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A MICROSIMULATION APPROACH TO EVALUATE OPERATIONS OF WEAVING SECTIONS AT URBAN UNCONVENTIONAL INTERSECTIONS IN CAIRO

Amr K. Soliman*[1] and Mostafa A. Abo-Hashema[1]

[1] Department of Civil Engineering, Faculty of Engineering, Fayoum University, Egypt.

Correspondence: Amr.solyma@gmail.com

ABSTRACT

Unconventional median U-turn intersections have been extensively implemented along major corridors in Cairo, Egypt. These unconventional intersections do not involve signalization at any point. They utilize a non-traversable median with a U-turn crossover at the downstream to manage all crossing movements and thus, creating two-sided weaving sections between the minor approach and the U-turn crossover. In this paper, VISSIM was used to model and simulate these weaving sections through an experimental analysis with 4 influential factors namely, major demand, minor demand, weaving length, and the minor through traffic split (% Mi THR). The experimental design resulted in 960 scenario runs, which were automated through an external Visual Basic program developed specifically for this study. The first stage of the analysis was dedicated to estimating the capacities of the weaving sections and the minor entrance, which were found negatively correlated. Increasing the major demand caused a decrease in the minor entrance capacity and an increase in the capacities of the weaving sections. It was also found that capacities increase with the increase in weaving length; however, increasing the length beyond 200 meters was not beneficial. Increasing the minor through split caused an increase in volume ratio and a decrease in capacities. Furthermore, regression analysis was used to develop various simulation-based capacity prediction models that resulted in a relatively high R2 values. The second stage of the analysis was dedicated to test the appropriateness of the HCM 2010 weaving methodology when applied to the urban weaving sections to predict capacities, lane change rates, and speeds. Comparisons between the predicted and the simulated estimates showed that the HCM 2010 methodology provided higher capacity predictions up to 1.6 times the simulated capacities. On the other hand, the developed regression models produced capacity estimations that were more realistic. This provided evidence that the structure of the developed models is more suited to represent capacities of similar weaving configurations. Further comparisons using paired t-tests and parity plots showed that the HCM 2010 methodology also underpredicted lane change rates; therefore, speed predictions were higher than the simulated speeds at each weaving section. Finally, an effort was carried out to calibrate and modify the speed prediction algorithms of the HCM 2010; however, the effort did not yield any significant results.

Keywords: VISSIM, Microscopic traffic simulation, Urban-weaving sections , HCM 2010, Capacity analysis, Unconventional intersection treatments

تقييم قطاعات النسيج في المناطق الحضرية باستخدام نماذج المحاكاة "المرورية

عمرو خليل محمد سليمان و مصطفي أمين أبو هشيمة

قسم الهندسة المدنية، كلية الهندسة، جامعة الفيوم، مصر.

بريد إلكتروني: Amr.solyma@gmail.com

الملخص

لقد شهدت الآونة الأخيرة ظهور طرق غير تقليدية لمعالجة بعض التقاطعات رباعية الارجل بمدينة القاهرة. هذه الطرق لا تتضمن استخدام إشارات مرورية للتحكم في التقاطع، ولكنها تتضمن اغلاق الجزيرة الوسطي بحيث يتم منع المرور المباشر من خلالها والاعتماد الكلي على فتحات الدوران الي الخلف وبالتالي تتقاطع مسارات الطريق الثانوي مع مسارات الطريق الرئيسي وتتكون قطاعات تقاطع المسارات على

جانبي الجزيرة الوسطي. هذه الدراسة تتناول النمذجة والمحاكاة المرورية لقطاعات تقاطع المسارات الناتجة عن هذا النوع من التقاطعات الرباعية وذلك باستخدام برنامج (VISSIM) للمحاكاة المرورية التي اتاحت اختبار القطاعات تحت تأثير احجام مرورية مختلفة واطوال قطاعات مختلفة كما اتاحت أيضا حساب السعة المرورية للقطاعات المختلفة وتصميم بعض المعادلات للتنبؤ بالسعة المتوقعة بطريقة تحليل الانحدار. تتضمن الدراسة ايضا حساب سرعات المسارات المختلفة بكل قطاع بالإضافة الي المعدل الكلي لتغير الحارة المرورية وذلك لمقارنتها بالقيم المحسوبة باستخدام المعادلات الموجودة بدليل سعة الطريق (HCM 2010) والخاصة بتصميم وتحليل قطاعات تقاطع المسارات. بعد المقارنة وجد ان معادلات دليل سعة الطريق (HCM 2010) لا تصلح لمثل هذا النوع من القطاعات ذلك لأن المعادلات الموضوعة تعطي قيم سعات مرورية أكبر وسرعات مسارات اعلي من المتوقع بالإضافة الي معدل اقل لتغير الحارة المرورية. لذلك توصي الدراسة بعدم استخدام المعادلات الخاصة بدليل سعة الطريق (HCM 2010) لتصميم او تقييم اداء قطاعات تقاطع المسارات من هذا النوع في المناطق الحضرية ويفضل استخدام النماذج المذكورة في هذا البحث بعد اجراء المعايرة المطلوبة.

الكلمات المفتاحية: VISSIM، محاكاة حركة المرور، قطاعات النسيج، HCM 2010، تحليل السعات المرورية، معالجات التقاطعات غير التقليدية.

INTRODUCTION

The HCM 2010 **[1]** defines weaving as the crossing of two or more traffic streams without the aid of traffic control devices along a significant length of highway. Traffic passing through the weaving section experience turbulence in excess of the normally present on a basic roadway. This additional turbulence causes a reduction in capacity and performance.

In Cairo, many urban intersections have been treated with U-turns as shown in figure 1, where the full median opening is substituted with a crossover, downstream of the intersection to handle all crossing movements. This treatment does not involve any signals control at any point. Conflicts between traffic streams are managed through yield signs, therefore, merging vehicles are forced to always yield to the mainstream traffic.

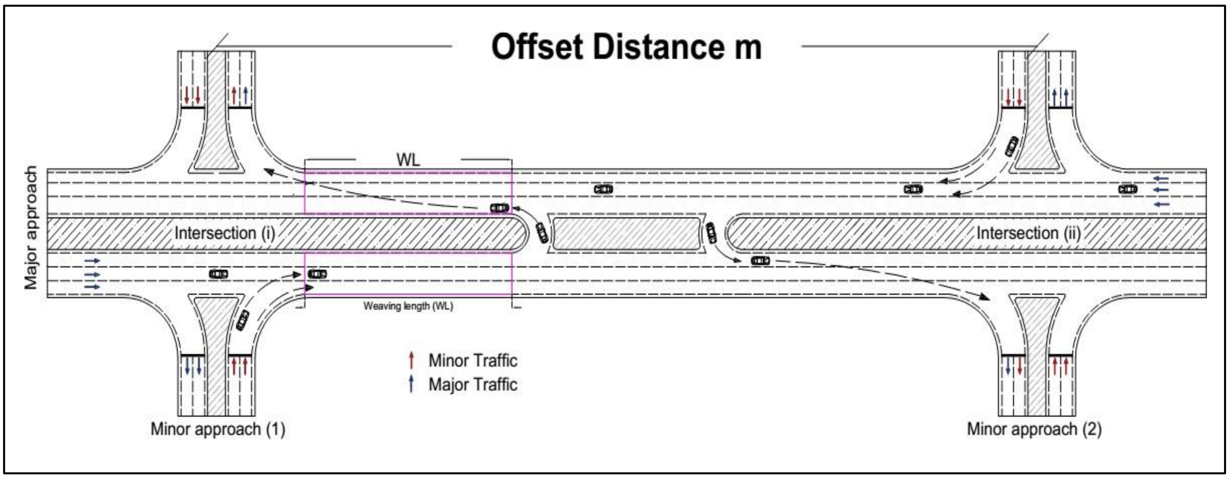


Figure 1: Typical unconventional intersection design at an urban corridor in Cairo

As a consequence of implementing this type of design, direct left turning vehicles of the minor street are forced to make a right turn followed by a U-turn (RTUT). On the other hand, minor through traffic (% Mi THR) are forced to make a RTUT and then a right turn (RT) into the minor street, downstream of the U-turn crossover. Left turning traffic of the main street must also utilize the median side lanes to make a U-turn followed by a right turn (UTRT) into the minor approach. The RTUT movement requires a series oflane changes to reach the inner most lane towards the U-turn crossover; similarly, UTRT movement must change lanes to reach the outer lane toward the downstream minor approach.

Figure 2 shows a closeup of the analyzed intersection and illustrates the formation of the urban weaving sections resulting from the local intersection treatment. Ramp to ramp (R-R) and ramp to arterial (R-A) flow components are also shown in the figure.

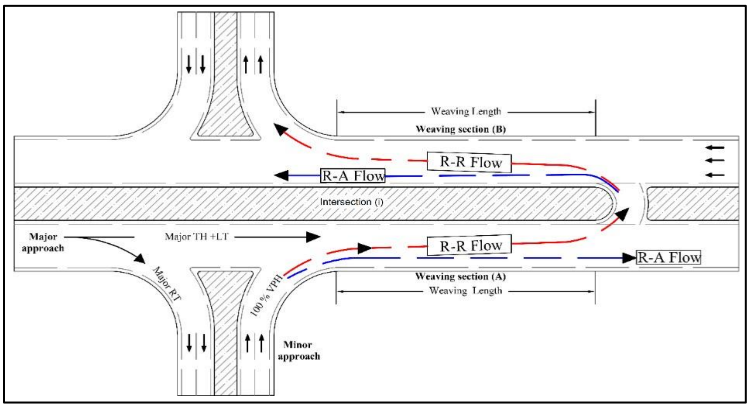


Figure 2: Formation of weaving sections at intersection (i) and flow components

Most of the weaving related research focused on freeway weaving sections due to the complexity of analyzing operations with interruptions to the traffic flow. In urban, environments, disturbances to the traffic flow could be caused by various elements, such as cross street access, driveways, traffic signals, yield control, stop signs, pedestrians, on street parking, etc. Despite being the latest state of the art transportation document, the highway capacity manual (HCM 2010) **[1]**, also stops short in addressing weaving in urban areas and provides a methodology limited to freeway conditions. Practitioners use the HCM 2010 methodology to design and analyze alternative weaving sections. However, using it to address urban sections is controversial.

