Analytical Procedures for Estimating Capacity of Freeway Weaving, Merge, and Diverge Sections

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ABSTRACT

The paper identifies a total of 34 different weaving section configurations that are modeled while operating at capacity using the INTEGRATION software for a wide range of weaving section lengths and travel demand distributions. Subsequently, the simulation results are utilized to develop analytical procedures for estimating the capacity of Type A, B, and C weaving sections. The proposed procedures overcome the shortcomings of the 2000 Highway Capacity Manual procedures by considering short (less than 150 m) in addition to long weaving section lengths, by accounting for the source and distribution of weaving flow, and by ensuring that the capacity of a weaving section reverts to basic freeway capacity when the volume ratio is zero (no weaving flows) regardless of the weaving section length. The model can also estimate the capacity of merge and diverge sections at the appropriate boundary conditions. The paper demonstrates that the proposed model capacity estimates are consistent with field data while the HCM procedures tend to overestimate weaving section capacities significantly (exceeding 100 percent).

Key words: Freeway weaving sections, capacity of freeway weaving sections, freeway capacity modeling, HCM 2000, and INTEGRATION software.

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INTRODUCTION

The freeway weaving analysis procedures in the 2000 Highway Capacity Manual (HCM 2000) are based on research conducted in the early 1970s through the early 1980s (Roess and Ulerio, 2000). Subsequent research efforts have shown that the method's ability to predict the operation of a weaving section is limited (Lertworawanich and Elefteriadou, 2002 and 2004; Rakha and Zhang, 2004), which is most probably due to the outdated and limited database that was utilized to develop these models. To estimate capacity of freeway weaving sections, some other methods, such as gap-acceptance and simulation methods, have been used as alternatives (Lertworawanich and Elefteriadou, 2002 and 2004; Stewart, Baker, and Van Aerde, 1996; Kwon, Lau, and Aswegan, 2000).

At this point it is important to present the definition of capacity that is used in this study and how it is measured. Capacity is defined as the maximum 15-min throughput (summation of mainline and off-ramp flows) that is measured downstream of a merge, diverge, or weaving section prior to traffic stream breakdown. In a simulation model, this measurement is achieved by summing the mainline and off-ramp flows while systematically increasing the traffic demand and maintaining a desired demand distribution until breakdown occurs. Breakdown is defined as a transition from uncongested to congested flow (i.e., a reduction in the weaving section space-mean speed below the speed at capacity).

Prior to describing the specifics of the approach, it is important to define two critical variables, the volume ratio (VR) and a newly defined variable known as the off-ramp weaving ratio (WR). VR is the ratio of the total weaving volume in units of passenger cars per hour (pc/h, ramp-to-freeway plus freeway-to-ramp) to the total demand loaded on the merge, diverge, or weaving section as

$$VR = \frac{v_{FR} + v_{RF}}{v_{FR} + v_{FF} + v_{RF} + v_{RR}}, \qquad [1]$$

where v_{FR} is the freeway-to-ramp volume (pc/h), v_{FF} is the freeway-to-freeway volume (pc/h), v_{RF} is the ramp-to-freeway volume (pc/h), and v_{RR} is the ramp-to-ramp volume (pc/h).

Off-ramp weaving ratio (*WR*) is defined as the ratio of the off-ramp weaving volume (freeway-to-ramp) to the total weaving volume (ramp-to-freeway plus freeway-to-ramp) as

$$WR = \frac{v_{FR}}{v_{FR} + v_{RF}}. \quad [2]$$

It should be noted that this definition is different from the HCM definition of the weaving ratio as will be discussed later in the paper. It should also be noted that both the volume ratio and weaving ratio can range from 0.0 to 1.0 (unitless). A more detailed description of these parameters and the logic behind selecting them is presented later.

This paper utilizes the INTEGRATION 2.30g software to estimate the capacity of weaving sections. The validity of the INTEGRATION software for modeling weaving sections and estimating the capacity of these sections is described in detail in the literature (Rakha and Zhang, 2004; Zhang and Rakha, 2005) and will be summarized later in the paper. Using a wide spectrum of simulation results, a new analytical model for estimating the capacity of weaving sections is developed. Initially, the paper identifies the sub-types and major configurations of weaving sections. Subsequently, a wide range of weaving section traffic demands is modeled using the INTEGRATION software for all identified major configurations. The model results are validated against independent field measurements that are documented in the literature. Finally, a sensitivity analysis is conducted considering different weaving section lengths and different traffic demands.

This paper initially describes the INTEGRATION framework for modeling weaving sections and the validity of this simulation tool for modeling weaving sections. Subsequently, the state-of-the-art studies on the capacity of weaving sections are presented. Then the identified common configurations are introduced, and the related characteristics of these configurations are described. Subsequently, the simulated capacity estimates are compared to the HCM procedure estimates. Afterwards, an analytical model for estimating the capacity of weaving sections is presented and compared to the simulation results, compared to the HCM 2000 procedures, and validated against field data. Finally, the paper presents findings and conclusions of the study.

INTEGRATION FRAMEWORK FOR MODELING WEAVING SECTIONS

The INTEGRATION software is a microscopic traffic simulation and assignment model that can represent traffic dynamics in an integrated freeway and traffic-signal network. The model has been successfully applied since the early 1990s in North America and Europe (Gardes and May, 1993; Bacon, 1994; Hellinga and Van Aerde, 1994; Rakha et al., 1998; Rakha et al., 2000; Rakha and Ahn, 2004; Dion et al., 2004). The INTEGRATION 2.30 lane-changing logic was described and validated against field data in an earlier publication (Rakha and Zhang, 2004). Furthermore, Zhang and Rakha (2005) demonstrated the validity of the INTEGRATION software for estimating the capacity of weaving sections by comparing the software to field-observed weaving section capacities. A brief description of these studies is presented in this section.

To validate INTEGRATION's lane-changing logic, Rakha and Zhang (2004) utilized an empirical data set that was constructed in the late 1980s by the University of California at Berkeley (Cassidy et al., 1990). This data set gathered traffic stream spatial distribution by movement at successive reference points on nine weaving sites. The traffic movements included the four possible Origin-Destination (O-D) demands on freeway weaving sections: Freeway-to-Freeway (FF), Freeway-to-Ramp (FR), Ramp-to-Freeway (RF), and Ramp-to-Ramp (RR). The volume counts were provided at 5-min intervals at a few reference points along the core weaving area. Using these data, the study demonstrated that the lane-changing behavior within a weaving section is a very complicated phenomenon that is affected by many factors including the geometric configuration of the weaving section, the O-D demand, and any upstream and downstream routing constraints. Rakha and Zhang demonstrated a high level of consistency between the INTEGRATION software and field data in the spatial and temporal distribution of lane-change intensity across the weaving lanes and falling within the margin of daily variability (i.e., a margin of error of 250 veh/h). Consequently, the study concluded that the INTEGRATION software was appropriate for the modeling of weaving sections.

