Analytical Procedures for Estimating Capacity of Type B Weaving Sections

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ABSTRACT

The paper identifies thirteen common configurations of Type B weaving sections. These configurations are modeled using the INTEGRATION software for a wide range of weaving section lengths and travel demands. Subsequently, the simulation results are utilized to develop analytical procedures for estimating the capacity of Type B weaving sections and compared to the HCM2000 procedures. The results demonstrate that the HCM2000 procedures suffer from four significant drawbacks. First, the procedures can only consider relatively long weaving sections (longer than or equal to 150 m). Second, the HCM procedures fail to capture the impact of the distribution of weaving flows between freeway and on-ramp demand on the capacity of weaving sections, which is demonstrated to be an important factor in the analysis weaving section capacities. Third, the procedures do not ensure that the capacity of a weaving section reverts to the basic freeway capacity when the volume ratio is zero (no weaving flows) regardless of the weaving section length. Finally, the HCM procedures do not ensure consistency between the weaving and merge/diverge procedures at the boundary conditions. The paper demonstrates that the proposed analytical model overcomes the four identified shortcomings of the HCM2000 procedures and estimates the capacity of weaving sections to within 14 percent of the simulated results compared to the HCM error of 151 percent.

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

INTRODUCTION

The freeway weaving analysis procedures in the 2000 Highway Capacity Manual *(1)* are based on research conducted in the early 1970s through the early 1980s *(2).* Subsequent research efforts have shown that the methods' ability to predict the operation of a weaving section is limited *(3, 4, 5),* which is most probably due to the outdated and limited database that was utilized to develop these models. As to capacity estimation of freeway weaving sections, some other methods such as gap-acceptance and simulation methods have been used as alternatives *(3, 4, 6, 7).*

In this paper the INTEGRATION software is utilized to estimate the capacity of weaving sections. The validity of the INTEGRATION software for modeling weaving sections and estimating the

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capacity of these sections is described in detail in the literature *(5, 8),* 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 within Type B weaving sections. Subsequently, a wide range of weaving section traffic demands is modeled using the INTEGRATION software for all identified major configurations. Specifically, a sensitivity analysis is conducted considering different weaving section lengths and different traffic demands. Subsequently, an analytical capacity model is developed for each configuration.

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, followed by a description of the field data that were utilized to validate the INTEGRATION capacity modeling procedures. Subsequently, the identified common configurations within Type B weaving sections 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 Type B weaving sections is presented and compared to the simulation results and the HCM2000 procedures. Finally, the findings and conclusions of the study are presented.

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 1990's in North America and Europe *(9, 10, 11, 12, 13, 14, 15)*. The INTEGRATION 2.30 lane-changing logic was described and validated against field data in an earlier publication *(5)*. Furthermore, Zhang and Rakha *(8)* demonstrated the validity of the INTEGRATION software for estimating the capacity of weaving sections by comparing to field observed weaving section capacities. A brief description of these studies is presented in this section.

Rakha and Zhang *(5)* utilized an empirical data set that was gathered in the late 1980's by the University of California at Berkeley *(16)* to validate the INTEGRATION lane-changing behavior within weaving sections. In this dataset, vehicle spatial distributions both total and by movement, at successive reference points on nine weaving sites, were gathered. The traffic movements included the four possible Origin-Destination (O-D) demands on freeway weaving sections, namely, 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 demonstrates 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 that fell 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 *(8)* validated the INTEGRATION software weaving section capacity estimates by comparing 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 average relative error less than 5 percent). Furthermore, the results demonstrated that the INTEGRATION capacity estimates were superior to the CORSIM and gap acceptance estimates when compared to field data. In addition, the study demonstrated that the weaving ratio, which is 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 length of weaving section has a larger impact on the capacity of weaving sections as the length of the weaving section decreases and the traffic demand increases. The study also demonstrated that there is no evidence to conclude that the speed differential between the freeway and ramp traffic has a significant impact on weaving section capacities. The study demonstrated that the HCM procedures for accounting for heavy duty vehicle impacts on weaving section capacities are reasonable.

STATE-OF-THE-ART WEAVING ANALYSIS PROCEDURES

A limited number of publications were found in the literature that was deemed related to this study. For example, Zarean and Nemeth *(17)* utilized the WEAVSIM microscopic simulation model, to investigate the effect of different arrival speeds on the operation of 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 weaving sections, which was not considered in the 1985 HCM procedures *(18)* and is not considered in the current HCM procedures (1). However, Zhang and Rakha *(8)* demonstrate that the speed differential between freeway and ramps has a minimal impact on the capacity of weaving sections.

Skabardonis *et al*. *(19)* applied the INTRAS microscopic simulation model 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. The researchers concluded that the INTRAS speed predictions were closer to the field measurements than the analytical procedure speed predictions. The researchers 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*. *(6)* evaluated the capability of INTEGRATION version 1.50 for the modeling of weaving sections. The study showed that both the 1985 HCM procedure and INTEGRATION offered identical conclusions for a given sample problem. However, the 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 continues to not be, captured in the HCM procedures. Alternatively, while the HCM 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.

Vermijs *(20)* reported on the efforts in developing the Dutch capacity standards for freeway weaving sections using FOSIM (Freeway Operations SIMulation), 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 deviation in the range of 200 ~ 400 veh/h/lane.

Finally, Lertworawanich and Elefteriadou *(3, 21)* 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 limits 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.