To date, there has not been a recognized procedure for the analysis of urban weaving sections. However, simulation seems to be a reliable and sophisticated analysis approach that is extensively used nowadays to address limitation of available methodologies and evaluate complex traffic phenomenon. Hence, a simulation approach using VISSIM microscopic simulator was adopted in this research to address urban weaving sections.

VISSIM is a sophisticated time step and behavioral based simulation model developed to model urban traffic, public transit, and pedestrian flow. VISSIM offers flexibility in several respects. The software's programmability overcomes the limitation of the graphical interface. In addition, the concept of links and connectors allows users to model geometries with any level of complexity.

The objective of this paper is to evaluate the capacity of Urban weaving sections using simulation models and test the appropriateness of using the HCM methodology to predict key operational measures namely, capacity, lane change rates, speed. The paper also presents an effort to develop several capacity predictions models and calibrate the Speed prediction algorithms of HCM 2010 using the simulation data.

BACKGROUND

Freeway weaving has been the subject of extensive research aimed at improving the HCM weaving analysis methodology. Efforts to design and analyze weaving sections trace back to the fifties with the first edition of the highway capacity manual HCM 1950, which contained the first weaving analysis methodology [**2**]. Later in 1965, the manual was updated, and the methodology was enhanced by Jack Leisch [**3**], who introduced the concept of out of the realm of weaving and quality of flow, which was later mapped into levels of service.

Over the period from 1965 to 1985, new methodologies and approaches emerged as researchers adopted concepts such as, the proportional use of lanes by weaving and non-weaving vehicles, and the introduction of geometric configurations. The1985 HCM [**4**] incorporated these new concepts and defined three types of geometric configurations: type A, type B and Type C. Further updates were carried out in 1994 and 1997 where coefficients of the speed prediction equations were revised, and the LOS was altered to be dependent on density rather than speed. The HCM 2000 [**5**] contained further improvements and introduced a multi-page table for the capacity estimation of weaving sections, which was a major improvement to methodology.

In 2006, the NCHRP sponsored project 3-75, which lead to the development of a new weaving analysis methodology **[6]** that was later incorporated in the HCM 2010 **[1]**. The study utilized new modern data using aerial photography and divided weaving sections into one-sided and two-sided weaving sections. The new approach relied on the lane changing activity within the weaving section to reflect the impact of configuration and type of operation on the performance of the section, a concept originally presented by Fazio in 1986 **[7].** The methodology also provided a straightforward equation to predict, the capacity of the weaving Section.

Although, various methodologies have been established to analyze weaving sections, simulation modeling has proven to be a reliable alternative analysis tool that allows researchers to explore various traffic phenomenon and conduct experimental analysis with real life or synthetic data using a computer program.

WEAVSIM is a microscopic freeway simulation program designed specifically for simulating weaving sections**.** WEAVSIM was used to investigate the effect of different arrival speeds on the overall speed and delay of ramp weaving sections and develop a regression model to predict these two measures of performance using 243 experimental simulation runs **[8]**.

INTRAS is a stochastic vehicle specific time stepping simulation model developed by Wicks and Lieberman **[9]**. Skabardonis, et al (1989) utilized INTRAS to simulate eight freeway- weaving sections in California with various types of geometric configurations. The researchers were able to predict weaving and non-weaving speeds that closely matched field data **[10]**. Fazio et al. (1990) also used INTRAS to simulate weaving sections and proposed the use of vehicle conflicts as a measure of effectiveness for weaving sections instead of speed **[11]**.

FRESIM is a simulation model enhanced and reprogrammed from its predecessor, INTRAS. It includes enhancements to its geometric and operational capabilities **[12]**. For urban areas, another simulator called NETSIM was designed to be more compatible with the characteristics of urban areas [**13**]. Nowlin (1998) used NETSIM to analyze urban two-sided weaving sections on one-way frontage roads. He used data from multiple simulations to develop a density prediction model and managed to set recommendations on the minimum and desired weaving length **[14]**.

INTEGERATION is a microscopic model developed by Michael Van Aerade [**15**]. Stewart et al (1996) estimated Capacities of the weaving sections using INTEGERATION and stated that weaving length affects capacity only for shorter weaving sections, while the number of lanes is the most critical factor affecting capacity [**16**]. Zhang & Rakha (2010) Used INTEGERATION to perform a capacity analysis of three weaving sections in Toronto, Canada and managed to obtain simulated capacity estimates that closely matched field capacities. The study also found that weaving ratio highly influenced the capacity even though it was neglected in the HCM2000 model **[17]**.

VISSIM is a microscopic time step and behavioral based simulation model developed to simulate urban traffic, public transport operations, and flows of pedestrians **[18]**. The model was developed at the University of Karlsruhe in Germany based on the work of R. Wiedemann **[19]**. Vu, et al (2007) used VISSIM to simulate a type B, six lane weaving section in Emeryville, California, using extremely detailed data provided by the next generation simulation team (NGSIM). The researchers also output data to generate speed-flow relationships and estimate capacities accordingly. The study further investigated speed-flow relationships at different volume ratios and found that capacities decrease noticeably with the increase in volume ratio **[20]**.

Another study by Fitzpatrick (2011) utilized VISSIM to investigate relationships between weaving length, speed, and overall vehicle operations for successive ramps on Texas freeways **[21]** where a VISSIM model was calibrated and used as an experimental test bed for a total of **360** scenarios. Factors that were used to design the experiment were traffic volume, weaving length, posted speed, and proportion of volumes. Evaluation of the simulation data revealed that weaving length was not a significant variable in predicting speed when included as a continuous variable that assumes a linear relationship between speed and weaving length. The study provided guidance on recommended distances between ramps and used simulation and field data to develop a speed prediction equation as function of geometry and traffic.

Liu et al (2012) used VISSIM to model the impact of cross weave maneuvers on the speed and capacity of freeways with managed Lanes [**22**]. The cross-weave maneuver is similar to the two-sided weaving maneuver described in the HCM 2010. A test bed VISSIM model was used to carry out multiple runs with different levels of mainstream demand, cross-weave demand, mainstream number of lanes, and minimum lane changing distance (LCW-min). Speed-flow curves were generated using Van Aerde's curve fitting, and capacities were estimated accordingly. The researchers also developed a simulation-based regression model to predict the reduction in the weaving section capacity as a function of cross weave flow rate, number of mainstream lanes, and weaving length with R^2 of 0.9837 indicating a perfect fit

Based on findings of previous research, VISSIM traffic simulator form PTV appeared to be the most suitable software for this research due to its modeling flexibility and capabilities in conducting weaving related studies of freeway and urban sections.

METHODOLOGY

The methodology adopted herein is an experimental analysis with synthetic demands using VISSIM microscopic simulation models to simulate urban weaving sections under various combinations of weaving lengths and demand. Experimental analysis often involves the investigation of numerous scenarios. However, VISSIM doesn't provide a scenario manager where one could predefine all the scenarios allowing the program to run them in sequence; therefore, an external program called **AUTOMATE** was developed in Visual Basic programming language to automate the simulation runs through the COM interface feature provided by VISSIM.

The experimental design allowed the simulation of the weaving sections at different weaving lengths and various levels of demand inputs. Some of these demand input combinations caused the weaving sections to reach capacity, which was pointed out. After capacities were derived, using the simulation, SPSS statistical package is utilized to develop simulation based logarithmic and linear capacity prediction models for the analyzed urban weaving sections.

Finally, the HCM 2010 weaving analysis methodology was applied to each weaving section to test the methodology's reliability in representing urban weaving operations. Key weaving operational measures were predicted using the HCM methodology namely: capacity, lane change rates, weaving and non-weaving speeds. These predicted measures were compared to those of the simulation models using statistical and graphical methods. Finally, an effort was made to calibrate and modify the HCM 2010 speed prediction models using the simulation data points to reflect urban conditions.

Simulated network

In this study, a network similar to Figure 1 was coded in VISSIM to serve as an experimental test bed to explore the effects of weaving length, minor demand, major demand and the percentage of minor through split on the operations of weaving section (A) and (B) as shown in Figure 2.

The simulated network depicts a typical intersection design that is widely adopted at major corridors in the city of Cairo. There is no traffic control at any of the conflict points; however, yield control is applied at the U-turns and at the major intersections through a combination of conflict areas and priority rule features provided by VISSIM.

The mainstream has 3 lanes each lane is 3.65 meter wide, while the minor approaches have 2 lanes also.
3.65 meters wide. U-turn slot is a single lane without any acceleration or deceleration bays at any point. The posted speed limit is 60 km/hr and a turning speed of 20 km/hr is assumed for all vehicles. The simulations were conducted using the default parameters of the urban driver behavior in VISSIM.

Experimental design

A general factorial design was adopted. The influential factors chosen for the experiment were the weaving length (WL), the minor approach demand, the major approach demand, and the percentage of minor through split (% Mi THR). Weaving length (WL) was measured as shown in Figure 2 with four levels starting from 100 meters to 400 meters with a 100-meter increment.

Hypothetical traffic volumes were used in this study. Minor approach demand ranged from 100 vph to 2000 vph, with a 100 vph increment up to a level of 1000 vph and then the increment is increased to 200 vph (i.e. 15 volume levels). Major approach demand ranged from 1000 vph to 2400 vph, with a 200 vph increment (i.e. 8 volume levels). These ranges were chosen based on the observed animations of a few trial simulations with high and low volume conditions to guarantee that these volumes covered a wide range of saturation levels.

All minor approach volume scenarios were modeled with 20% left turn volumes. The major approach was modeled with a 10% major LT and 10% major RT. Minor through split (% Mi THR) was defined as 25% of the minor approach demand for the first minor through split-level (% Mi THR) and then increased to 50% of the minor demand for the second level of (% Mi THR). Increasing the minor through split was intended to increase the intensity of weaving. Increasing the minor through from 25% to 50% increases the percentage of ramp-to-ramp vehicles from 45% to 70% of the minor demand approach.

In total, 960 combination runs were generated using a general factorial design. Each weaving length had 120 combination runs for each level of the % Mi THR split (25% and 50%). Weaving sections of different length and traffic splits required different network configurations; therefore, two test beds corresponding to both levels of % Mi THR split for each weaving section length were coded. In total, 8 VISSIM models were prepared to run 120 combinations of minor and major volume levels.