Zhang and Rakha (2005) validated the INTEGRATION software weaving section capacity estimates by comparing them to field-observed capacities. The study concluded that the capacity estimates of the

INTEGRATION software were consistent with field data both in terms of magnitude and trends (mean relative error less than 5%). Furthermore, the results demonstrated that the INTEGRATION capacity estimates were superior to the CORSIM and gap acceptance model estimates (Lertworawanich and Elefteriadou, 2002 and 2004) when compared to field data. In addition, the study demonstrated that the weaving ratio, which is defined in the HCM as the ratio of the lowest weaving volume to the total weaving volume, has a significant impact on the capacity of weaving sections. Unfortunately, the weaving ratio is not considered in the HCM 2000 capacity procedures. Furthermore, the study demonstrated that the impact of weaving section length on the capacity of weaving sections increases as the length of the weaving section decreases and the traffic demand increases. The study also showed no evidence that the speed differential between the freeway and ramp traffic has a significant impact on weaving section capacities. Finally, the study demonstrated that the HCM procedures accounting for heavy duty vehicle impacts on weaving section capacities are valid and reasonable.

STATE-OF-THE-ART WEAVING ANALYSIS PROCEDURES

A literature review found a limited number of publications related to this study. For example, Zarean and Nemeth (1988) utilized the WEAVSIM microscopic simulation model to investigate the effect of different arrival speeds on the operation of uncongested weaving sections. Subsequently, the researchers developed a regression model for the modeling of weaving sections based on the simulation results. The simulation results demonstrated that the speed differential between the mainline and on-ramp arrivals had a significant effect on the operation of uncongested weaving sections, which was not considered in the 1985 HCM procedures and is not considered in the current HCM 2000 procedures (HCM, 2000). Zhang and Rakha (2005) demonstrated that the speed differential between freeway and ramp traffic has a minimal impact on the capacity of weaving sections given that, at capacity, vehicles are typically not traveling at free speed. Consequently, while the speed differential may have a significant impact on the operation of weaving sections during uncongested conditions, these impacts are minimal at capacity.

Skabardonis et al. (1989) used the Federal Highway Administration Integrated Traffic Simulation (INTRAS) microscopic simulation software to evaluate the operation of a few major freeway weaving sections. INTRAS was modified to predict the speeds of weaving and non-weaving vehicles and was applied to eight major freeway weaving sections. Vehicle speeds within the weaving sections were compared to a few analytical procedures that included the 1985 HCM procedure, Leisch's procedure, JHK's procedure, Fazio's Procedure, and the Polytechnic Institute of New York (PINY) procedure. Skabardonis et al. concluded that the INTRAS speed predictions were closer to the field measurements than the analytical procedure speed predictions. In addition, Skabardonis et al. concluded that simulation tools could be utilized with field data to enhance existing state-of-the-art analytical procedures for the modeling of weaving section operations.

Stewart et al. (1996) evaluated the capability of INTEGRATION version 2.0 to model weaving sections. The study showed that both the 1985 HCM procedure and INTEGRATION offered identical conclusions for a given sample problem. However, Stewart's study demonstrated differences between the two approaches on critical design parameters of weaving sections. Specifically, INTEGRATION identified the number of lanes in the core area as a critical factor that affects the capacity of weaving sections, which was not and still is not captured in the HCM 2000 procedures. Alternatively, while the HCM 1985 procedures demonstrated that the length of the core area was critical in the design of weaving sections, the INTEGRATION results demonstrated that this factor was critical for short lengths but was less critical as the weaving section length increased. Later, Al-Kaisy et al. (1999a, 1999b, and 1999c) used the INTEGRATION 2.0 software to estimate the capacity of weaving, merge, and diverge sections. These studies, however, did not develop analytical procedures for the estimation of weaving sections.

Vermijs (1998) reported on developing the Dutch capacity standards for freeway weaving sections using Freeway Operations SIMulation (FOSIM), a microscopic simulation software developed in the Netherlands. Specifically, a total of 315 Type A weaving sections with different configurations and traffic factors were simulated. All simulation runs were repeated 100 times using different random seeds. The 100 simulation results for capacity appeared to be normally distributed with standard deviations in the range of about 200 to 400 veh/h/lane.

Finally, Lertworawanich and Elefteriadou (2002, 2003) proposed an analytical capacity estimation method for weaving sections based on gap acceptance and linear optimization techniques. It should be noted, however, that the gap acceptance method makes a number of simplifying assumptions that limit the applicability of the procedures. For example, the procedures are insensitive to the effect of the weaving section length on the capacity of weaving sections.

The research effort presented in this paper extends the state-of-the-art procedures for estimating the capacity of concentrated turbulent flow regions including weaving, merge, and diverge sections first by identifying a set of critical variables affecting the capacity of such sections. Subsequently, the study develops analytical models for the estimation of the capacity of merge, diverge, and weaving sections.

EXPERIMENTAL DESIGN

According to the HCM 2000, it is the lane changing required of weaving vehicles within a weaving section that characterizes Type A, B, and C weaving sections. Specifically, if both of the weaving movements can be achieved by making at least one and only one lane change, such a section is characterized as a Type A weaving section. Types B and C weaving sections include a weaving movement that does not require any lane changes. While Type B weaving sections have a second movement that requires at most a single lane change, Type C weaving sections require at least two lane changes.

Fig. 2 illustrates the identified configurations for weaving sections. Three ramp (Ax1, Ax2, and Ax3) and two major weave (Ay1 and Ay2) configurations are identified within Type A weaving sections. The ramp configurations provide an opportunity to model merge and diverge sections by setting either the FR or RF demand to zero, respectively. Furthermore, the study considers three sub-types of Type B weaving sections (Bx, By, and Bz). Sub-type Bx weaving sections require only one lane change for the FR movement and no lane changes for the RF movement, while Sub-type By weaving sections involve no required lane changes at the entry gore with a required lane change at the exit gore due to an imbalance in the exit versus entry lanes. Sub-type Bz weaving sections require no lane changes at the entrance and exit gores because there is lane balance between entry and exit sections. Because Type B weaving sections may typically have three, four, or five lanes in the core area, a total of 18 configurations are investigated. For Type C weaving sections, two subtypes are identified according to the minimum number of lane changes required by the two weaving movements. Sub-type Cx weaving sections require no lane changes for the FR movement and at least two lane changes for the RF movement, while Sub-type Cy requires at least two lane changes for the FR movement and no lane change for the RF movement.

In terms of the simulation runs, the input free-flow speed along the freeway was set at 110 km/h (69 mi/h), while the free-flow speed on the ramps was set at 90 km/h (56 mi/h) if the ramp was a single lane; otherwise, the ramp free-flow speed was set at 110 km/h. No heavy vehicles were considered as part of the analysis because Zhang and Rakha (2005) demonstrated that the heavy vehicle factor within the HCM 2000 procedures efficiently captures the effects of heavy vehicles on the capacity of weaving sections and thus does not require further enhancement. It should be noted that Zhang and Rakha (2005) demonstrated that the on- and off-ramp free-flow speeds have minimum impacts on weaving section capacities. Consequently, no further analysis of different on- and off-ramp free-flow speeds was conducted. The lane capacity was set at 2,350 and 2,000 veh/h/lane for facilities with free-flow speeds of 110 km/h and 90 km/h, respectively, which is consistent with the HCM 2000 procedures. The speed-at-capacity was set at 80% of the free speed, which has been demonstrated to be the norm on North American freeways (Van Aerde and Rakha, 1995). It should be noted that the lane capacity values that are input to the INTEGRATION software represent an ideal capacity in the absence of lane changing. The introduction of lane changes within the traffic stream reduces this base capacity in a fashion that is proportional to the level of turbulence within merge, diverge, or weaving sections. By comparing the maximum system throughput to the input base capacity, one can compute the reduction in capacity as a result of traffic stream turbulence.

