Modelling Speeds of Arterial Weaving Sections in Metro Manila

Ronald John Galiza[1,2] and Jose Regin Regidor[2]

[1]Intelligent Transport Systems Laboratory, University of Queensland
[2]Institute of Civil Engineering, University of the Philippines

Abstract: The closure of signalized intersections and the rerouting of traffic into midblock U-turn median openings paved the way for free-flow traffic conditions in an intersection. However, direct left turn vehicles will now have to take a series of right-turn plus U-turn manoeuvres in order to duplicate the same path taken prior to the closure. As a consequence, right-turn plus U-turn vehicles must weave across into the innermost lane towards the U-turn. Currently, methods for analysing the speeds in the weaving segment were derived exclusively on freeway weaving sections. The weaving manoeuvre that closely compares to the weaving of a right-turn plus U-turn vehicle is the two-sided Type C freeway weave. The ramp weave model developed by Messer and Bonneson was used to predict weaving and non-weaving speeds. Results of the calibrated models accurately predicted the observed speeds with a 95% level of confidence. The resulting models can be used to estimate weaving and non-weaving speeds and eventually the capacity in the weaving sections in other sites in Metro Manila having the same configuration.
Keywords: Arterial weaving, modelling, speed estimation, U-turn

1. INTRODUCTION

The closure of a significant number of signalized intersections and the rerouting of traffic into midblock U-turn median openings (U-turn slots) by the Metro Manila Development Authority (MMDA) paved the way for free-flow traffic conditions (uninterrupted flow) and increased progression of through vehicles in the arterial. This progression is at the expense of traffic from the side street as they are the subject of diversion. Direct left turn (DLT) movements will now have to take a right-turn plus U-turn (RTUT, for vehicles from the side street) or U-turn plus right-turn movements (UTRT, for those from the arterial) as shown in *Figure 1*. Whereas, through movements from the side street is replaced by a series of the two previous movements, RTUTR (2003). As a consequence, weaving areas are formed between the intersection approach and the adjacent midblock median U-turn opening.

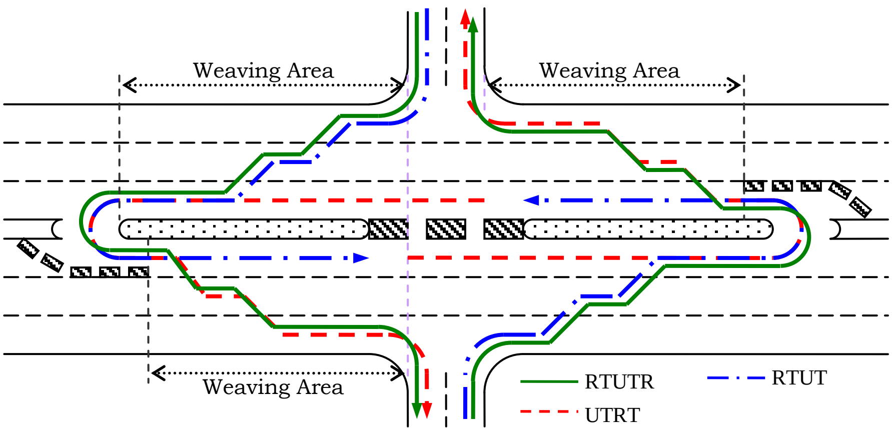

Figure 1. Alternative paths formed after closing intersection

The paper is organized as follows. In section 2 we give a review of literature in weaving analysis. Next, we describe the characteristics of arterial weaving in section 3 followed by the data collection methodology in section 4. In section 5 we provide an overview of the ramp weave model developed by Messer and Bonneson for weaving analysis. The results of the modelling and discussion follow in sections 6. Finally, concluding remarks and future research directions are in section 7.

2. WEAVING ANALYSIS

The Highway Capacity Manual (HCM) 2000 defines weaving as the crossing of two or more traffic streams travelling in the same general direction along a significant length of highway, without the aid of traffic control devices (TRB 2000). Traffic in a weaving section is subject to turbulence in excess of that normally present in a regular highway segment. This turbulence results in significant speed reductions to the non-weaving traffic movements (Messer and Bonneson 1997). A typical weaving area on a freeway is shown in *Figure 2*.

