, lane width is known to affect work zone capacity if less than the 12 ft width defined for base capacity. Another factor is whether the lane closure layout involves a crossover or not. To date, there has not been sufficient data to investigate the impact of these factors on work zone capacity. However, one previous study on short-term maintenance sites *(9)* suggested that work zone capacity can be reduced by the average volume of entrance ramps located within the transition area or within 500 ft downstream of the beginning of the activity area, but by no more than one half of the capacity of one open lane through the work zone.

5. MODELING WORK ZONE CAPACITY

In the previous section, base capacity estimates and factors that have an impact on work zone capacity were discussed individually. In general, the approach followed was to examine each factor while controlling, as much as possible, the effect of other factors. The next step is to use this information to develop a mathematical model (or models) that could be used to estimate work zone capacity under the effect of various geometric, traffic, and environmental conditions. Two benefits are envisioned by

developing such models; the first is to provide a systematic procedure for estimating work zone capacity, while the second is to investigate the combined effect of two or more variables on capacity, a matter not possible using the individual approach described above. In this regard, an earlier investigation *(24)* confirmed that the combined effect of two or more factors on work zone capacity may not be equivalent to the mathematical sum of individual effects.

5.1. Model Conceptualization

Two model formats were viewed as appropriate candidates for developing the prospective capacity model(s). The first is a multiplicative model where an ideal (base) capacity is multiplied by adjustment factors to account for the impact of various variables. The general form of this model is shown below:

$$C = C_b \times f_1 \times f_2 \times f_3 \times \cdots \times f_n$$

Where:

C = Capacity per lane under given traffic, geometric, and environmental conditions

C_b= Capacity per lane under a pre-specified set of base (ideal) conditions

$f_1, f_2, \ldots, f_n$ = Adjustment factors to account for conditions described as non-base

The form of the model above has been used frequently by the HCM procedures such as the models to estimate the maximum service flow rate on basic freeway sections in the 1985 and 1994 versions of the HCM *(15, 16)*. Also, a recent study on the capacity of short-term maintenance zones presented a model with a similar format *(12).*

The second candidate format is an additive model where the impacts of various variables are added to (or subtracted from) a base (ideal) capacity using a typical regression model. The general form of the additive model is shown below:

$$C = C_b + I_1 + I_2 + I_3 + ... + I_n$$

Where:

C, C_b = As defined above

I_1, I_2, …., I_n = Impacts to account for conditions considered as non-base

The Highway Capacity Manual 1997 and 2000 *(17, 18)* utilize a model with similar format to predict free-flow speed on freeways and multilane highways. Also, two recent studies on the capacity of maintenance work zones proposed models with an additive format *(11, 12).*

5.2. Site-Specific Capacity Models

Due to significant differences among the study sites in terms of data formats and units, geometrics, and configurations, data cannot be aggregated across all sites and used mathematically or statistically to develop a "generic" capacity model. The factors that have been discussed in the previous section are all ones that can and do vary within a site, whereas the differences across sites are ones that are likely to confound any statistical relationship among the ones for which there is data. Hence our approach was to develop capacity models for sites 5 and 6, which had similar conditions and extensive capacity observations. This data involved all the factors that were discussed in section

4.2 except for light condition as data was collected during daylight. A total of 847 15-minute capacity observations at both sites were aggregated and then used in developing additive and multiplicative site-specific models. These site-specific models will then be used with the results of preliminary investigations in developing a "generic" capacity model.

5.2.1. Multiplicative Capacity Model

A multiplicative capacity model was developed using the solver optimization tool in Microsoft Excel. The variables included in this model are driver population, proportion of heavy vehicles, work activity at site, side of lane closure, and rain. The design variables that are used in the optimization procedure involved base (ideal) capacity and adjustment factors for all the variables mentioned above except for heavy vehicles where the equivalency factor was used instead. The multiplicative model took the following form:

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

Where:

C = Work zone capacity (vphpl)

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

f_{HV} = Adjustment factor for heavy vehicles

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

f_{d2} = adjustment factor for weekend driver population (weekend= f_{d2} , else=1)

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

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

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

The adjustment factor for heavy vehicles was computed using the same formula provided by the HCM *(18)*:

$$f_{HV} = \frac{1}{1 + P_{HV}(E_{HV} - 1)}$$

Where:

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

E_{HV} = Passenger Car Equivalency factor used for heavy vehicles

The objective function was to minimize the sum of squared errors which is the same objective function of the least-square regression:

$$f = Minimize \cdot \sum (C_{observed} - C_{estimated})^2$$

In optimization, the following constraints were specified:

C_i <= 2400 pcphpl

C_i >= 1000 pcphpl

E_{HV} >= 1.0

E_{HV} <= 10.0

f_{d1} <= 1.0

f_{d2} <= 1.0

f_w <= 1.0

f_s <= 1.0

f_r <= 1.0

The multiplicative model developed from optimization had the following parameters:

Base capacity = 2050

E_{HV} = 2.778

f_{d1} = 0.961

f_{d2} = 0.825

f_w = 0.966

f_s = 0.943

f_r = 0.976

The coefficient of determination for the above model was found to be 0.63. The base capacity estimate as suggested by this model is reasonably close to that estimated in section 4.1 using capacity observations at the study sites. Also, the equivalency factor for heavy vehicles in this model falls between the equivalency factors that were developed in the two directions of travel using the same data but a different approach *(21).*

The first adjustment factor for driver population (weekdays-off peak) suggests a capacity reduction in the order of 4%. The results in Section 4.2.2 suggested a higher capacity reduction of around 7%. Partitioning the data by individual days in the previous

study (22) may have contributed to this difference in estimating this impact. However, better agreement is demonstrated between the adjustment factor for weekend driver population and the results of that same study. The multiplicative model suggests a capacity reduction of around 17.5% during weekends versus around 16% as suggested by that study.

The adjustment factor for work activity suggests a capacity reduction of around 3.5% due to presence of work activity at site. This value is relatively low when compared with results from the individual investigation (conducted on the same data) and included in Table 3. However, this optimization model controls for the effects of some of the other factors, which could not be done in the Table 3 analysis.
Likewise, the effects of rain and side of lane closure in this model are lower than those found from the individual investigations using the same data. Specifically, this model suggests a capacity reduction of 5.7% due to closure of left lanes (when compared to closure of right lanes), as opposed to a reduction of 8.5% in the individual investigation. Also, the model suggests a capacity reduction in the presence of rain of around 2.5% versus 4.4% Toronto-bound and 7.8% Niagara-bound as suggested by the individual investigation using the same data.

5.2.2. Additive Capacity Model

Multivariate linear regression was used to develop the additive model(s) using the same data previously used in developing the multiplicative model. Most variables included in the regression had binary values (dummy variables) except for heavy vehicles that were represented as a number or percentage. The intercept represented base capacity in passenger cars per hour per lane (pcphpl). The independent variables considered for

inclusion in the additive model are the same as those included in the multiplicative model; i.e. presence of heavy vehicles, driver population, rain, location of lane closure and work activity at site. The interaction between these independent variables was also tested using multiple linear regression and those having significant effect were included in the model. Specifically, the interaction between the following pairs of variables was tested:

1. Work activity on site and commuter driver population
2. Side of lane closure and commuter driver population
3. Work activity on site and weekend driver population
4. Side of lane closure and weekend driver population
5. Rain and commuter driver population
6. Rain and weekend driver population

Only the first and the fifth pairs of variables demonstrated no significant interactive effect on work zone capacity at the 95% confidence level, and were therefore excluded from the proposed model.

Two models were developed; the first with heavy vehicles expressed by their counts (numbers) in the traffic stream, and the second with heavy vehicles expressed as a percentage of total traffic. These models are shown below:

First Model:

$$C = 1950 - 2.33N_{HV} - 134D_1 - 350D_2 - 208W - 134S - 88R + 58SD_1 + 221WD_2 + 64SD_2 + 129RD_2$$

R^2 = 0.55

Std. Error = 105

Second Model:

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

R^2 = 0.68

Std. Error = 89

Where:

C = Capacity in vphpl

N_{HV} = Number of heavy vehicles per hour per lane

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

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

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

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

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

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

SD_1, WD_2, SD_2, and RD_2 = Interactive variables

The second model has a higher coefficient of determination and lower standard error than the first model. This means that the model better explains the variation in the dependent variable and hence is expected to provide a better estimate of work zone capacity. It was surprising to see such a large improvement in the model merely by changing the units of measuring heavy vehicles. This suggests that the heavy vehicles percentage in a traffic stream is better than the absolute number of heavy vehicles in measuring their effect on work zone capacity.

The two regression models provide a base capacity estimate that is slightly lower than, yet still reasonably close to the estimate discussed in section 4.1.