The first step in this study was to simulate all configurations in INTEGRATION considering different weaving section lengths and different O-D demand distributions. Weaving section lengths of 50, 75, 100, 150, 300, 450, 600, and 750 m were considered in the study, which covers the maximum range of the HCM 2000 procedures in addition to lengths shorter than what is considered in the HCM procedures. Different

O-D patterns were considered by changing the mix of FF, FR, RF, and RR demands as illustrated by the dots in the example illustration of Fig. 3 for Type A weaving sections. An attempt was made to cover the entire possible range of O-D demands, including the extreme conditions (curved lines in figure) when the weaving section converges to a basic freeway, a merge section, or a diverge section as in the case of the Ax configurations. The coverage of these extreme conditions ensures that the modeling of weaving section capacity is consistent with the modeling of basic freeway, merge, and diverge sections because these scenarios represent a special case of a weaving section O-D demand. Specifically, a merge scenario includes only FF and RF demands while a diverge scenario includes only FF and FR demands.

SIMULATION RESULTS AND PROPOSED MODEL

As was discussed earlier, the lack of comprehensive procedures in the literature demonstrates the need to develop comprehensive analytical procedures for estimating the capacity of merge, diverge, and weaving sections. This section describes sample results derived from the study together with the proposed analytical models for the estimation of the capacity of weaving sections. In addition, the HCM 2000 capacity estimates are presented for comparison and illustration purposes. The results are validated by comparison to independent field measurements that were obtained from the literature. An example illustration of the proposed model is presented followed by a demonstration of how the model can be utilized to estimate merge and diverge section capacities.

For each configuration, a wide variety of traffic conditions and core weaving section lengths were simulated using the INTEGRATION software. The resulting capacities were derived as the maximum 15-min flow rate through the weaving section by increasing the O-D demand while maintaining the same O-D demand distribution (i.e., same percentage of FF, FR, RF, and RR demands). The HCM capacities were calculated according to the capacity tables (Exhibit 24-8) in Chapter 24 of the HCM 2000 using interpolation. Since the HCM 2000 procedures do not cover weaving section lengths of 50, 75, and 100 m and only consider a maximum volume ratio of 80%, the simulation scenarios go beyond the confines of the HCM procedures.

To produce results that can be generalized to account for different base lane capacities, a capacity reduction factor that captures the reduction in the base capacity as a result of traffic stream turbulence is computed. This factor, when multiplied by the base capacity upstream of the weaving section, provides an estimate of the weaving section capacity. The normalized capacity factor is computed as the maximum section throughput divided by the base input capacity of the roadways directly upstream of the weaving section (sum of upstream freeway and on-ramp capacities). For example, the base capacity directly upstream of the weaving section for configuration Bx1 is 9,400 veh/h (2×2,350 + 2×2,350). It should be noted that a factor of 1.0 reflects a maximum throughput that is equal to the base capacity of the entry section. In some instances, the capacity of the weaving section is governed by the capacity of the outbound roadways, as opposed to the inbound roadways, and thus the reduction factor may potentially be less than 1.0 when the volume ratio is set to zero (sum of RF and FR volumes equals 0).

Numerous researchers have argued that roadway capacity is stochastic, and thus the use of a single capacity estimate may not be appropriate. By considering a capacity reduction factor, the weaving section capacity can be easily computed as a stochastic variable by varying the base input capacity. For example, if we consider the capacity of a Bx1 weaving section to vary between 8,000 and 10,000 pc/h, using a capacity reduction factor of 0.5, the weaving section capacity could vary between 4,000 and 5,000 pc/h.

Comparison of Simulated and HCM Capacity Estimates

For ease of comparison, the capacities derived from the HCM procedures are also normalized to compute capacity reduction factors similar to those described earlier. Due to space limitation, the results for only three configurations are illustrated in Fig. 4. The figure clearly demonstrates that the differences between the simulated and HCM capacity estimates are significant in both absolute values and trends. For example, the HCM procedures demonstrate that the volume ratio has no impact on the weaving section capacity for small volume ratios for a 450-m Cx1 configuration. Furthermore, the simulated capacity estimates demonstrate a zigzag pattern that may appear as noise in the data at first glance; however, these oscillations reflect the impact of other factors, not included in the graph, on the weaving section capacity, including the off-ramp weaving ratio (ratio of off-ramp weaving volume to the total weaving volume). Zhang and Rakha (2005) demonstrated that the weaving ratio does have a significant impact on the capacity of freeway weaving sections.

The figure also clearly demonstrates that the HCM capacity estimates are significantly greater than the simulated capacity estimates for most of the configurations. Given that calibrated INTEGRATION weaving section estimates have been demonstrated to be consistent with field data (Zhang and Rakha, 2005), it is fair to conclude that the HCM procedures tend to overestimate the capacity of weaving sections. This conclusion will be verified later in the paper using independent field data.

Proposed Weaving Section Capacity Model

From the literature discussed above and empirical analysis, it is obvious that enhancements to the HCM procedures are required to develop more accurate procedures for estimating the capacity of weaving sections. As part of this study, a simplistic mathematical function is developed to estimate the reduction in roadway capacity caused by traffic stream turbulence. Prior to describing the model, the relationships between the capacity factor and various influencing factors, including the volume ratio, weaving ratio, and weaving section length, are analyzed separately.

As illustrated Fig. 5, the underlying relationship between the volume ratio and capacity factor can be characterized by an exponentially decaying function as

$$F_1 = \mathrm{a}_0 \cdot e^{t \cdot VR}, \qquad [3]$$

where F_1 is the component of the capacity reduction factor that is associated with the weaving section length, VR is the volume ratio, and a_0 and t are weaving-section-specific model coefficients that require calibration. The relationship between the constant t in Equation [3] and the weaving section length (x) was found to follow a logarithmic function as

$$t = a_1 \ln x + a_2, \qquad [4]$$

where a_1 and a_2 are model coefficients and x is the weaving section length in meters. Combining Equations [3] and [4], the relationship between the F_1, VR, and x can be expressed as

$$F_1 = a_0 \cdot e^{(a_1 \ln x + a_2)VR}. \quad [5]$$

It should be noted that in most cases, the exponent is negative, and thus an exponential decay function is typically established. However, in some rare instances, for example the Cx1 configuration, the exponent is not necessarily negative, as illustrated in Fig. 4. The need to capture other underlying functions and the oscillations that are observed in the simulated results of Fig. 4 necessitate the introduction of a second term. In this term we use the WR variable that was presented earlier in Equation [2] to reflect the asymmetric nature of the weaving ratio. The second adjustment factor is computed as

$$F_2 = \sin(a_3 \cdot WR - a_4) \cdot \sin(a_5 \cdot VR), \quad [6]$$

where F_2 is the component of the capacity reduction factor accounted for by the weaving ratio, and a_3, a_4, and a_5 are model coefficients calibrated for specific weaving section configurations. The function of Equation [6] also introduces a sine function of the VR to allow the model to capture underlying trends other than exponentially decaying functions, as demonstrated in the results of the Ax1 weaving section in Fig. 5.

The final turbulent flow capacity reduction factor (F), which ranges between 0.0 and 1.0, is estimated as

$$F = a_0 \cdot e^{(a_1 \ln x + a_2)VR} + \sin(a_3 \cdot WR - a_4) \cdot \sin(a_5 \cdot VR). \quad [7]$$

Apart from the a_3 coefficient in configuration Bz1, all model coefficients were statistically significant. However, in order to maintain the same structure across all models, the a_3 coefficient was not removed from the Bz1 model. Table 1 demonstrates a very high-quality fit to the data, with coefficients of determination in excess of 93%.