Weaving sections have unique operational characteristics and require special design consideration. In the past, weaving section research has concentrated almost exclusively on freeway weaving sections. As a result, transport practitioners are in the dark when analysing urban arterial weaving sections. A procedure is needed for analysing arterial weaving sections for the purpose of the estimating capacity of this type of facility. A first step towards this goal is the evaluation of existing weaving models for applicability in urban arterials.

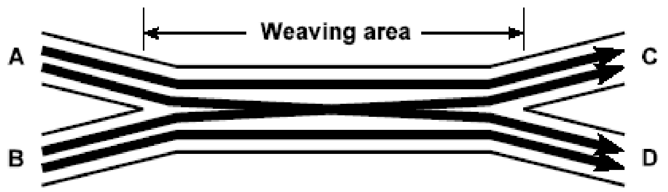

Figure 2. Weaving area as defined by HCM 2000

Weaving areas have been the subject of a great deal of study since the early 1950s. One of the first methods for analysing the operation and design of freeway weaving sections was published in the 1950 edition of the HCM (BPR 1950). The weaving area analysis methodology in the 1965 edition of the HCM was developed by Leisch between 1958 and 1964 (Leisch 1958-64). The approach adopted was based upon several curves relating weaving volume, length of weaving section, and quality of flow, a partial level of service (LOS) measure.

In 1976, the Polytechnic Institute of New York (PINY) developed a methodology that was published in National Cooperative Highway Research Program (NCHRP) Report 159 (Pignataro, McShane et al. 1975). The PINY procedure which was based on analytic or nomographic solutions was found to be difficult to apply because of its complexity and therefore was not widely accepted as a useful methodology. Federal Highway Administration (FHWA) sponsored a project from 1983 through 1984 to compare the PINY and Leisch (Leisch 1984) procedures and make recommendations for a procedure to be included in the 1985 HCM. This study, conducted by JHK & Associates, concluded that neither method was adequate for analysing operations of freeway weaving areas. The study proposed a method consisting of two equations: one for the prediction of the average speed of weaving vehicles, and one for the prediction of the average speed of non-weaving vehicles (Reilly, Kell et al. 1984).

Fazio revised the JHK method by using an increased amount of calibration data and introducing a new “lane shift” variable into the speed equations. This variable represents the minimum number of lane shifts that must be executed by the driver of a weaving vehicle from the lane of origin to the closest destination lane (Fazio and Rouphail 1986).

Cassidy and May (1991) developed a new analytical procedure for the capacity and level of service (LOS) for freeway weaving sections that uses prevailing traffic flow and geometric conditions to predict vehicle flow rates in critical regions within the weaving section. Predicted flows are then used to assess the capacity sufficiency or LOS of a weaving area.

Many other researchers have conducted studies of weaving sections on freeways and highways, but little research has been done concerning arterial weaving. While the HCM acknowledges the existence of arterial weaving, it does not explicitly provide analysis procedures for this type of weaving; however, it does suggest that the freeway procedures can be used as an approximation. The HCM methodology was developed for freeway weaving analysis but could be used as guidance for adapting the procedure to weaving segments on multilane highways. It is also defined in the HCM that the procedures are not appropriate for analysis of weaving on urban areas involving signalization issues, but could be used with an approximation for weaving areas on urban streets (TRB 2000).

Currently, there is no procedure in the analysis of weaving on urban streets. The HCM 2000 presents a methodology for the prediction of weaving and non-weaving speeds in a freeway weaving section. Sometimes, the procedure is applied to facilities having lower speeds although a modification should be applied (McShane and Roess 1998).

Messer and Bonneson (1997) also studied weaving problems from off-ramp terminals to the cross street arterial for NCHRP. They developed ramp weaving and non-weaving speed models to predict the manoeuvre speed of vehicles passing through an arterial weaving section. The models developed in that study form the basis for the models employed in this paper.