Automation program development

All 960 scenarios generated by the factorial design were simulated using VISSIM traffic simulator through an external program developed in visual basic script. Each scenario needed to be run 3 times with different random number seeds, which makes it 2880 run. This would have been very time-consuming, therefore efficiency required automation of the process using computer programming.

A computer program called **AUTOMATE** was developed using Excel Visual Basic scripts to automate the scenario runs generated by the factorial design. The program simply changes the major and minor demand volume for each iteration (scenario) automatically using a visual basic for next loop. Once iterations are completed, the program moves to another network and the code is repeated until all networks are processed. Figure 3 depicts the logic of the developed program where each iteration (scenario) has a unique run order.

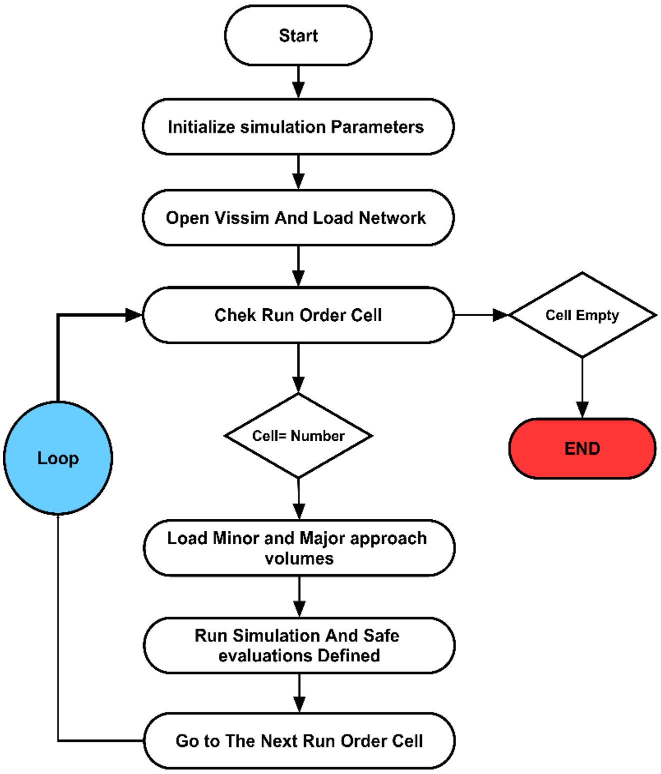


Figure 3: Logic of the VBA program AUTOMATE

WEAVING SECTION MODELLING

The VISSIM network is modeled using a system of links and connectors. Conflict areas and priority rules were used to accurately depict the interaction between crossing streams. Vehicle inputs in (vph) were loaded and changed automatically by the developed VBA program.

The VBA program immediately loads the predefined network and then the vehicle input object in VISSIM is accessed through COM interface to assign vehicle inputs at the proper chosen links. The assigned vehicle input value corresponds to a specific run (scenario) according to the run matrix generated by factorial design and embedded within the program.

Static routing was used to route vehicles from a start point (red) to any of the defined destinations (green) using a static percentage for each destination. Routing decisions are similar for each VISSIM network. Figure 4 shows all routing decisions as specified in VISSIM and Table 1 summarizes the traffic split for each route.

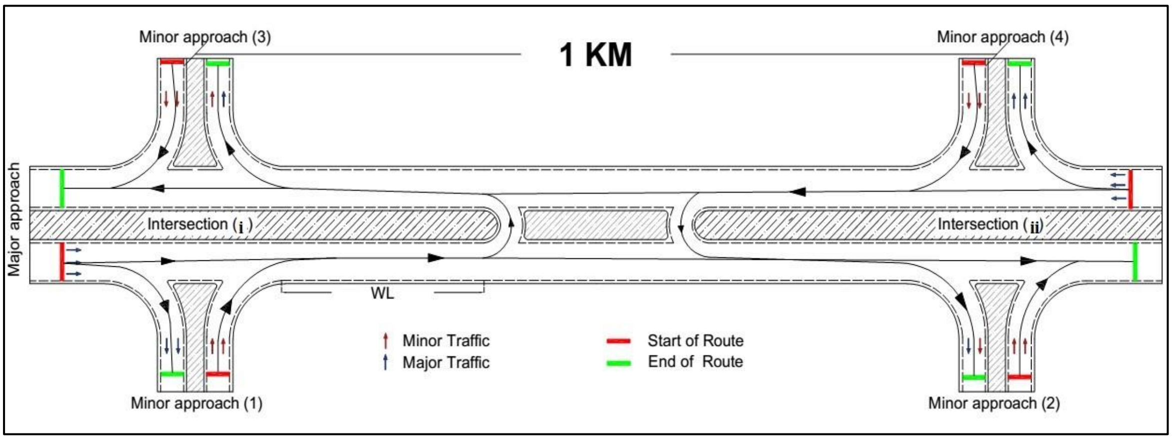


Figure 4: Routing decisions as modeled in VISSIM.

Table 1: Traffic splits

Intersection (i) or (ii)	25 % minor Through	50 % minor Through
	Percentage	
Major Through	70%	70%
Major Left Turn	10%	10%
Major Right turn (1)	10%	10%
Major Right Turn (2)	10%	10%
Minor Left turn	20%	20%
Minor Right turn	55%	30%
Minor Through	25%	50%

The percentage of heavy vehicles were assumed 2% for all cases; therefore, all compositions of traffic were 98% passenger cars and 2% heavy vehicles. Each vehicle type had a stochastic distribution of desired speed and for this research the speed distribution for cars was 60 km/hr (58 km/hr: 68 km/hr) while for the heavy vehicles (HGV) the desired speed distribution was selected as 50 km /hr (48km/hr:58 km/hr).

VISSIM provides a wide range of evaluations that must be defined and configured to get the desired model output from a simulation run. The common form of these outputs are offline text files containing the results and delimited by a semicolon. The period of each run is set to 4500 seconds; however, the first 900 seconds were considered warm up and outputs were collected for the last 3600 seconds of simulation.

For this research, the following evaluations were activated and configured in VISSIM:

- **Link evaluation**: The link evaluation feature allows the collection of simulation results based on the area of weaving such as (density, Throughput, average speed).

- **Lane change rates**: Allows the collection of the total lane change rates executed within each weaving section.
- **Data collection Points**: Collects vehicle counts and spot speeds at the major and minor entrance upstream of weaving section (**A**).
- **Travel time sections**: Allows the collection of travel times and vehicle counts. Travel times sections are set up to capture weaving and non-weaving flow rates and speeds as shown in figure 5.

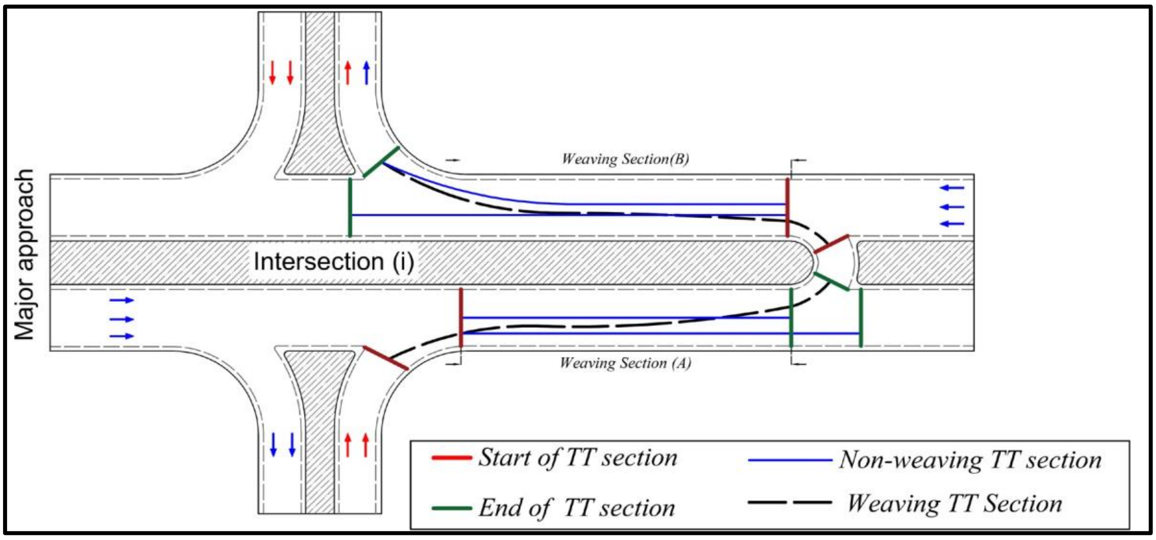


Figure 5: Travel time sections as defined in VISSIM

From the HCM 2010 **[1]** perspective, these local weaving sections are similar in their characteristics to the two-sided weaving sections. The HCM 2010 methodology states that in case of two-sided weaving sections the ramp-to-ramp movement is the only weaving movement, while all other movements are considered non-weaving. To maintain consistency with HCM, this research paper adopts the same definitions to differentiate between weaving and non-weaving flows. Therefore, travel time sections were set accordingly as shown in figure 5, where the dashed line represents the weaving flow, and the solid lines represent the non-weaving flows.

At weaving section (A), the minor entrance represents the on ramp and the U-turns represent the off-ramp while at weaving section (B), the U-turns becomes the on-Ramp, and the minor approach downstream is the off ramp.

Travel time sections produce the average travel time of a number of vehicles passing a user defined travel time section with a known distance during a specific time interval. By dividing the average travel time by the length of the travel time section, the space mean speed of each movement is easily calculated.

ANALYSIS OF SIMULATION RESULTS

After 960, simulation runs with 3 different random number seeds were conducted, a total of 2880 evaluation output files were generated for each individual evaluation type previously configured in VISSIM (link evaluation, lane change rates, travel times, and data collection points). To be able to extract the simulation outputs from each file, 4 Visual Basic programs were developed for the extraction and manipulation of the output data. The 4 programs were developed using the same data extraction logic; however, the only difference is how the data was organized for each evaluation type.