Sample model predictions superimposed on the simulation results and HCM capacity factor predictions clearly demonstrate the efficiency of the proposed analytical model in capturing the impact of the various variables on the capacity of weaving sections, as illustrated in Fig. 5. The figure also demonstrates that the

HCM procedures not only produce much greater capacity estimates but also are unable to capture the impact of the source of weaving flow on the capacity of weaving sections.

Model Validation

In order to quantify the differences between the simulated capacity estimates and the various analytical model estimates, the models were compared for all configurations. Four error measures were estimated for each data set: the mean relative error (MeRE), the maximum relative error (MaRE), the mean absolute error (MeAE), and the maximum absolute error (MaAE). These errors were computed as

$$MeRE_{A-B} = \sum_{i=1}^{n}\left(|y_A - y_B| / y_S\right) \Big/ n, \quad [8]$$

$$MaRE_{A-B} = \max\left(|y_A - y_B| / y_S\right), \quad [9]$$

$$MeAE_{A-B} = \sum_{i=1}^{n}\left(|y_A - y_B|\right) \Big/ n, \text{ and} \quad [10]$$

$$MaAE_{A-B} = \max\left(|y_A - y_B|\right). \quad [11]$$

where y_s is the simulated capacity factor, y_A and y_B represent the capacity-factor estimates for two scenarios being compared (potential scenarios include simulation results, HCM, and proposed model), and n is the number of observations analyzed for each scenario.

The results demonstrated that the difference between the proposed model and simulated capacity factors was the smallest among all three comparisons. Specifically, the average MeRE was 6%, 6%, and 12% for Type A, B, and C weaving sections, respectively, which represents a considerable improvement over the HCM model estimates (average MeRE of 50%, 57%, and 105% for Type A, B, and C weaving sections, respectively).

In addition to validating the results against simulated data, further validation was conducted using independent field measurements obtained from the literature (Lertworawanich and Elefteriadou, 2004). The first site was a Type B weaving section on the Queen Elizabeth Way (QEW) in Toronto, Canada. The weaving section had the geometry of configuration Bx4 with a length of 550 m. The posted speed limit on the QEW was 100 km/h at the time of the study with a 10% heavy vehicle population. The selected site operated under congested conditions because of the intense lane-changing behavior within the weaving section. The section capacity and total traffic demand classified by on-ramp, off-ramp, upstream mainline, and downstream mainline flows were recorded in a data set. The weaving section capacity was computed as the maximum observed pre-breakdown, 15-min flow rate and was recorded for a total of 10 days. Using the traffic volumes on all four legs of the weaving section, a range of possible O-D demands was deduced. Using these O-D demands, capacity factors were computed using the HCM procedures and the proposed model, as illustrated in Fig. 6. The results clearly demonstrate a good match between the proposed model capacity-reduction factors and the field-observed factors. The figure also clearly demonstrates that the HCM procedures tend to overestimate the capacity reduction factors.

The models were also tested on two Type C weaving sections on the QEW. One of these sections had the geometry of configuration Cx4 with a length of 550 m, and the other had the geometry of configuration Cx2 with a length of 500 m. Again, the posted speed limit on these roadway segments was 100 km/h at the time of the study with a 10% heavy-vehicle population. The sites operated under congested conditions because of the intense lane-changing behavior within the weaving section. It is worth mentioning that the lane capacity of these two weaving sections was high compared to the HCM recommended values. Specifically, the capacity data obtained from Lertworawanich and Elefteriadou (2004) were 2,644 veh/h/lane and 2,884 veh/h/lane for the ramp and freeway lanes, respectively, even with 10% heavy vehicles. By assuming a passenger car equivalency (pce) of 1.5 for trucks and using the two maximum throughput rates, the lane capacities for on-ramp and freeway lanes were set as 2,777 pc/h/lane and 3,029 pc/h/lane, respectively. The results of the validation of these two weaving sections are illustrated in Fig. 6. The results clearly demonstrate that the proposed model capacity bands enclose the field-observed capacities for most of the observations. Alternatively, as was the case with Type B weaving sections, the HCM procedures tend to overestimate the weaving section capacities for both weaving section configurations. It should be noted that the gray bands reflect the range of values depending on the assumption of the Origin-Destination (O-D) demand patterns. Finally, the figure demonstrates that the HCM procedures may produce capacity reduction factors in excess of 1.0 at the boundary conditions, which highlights an inconsistency between the HCM base freeway and weaving section procedures.

The results of the study are consistent with the findings of Lertworawanich and Elefteriadou (2004) and Zhang and Rakha (2005) who demonstrated that the HCM 2000 procedures tend to overestimate the capacity of Type B weaving sections. Consequently, we conclude that the HCM 2000 procedures overestimate the capacity of weaving sections and that the proposed models provide capacity estimates that are more consistent with field data.

Example Illustration

In order to demonstrate how the proposed model can be applied for the estimation of weaving section capacities, an example illustration is presented in Fig. 1. Five steps are required: (1) estimate passenger car flows, (2) compute VR and WR, (3) determine the configuration type, (4) compute the capacity factor, (5) compute the incoming capacity, and (6) compute the weaving section capacity. The estimation of passenger car equivalent flow is based on the HCM 2000 procedures, which were demonstrated to be reasonable in an earlier study (Zhang and Rakha, 2005). The volume and weaving ratios are computed using Equations [1] and [2], respectively. The configuration type is done by matching the study section to the configurations illustrated in Fig. 2. Once the configuration is identified, the appropriate model is selected and the capacity reduction factor is computed. The capacity of the incoming legs to the weaving section is then computed, and the weaving section capacity is estimated as 5,734 pc/h. It should be noted that the HCM 2000 procedures estimate the capacity of the weaving section to be 7,258 pc/h.

Estimation of Diverge and Merge Capacities

In order to demonstrate how the proposed models can be utilized to estimate the capacity of merge and diverge sections, we present an example illustration for a single-lane merge/diverge section to a two-lane and then a four-lane highway (configurations Ax1 and Ax3). The results, which are presented in Fig. 7, demonstrate that the capacity reduction caused by traffic-stream turbulence within a merge section is less than that within a diverge section. It should be noted that the capacity reduction factors for diverge sections were adjusted to reflect the absence of upstream on-ramp lanes (multiplied by 6,600/4,600 in the case of the Ax1 configuration). Consequently, although the capacity reduction factors are similar in the case of the two-lane highway, the capacity estimates are lower because the number of lanes upstream of the diverged section are fewer. The reason for the lower capacities at diverge sections can be attributed to the higher intensity of lane-changing maneuvers upstream of the diverge section (potential for up to two lane changes) while merge vehicles make only a single lane change to join the freeway. The results also demonstrate, as would be expected, that the impact of a merge or diverge section on roadway capacity decreases as the number of highway lanes increases. Furthermore, the results demonstrate that merge/diverge section capacities increase as the length of the acceleration/deceleration lanes increase. Finally, it should be noted that the capacity of merge sections may be constrained by the capacity of downstream bottlenecks as is the case for the four-lane highway with an acceleration lane longer than 200 m (maximum capacity of 9,200 veh/h).