3. PHYSICAL AND OPERATIONAL CHARACTERISTICS OF ARTERIAL WEAVING

As a result of the closure of a significant number signalized intersections and the rerouting of the subsequent traffic into midblock U-turn median openings, DLT vehicles will have to negotiate a RTUT manoeuvre. A typical RTUT manoeuvre requires four steps: (1) stop at the side street opening, and make a right turn when a suitable (acceptable) gap in the arterial through traffic presents itself; (2) accelerate and weave to the innermost lane, and decelerate to a stop at the U-turn median opening; (3) wait for a suitable gap to make a U-turn (if U-turn slot is not barrier protected); and (4) accelerate to the operating speed of through traffic. Steps 2 and 3 (weaving and U-turns) are the key elements for completing this type of manoeuvre (Zhou, Hsu et al. 2003). The weaving element is the subject of this study.

The weaving manoeuvre that closely compares to that of the weaving on an RTUT manoeuvre is the two-sided Type C freeway weave as described in Figure 3. This type of weaving configuration is formed by a right-hand on-ramp followed by a left side off-ramp. The through volume of the freeway functionally acts as a weaving movement and does not require a lane change (except in avoiding slow moving vehicles). The other movement, the ramp-to-ramp flow on the other hand would require vehicles to cross all the lanes. Similarly, the RTUT manoeuvre has to perform cross all the lanes upon entering the roadway to stopping at the adjacent median opening on the arterial. Arterial through traffic does not have to change lanes except to avoid conflicts with slow weaving vehicles in the weaving section or preposition to the next lane.

3.1 Angle of Entry and Exit

Weaving vehicles from the side street enter the through traffic stream from a stopped or slowed speed. This is due to the sharp angle of entry and lack of sight distance of the entering vehicle. The angle between the side street and the arterial is relatively steep (~90^o, right-angle) compared to the off-ramp entering the freeway which is smoother (<<90^o). Although tapering can be introduced at the entry of the arterial, entry speeds of weaving vehicles are still substantially lower versus freeway entry speeds. Also, tapering in an intersection corner is restricted by the existence of development in the urban intersection. In addition, the driver has to select an acceptable gap before entering the arterial. Acceleration and deceleration ramp lanes are also provided in freeways such that the weaving vehicles have appropriate entering and exiting speeds whereas in urban arterials, most of the time there is none.

3.2 Weaving Length

For simplicity in this study, weaving length for the two-sided weave was simplified as shown in *Figure 3*. The length of the weaving segment in an urban arterial is comparably shorter than the freeway segment. In NCHRP 420, three types of weaving patterns of a RTUT were defined based on the weaving length. They are: (1) When the weaving distance is short (i.e., 75-150 meters (250-500 feet), less than the left-turn deceleration lane in a major road), many drivers will select a suitable gap in all through lanes and make a direct entry into the left-turn deceleration lane. (2) When the weaving distance is medium (i.e., 150-305 meters (500-1,000 feet), not long enough to make a comfortable lane change), many drivers will select a suitable simultaneous gap in all through lanes and make a direct entry into the most inside lane. (3) When the weaving distance is long (i.e., >350 meters (>1,000 feet)), a driver will select a suitable gap, turn into the right-side lane, accelerate to the appropriate speed, then make a lane change into the left through lane (Gluck, Levinson et al. 1999).

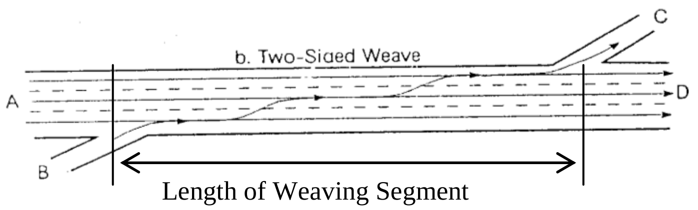

Figure 3. Length of weaving segment for Type C: 2-sided weave (HCM 2000)