EXPERIMENTAL DESIGN

According to the HCM 2000 procedures, the unique lane changing requirements that characterize Type B weaving sections include a weaving movement that does not require any lane changes and the weaving movement that requires at most a single lane change. In this study, three sub-types of Type B weaving sections are considered (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. Alternatively, Sub-type Bz weaving sections require no lane changes at the entrance and exit gores (lane balance between entry and exit sections). Because Type B weaving sections typically have three, four, or five lanes in the core area, a total of 13 configurations are investigated, as shown in Figure 1.

In terms of the simulation runs, the input free-flow speed along the freeway was set at 110 km/h (68.75 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 *(8)* 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. 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 percent the free-speed, which has been demonstrated to be the norm on North American freeways *(22).*

The first step in this study was to simulate all thirteen configurations in INTEGRATION considering different weaving section lengths and different Origin-Destination (O-D) demands. Weaving section lengths of 50, 75, 100, 150, 300, 450, 600, and 750 meters were considered in the study, which covers the maximum range of the HCM 2000 procedures in addition to covering 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. An attempt was made to cover the entire possible range of O-D demands including the extreme conditions when the weaving section converges to a basic freeway section, a merge section, or a diverge section. 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 only includes FF and RF demands while a diverge scenario only includes FF and FR demands.

SIMULATION RESULTS AND PROPOSED MODEL

This section presents the simulation results and corresponding HCM results. It should be noted that the HCM 2000 does not include any analytical procedures for estimating the capacity of weaving sections. Instead, the procedures provide lookup tables for estimating the capacity of weaving sections. Consequently, there is a need to develop some form of analytical procedures that are capable of estimating the capacity of weaving sections. Furthermore, because of the observed differences between the simulation results and HCM procedures, a refined capacity model is desired.

As was stated earlier, for each configuration, a wide variety of traffic conditions and core weaving area lengths are simulated using the INTEGRATION software. The simulated capacities are estimated as the maximum 15-minute flow rate that proceeds through a weaving section by systematically increasing the O-D demand. Alternatively, the HCM capacities are 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 meters and only consider a maximum volume ratio of 80 percent, the simulation scenarios go beyond the confines of the HCM procedures.

In order to generalize the results of this study to consider differing basic freeway section and ramp capacities, a capacity factor is computed. The normalized capacity factor is computed as the maximum section throughput divided by the capacity of the roadway section directly upstream of the weaving section (sum of upstream freeway and on-ramp capacities). For example, the 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 capacity of the entry section. The capacity of a weaving section can be computed as the product of the reduction factor with the capacity of the entry feeds to the weaving section. It should be noted that 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 would not necessarily equal to 1.0 when the volume ratio is set to zero (sum of RF and FR volumes equals 0).

Comparison between Simulated and HCM Capacity Estimates

For ease of comparison, the capacities derived from the HCM procedures are also normalized in the same fashion as was described earlier. Due to space limitation, only the results for configurations Bx1, By1, and Bz1, for lengths of 100, 300, and 600 meters are illustrated in Figure 2 through Figure 4. The figures clearly demonstrate 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. Furthermore, the HCM procedures indicate that the effect of the volume ratio on the weaving section capacity decreases as the weaving length increases. These trends, however, were not observed in the simulation results. 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 on the weaving section capacity including the weaving ratio (ratio of weaving volume to the total arrival volume). Zhang and Rakha *(8)* have demonstrated that the weaving ratio does have a significant impact on the capacity of freeway weaving sections.

The figures also clearly demonstrate that the HCM capacity estimates are significantly higher than the simulated capacity estimates. Given that the INTEGRATION weaving section estimates have been demonstrated to be consistent with field data *(8)* it is fair to conclude that the HCM procedures tend to over-estimate the capacity of weaving sections.

Proposed Weaving Section Capacity Model

From the above analysis it is obvious that an analytical procedure is required to estimate the capacity of weaving sections. As part of this study a simplistic mathematical function is developed to estimate the capacity of weaving sections. In understanding the relationship between the capacity factor and the various influencing factors including the volume ratio, weaving ratio, and weaving section length, each factor was analyzed separately.

While the model structure was the same for all 13 configurations, configuration Bx2 is used to illustrate the model development process. First, the relationship between volume ratio and capacity factor is investigated. For configuration Bx2, this relationship is plotted for each weaving section length. The upper side of Figure 5 illustrates the relationship for all the simulation results of configuration Bx2 for a weaving section length of 100 meters. The figure demonstrates that an exponentially decaying relationship appears to be characteristic of the general behavior (negative exponential function). The structure of the relationship is provided in Equation 1. Similar trends were observed for the other weaving section lengths. Since the maximum value of capacity factor for this configuration is 1.0 (weaving section inbound roadways have a lower capacity than the outbound roadways), the value of the constant *a* is set to 1.0.

$$F = a \cdot e^{t \cdot VR} \qquad [1]$$

In Equation 1 *F* is the capacity factor, *VR* is the volume ratio, and *a* and *t* are model coefficients that are calibrated. The coefficient of determination was reasonable (78 percent), however, as will be discussed later, the model is enhanced by considering other factors in the analysis.

Subsequently, having established the relationship between *VR* and *F*, the relationship between the constant *t* in Equation 1 and the weaving section length (*x*) was investigated. As shown in the lower side of Figure 5, the relationship between *t* and *x* can be modeled as a logarithmic function as

$$t = b \ln x + c \,. \qquad [2]$$

Where *b* and *c* are model coefficients and *x* is the weaving section length in units of meters. It should be noted that the coefficient of determination was extremely high ($R^2 \geq 0.95$) and all constants were statistically significant.