Sensitivity Analysis

A simple sensitivity study was conducted using both the proposed model and the HCM 2000 procedures. The first sensitivity analysis characterized the model behavior for different weaving section lengths and volume ratios, as illustrated in Fig. 8. The figure demonstrates that the HCM capacity estimates are only sensitive to the weaving section length when the volume ratio is less than 0.4, which is not the case with the proposed model, where the weaving section length affects the capacity for the full range of volume ratios. Both models indicate that the weaving section capacity is not impacted by its length when the volume ratio is set to zero (i.e., both procedures revert to base freeway capacities at a volume ratio of zero).

The second sensitivity analysis investigated the impact of the weaving ratio on model performance. The curves cover only the valid range of data that were identified earlier in Fig. 3. Because the HCM 2000 procedures ignore the impact of the weaving ratio on roadway capacity, a single curve is illustrated.

Alternatively, the proposed model demonstrates significant differences in capacity estimates as a function of the weaving section weaving ratio. Finally, unlike the HCM 2000 procedures, the analytical model demonstrates a continuous decay in the capacity reduction factor even for low volume ratios.

FINDINGS AND CONCLUSIONS

The paper presents a very simple analytical model for estimating the capacity of weaving sections. The model includes three independent input variables: the weaving section length, the weaving section volume ratio, and a newly defined variable called the freeway weaving ratio ($WR = v_{FR}/(v_{FR}+v_{RF})$). Specifically, the paper introduces a new definition for the weaving ratio that explicitly accounts for the source of the weaving volume. The procedures developed in this study define a number of critical issues. First, the capacity of a weaving section reverts to the bottleneck capacity if the weaving volume ratio is set to zero irrespective of the length of the weaving section. Second, the weaving section capacity reverts to a merge section capacity when WR is zero. Similarly, the weaving section capacity reverts to a diverge section capacity when *WR* is 1.0. The paper demonstrates that the proposed model capacity estimates are consistent with field data. Furthermore, the study demonstrates that the HCM 2000 procedures tend to overestimate weaving section capacities significantly (errors in excess of 100% in some instances).

Further research is needed to study how vehicles behave as they approach a roadway divergence, specifically, a characterization of when and where vehicles select lanes depending on their speed, the availability of gaps in adjacent lanes, the roadway configuration, and routing considerations.

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LIST OF TABLES

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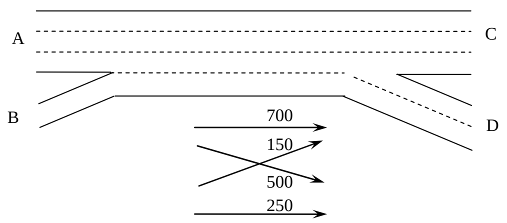
Table 1. Proposed Turbulence Capacity Reduction Models

Scenario	Configuration	Model	R^2
1	Ax1	$F = 0.97e^{(0.13\ln x - 2.49)VR} + \sin(2.43WR - 5.45)\sin(0.52VR)$	0.980
2	Ax2	$F = 1.00e^{(0.11\ln x - 2.94)VR} + \sin(1.24WR - 4.38)\sin(1.13VR)$	0.982
3	Ax3	$F = 1.00e^{(0.12\ln x - 3.70)VR} + \sin(0.93WR - 4.11)\sin(1.70VR)$	0.987
4	Ay1	$F = 0.96e^{(0.27\ln x - 3.84)VR} - \sin(0.01WR + 3.41)\sin(1.96VR)$	0.951
5	Ay2	$F = 0.95e^{(0.34\ln x - 4.27)VR} + \sin(0.14WR - 3.47)\sin(2.02VR)$	0.967
6	Bx1	$F = 0.98e^{(0.21\ln x - 2.91)VR} + \sin(0.28WR - 3.47)\sin(2.53VR)$	0.987
7	Bx2	$F = 1.00e^{(0.31\ln x - 4.05)VR} + \sin(0.34WR - 3.57)\sin(2.53VR)$	0.988
8	Bx3	$F = 0.97e^{(0.19\ln x - 2.63)VR} + \sin(0.14WR - 3.29)\sin(2.69VR)$	0.981
9	Bx4	$F = 0.97e^{(0.12\ln x - 1.76)VR} - \sin(0.11WR + 3.08)\sin(3.89VR)$	0.987
10	Bx5	$F = 0.96e^{(0.09\ln x - 1.32)VR} + \sin(0.23WR - 3.25)\sin(3.80VR)$	0.983
11	Bx6	$F = 0.96e^{(0.09\ln x - 1.33)VR} - \sin(0.23WR + 3.02)\sin(3.77VR)$	0.984
12	Bx7	$F = 0.98e^{(0.20\ln x - 2.67)VR} - \sin(0.04WR + 3.19)\sin(2.61VR)$	0.988
13	Bx8	$F = 0.96e^{(0.11\ln x - 1.88)VR} - \sin(0.15WR + 3.07)\sin(4.36VR)$	0.980
14	By1	$F = 0.73e^{(0.24\ln x - 3.87)VR} + \sin(0.34WR - 3.54)\sin(2.24VR)$	0.961
15	By2	$F = 0.73e^{(0.14\ln x - 2.04)VR} + \sin(0.36WR - 3.29)\sin(4.37VR)$	0.965
16	By3	$F = 0.76e^{(0.10\ln x - 1.77)VR} + \sin(0.18WR - 3.20)\sin(7.50VR)$	0.958
17	By4	$F = 0.83e^{(0.42\ln x - 6.17)VR} + \sin(0.51WR - 3.70)\sin(2.40VR)$	0.976
18	By5	$F = 0.77e^{(0.21\ln x - 3.45)VR} - \sin(0.09WR + 3.27)\sin(2.77VR)$	0.958
19	By6	$F = 0.77e^{(0.09\ln x - 1.91)VR} + \sin(0.22WR - 3.23)\sin(6.12VR)$	0.932
20	Bz1	$F = 0.73e^{(0.09\ln x - 1.82)VR} + \sin(0.02WR - 3.21)\sin(2.16VR)$	0.958
21	Bz2	$F = 0.77e^{(0.18\ln x - 3.09)VR} - \sin(0.13WR + 3.24)\sin(2.59VR)$	0.971
22	Bz3	$F = 0.77e^{(0.16\ln x - 2.28)VR} - \sin(0.19WR + 3.08)\sin(4.15VR)$	0.975
23	Bz4	$F = 0.76e^{(0.11\ln x - 2.01)VR} + \sin(0.07WR - 3.16)\sin(8.19VR)$	0.939
24	Cx1	$F = 0.58e^{(0.07\ln x - 0.28)VR} - \sin(1.33WR + 2.15)\sin(1.53VR)$	0.979
25	Cx2	$F = 0.74e^{(0.26\ln x - 2.96)VR} - \sin(0.58WR + 3.09)\sin(2.40VR)$	0.932
26	Cx3	$F = 0.67e^{(0.01\ln x + 0.35)VR} - \sin(1.72WR + 1.57)\sin(1.38VR)$	0.982
27	Cx4	$F = 0.75e^{(0.25\ln x - 2.67)VR} - \sin(0.35WR + 3.10)\sin(2.55VR)$	0.938
28	Cx5	$F = 0.78e^{(0.38\ln x - 3.96)VR} - \sin(0.52WR + 3.12)\sin(2.37VR)$	0.955
29	Cy1	$F = 0.59e^{(0.17\ln x - 2.98)VR} + \sin(0.74WR - 3.73)\sin(2.38VR)$	0.964
30	Cy2	$F = 0.71e^{(0.04\ln x - 0.92)VR} + \sin(0.64WR - 3.39)\sin(2.76VR)$	0.979
31	Cy3	$F = 0.74e^{(0.15\ln x - 2.18)VR} + \sin(0.35WR - 3.42)\sin(2.88VR)$	0.951
32	Cy4	$F = 0.77e^{(0.10\ln x - 2.21)VR} + \sin(0.67WR - 3.62)\sin(2.49VR)$	0.983
33	Cy5	$F = 0.82e^{(0.24\ln x - 3.48)VR} + \sin(0.33WR - 3.52)\sin(2.58VR)$	0.957
34	Cy6	$F = 0.77e^{(0.10\ln x - 1.39)VR} + \sin(0.14WR - 3.21)\sin(5.43VR)$	0.957