3.3 Manoeuvre

Based on field observations, there are generally three classifications of the weaving manoeuvres of the vehicles coming from the side street in a weaving section regardless of the length of the weaving section (illustrated in *Figure 4*). They are: (1) Drivers will select an acceptable simultaneous gap in all through lanes and make a direct entry into the innermost lane in order to make the U-turn median opening (Movement 1, Aggressive drivers). Gap-forcing sometimes occur if there are no simultaneous gap available. (2) A suitable gap in the outermost lane is selected, turn into the lane, accelerate, and then make lane changes gradually into the innermost lane towards the U-turn (Movement 2, Conservative drivers). (3)

The driver turns into the right-side lane, accelerates, changes lane but takes the U-turn from a lane other than the innermost (Movement 3, Unfamiliar drivers). This happens either when the queue in the innermost lane is long or the driver is not familiar with the proximity of the U-turn slot (Galiza 2006).

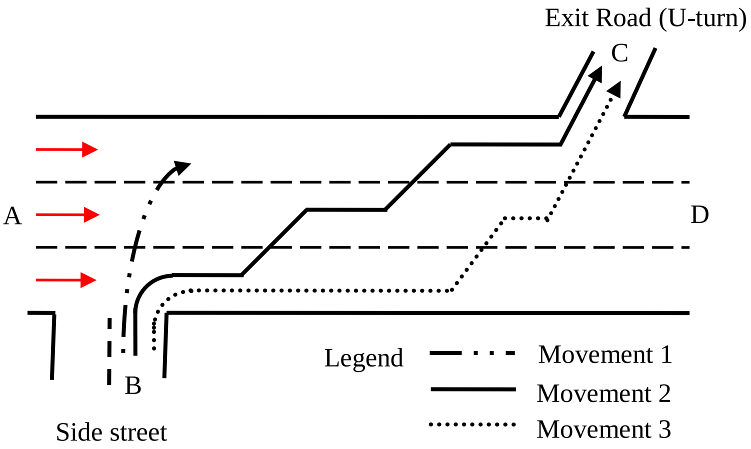

Figure 4. Classification of weaving manoeuvres based on field observations

4. RAMP WEAVE MODEL

The ramp weave models developed by Messer and Bonneson from a study commissioned by the NCHRP were the model evaluated in this study. The weaving manoeuvre considered in their study was the off-ramp right-turn movement that weaves across the arterial to make a left-turn at the downstream intersection as shown in *Figure 5*. The manoeuvre is comparable to a two-sided Type C freeway weave. One major difference pointed out is that in a freeway weaving section, the weaving length has a fixed length that is based on the distance between its entry and exit points while an arterial weaving section has a varying length as a result of downstream queues. However, if there are no vehicles on the downstream segment at the start of the intersection signal phase, then the effective distance would equal the distance to the through movement stop line at the downstream intersection.

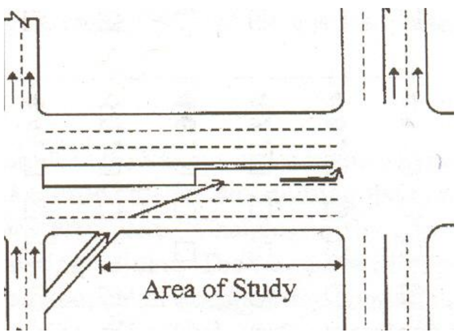

Figure 5 – Ramp weave on arterial cross streets in interchange areas

The speed models developed were based on empirical formulations that adhered to logical boundary conditions. The form of each model is similar; however, there is some variation in the model variables due to the differences in the priority assigned to the two vehicle classes (i.e., major and minor movement).

4.1 Weaving Speed Model

The weaving speed model is,

$$U_w = b_o U_a^{b_1} e^{(-b_2(1-P_U)V_w/3600)} \qquad \textit{Equation (1)}$$

where:

U_w = average manoeuvre speed for weaving vehicles, m/s;

U_a = average arterial speed entering the weaving section, m/s;

P_U = probability of a weaving vehicle being unblocked (i.e., able to change lanes freely);

V_w = weaving flow rate, vph; and

b_o, b_1, b_2 = regression coefficients.