Combining Equations 1 and 2, the relationship between the *F*, *VR*, and *x* can be expressed as

$$F = a \cdot e^{(b \ln x + c) VR} \,. \qquad [3]$$

It should be noted that given the typical values of the *b* and *c* coefficients and the fact that we take the natural logarithm of the weaving section length, the exponent is always negative and thus the relationship ensures that an exponential decay function is established.

Finally, in order to consider the impact of the weaving ratio on the capacity of weaving sections, a further analysis of the data was conducted. It should be noted that the HCM 2000 defines the weaving ratio as the ratio of the smaller of the two weaving flows to the total weaving flow. This definition does not distinguish between the FR and RF weaving flows. For example, there are two possible situations for a weaving ratio of 0.30. One possibility is that the FR demand constitutes 30 percent of the total weaving volume or alternatively that the RF demand constitutes 30 percent of the total weaving flow. An analysis of the simulation results revealed significant capacity estimates depending on the source of the weaving volume (FR or RF). In other words the weaving ratio distribution is asymmetric. Consequently, we introduce a new definition of the weaving ratio as

$$WR_F = FR / (FR + RF) \,. \qquad [4]$$

In this model three ranges of WR_F are identified. Two threshold values s_1 and s_2 (where $s_1 < s_2$) are identified to establish three regimes. When WR_F is less than s_1, the majority of the weaving volume is on-ramp to freeway traffic (i.e. predominantly merge traffic). Alternatively, when WR_F is greater than or equal to s_1 but less than s_2, there is a more balanced distribution of the weaving volumes. Finally, when WR_F is greater than or equal to s_2, the majority of the weaving volume is from freeway to off-ramp (i.e. predominantly diverge traffic). In order to account for differences in behavior as a function of the weaving volume composition, the simulation results are categorized into three categories according to the value of freeway weaving ratio ($WR_F \le s_1$, $s_1 < WR_F < s_2$, $WR_F \ge s_2$). The breakpoints s_1 and s_2 were computed by minimizing the sum of squared error between the estimated and simulated capacity factor estimates as

$$\text{Min Z} = \sum_{r=1,3}\sum\left(a_r \cdot e^{(b_r \ln x + c_r)VR} - F_{sim}\right)^2 . \qquad [5]$$

It should be noted that Equation 5 computes the total error relative to the simulated capacity factor (F_{sim}) over all observations within each of the three regimes (r = 1,2, and 3). Consequently, the model coefficients of Equation 5 are regime-specific (i.e. the coefficients have a subscript r as a_r, b_r, and c_r).

The proposed capacity models for all the identified 13 configurations are summarized in TABLE 1. It should be noted that the model always reverts to the basic capacity when VR is set to zero. Given that the overall capacity is governed by the lowest capacity bottleneck within the system the constant over the three sections, namely the inbound lanes, the weaving lanes, and the outbound lanes. In the cases that the capacity is constrained by the inbound lanes the coefficient (a) is equal to 1.0, as in the case of scenarios Bx1, Bx2, and Bx3.

Reanalyzing Figure 2 through Figure 4 demonstrates that by incorporating the weaving ratio as a variable within the proposed model, the model is able to capture the majority of oscillations that are observed in the simulated data. Furthermore, these oscillations are demonstrated to not be a result of a random process; instead they reflect the impact of other factors that are significant and not considered in the current HCM procedures.

Significance of Coefficients

To eliminate any redundant variables from the proposed models, the 95% confidence intervals of all coefficients were computed, as demonstrated in TABLE . The intervals that include a zero value are shaded in the table because they highlight coefficients that are not significant within the proposed model. For example, in TABLE for configurations Bz2, Bz3, and Bz4 the 95% confidence intervals for the b coefficient include 0 indicating that the weaving section length is not significant for the modeling of diverge conditions for these three configurations. Consequently, we suggest the use of a b coefficient equal to 0 in these three models.

Proposed Capacity 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 the scenarios. Four error measures were estimated for each of the data sets. These error measures are the mean relative error (MeRE), the maximum relative error (MaRE), the mean absolute error (MeAE), and the maximum absolute error (MaAE). The errors were derived as

$$MeRE_{A-B} = \sum_{i=1}^{n}\left(\left|y_A - y_B\right|/y_S\right)\Big/n ,$$
$$MaRE_{A-B} = \max\left(\left|y_A - y_B\right|/y_S\right),$$
$$MeAE_{A-B} = \sum_{i=1}^{n}\left(\left|y_A - y_B\right|\right)\Big/n , \text{ and}$$
$$MaAE_{A-B} = \max\left(\left|y_A - y_B\right|\right).$$

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

The results demonstrate that the difference between the proposed model and simulated capacity factors is the smallest among the three comparisons, as illustrated in TABLE 2. Specifically, the mean absolute error does not exceed 0.04 and the mean relative error is less than 14 percent for all thirteen configurations. However, it should be noted that the maximum absolute error is 0.28 and the maximum relative error for configuration is 106 percent (configuration By2). The error estimates, however, are significantly lower than the current HCM procedures and thus the proposed models offer significant improvements to the current state-of-the-art procedures.

Sensitivity Analysis

A simple sensitivity study is conducted on both the proposed model and the HCM procedures. The sensitivity study covers different weaving section lengths, volume ratios, and three levels of weaving ratios, which corresponds to the previously mentioned three regimes (merge, weaving, and diverge). In Figure 6, the left side shows the sensitivity study results from the proposed model, and on the right side are the results from HCM procedures.