An important observation here is the different effect of heavy vehicles on capacity as suggested by these two models. The first model suggests an effect that is equivalent to a PCE factor of 3.33 while in the second model, this effect is mostly equivalent to a PCE factor that falls in the range of 2.1 to 2.4 (based on capacity range of 1500-1900 vphpl). In light of the value of 2.4 presented in section 4.2.1, it seems that the effect of heavy vehicles may be overestimated by the first model but only slightly underestimated by the second one. Other effects as suggested by the two models are roughly comparable except for the effect of peak-hour driver population (D1) and work activity on site (W), which are considerably lower in the second model.

A direct comparison between the effects of driver population, work activity on site, side of lane closure, and rain as suggested by these two models and the results from individual investigations is not valid due to the presence of interactive variables in the additive models.

An observation that confirms the finding of previous research *(24)* is that the combined effect of two variables may not be additive, i.e. equivalent to the sum of individual effects. This is clear in the last three terms of the two models. As expected, the combined effect of any two variables is less than the sum of the individual effects.

5.3. Proposed Work Zone Capacity Model

In this section, a model to predict long-term reconstruction zone capacity is developed based on the site-specific capacity models presented in the previous section and results from the individual investigations that were included in section 4. Overall, the

multiplicative capacity model at the Burlington Bay Skyway seems the most promising, for two reasons. It provides a reasonable estimate for the effect of heavy vehicles when compared to the additive models, and its multiplicative format is easy to understand. The effects of different variables on capacity are typically expressed as capacity reductions (losses) measured in percentages of base capacity. The coefficient of determination of the multiplicative model is close to that of the second additive model (0.63 versus 0.68) despite the fact that this model does not include interaction effects.

On the other hand, the interaction variables of the additive models were found significant and their inclusion in a "generic" capacity model may be important to improve the accuracy of capacity prediction.

Therefore, a "generic" capacity model would ideally have a multiplicative format and account for the interaction between variables (i.e. those included in the additive models). Also, it should include effects that were investigated by this research but not included fully or partially in the site-specific models (mainly the effect of light conditions and heavy rain). Such a model can be represented by the following formula:

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

Where:

C = Work zone capacity (vphpl)

C_b = Base work zone capacity (pcphpl):

f_{HV} = Adjustment factor for heavy vehicles

f_d = Adjustment factor for driver population

f_w = Adjustment factor for work activity

f_s = Adjustment factor for side of lane closure

f_r = Adjustment factor for rain

f_l = Adjustment factor for light condition

f_i = Adjustment factor for non-additive interactive effects

As discussed in section 4.1, a base capacity of 2000 pcphpl would be an appropriate estimate for use in the generic capacity model. The adjustment factors recommended for use with the proposed model are included in Table 5. The values shown were developed based on the results of the individual capacity investigations and the site-specific models at the BBS sites. A conservative value for nighttime effect (4% versus 5% in the individual investigations) was recommended as it was not possible to test the interaction between this variable and the other variables included in the proposed model. Also, it is clear that lane width, which is used in defining base work zone capacity, is absent from the proposed model. For non-ideal lane widths at reconstruction sites, it is suggested that capacity from the proposed model be adjusted in the same proportions as capacity at normal freeway sections using the current HCM procedures. That more research is needed to investigate freeway capacity at reconstruction sites is evident from the absence of some factors that are expected to affect capacity but have not been addressed (such as lane width), and the partial treatment of some other factors due to limited empirical observations. We hope to be able to extend this work in the future.

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TABLE TITLES

TABLE 1 Description of configuration and data collected at study sites

TABLE 2 Mean capacity observations at the study sites (except site 7) during weekdays peak hours, daylight, and clear weather conditions

TABLE 3 Work zone capacity by location of lane closure (left lanes versus right lanes) at the Burlington Bay Skyway reconstruction sites

TABLE 4 Work zone capacity with and without work activity on site (Burlington Bay Skyway reconstruction sites)