The model relates the weaving manoeuvre speed (U_w) to the average speed of arterial vehicles entering the weaving section (Zhou, Hsu et al.). The average speed of arterial vehicles entering the weaving section was measured as a spot speed at the point of entry to the section. It represents the speed of arterial drivers for the given arterial volume conditions when there is no weaving activity.

4.2 Non-weaving Speed Model

The arterial manoeuvre speed model is similar in form to that of the weaving speed model and is herein will be referred to as non-weaving speed model. Its form is,

$$U_{nw} = b_3 U_a^{b_4} e^{(-b_5 V_a/3600)} \qquad \textit{Equation (2)}$$

where:

U_{nw} = average manoeuvre speed for non-weaving through vehicles, m/s;

U_a = average arterial speed entering the weaving section, m/s;

V_a = arterial flow rate entering the weaving section, vph; and

b_3, b_4, b_5 = regression coefficients.

Like the rationale for the weaving manoeuvre speed model, the non-weaving manoeuvre speed model is based on the assumption that weaving speed should equal the arterial entry speed when the weaving flow rate is negligible. The variable for arterial flow rate is included in the model rather than weaving flow rate because it was found to be more strongly correlated with arterial manoeuvre speed. Logically, the two flow rates are positively correlated such that an increase in the arterial flow rate would likely be associated with an increase in weaving flow rate. Hence, the use of a surrogate variable for weaving flow rate that improved the quality was determined to be acceptable.

5. DATA COLLECTION

In this research, operational data were collected using video recording equipment that was mounted on a tripod and stationed at the adjacent pedestrian overpass immediately upstream of the subject weaving areas. The video camera was positioned such that the operation of the entire weaving section could be observed. One video camera was used to record the operation of the vehicles coming from the side street and arterial weaving manoeuvres in the weaving segment. This video camera captured the movement of each vehicle within the weaving section. This weaving segment was defined as the area on the arterial road between the side street and the adjacent U-turn median opening as described in *Figure 3*. Once captured on video, the video recordings were then transferred and converted into digital format on a computer. The appropriate operational data were extracted directly by repeated viewing of the recording on a computer.

Data was collected during weekdays under normal traffic conditions, good weather, and dry pavement conditions. Weekdays are considered as from Monday through Thursday, where normal conditions are expected to prevail.

5.1 Survey Site Description

Two study sites were considered for this research both of which are located in the same segment of the arterial roadway (Quezon Avenue). Both arterial roads support 8 lanes (2-way) divided by a 5-meter non-traversable median. The side streets are two lanes each. Basically, they have the same geometric configurations except for the weaving lengths. The weaving length of Site 1 (Banaue – Quezon Ave.) is 185-meters while Site 2 (Scout Borromeo – Quezon Ave.) supports a 120-meter segment.

Figure 6 shows a snapshot of the perspective from the video recording equipment. Required data were processed through repeated viewing of the recording on a large computer monitor.

Figure 6 - Snapshot of Site 1 (left) & Site 2 (Galiza and Regidor 2009)

5.2 Data Reduction

Data collection activities for this study included traffic volume, vehicle classification, speed, and weaving section geometry. All operational data were collected using the video recording equipment. The weaving section geometry was obtained from field measurements.

6. MODELLING RESULTS AND DISCUSSION

Two separate models were developed for the two survey sites selected for this study. Site 1 (Banaue) which supports a weaving length of 185 meters, while Site 2 (Scout Borromeo) has a 120-meter weaving segment and also four lanes, both four lanes (one-way).

6.1 Correlation Analysis

A correlation analysis is conducted first using SPSS® (SPSSInc. 2006). *Table 1* shows the significant correlations for the weaving (U_w) and non-weaving (U_{nw}) speeds. For weaving speeds, the variables that demonstrate a high degree of linear correlation are approach speed, non-weaving speed and weaving flow rate. There is a positive correlation for approach speed and non-weaving speed while a negative linear correlation exists for weaving flow rate. It is also interesting to note that, weaving speeds has a negative coefficient of correlation against arterial flow rate although it is not significant in the level of confidence used for the analysis. For non-weaving speed, the variables are weaving speed, approach speed, and arterial flow rate. There is a positive linear correlation for weaving speed and approach speed but a negative correlation for arterial flow rate. The same can be said about Site 2 parameters in *Table 1*.