Since the HCM procedures do not consider the weaving ratio in the analysis, the results for the three weaving ratio levels are identical. Alternatively, the proposed model demonstrates that apart from a VR of 0, higher weaving ratios result in lower capacity factors. This is reasonable since for configuration Bx2 higher weaving ratios result in a higher intensity of lane-changing behavior within the weaving section and thus more turbulence within the traffic stream. The HCM procedures demonstrate that the impact of the VR increases as the VR increases. Alternatively, the proposed model demonstrates an opposite trend (i.e. the impact of the VR on the capacity factor decreases as the VR increases). Finally, the results demonstrate that the weaving section length only impacts the HCM capacity factor when the volume ratio is less than 60 percent which is not the case for the proposed model.

FINDINGS AND CONCLUSIONS

The research presented in this paper examined one of the most important aspects of analysis of freeway weaving sections, namely the capacity analysis. In this paper the capacity of Type B weaving sections was evaluated using simulation. The simulation results demonstrated that the HCM procedures are not only inadequate but fail to capture critical variables that impact the capacity of weaving sections including the weaving ratio and the distribution of weaving volume between freeway to off-ramp and on-ramp to freeway demands.

The paper presents a very simple analytical model for estimating the capacity of Type B 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_F = FR/(FR+RF)). Specifically, the paper introduces a new definition for the weaving ratio that explicitly accounts for the source of the weaving volume. The paper demonstrates that the proposed analytical model estimates the capacity to within 14 percent of the simulated data. Alternatively, the HCM procedures exhibit errors in the range of 151 percent. The procedures that are developed in this study ensure 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_F is low. Similarly, the weaving section capacity reverts to a diverge section capacity when the WR_F is high.

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TABLE 1 Proposed Capacity Model for Type B Weaving Sections

Config.	s_1	s_2	$WR_F < s_1$	$s_1 \le WR_F < s_2$	$WR_F \ge s_2$
Bx1	0.67	0.86	$F = e^{(0.1552\cdot\ln x - 1.9558)VR}$	$F = e^{(0.2723\cdot\ln x - 2.9245)VR}$	$F = e^{(0.3907\cdot\ln x - 4.0729)VR}$
Bx2	0.55	0.80	$F = e^{(0.2134\cdot\ln x - 2.3457)VR}$	$F = e^{(0.2197\cdot\ln x - 2.610)VR}$	$F = e^{(0.2679\cdot\ln x - 3.5733)VR}$
Bx3	0.70	0.83	$F = e^{(0.1643\cdot\ln x - 2.2578)VR}$	$F = e^{(0.2331\cdot\ln x - 2.8589)VR}$	$F = e^{(0.3406\cdot\ln x - 3.9932)VR}$
By1	0.22	0.47	$F = 0.75e^{(0.0885\cdot\ln x - 1.4504)VR}$	$F = 0.75e^{(0.1006\cdot\ln x - 1.7609)VR}$	$F = 0.75e^{(0.2900\cdot\ln x - 3.3454)VR}$
By2	0.01	0.53	$F = 0.80e^{(0.0959\cdot\ln x - 1.3420VR}$	$F = 0.80e^{(0.1766\cdot\ln x - 2.4714VR}$	$F = 0.80e^{(0.5771\cdot\ln x - 5.6133VR}$
By3	0.21	0.50	$F = 0.80e^{(0.1422\cdot\ln x - 2.0922)VR}$	$F = 0.80e^{(0.0852\cdot\ln x - 1.9610)VR}$	$F = 0.80e^{(0.5582\cdot\ln x - 5.2669)VR}$
By4	0.01	0.59	$F = 0.83e^{(0.1122\cdot\ln x - 1.5191)VR}$	$F = 0.83e^{(0.1300\cdot\ln x - 2.4920)VR}$	$F = 0.83e^{(0.5862\cdot\ln x - 6.1816)VR}$
By5	0.01	0.50	$F = 0.83e^{(0.2470\cdot\ln x - 3.3307)VR}$	$F = 0.83e^{(0.1330\cdot\ln x - 2.3581)VR}$	$F = 0.83e^{(0.3830\cdot\ln x - 4.3525)VR}$
By6	0.22	0.59	$F = 0.83e^{(0.1415\cdot\ln x - 2.3244)VR}$	$F = 0.83e^{(0.0419\cdot\ln x - 1.9985)VR}$	$F = 0.83e^{(0.7440\cdot\ln x - 6.8719)VR}$
Bz1	0.16	0.50	$F = 0.75e^{(0.0794\cdot\ln x - 1.5439)VR}$	$F = 0.75e^{(0.0983\cdot\ln x - 1.8310)VR}$	$F = 0.75e^{(0.1349\cdot\ln x - 2.7572)VR}$
Bz2	0.13	0.50	$F = 0.80e^{(0.1242\cdot\ln x - 2.1622)VR}$	$F = 0.80e^{(0.1365\cdot\ln x - 2.3870)VR}$	$F = 0.80e^{(0.0931\cdot\ln x - 3.0546)VR}$
Bz3	0.01	0.56	$F = 0.83e^{(0.2468\cdot\ln x - 3.9444)VR}$	$F = 0.83e^{(0.1852\cdot\ln x - 2.8055)VR}$	$F = 0.83e^{(-0.1847\cdot\ln x - 1.7642)VR}$
Bz4	0.05	0.31	$F = 0.83e^{(0.2946\cdot\ln x - 3.4451)VR}$	$F = 0.83e^{(0.1905\cdot\ln x - 2.9037)VR}$	$F = 0.83e^{(0.0013\cdot\ln x - 2.1496)VR}$