TABLE 5 Recommended adjustment factors for the proposed capacity model

TABLE 1 Description of Configuration and Data Collected at Study Sites

Site	Type of Closure	Form of Data Collected	Data Collection Technique	Data Used		Comments
				Days	Hours	
Gardiner Expressway-WB	3 ---- 2	20-sec volume counts, speeds, & occupancies	Loop Detectors	4	38	• No vehicle classification • No work activity information • Slight downgrade
Gardiner Expressway-EB	3 ---- 2	20-sec volume counts, speeds, & occupancies	Loop Detectors	2	15	• No vehicle classification • No work activity information • Slight upgrade
HWY 403-WB	Right Shoulder	5-min volume counts	Video Recording	9	13	• Slight downgrade • No work activity at site • Wide left shoulder open • HCM PCEs used
QEW at Burlington – WB	Left & Right Shoulders	5-minute volume counts	Video Recording	6	8	• Local upgrade • Work activity on site • HCM PCEs used
QEW at BBS-Toronto-bound	4 ---- 2	15-minute volume counts	Loop Detectors	20	148	• Work activity & weather info • 1 km, 3% Upgrade • HCM PCEs used
QEW at BBS-Niagara-bound	4 ---- 2	15-minute volume counts	Loop Detectors	13	67	• Work activity & weather info • 1 km, 3% Upgrade • HCM PCEs used
QEW at Burloak - EB	No closure	5-minute counts	Video recording	29	51	• Not a reconstruction zone • 3-lane directional mainline • Bottleneck at end of long acceleration lane

TABLE 2 Mean Capacity Observations at the Study Sites (Except Site 7) During Weekdays, Commuter Peak Period, Daylight, and Clear Weather Conditions

Site	Type of Closure	Mean Capacity	Data (hrs)
Gardiner Expressway - WB	3 ---- 2	2102 vphpl	2.3
Gardiner Expressway - EB	3 ---- 2	1950 vphpl	2.3
HWY 403-WB	Right Shoulder	2252 pcphpl	10.5
QEW at Burlington – WB	Left & Right Shoulders	1853 pcphpl	6.7
QEW at BBS-Toronto-bound	4 ---- 2	1989 pcphpl	33
QEW at BBS-Niagara-bound	4 ---- 2	1985 pcphpl	18

TABLE 3 Work Zone Capacity by Location of Lane Closure (Left Lanes Versus Right Lanes) at the Burlington Bay Skyway Reconstruction Sites

	Capacity (pcphpl)		% Difference	t-test
	Right Lanes Closed	Left Lanes Closed		
Total				
All observations	1948	1782	8.5	Significant
No rain, no work activity	1947	1807	7.2	Significant
Weekdays, no rain, no work	1987	1872	5.8	Significant
Toronto-Bound				
All observations	1905	1805	5.2	Significant
No rain, no work activity	1892	1829	3.3	Significant
Weekdays, no rain, no work	1936	1987	2.5	Significant
Niagara-Bound				
All observations	2110	1747	17.2	Significant
No rain, no work activity	2198	1767	19.6	Significant
Weekdays, no rain, no work	2108	1841	12.6	Significant

TABLE 4 Work Zone Capacity With and Without Work Activity on Site (Burlington Bay Skyway Reconstruction Sites)

	Capacity (pcphpl)		% Capacity Drop	Data Sets (Total hrs)	t-test
	No Work Activity	Work Activity			
All observations	1875	1739	7.25	31 (143)	Significant
Weekdays, left-lane closure, no rain	1883	1647	12.7	13 (58)	Significant
Weekdays (AM Peak), right lane closure, no rain	2003	1966	1.85	7 (28)	Not significant
Weekends, left-lane closure, no rain	1659	1621	2.3	3 (15)	Not significant

TABLE 5 Recommended Adjustment Factors for the Proposed Capacity Model.

Adjustment Factor	Recommended Values for Proposed Capacity Model
Heavy Vehicles (f_{HV})	Model utilizes the same HCM formula for heavy vehicles adjustment factor. However, the recommended equivalency factors for trucks and buses at freeway reconstruction sites are: E_{HV} = *2.4 level terrain* E_{HV} = *3.0 3% 1-km upgrade* *For other grades with similar length (around 1-km), linear interpolation may provide a reasonable approximation.* *For specific grades with different lengths, the values for 1-km length may be adjusted in the same proportions calculated using the HCM 2000 equivalency factors for trucks and buses.*
Driver Population (f_d)	f_d = *1.00 peak hours – weekdays* f_d = *0.93 off-peak - weekdays* f_d = *0.84 weekends*
Work Activity (f_w)	f_w = *1.00 no work activity at site* f_w = *0.93 work activity at site*
Side of Lane Closure (f_s)	f_s = *1.00 closure of right lanes* f_s = *0.94 closure of left lanes*
Rain (f_r)	f_r = *1.00 no rain* f_r = *0.95 light to moderate rain* f_r = *0.90 heavy rain*
Light Condition (f_l)	f_l = *1.00 daytime* f_l = *0.96 nighttime with illumination*
Non-Additive Interactive Effect (f_i)	f_i = *1.03 for left-lane closures during weekdays-off peak* f_i = *1.08 for weekends when work activity is present* f_i = *1.02 for left-lane closures during weekends* f_i = *1.05 for rain during weekends* f_i = *1.00 for all other conditions*