Table 1. Correlation analysis for Site 1 and Site 2 models

		Uw	Ua	Va	Unw	Vw
Site 1	Uw	1.0	0.452(**)	-0.286	0.476(**)	-0.404(**)
	Unw	0.476(**)	0.706(**)	-0.382(*)	1.0	0.079
Site 2	Uw	1.0	0.648(**)	-0.666(**)	0.795(**)	-0.490(**)
	Unw	0.795(**)	0.746(**)	-0.686(**)	1.0	-0.069

Note: ** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

U_w = average manoeuvre speed for weaving vehicles

U_a = average arterial speed entering the weaving section

V_a = arterial flow rate entering the weaving section

U_{nw} = average manoeuvre speed for non-weaving through vehicles

V_w = weaving flow rate

6.2 Model Parameters and Statistics

The speed models for Site 1 and 2 were calibrated using 35 and 18 data points, respectively. The nonlinear regression procedure in SPSS® was used to determine the regression coefficients of the weaving and non-weaving models.

Table 2 lists several statistics that indicate the quality-of-fit for each speed model. For Site 1, the weaving speed model accounts for 45 percent of the variability while the non-weaving speed model accounts for 54 percent variability in the data. The tests were conducted with a 95 percent level of confidence. The root mean square error (RMS) of each model, combined with the number of observations, produces a minimum precision of ±0.08 m/s for both estimates of average weaving and non-weaving speeds respectively.

For Site 2, the weaving speed model accounts for 44 percent while non-weaving accounts for 66 percent variability. The minimum precision was ±0.10 m/s for both estimates of average weaving and non-weaving speeds.

Table 2. Site 1 and Site 2 manoeuvre speed models regression coefficients and statistics

Site No.	Manoeuvre	Precision	RMS Error	b_0	b_1	b_2	b_3	b_4	b_5	R^2
Site 1	Weaving	±0.08 m/s	0.490 m/s	3.1140	0.4675	-4.9744				0.44997
	Non-weaving	±0.08 m/s	0.447 m/s				3.0603	0.5261	-0.3339	0.54191
Site 2	Weaving	±0.10 m/s	0.444 m/s	1.8363	0.5422	-0.6163				0.44019
	Non-weaving	±0.10 m/s	0.425 m/s				4.2738	0.4253	-0.5568	0.66295

6.3 Model Validation

For the validation of the calibrated models, a separate data set was used (N = 12) in order to measure the accuracy of the developed models. Statistical analysis was conducted for comparing the modelled and observed results by using the paired t-test as outlined in *Table 3*. From the results of the paired t-test for Site 1, it was found that for weaving and non-weaving speeds, there was no significant difference in the means between the observed speeds and the modelled speeds at a 95 % confidence level. This observation was supported by the parity plot in *Figure 7*. The observed and modelled values also demonstrated a high degree of linearity for the weaving and non-weaving speeds (0.660 and 0.686 respectively). Both weaving and non-weaving speeds showed large magnitude of fit.

For Site 2, a similar result was found in the relationship between the observed and predicted for non-weaving speeds. The observed and predicted values also demonstrated a high degree of linearity for the weaving and non-weaving speeds (0.788 and 0.629 respectively). The weaving speed showed very large magnitude of fit while non-weaving speed demonstrated only a large magnitude of fit. Figure 8 visually confirms the results of the paired t-test in the parity plots of the observed and modelled speeds for weaving and non-weaving speeds.