TABLE 2 Differences among Simulated Capacity, HCM Capacity, and Model Capacity

	H - M				H - S				M - S			
	MeRE	*MaRE*	*MeAE*	*MaAE*	*MeRE*	*MaRE*	*MeAE*	*MaAE*	*MeRE*	*MaRE*	*MeAE*	*MaAE*
Bx1	0.97	1.17	0.56	1.00	0.96	1.00	0.55	0.99	0.04	0.18	0.02	0.10
Bx2	0.98	1.18	0.52	1.00	0.98	1.24	0.51	0.99	0.06	0.27	0.03	0.12
Bx3	0.95	1.15	0.52	1.00	0.95	1.00	0.52	0.99	0.04	0.23	0.02	0.10
By1	1.60	2.83	0.51	0.80	1.10	1.58	0.44	0.72	0.08	0.48	0.03	0.13
By2	1.23	1.63	0.50	0.80	1.38	2.13	0.48	0.77	0.13	1.06	0.04	0.27
By3	1.70	3.31	0.51	0.80	1.15	1.04	0.48	0.77	0.08	0.75	0.03	0.28
By4	1.21	1.41	0.48	0.80	1.51	2.48	0.48	0.78	0.14	0.80	0.04	0.20
By5	1.32	1.75	0.50	0.80	1.17	1.12	0.48	0.82	0.08	0.34	0.03	0.16
By6	1.06	1.30	0.47	0.75	1.23	1.35	0.49	0.83	0.09	0.81	0.03	0.26
Bz1	1.15	1.31	0.49	0.80	1.07	1.00	0.47	0.72	0.09	0.39	0.04	0.16
Bz2	1.19	1.26	0.48	0.80	1.17	1.02	0.49	0.78	0.09	0.40	0.03	0.16
Bz3	1.23	1.42	0.50	0.80	1.21	1.38	0.48	0.82	0.10	0.42	0.04	0.17
Bz4	0.96	1.34	0.55	1.00	1.25	1.02	0.50	0.80	0.07	0.43	0.04	0.19

H: Results from HCM
S: Simulation results
M: Proposed model results

TABLE 3 95 percent Confidence Intervals for Exponential Model Coefficients

Config.	$WR_F < s_1$		$s_1 \le WR_F < s_2$		$WR_F \ge s_2$	
	b	*c*	*b*	*c*	*b*	*c*
Bx1	[0.15 0.17]	[-2.01 -1.90]	[0.24 0.30]	[-3.11 -2.74]	[0.34 0.44]	[-4.39 -3.76]
Bx2	[0.19 0.23]	[-2.45 -2.24]	[0.20 0.24]	[-2.71 -2.51]	[0.22 0.32]	[-3.87 -3.28]
Bx3	[0.16 0.17]	[-2.31 -2.21]	[0.19 0.27]	[-3.07 -2.64]	[0.29 0.39]	[-4.29 -3.70]
By1	[0.07 0.11]	[-1.56 -1.34]	[0.08 0.12]	[-1.88 -1.64]	[0.25 0.33]	[-3.59 -3.10]
By2	[0.00 0.19]	[-1.86 -0.83]	[0.15 0.20]	[-2.63 -2.32]	[0.49 0.66]	[-6.10 -5.12]
By3	[0.12 0.16]	[-2.21 -1.97]	[0.06 0.11]	[-2.10 -1.82]	[0.41 0.71]	[-6.14 -4.39]
By4	[0.01 0.21]	[-2.09 -0.95]	[0.10 0.16]	[-2.67 -2.32]	[0.50 0.67]	[-6.66 -5.70]
By5	[0.16 0.34]	[-3.82 -2.84]	[0.11 0.15]	[-2.46 -2.26]	[0.29 0.47]	[-4.86 -3.84]
By6	[0.11 0.17]	[-2.51 -2.14]	[0.02 0.07]	[-2.14 -1.86]	[0.61 0.88]	[-7.67 -6.07]
Bz1	[0.05 0.11]	[-1.69 -1.40]	[0.07 0.12]	[-1.96 -1.70]	[0.04 0.23]	[-3.31 -2.21]
Bz2	[0.08 0.16]	[-2.40 -1.93]	[0.11 0.16]	[-2.54 -2.23]	[-0.10 0.29]	[-4.11 -2.00]
Bz3	[0.12 0.38]	[-4.66 -3.23]	[0.16 0.21]	[-2.95 -2.66]	[-0.37 0.00]	[-2.70 -0.83]
Bz4	[0.16 0.43]	[-4.19 -2.70]	[0.14 0.24]	[-3.17 -2.64]	[-0.06 0.06]	[-2.45 -1.85]