When executing the program, it automatically prompts the user for the output folder directory. After choosing the directory, the program loops through all the output files importing each file into Microsoft excel and extracting the evaluation data. The program also calculates the average of each repeated simulation run with different number seeds and performs any necessary calculations such as converting travel times into speeds and converting vehicles into Passenger car equivalents.

Capacity estimation using simulation

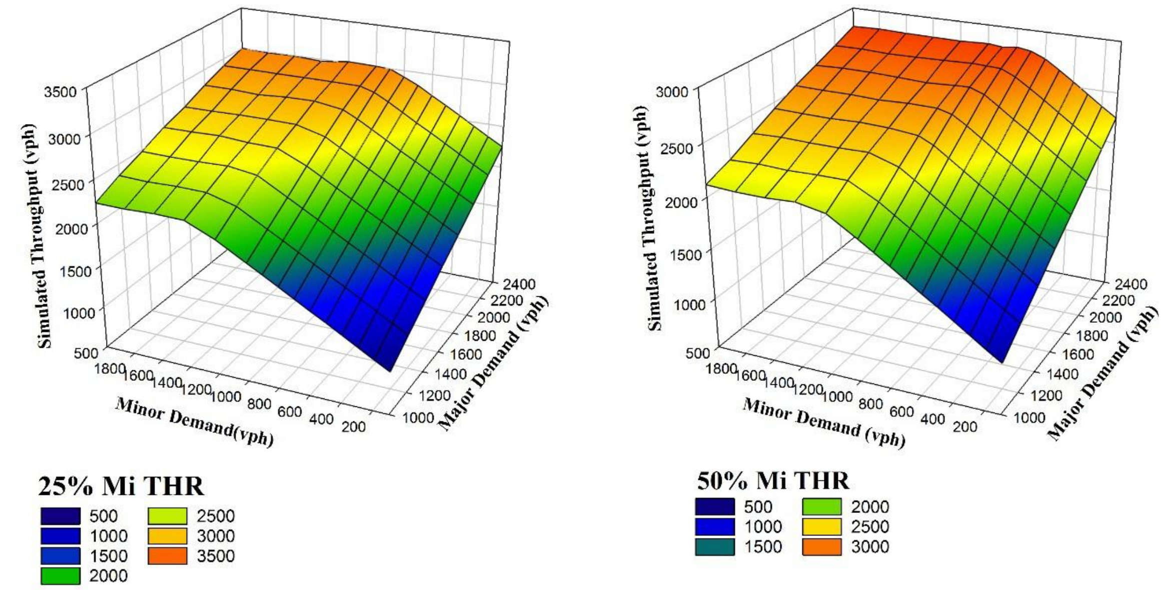
VISSIM or any other simulation tool does not produce capacity estimates directly. The easiest way to estimate Capacity is to observe the link (Study segment) throughput against an increasing demand input. The throughput represents the actual vehicles processed by VISSIM, while the demand represents the vehicle inputs that are assigned to the simulated network.

At first, the throughput equals the input demand up to a certain point, and then levels off indicating that the system is not able to accommodate any more vehicles and is operating at capacity. It was also expected to observe that the throughput of weaving section (**A**) is almost equal to the throughput of section (**B**). Theoretically, the throughput of weaving section (**A**), should be exactly equal to the throughput of weaving section (**B**) assuming similar volume inputs and routing decisions at the next consecutive intersection of the network.

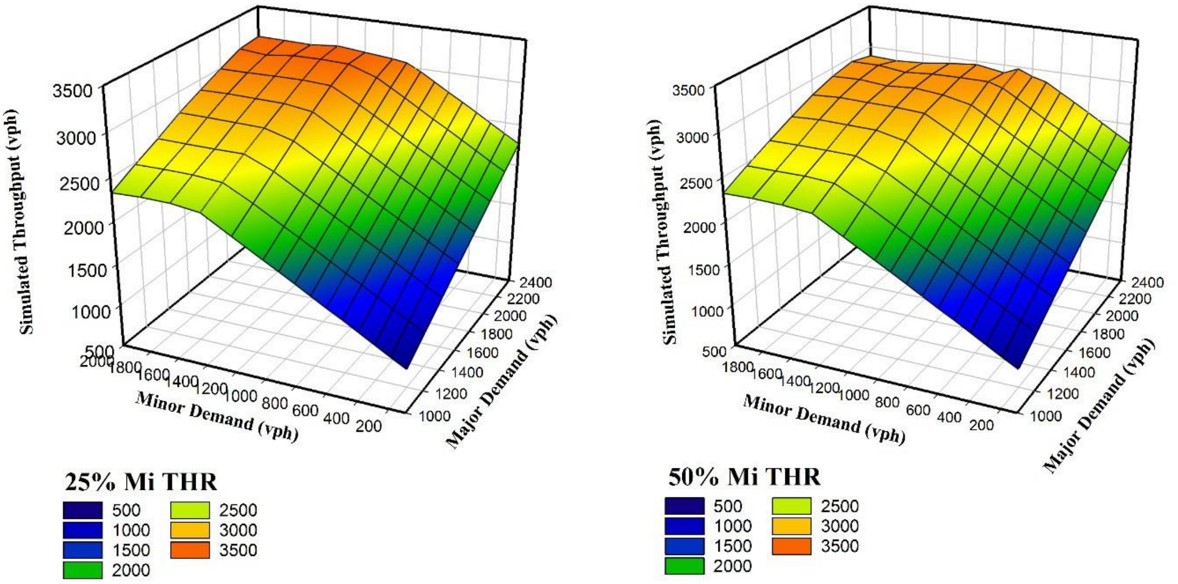
Figures 6 shows the relationship between the total demand and throughput of weaving section (**A**), for 100 meters and 200 meters weaving lengths as an example. From Figure 6, it is noticeable that the throughput increases with the increase in total demand (Minor + Major) until reaching a certain threshold where it becomes nearly constant and unresponsive to further increase in demand. The point of maximum constant throughput represents the capacity of the weaving section. The figure also shows that the capacity of the section is directly proportional to the major demand level and to the weaving length. From the same figure, it is also noticed that the throughput decreases when the minor through traffic split increased from 25% to 50%. The decrease in capacity is attributed to the fact that increasing the percentage of minor vehicles through increased the weaving flow from 45% of the minor demand to 70% leading to a higher volume ratio (VR), which causes higher lane changing related turbulence, and lower capacities.

Figure 7 shows the simulated capacities of all weaving lengths at each major demand level. When length was increased beyond 200 meters, the capacities increased with major demand up to a certain point and then started to level after major demand exceeded 2000 and 1600 vph for 25% and 50% Mi THR split, respectively for both weaving sections. It was found that increasing the weaving length beyond 200 meters did not increase the capacity of the sections, on the contrary capacities was less than the values associated with the shorter weaving length (200 meter) for major demand levels greater than 2000 and 1600 vph at 25% and 50% Mi THR respectively.

Capacity difference between sections (**A**) and (**B**) at both levels of % Mi THR (25% and 50%) was neglected, as the maximum difference did not exceed 2.5 %. The slight variation in throughputs between Weaving section (**A**) and (**B**) is only attributed to the stochastic behavior of the simulation model.



a. Simulated throughput of weaving section (A) at WL= 100m



b. Simulated throughput of weaving section (A) at WL= 200m

Figure 6: Relationship between total demand and throughput of weaving section (A) at different weaving lengths

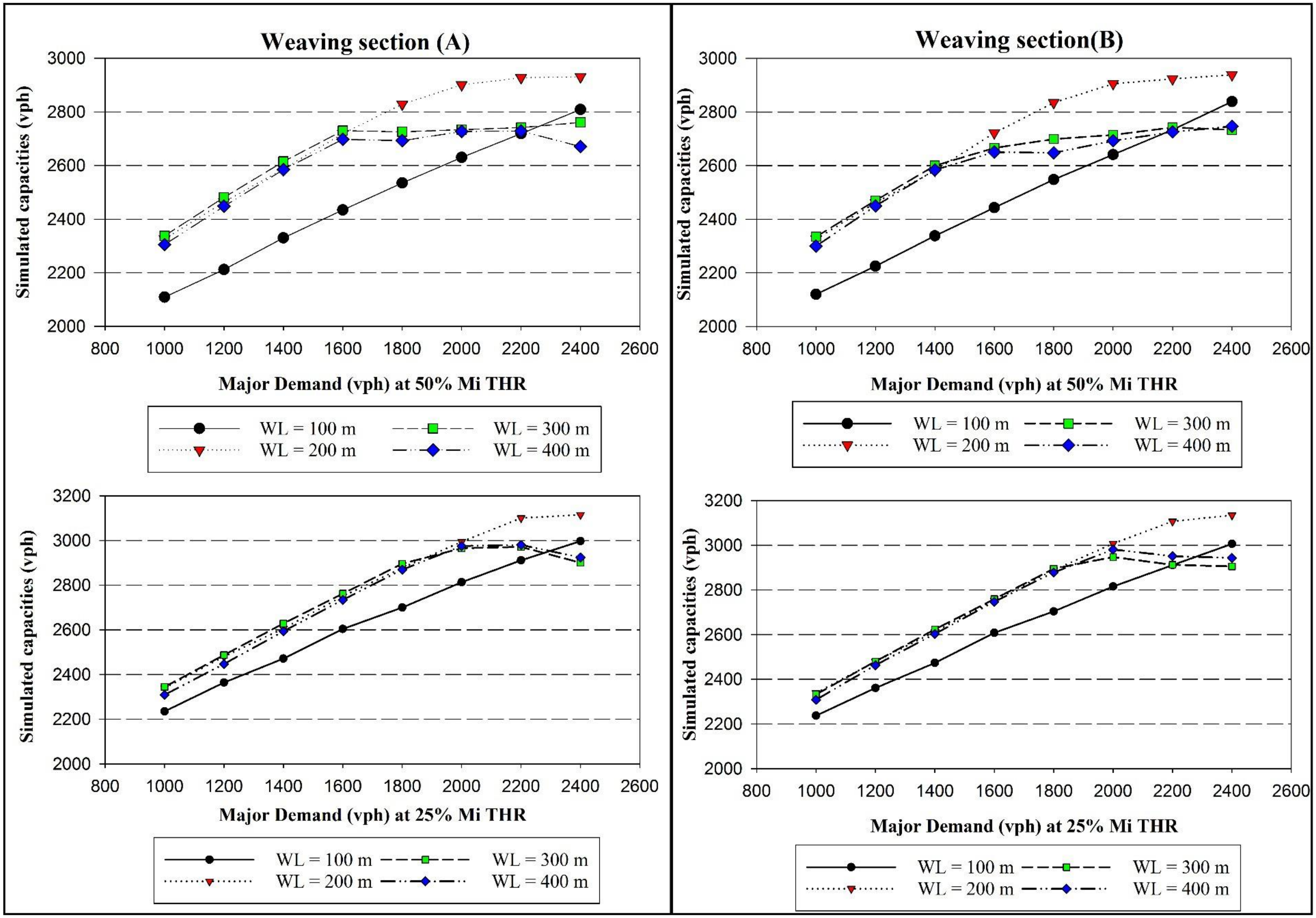


Figure 7: Simulated capacities at different weaving lengths

The impact of volume ratio on capacity is summarized in figures 8 and 9. The points on each graph represent the capacity at a certain major demand level. Figure 8 shows the relationship between capacity and volume ratio for a weaving length of 100 meters as an example. Capacity of the weaving sections increases with the decrease in volume ratio for both cases of minor through split.