Table 3. Site 1and 2 comparison of observed and modelled weaving and non-weaving speeds

Site	Manoeuvre		Mean	N	Std. Dev.	Std. Err Mean	Correlation	Sig.	R^2
Site 1	Weaving	Obs	5.729	12	0.7175	0.2071	0.660	0.019	0.4399
		Model	5.763	12	0.4332	0.1250			
	Non-weaving	Obs	7.475	12	0.5415	0.1563	0.686	0.014	0.471
		Model	7.667	12	0.3904	0.1127			
Site 2	Weaving	Obs	6.292	12	0.4338	0.1252	0.788	0.002	0.6199
		Model	6.161	12	0.2169	0.0626			
	Non-weaving	Obs	8.02	12	0.5203	0.1502	0.629	0.028	0.3956
		Model	8.036	12	0.3172	0.0916			

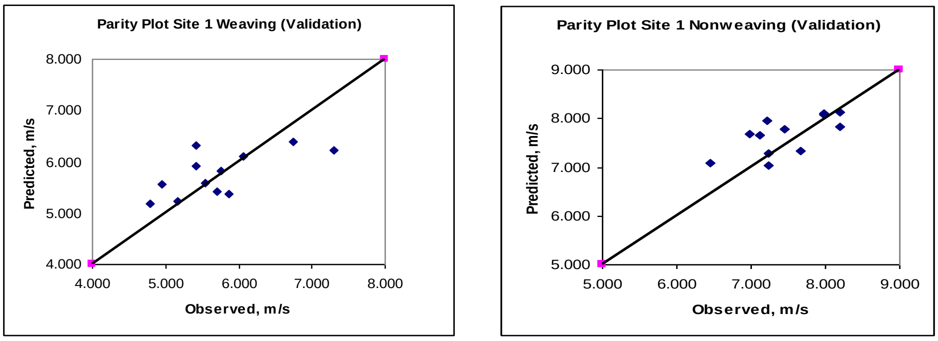

Figure 7. Site 1 parity plot of observed and modelled speeds

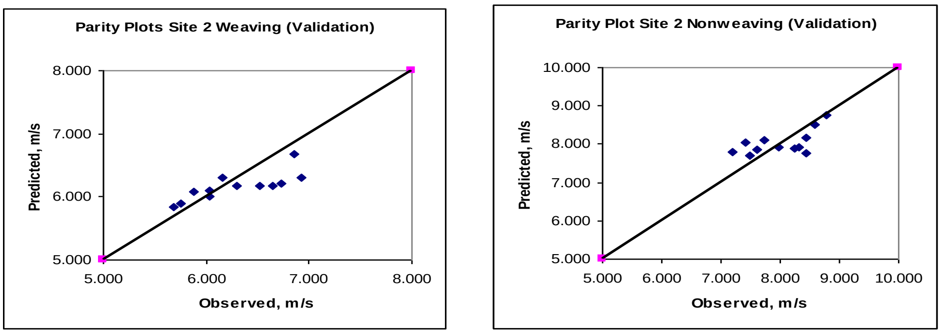

Figure 8. Site 2 parity plot of observed and modelled speeds

7. CONCLUSION AND FUTURE RESEARCH

Field data were collected from video surveys to test whether the ramp weave models can accurately predict weaving and non-weaving speeds in an arterial weaving section. A statistical analysis was conducted to test whether predicted speeds were acceptable. Based on the correlation analysis of field data collected at the study sites, arterial through flow rates and weaving flow rates were found to affect weaving speed. Weaving speed decreases as the arterial through flow rates increases. Similarly, weaving speeds decrease with increased weaving flow rates. Likewise, non-weaving speeds were affected by weaving and arterial flow rates. An increase in weaving or arterial flow rate results in lower non-weaving speeds.

The results of the calibration models reveal that weaving and non-weaving speeds can be accurately predicted using the models developed for the range of data used and with similar geometric characteristics. Two models were developed for each study sites to predict weaving and non-weaving speeds of vehicles passing through the arterial weaving section. Both models predict weaving and non-weaving speeds that show strong correlations with the measured speeds.

More extensive data collection from other sites having different weaving lengths and configurations in order to develop a family of models that can be used to predict speeds in an urban arterial weaving section is recommended for future research. Also, use computer simulation to evaluate the weaving and non-weaving speeds within the urban arterial weaving sections.

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