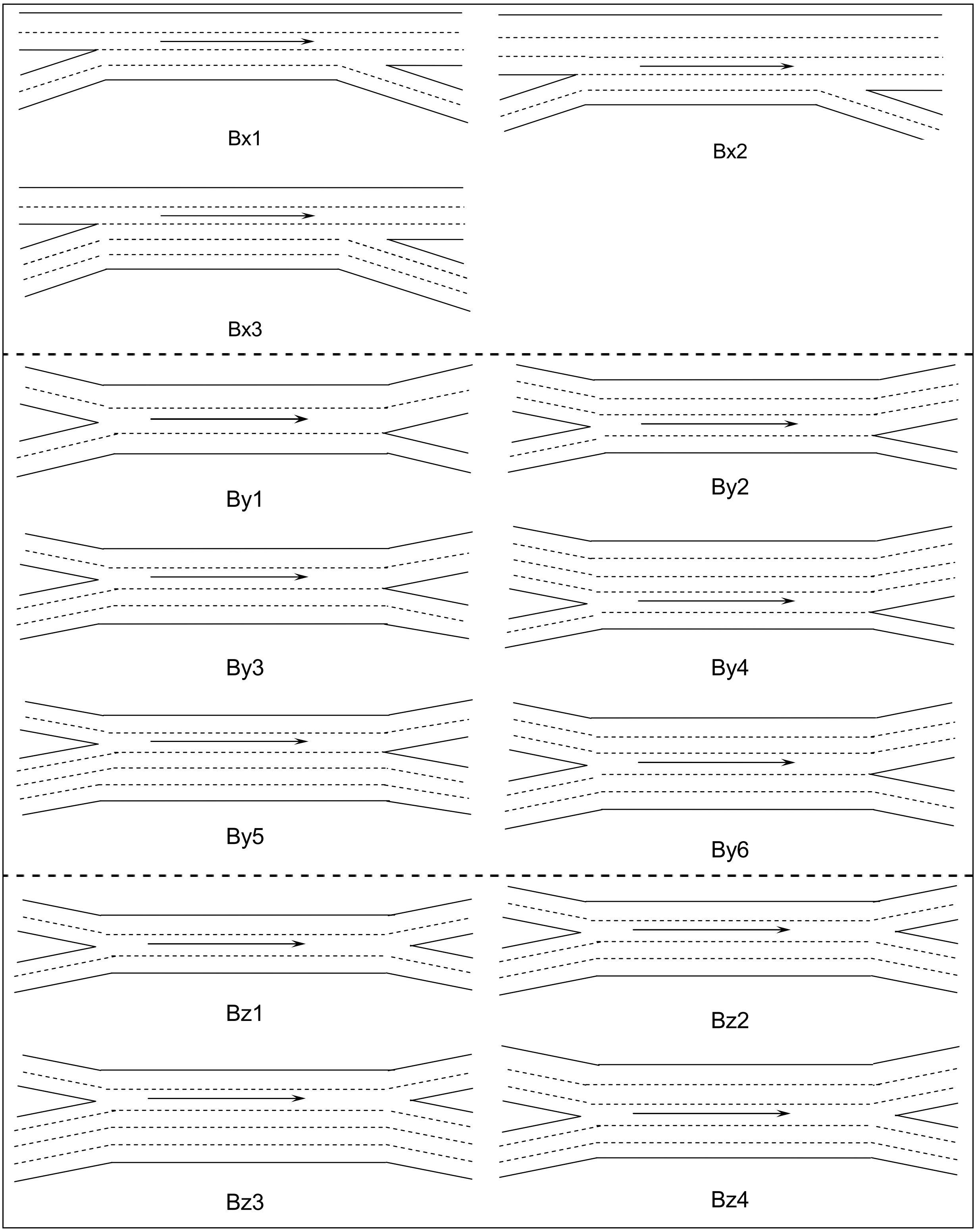
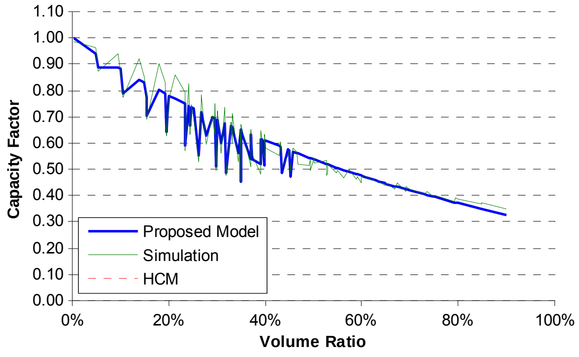
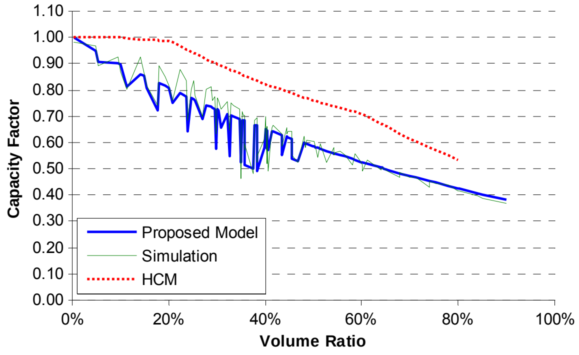


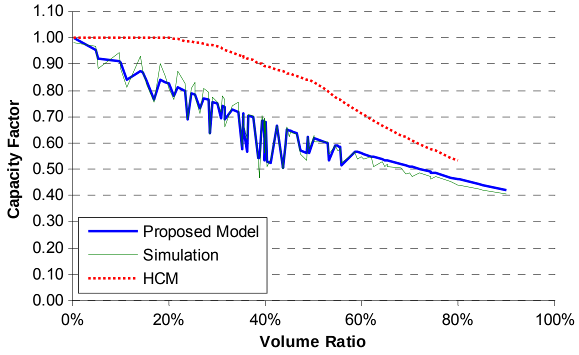
Figure 1 Configurations of Type B Weaving Sections.