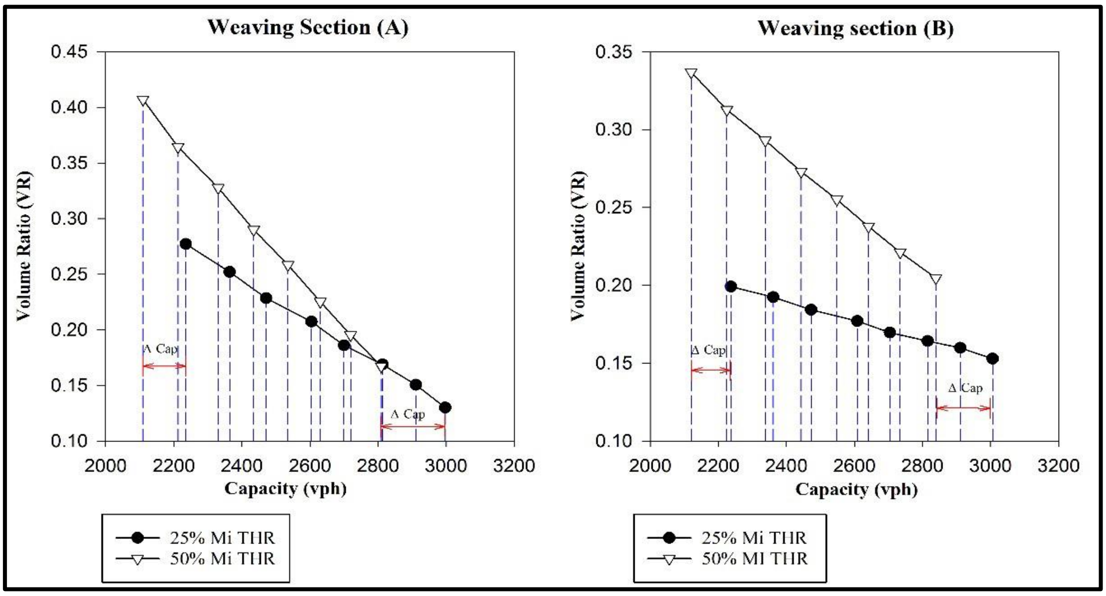


Figure 8: Capacity versus volume ratio for WL= 100

The reduction in capacity for each pair of capacity estimates at different % Mi THR split is represented by a ΔCap on the graph. Although capacities of section (**A**) and (**B**) are equal, volume ratio at capacity of weaving section (**B**) is noticeably lower than its corresponding value of section (A) for both levels of minor through traffic. This explains why sections (**B**) at some points will operate at a relatively higher LOS than section (**A**) which is why it should be treated as a separate weaving configuration.

When the weaving length was increased beyond 200 meters as shown in figure 9, capacities did not increase after major demand exceeded 2000 (vph) and 1600 (vph) for 25% and 50% Mi THR respectively even though volume ratio seems to be decreasing. Form figure 9 it is also noticeable that Δ Cap associated with a major demand < 1400 (vph) for weaving sections (**A**) and (**B**) respectively is minimum. Which indicates that the turbulence resulting from increasing the % Mi THR split from 25% to 50% is sustained for major demand levels ≤ 1400 (vph).

It is worth mentioning that when the length was increased to 200 meters the simulated volume ratios increased. However, the estimated capacities were higher than the shorter weaving section (100 meters) as the extra length compensates for the capacity losses due to the increase in the volume ratio. The volume ratio increases with length due to an increase in the minor entrance throughput, upstream of weaving section (**A**).

When investigating the relationship between the throughput of the minor entrance, and the minor demand, it was noticed that capacities of the minor entrance have a negative correlation with the capacities of the weaving sections. The Capacities of the Minor entrance is inversely proportional to the major demand and directly proportional to the weaving length up to 200 meters. Increasing the length beyond 200 meters does not increase the capacity of the minor approach as shown in Figure 10.

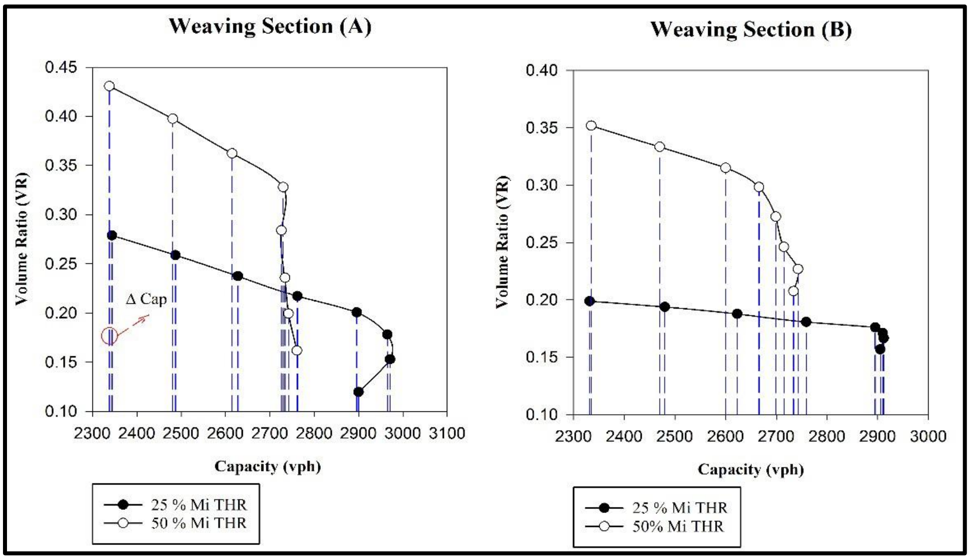


Figure 9: Capacity versus volume ratio for WL= 300

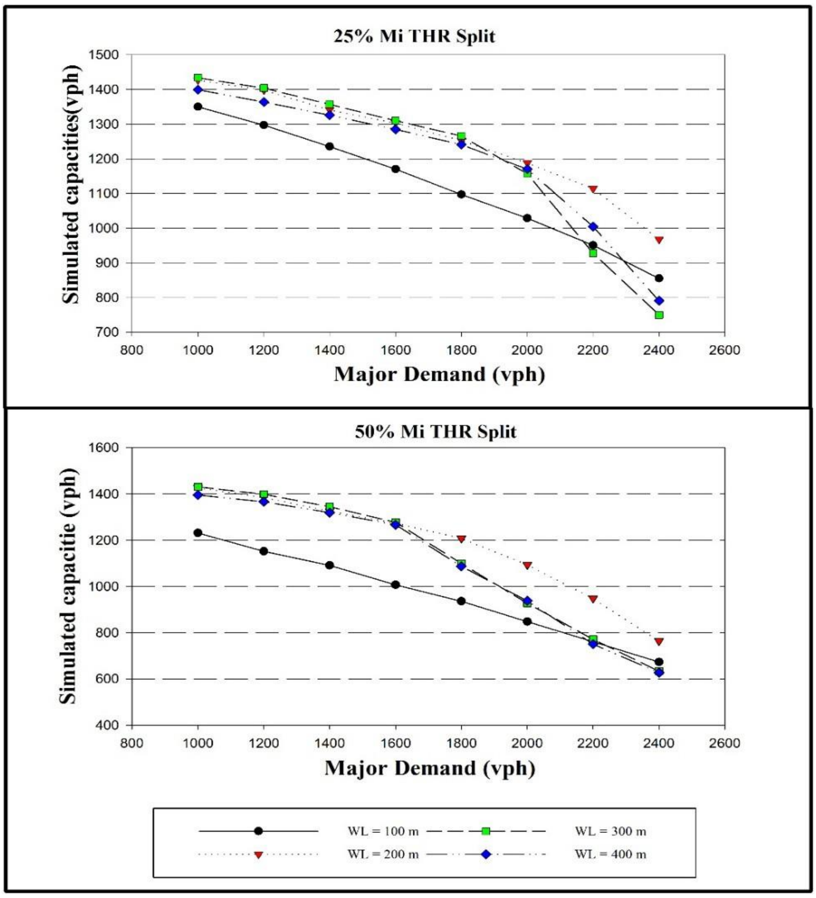


Figure 10: Minor entrance capacities at all levels of major demand and at different weaving lengths

Simulation based capacity prediction models.

Simulation based Capacity prediction models were developed to predict the capacity of weaving section (**A**) and (**B**). These models, however, are limited to a specific weaving length and the range of data used to develop the models. In addition, the models are constrained to the assumptions made for the study network. Increasing the weaving length beyond 200 meters was not beneficial as illustrated before, and therefore no models were developed for these lengths.

Linear and non-linear regression procedures provided by the Statistical analysis software SPSS were utilized to develop two capacity prediction models as illustrated below.