Input:
Volume (A-C) = 700 veh/h - Volume (A-D) = 500 veh/h
Volume (B-C) = 150 veh/h - Volume (B-D) = 250 veh/h
15 percent trucks - PHF = 0.85 - Rolling terrain - Drivers are regular commuters
FFS = 100 km/h for freeway - Capacity of 2,000 pc/h for on-ramp - Weaving section length = 300 m

1. Convert volumes into passenger car flows	$v = \dfrac{V}{(PHF)(f_{HV})(f_p)}$ f_p = 1.0 $f_{HV} = \dfrac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)} = \dfrac{1}{1 + 0.15(2.5 - 1)} = 0.816$ $v(\text{A-C}) = \dfrac{700}{(0.85)(0.816)(1.0)} = 1{,}009 \text{ pc/h}$ $v(\text{A-D}) = 721 \text{ pc/h}$, $v(\text{B-C}) = 216 \text{ pc/h}$, $v(\text{B-D}) = 360 \text{ pc/h}$
2. Compute critical variables	$v_w = 721 + 216 = 937 \text{ pc/h}$ $v_{nw} = 1{,}009 + 360 = 1{,}369 \text{ pc/h}$ $v = 937 + 1{,}369 = 2{,}306 \text{ pc/h}$ $VR = \dfrac{937}{2{,}306} = 0.406$ $WR = \dfrac{721}{937} = 0.769$ (different from HCM definition)
3. Determine configuration type	Bx4
4. Compute capacity factor	$F = 0.96e^{(0.14\ln x - 1.77)VR} - \sin(0.11WR + 3.08)\sin(7.02VR)$ $F = 0.96e^{(0.14\ln(300) - 1.77)0.406} - \sin(0.11 \times 0.769 + 3.08)\sin(7.02 \times 0.406)$ $F = 0.96e^{-0.394} - \sin(3.165)\sin(2.85)$ $F = 0.96 \times 0.674 - 0.055 \times 0.050 = 0.644$
5. Compute incoming capacity	$C_{\text{incoming}} = 2{,}300 \times 3 + 2{,}000 = 8{,}900 \text{ pc/h}$
6. Compute weaving section capacity	$\text{Capacity} = F \times C_{\text{incoming}} = 0.644 \times 8{,}900 = 5{,}734 \text{ pc/h}$