Length of Core Weaving Area = 100 m

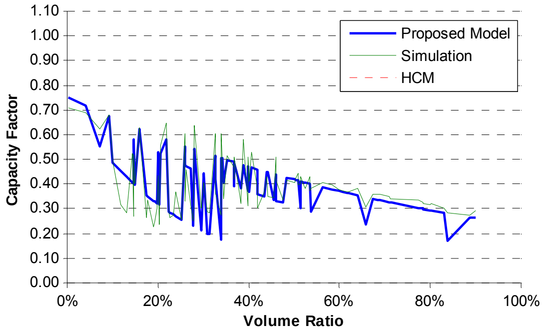


Length of Core Weaving Area = 300 m

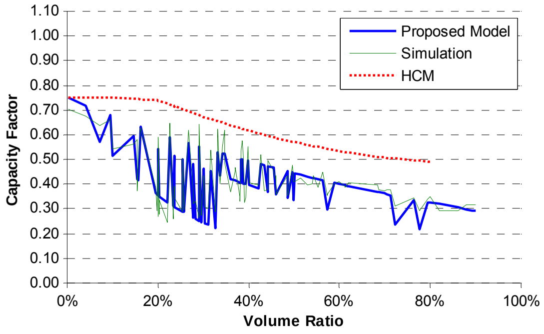


Length of Core Weaving Area = 600 m

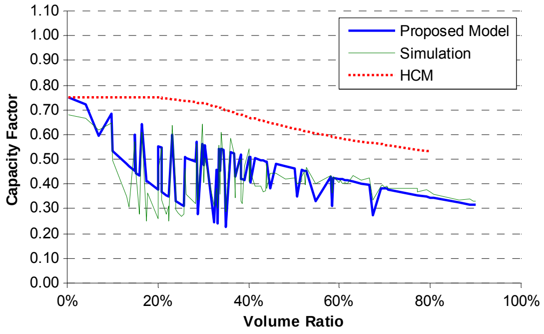
Figure 2 Configuration Bx1 Weaving Sections.



Length of Core Weaving Area = 100 m

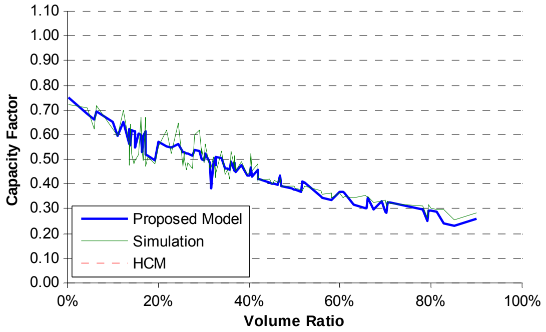


Length of Core Weaving Area = 300 m

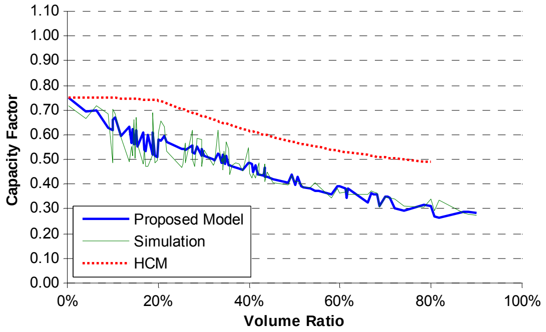


Length of Core Weaving Area = 600 m

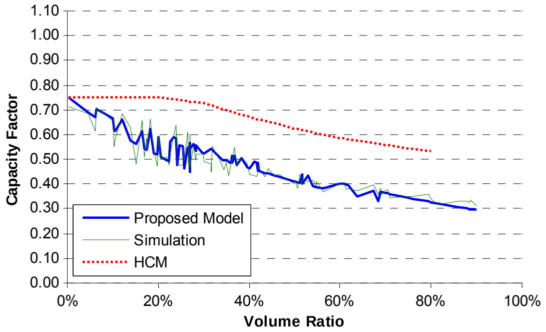
Figure 3 Configuration By1 Weaving Sections.