For WL of 100 m the following models were developed:

Model 1: Logarithmic Capacity Prediction Model

For section (A): $\mathbf{CAP = 875.18 * \ln(MD) - 1.287523 * VR * MD - 3433.603297}$

For Section (B): $\mathbf{CAP = 1053.65 * \ln(MD) - 1.068 * VR * MD - 4846.67}$

Model 2: Linear Capacity Prediction Model

For section (A): $\mathbf{CAP = 2510.466 + 0.33 * MD - 0.865\ V_W}$

For Section (B): $\mathbf{CAP = 2108.76 + 0.5 * MD - 0.71\ V_W}$

Where,

CAP Weaving section capacity in vph,
MD Major approach demand in vph,
VR Volume ratio at weaving section (A) or (B),
V_W Weaving flow in vph (i.e. the ramp-to-ramp vehicles).

The R^2 values of the logarithmic models are relatively high (0.992) which indicates a perfect fit. The negative sign for the coefficient of volume ratio is also logical which means that when volume ratio is increased the capacity decreases. The R^2 value of the linear models are also high, (0.975) and (0.986) respectively. All coefficient signs are also relevant indicating logical correlation between the dependant variable and the predictors.

For WL of 200 m the following models were developed:

Model 3: Logarithmic Capacity Prediction Model

For section (A): $\mathbf{CAP = 866.13 * \ln(MD) - 0.298 * VR * MD - 3538.47}$

For section (B): $\mathbf{CAP = 949.27 * \ln(MD) - 0.42 * VR * MD - 4111.98}$

Model 4: Linear capacity prediction model

For section (A): $\mathbf{CAP = 1977.41 + 0.495 * MD - 0.1V_W}$

For section (B): $\mathbf{CAP = 1968.56 + 0.52 * MD - 0.16\ V_W}$

The R^2 values of the logarithmic models equal (0.961) and (0.968) respectively, which is relatively high, while the linear models have an R^2, values of (0.929) and (0.932) respectively. All models' coefficient yielded relevant signs.

APPLICABILITY OF HCM 2010 WEAVING ANALYSIS METHODOLOGY

To facilitate the application of HCM, an excel based calculation sheet was developed to calculate the operational measures of weaving section (**A**) and (**B**) using the simulated weaving and non-weaving volumes obtained from 960 simulation runs. All the algorithms embedded in the calculation sheet is found in the HCM 2010 chapter 12 **[1]**.

Capacity

The HCM 2010 presents a straightforward equation to estimate the lane capacity of the weaving section, which in this case will be a two-sided weaving section. To make comparisons possible some adjustments were made to the capacity values derived using the HCM 2010 to be more compatible with the capacities estimated using VISSIM. These adjustments are as following:

- Simulated capacities are provided for the entire section therefore, HCM capacities are multiplied by the number of lanes N= 3.
- Simulated capacities were obtained in vph therefor; HCM capacities should be adjusted to vph using the heaving vehicle factor FHV.
- Weaving Length should be in units of feat.

The following equation is used to estimate the capacity of the weaving section in HCM 2010:

$$C_{IWL} = C_{IFL} - [438.2(1 + VR)^{1.6}] + [0.0765 L_S] + [119.8 N_{WL}]$$

Where,

C_{IWL}	capacity of the weaving segment under equivalent ideal conditions, per lane (pc/h/ln),
C_{IFL}	capacity of a basic freeway segment with the same FFS as the weaving segment under equivalent ideal conditions, per lane (pc/h/ln)
VR	volume ratio, v_W/v,
L_S	length of the weaving segment (ft),
N_{WL}	number of lanes from which a weaving maneuver may be made with one or no lane changes (for two-sided weaving section N_{WL} =0)

The comparison is established for the urban weaving sections studied in this research, i.e. number of lanes is 3 lanes, configuration is a two-sided weaving section, N_{WL}= 0, and FFS = 60 km/h (37.5 mph). No base capacity was established for speeds less than 55 mi/h in HCM 2010 therefore, base capacity per lane was assumed 1800 vph. Factor of heavy vehicles was calculated using the methodology provided in chapter 11 of the HCM 2010 [1]. However, heavy vehicle factor could be ignored, as 2% heavy vehicles is insignificant. Figure 11 shows the relationship between the simulated capacities and the capacities predicted using the developed models and the HCM 2010 model for weaving section (A).

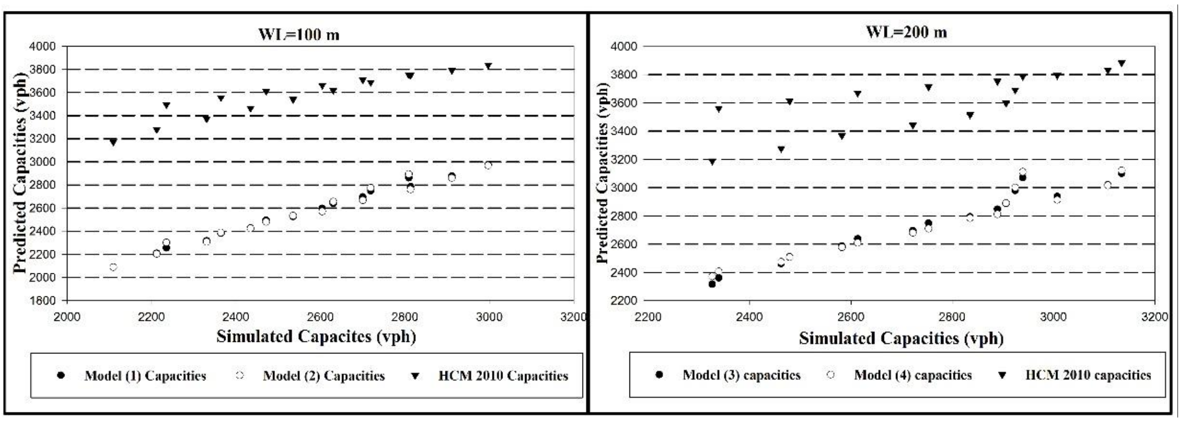


Figure 1: Predicted capacities using HCM2010 and the developed models for weaving section (A)

It is evident that the HCM 2010 model over predicts capacities and should not be used for similar urban configurations. Capacities predicted by HCM 2010 are at some points 1.6 times the simulated capacities, while the developed regression models seem to be more accurate and better suited for the capacity prediction of this type of urban weaving section.

Lane change rates

The speed prediction models of the HCM 2010 mainly depend on the rate of lane changes within the weaving section of study. The total lane-changing rate of all vehicles in the weaving section is computed by combining weaving lane change rates and non-weaving lane change.

The model for predicting weaving lane changing rate in HCM 2010 is as following:

$$LC_{MIN} = LC_{RR} \times V_{w}$$

$$LC_{W} = LC_{MIN} + 0.39\,[(L_{S}-300)^{0.5}\, N^{2}\, (1+ ID)^{0.8}]$$

Where,

LC_{MIN}	Minimum equivalent hourly rate weaving vehicles must make to successfully complete all weaving maneuvers
LC_{RR}	Minimum number of lane changes that must be made by one ramp to ramp vehicle to execute the desired maneuver successfully
V_{W}	Weaving volume in pc/h
LC_{W}	Equivalent hourly rate at which weaving vehicles make lane changes within the weaving section (Lc/h);
L_{S}	Length of the weaving section (ft);
N	Number of lanes within the weaving section;
ID	Interchange density.

For the urban two-sided weaving sections studied in this research $LC_{RR} = 2$, and ID is assumed 0.67.

The model for predicting non-weaving lane changing rate in HCM 2010 is as following:

First, a non-weaving vehicle index, ”I_{NW}, needs to be calculated and then depending on the index the non-weaving lane changing rates are calculated using one of the three non-weaving lane change rate equations below.

$$I_{NW} = \frac{L_{S} * ID * V_{NW}}{10000}$$

If $I_{NW} \leq 1300$ **then** $LC_{NW} = LC_{NW1}$
If $I_{NW} \geq 1950$ **then** $LC_{NW} = LC_{NW2}$
If $1300 < I_{NW} < 1950$ **then** $LC_{NW} = LC_{NW3}$

$$LC_{NW1} = (0.206*V_{NW}) + (0.542*L_{S}) - (192.6*N)$$

$$LC_{NW2} = 2{,}135 + 0.223(V_{NW} - 2{,}000)$$

$$LC_{NW3} = LC_{NW1} + (LC_{NW2} - LC_{NW1})*((1/650)\,(I_{NW} - 1300))$$

The total lane-changing rate of all vehicles in the weaving section is then computed by combining LC_{W} and LC_{NW}.

$$LC_{ALL} = LC_{W} + LC_{NW}$$

In VISSIM, lane change evaluations were set to calculate the total number of lane changes per hour that occurs at each weaving section. Paired t-tests were executed using SPSS statistical package to test the null hypothesis, which states that there is no significant difference between the simulated and the predicted lane changes at section (**A**) and (**B**) for each weaving length.

Parity plots of the simulated versus predicted estimates were also generated, which gives a visual description of the relationship between the simulated and the predicted values. The closer the plot of points to the 45º Line, the more accurate the predicted speeds. If points are on the left of the 45º Line, predicted lane changes are generally larger while predicted lane changes are lower for values on the right of the line.