Fig. 1. Example Illustration of Proposed Procedure

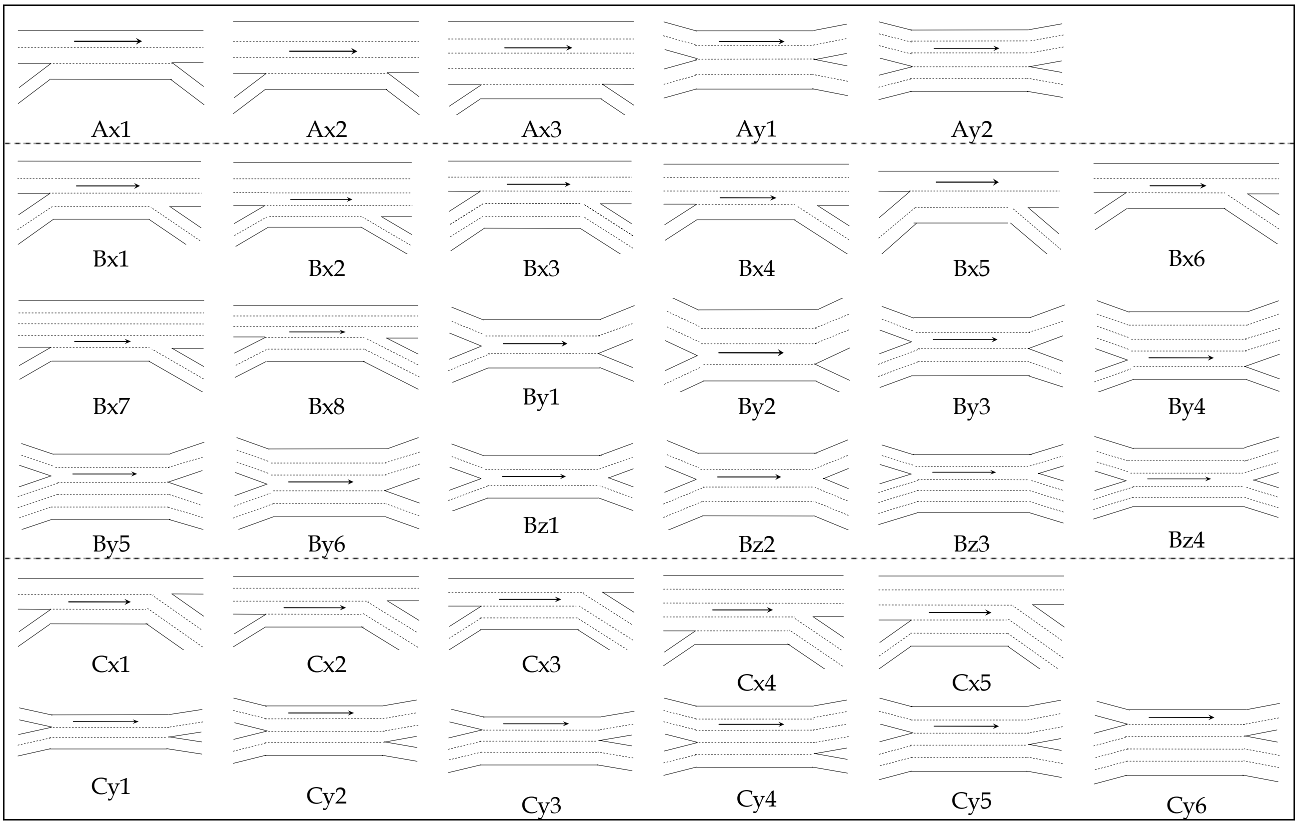


Fig. 2. Weaving Section Configurations

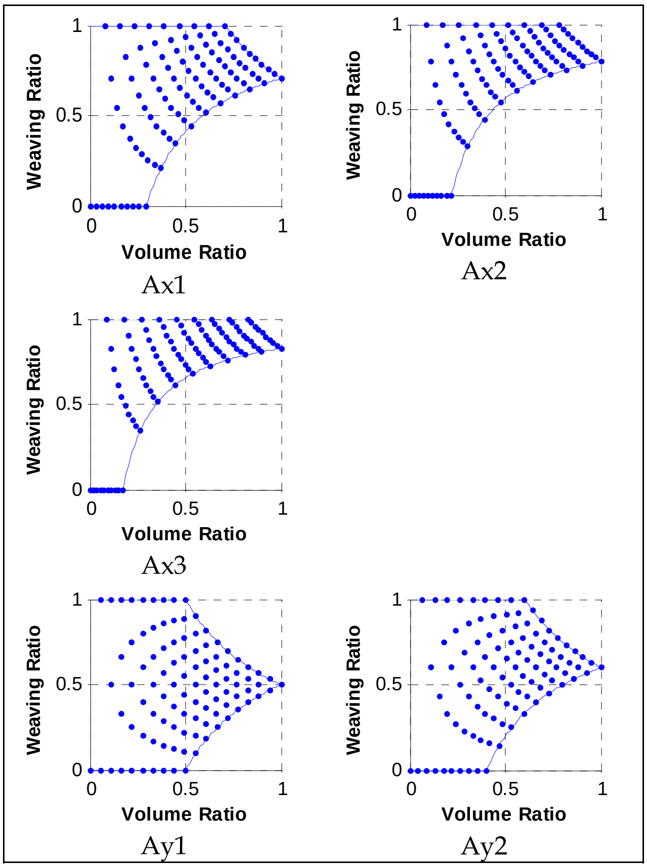


Fig. 3. Distribution of Simulated Data Points in VR-WR Plane (Demand)

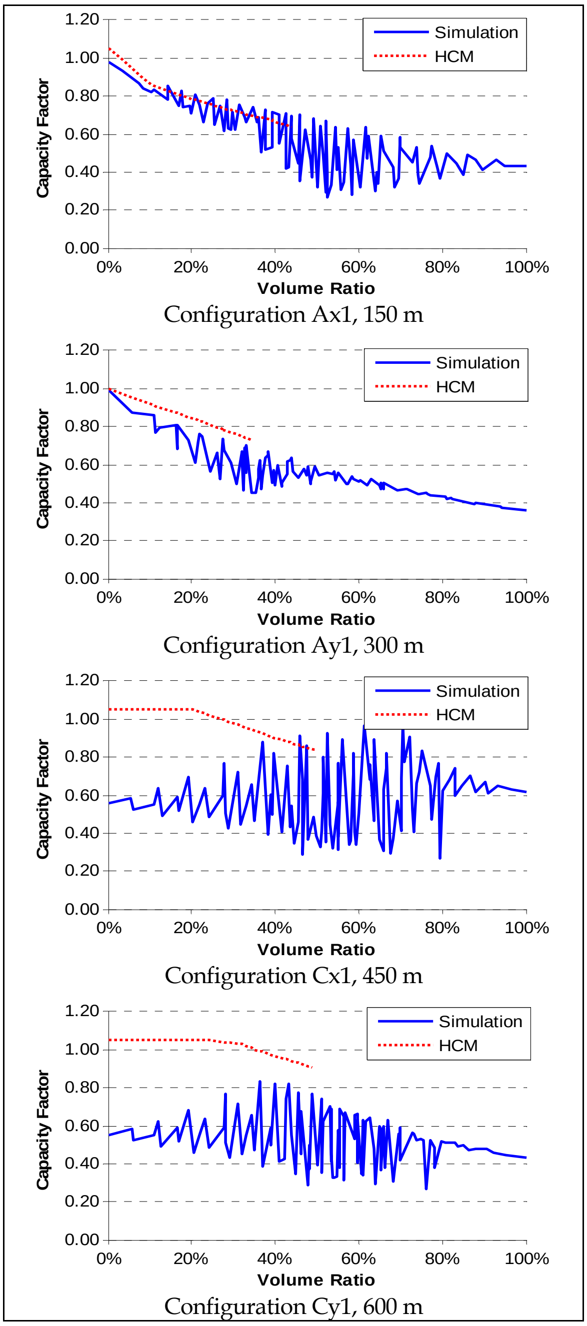
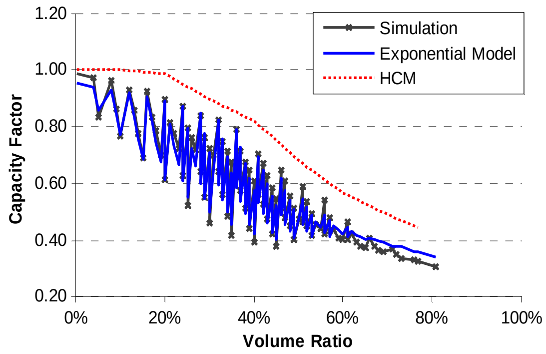
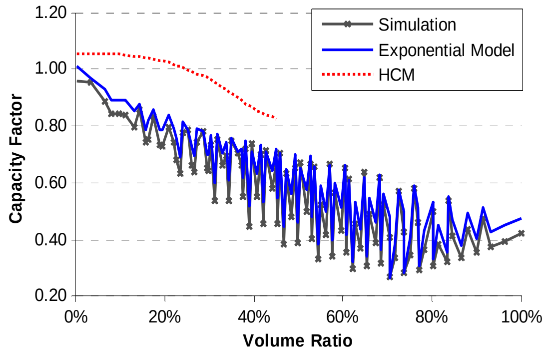