Length of Core Weaving Area = 100 m

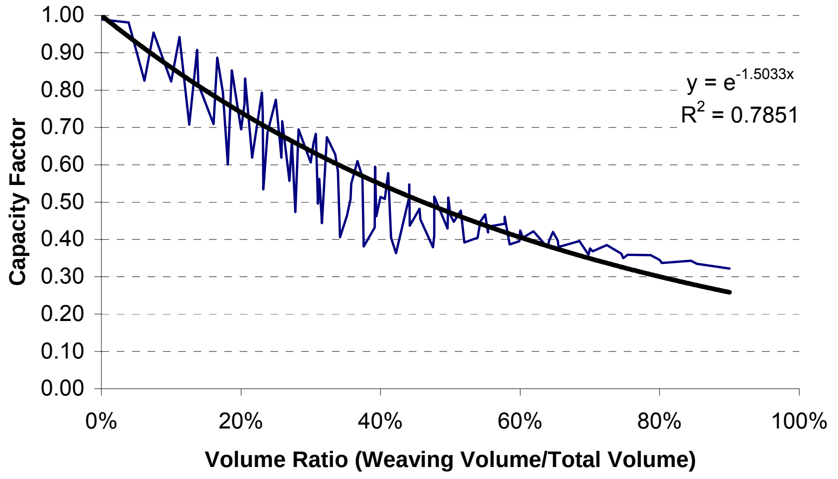


Length of Core Weaving Area = 300 m

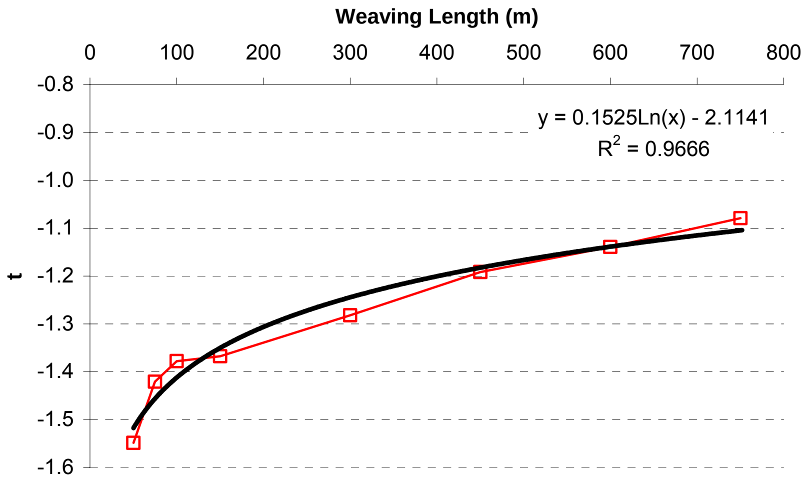


Length of Core Weaving Area = 600 m

Figure 4 Configuration Bz1 Weaving Sections.

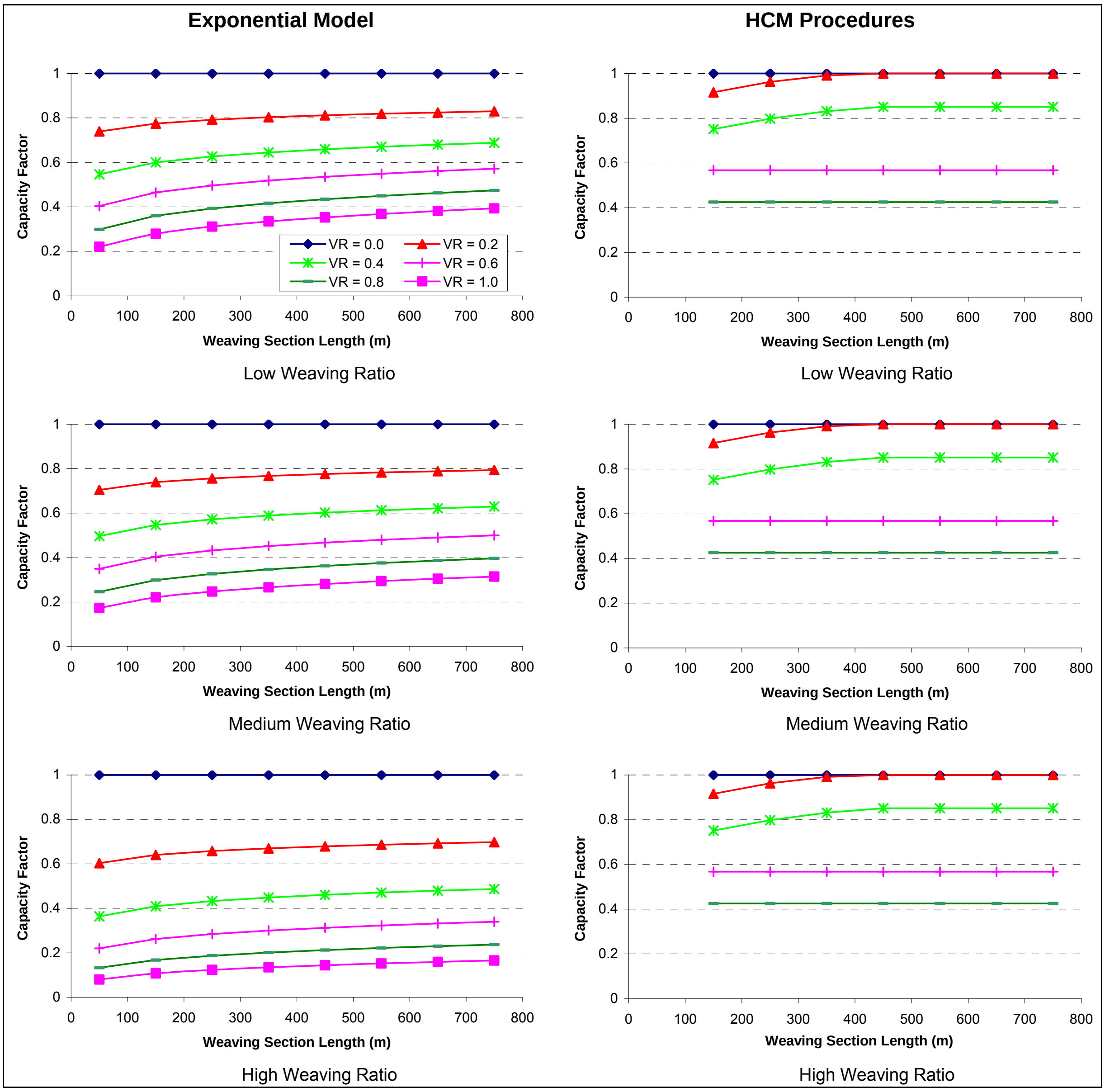


Relationship between Capacity Factor and VR (Site Bx2, weaving length of 100 m)



Relationship between t and Weaving Section Length

Figure 5 Illustration of Model Development.



Exponential Model

HCM Procedures

Low Weaving Ratio

Low Weaving Ratio

Medium Weaving Ratio

Medium Weaving Ratio

High Weaving Ratio

High Weaving Ratio

Figure 6 Sensitivity Study Results from the Proposed Model and HCM Procedures for Configuration Bx2.