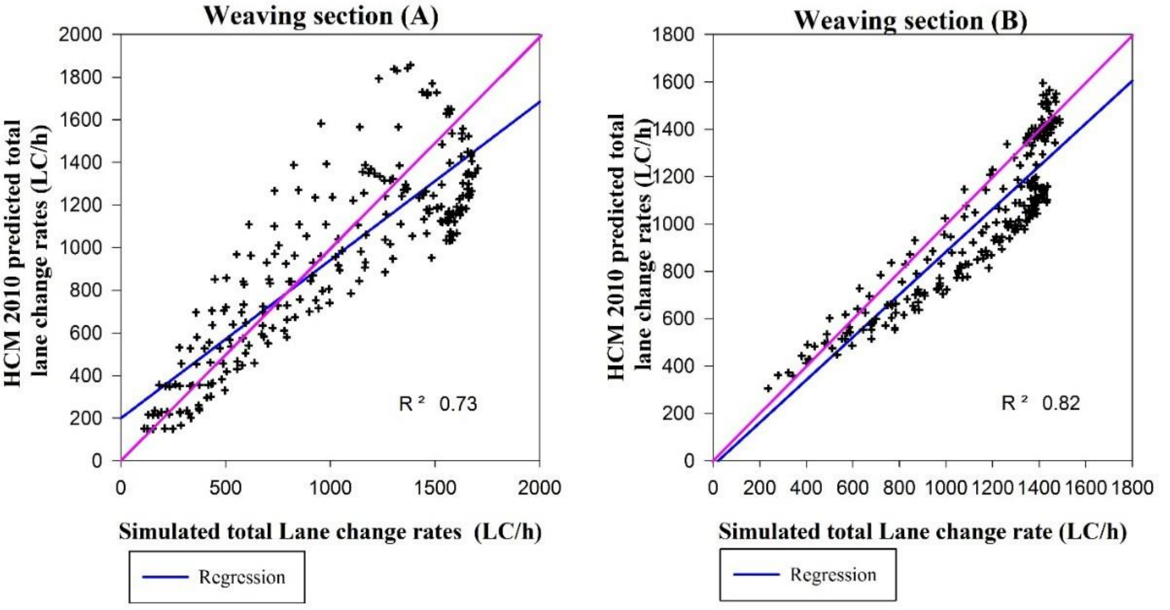
Parity plots are shown in figure 12 for weaving lengths of 100 and 200 meters as an example. By examining the plots, it is evident that there is a moderate to high magnitude of fit and a high positive correlation between the predicted and the simulated values. Clearly most of the points are to the right of the 45°line, which indicates that the simulated lane change rate is higher than predicted. The same analogy can be applied on the rest of the weaving lengths in this study.

The following table shows the result of paired t-test with a significance value < 0.05 indicating that there is a statistically significant difference between the simulated, the predicted values, and thereby rejecting the null hypothesis.

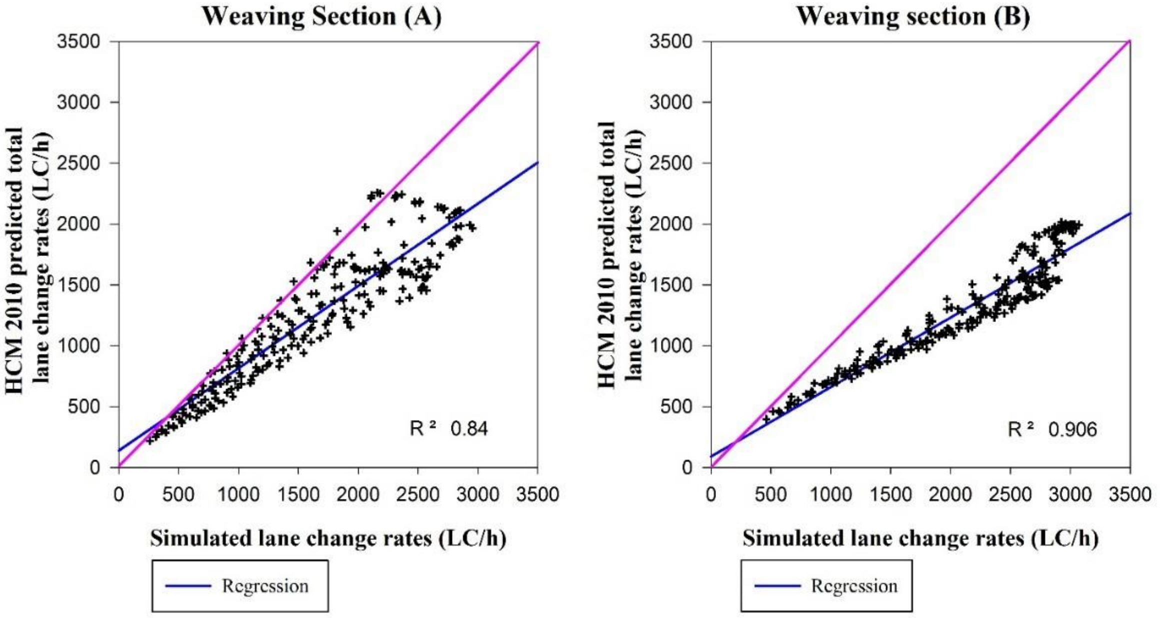
Table 2: Lane change rates Paired Samples Test

				Paired Differences					**t**	**df**	**Sig. (2-tailed)**
Samples	**WL**	**Section**	**Lane change rates**	**Mean**	**Std. Deviation**	**Std. Error Mean**	**95% Confidence Interval of the Difference**				
							Lower	**Upper**			
Pair 1	100	A	Simulated_ LC – HCM _LC	63.64	257.64	16.63	30.87	96.40	3.83	239.00	.00
Pair 2		B	Simulated_ LC – HCM _LC	130.71	137.49	8.87	113.22	148.19	14.73	239.00	.00
Pair 3	200	A	Simulated_ LC – HCM _LC	396.49	317.66	20.50	356.09	436.88	19.34	239.00	.00
Pair 4		B	Simulated_ LC – HCM _LC	821.62	326.68	21.09	780.08	863.16	38.96	239.00	.00
Pair 5	300	A	Simulated_ LC – HCM _LC	490.53	389.40	25.14	441.01	540.04	19.51	239.00	.00
Pair 6		B	Simulated_ LC – HCM _LC	646.39	391.31	25.26	596.63	696.15	25.59	239.00	.00
Pair 7	400	A	Simulated_ LC – HCM _LC	352.22	411.38	26.55	299.91	404.53	13.26	239.00	.00
Pair 8		B	Simulated_ LC – HCM _LC	524.27	430.23	27.77	469.57	578.98	18.88	239.00	.00

From the previous section, it was concluded that the lane change prediction models provided by HCM 2010 clearly underpredicts the rate of lane changes for this type of urban weaving sections. Consequently, the predicted speeds are likely to be higher than the actual speeds.



a. HCM 2010 Predicted total lane change rates versus Simulated total lane change rates for WL=100 m



b. HCM 2010 Predicted total lane change rates versus Simulated total lane change rates for WL=200 m

Figure 12: Parity plots of the simulated verses predicted lane change rates for WL=100 and 200 meters

Weaving and non-weaving speed (s_W, s_{NW})

The HCM 2010 presented two models for the prediction of weaving and non-weaving speeds. These models and dependant on the rate of lane changes where speeds would decrease with increasing lane-changing activity – a real measure of weaving intensity. It is worth mentioning that the prediction of non-weaving vehicle speed is the weakest part of the HCM 2010 methodology **[6]**.

$$S_W = 15 + \frac{FFS-15}{1+W} \quad , \quad W = O.226 * \left(\frac{LC_{ALL}}{L_S}\right)^{0.789}$$ **(Weaving speed prediction model)**

$$\boldsymbol{S_{NW} = FFS - (0.0072 * LC_{MIN}) - (0.0048 * \frac{V}{N})}$$ **(Non-weaving speed prediction model)**

Where,

S_W	Average speed of weaving vehicles in (mi/h),
Snw	Average speed of non-weaving vehicles in (mi/h),
LC_{Min}	Minimum Lane change rate depending on geometry,
LC_{ALL}	Total rate of lane changes,
N	Number of lanes in the weaving section,
FFS	Free flow speed,
V	Total flow rate in pcu,
W	Weaving intensity factor,
V	Total flow rate in pcu,
LS	Weaving length in ft

In VISSIM, travel time sections were utilized to capture the weaving and non-weaving speeds for both weaving section (**A**) and (**B**). The travel time sections were set based on the HCM definitions of weaving and non-weaving movements to maintain consistency when comparing simulated and predicted samples. Speeds that were estimated using HCM were converted into Km/h for consistency as well.

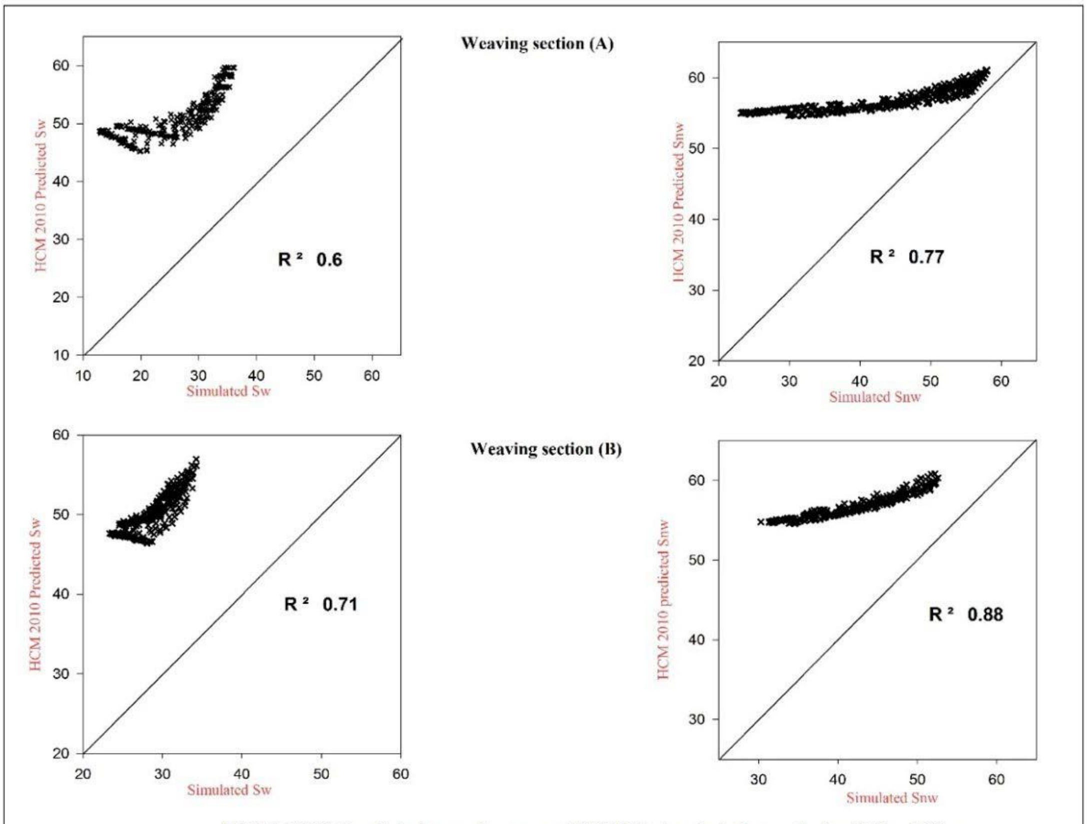
A Paired sample t-test was carried out to compare the simulated and predicted weaving and non-weaving speeds and parity plots were generated for each weaving length. Figure 13 shows parity plots for weaving length of 100 and 400 meters as an example.