Fig. 4. Comparison of Simulation and HCM Procedure Capacity Factor Estimates



(a) Weaving Section: Bx2 –Length: 300m



(b) Weaving Section: Ax1 –Length: 750m

Fig. 5. Sample Model Estimates

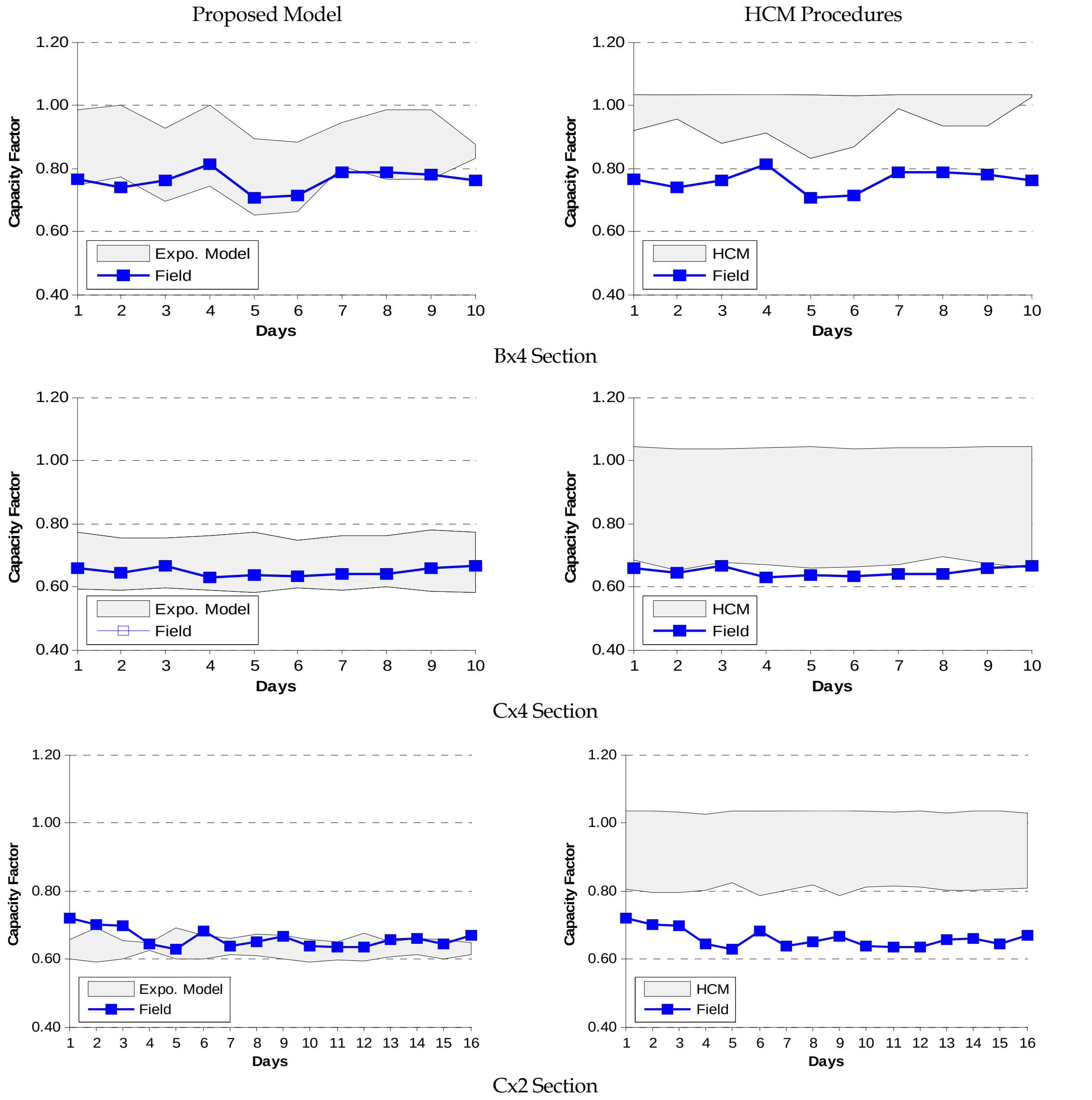


Fig. 6. Model and HCM Validation against Field Data Capacity Measurements

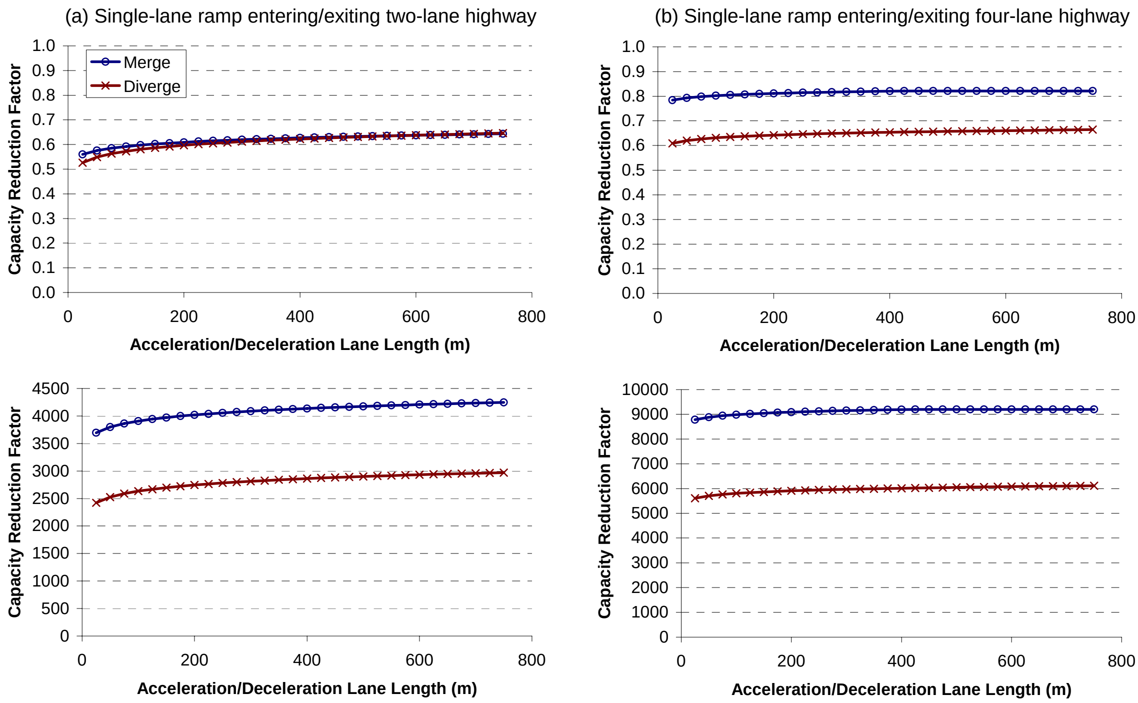
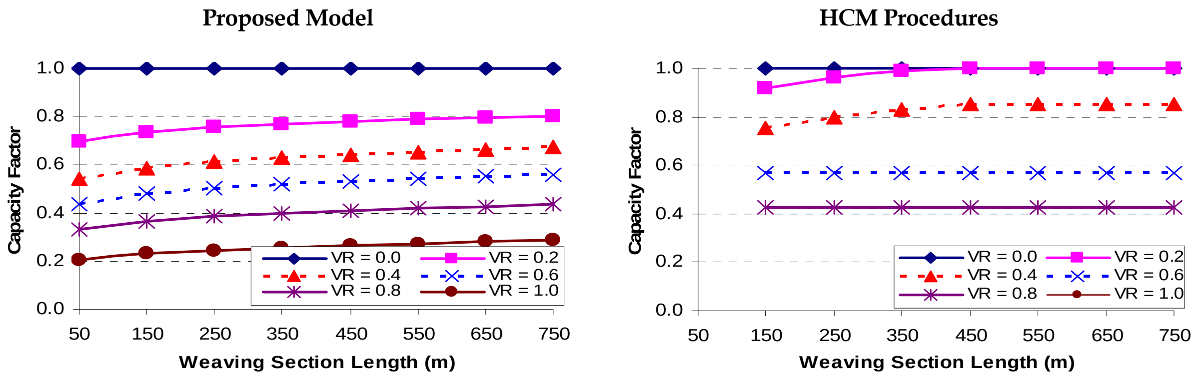
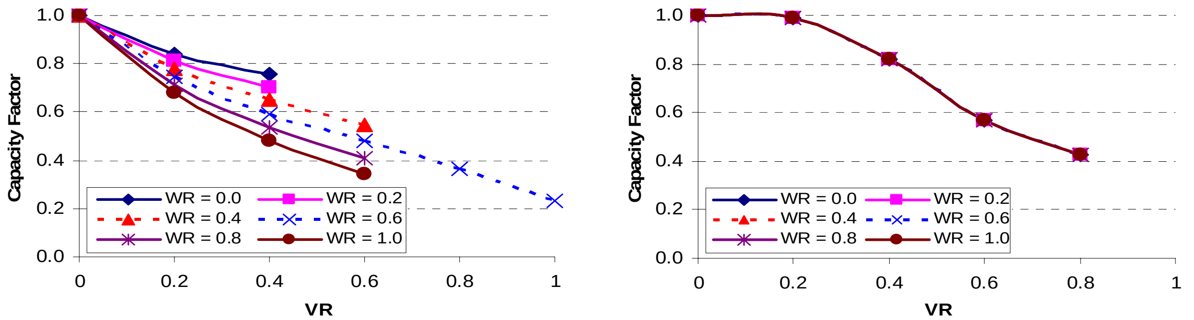


Fig. 7. Variation in Capacity Reduction Factor for Single-Lane Merge and Diverge Sections to Two-Lane Highways



(a) Bx2 Section – WR = 0.50



(b) Bx2 Section – Length 300m

Fig. 8. Model Sensitivity Analysis