As expected, the HCM models over predicted the speeds of all movements as shown in the plots. The Goodness of fit (R^2) was very small and all the plotted points were on the left side of the 45°line, which means that the predicted speeds are higher.

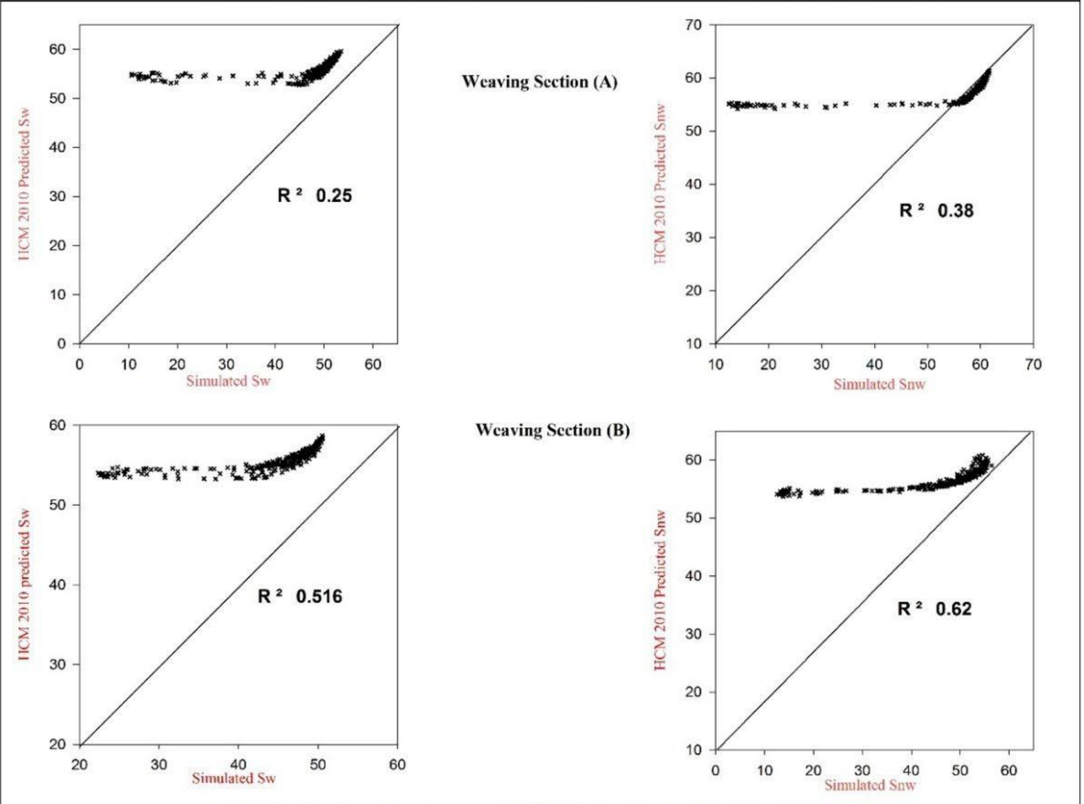
It is also noticeable that the simulated speeds were more spread compared to that of the predicted speeds; however, there is a significant degree of linearity and a positive correlation. The weaving and non- weaving speeds failed the T-test with significance value < 0.05 and it was concluded that the speeds were significantly different as shown in Table 3.

Table 3: Weaving and non-weaving speeds Paired Samples Test

Pairs	W	S	Weaving and non-weaving speeds	Paired Differences					t	df	Sig (2-tailed)
				Me	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
							Lower	Upper			
Pair 1	WL=100	A	Simulated Sw –HCM Sw	-25.43	4.43	.29	-25.99	-24.87	-89.01	239.00	.00
Pair 2			Simulated_Snw –HCM Snw	-13.84	8.72	.56	-14.95	-12.73	-24.58	239.00	.00
Pair 3		B	Simulated Sw –HCM Sw	-21.41	1.48	.10	-21.60	-21.22	-223.38	239.00	.00
Pair 4			Simulated_Snw –HCM Snw	-14.68	4.54	.29	-15.26	-14.11	-50.13	239.00	.00
Pair 5	WL=200	A	Simulated Sw –HCM Sw	-17.80	6.41	.41	-18.62	-16.99	-43.02	239.00	.00
Pair 6			Simulated_Snw –HCM Snw	-5.77	7.52	.49	-6.72	-4.81	-11.88	239.00	.00
Pair 7		B	Simulated Sw –HCM Sw	-17.38	3.73	.24	-17.86	-16.91	-72.11	239.00	.00
Pair 8			Simulated_Snw –HCM Snw	-15.97	8.92	.58	-17.10	-14.84	-27.72	239.00	.00
Pair 9	WL=300	A	Simulated Sw –HCM Sw	-14.03	10.74	.69	-15.39	-12.66	-20.24	239.00	.00
Pair 10			Simulated_Snw –HCM Snw	-6.53	12.84	.83	-8.16	-4.90	-7.88	239.00	.00
Pair 11		B	Simulated Sw –HCM Sw	-27.11	3.75	.24	-27.59	-26.63	-112.00	239.00	.00
Pair 12			Simulated_Snw –HCM Snw	-14.80	11.58	.75	-16.28	-13.33	-19.80	239.00	.00
Pair 13	WL=400	A	Simulated Sw –HCM Sw	-11.48	11.17	.72	-12.90	-10.06	-15.91	239.00	.00
Pair 14			Simulated_Snw –HCM Snw	-4.47	13.04	.84	-6.12	-2.81	-5.31	239.00	.00
Pair 15		B	Simulated Sw –HCM Sw	-12.79	7.24	.47	-13.71	-11.87	-27.37	239.00	.00
Pair 16			Simulated_Snw –HCM Snw	-13.07	11.93	.77	-14.59	-11.56	-16.97	239.00	.00



a. HCM 2010 Predicted speeds versus VISSIM simulated speeds for WL= 100 m



a. HCM 2010 Predicted speeds versus VISSIM simulated speeds for WL =400

Figure 13: Parity plots of the simulated verses the predicted weaving and non-weaving Speeds

Calibrating the HCM speed prediction models

Using the non-linear regression procedure in SPSS, an effort was undertaken to calibrate and modify the HCM speed prediction algorithms using the simulation data points to represent urban conditions more accurately. The models in their original forms use a minimum speed of 15 mph and a maximum speed equal to the free flow speed (FFS).

The minimum value observed from the simulation models were lower than 15 mph/; therefore, the original models were modified by using the actual observed minimum speed of 6 mph. Also, all lengths were used in units of feat.

Each weaving section was considered as a separate configuration. Free flow speed (FFS) value of 37.5 mi/h (60 km/h) was used for substituting the FFS in SPSS; therefore, the model format was used as following:

$$S_W = 6 + (FFS - 6) / (1 + (b * (L_{CALL}/L_S)^{C})$$

Calibrated Weaving speed prediction model for Section (A)

$$S_W = 6 + \frac{FFS - 6}{1 + W} \qquad where \qquad \mathbf{W = 0.322437 * \left(\frac{LC_{ALL}}{L_S}\right)^{1.386716}}$$

The calibrated model resulted in R^2 of 0.54, which is not bad when compared to a value of 0.614 obtained by freeway-based data **[6]**.

Calibrated Weaving speed prediction model for Section (B)

$$S_W = 6 + \frac{FFS - 6}{1 + W} \qquad where \qquad \mathbf{W = 0.557494 * \left(\frac{LC_{ALL}}{L_S}\right)^{0.787467}}$$

The calibrated model resulted in an R^2 of 0.343.

Attempts to calibrate the non-weaving speed prediction model failed to produce any significant results, which was quite expected given that, the non-weaving speed prediction model was a weak part of the HCM 2010 weaving analysis methodology. Therefore, it is not recommended for any future Attempts.

In view of the above, it is evident that speed prediction is extremely difficult and rarely results in statistically acceptable models.

CONCLUSION

This paper presented an effort to model and simulate urban weaving sections resulting from an unconventional intersection design adopted widely in Cairo, Egypt. Due to this design type, and the lack of traffic control, merging of minor traffic into the mainstream and its ability to cross-weave is greatly affected by major approach demand. Higher major approach volumes produce lesser gaps for the minor merging traffic, therefore lesser minor approach throughput and capacity. Each level of major demand was associated with a maximum throughput that can propagate through the entrance ramp i.e. capacity of the entrance ramp.

It was found that at some point, continuous increase in weaving length does not necessarily improve traffic operations and could reduce the capacity and LOS. It was also concluded that 200 meters is the optimum length for maximum capacity and throughput of the weaving sections and the minor entrance. However, it is recommended to try to experiment lengths between 200 and 300 meters for future work.

From the comparative analysis with HCM 2010 methodology, it was concluded that using the methodology for these types of urban weaving configurations would produce unreliable results. HCM 2010 models are more likely to predict lower lane changing rates, overestimated capacities, and higher speeds. This is probably attributed to the fact that the prediction models of the HCM 2010 were designed for freeway conditions, which naturally involves lower rates of conflicts, lower lane changes, higher speeds and higher capacities compared to urban conditions.

Efforts to calibrate the speed prediction algorithms revealed that the original structure of the models is not suited to represent weaving operation even when fitted and calibrated with the simulation data points. It was also concluded that speed prediction of weaving operations is extremely difficult, and rarely produces “statistically acceptable” results.

Utilizing this intersection design at areas with high crossing demand volumes are likely to cause spills back into the minor approach and enhances the chances of forming a bottleneck at the conflict point between the arterial and the crossing.

At high crossing demands, mainstream vehicles penetrate through the section with very low speeds and could be forced to queue with the U-turning vehicles until sufficient gap arises. Therefore, for efficient weaving operations the design should be implemented at areas with low crossing demand conditions and cannot be used at major intersections.

This study assumed similar volume condition at both intersections of the simulated network. Intersection with different volume conditions will result in a more complex weaving operation with 4 weaving sections interacting with each other. This case is left for future work.

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