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16. Abstract Over the past few years, there have been many studies concerning the effects of weaving on freeway operations; however, there have been few attempts to study the effects of weaving at "non-freeway" sites, such as freeway frontage roads. As part of a larger study that is developing a level of service evaluation procedure for freeway frontage roads, this report addresses the issues associated with one-sided weaving on one-way frontage roads. The objectives of this study were to develop a technique for evaluating one-sided weaving operations, and to develop recommendations on minimum and desirable ramp spacing. To meet these objectives, both field data and computer simulation were used. From the results of this study, the following three levels of service were defined: unconstrained (weaving volume < 1500 vph), constrained (weaving volume from 1500 - 3000 vph), and undesirable (weaving volume > 3000 vph). Concerning ramp spacing, the results revealed that it is desirable to have a weaving length greater than 300 meters with a minimum value of 200 meters.					
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ONE-SIDED WEAVING ANALYSIS ON ONE-WAY FRONTAGE ROADS

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Research Report 1393-1
Research Study Number 0-1393
Research Study Title: Determination of Capacity and Level of Service
on Freeway Frontage Roads

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IMPLEMENTATION STATEMENT

This report is part of a larger study that is developing a level of service evaluation procedure for freeway frontage roads. The results from this report will aid engineers in evaluating existing one-sided weaving sections on one-way frontage roads. The procedures developed are designed to estimate the level of service at these types of sections. This, in turn, will aid engineers in prioritizing frontage road improvement projects. Also provided are recommended desirable and minimum weaving lengths for one-sided weaving areas. The results from this study will be included with the final frontage road analysis package.

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation (TxDOT) or the Federal Highway Administration (FHWA). This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. This report was prepared by Kay Fitzpatrick (PA-037730-E) and Lewis Nowlin.

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SUMMARY

The effects of weaving vehicles on the operations of a facility can have a heavy influence on the quality of service provided to motorists. The influence can be especially notable when the weaving is occurring in relatively short distances and/or when the weaving section also contains other elements that disturb traffic flow such as driveways, pedestrians, and parking. Most of the previous studies concerning weaving have been focused on freeway weaving operations; therefore, techniques to evaluate “non-freeway” weaving are limited. This report focuses on investigating one-sided weaving operations on one-way frontage roads. The objectives were to develop a technique for evaluating one-sided weaving operations, and to develop recommendations on minimum and desirable ramp spacing.

To meet the above objectives, both field data and computer simulation were used. The field data consisted of six frontage road sections that contained one-sided weaving areas. NETSIM 5.0 (Beta Test Version) was used for computer simulation. The field data were used to calibrate and validate the NETSIM model. Both field data and NETSIM support the study of potential relationships of various measures of effectiveness (i.e., speed, delay, number of lane changes, and volume) at one-sided weaving areas.

After the analyses of the field data and NETSIM results, researchers concluded that the average speed on the weaving link would be the proposed measure of effectiveness for evaluating the operations on one-sided weaving areas. Speed is currently used in the *Highway Capacity Manual* for evaluating arterial streets; it is easy to measure in the field, and it is easy to explain and understand. Conclusions suggest that weaving speed is most closely related to lane change activity.

The NETSIM results indicated that as the lane change activity increased, weaving speed decreased. Studying this relationship, there appeared to be certain critical values for the lane change activity (number of lane changes per hour) in which the weaving speeds began to drop more rapidly or become more variable. These critical points occurred at approximately 2000 and

4000 lane changes per hour. Using these critical points, three levels of operations were defined: unconstrained (lane changes < 2000 lcph), constrained (lane changes from 2000–4000 lcph), and undesirable (lane changes > 4000 lcph). The location of the critical points was independent of the number of lanes in the weaving section and the weaving length.

Results from the field data showed that a linear relationship existed between weaving volume (exit ramp volume + entrance ramp volume) and the number of lane changes: average number of lane changes = $1.33 \times$ weaving volume. Using this relationship, the level of service can be defined using weaving volume as follows: unconstrained (weaving volume < 1500 vph), constrained (weaving volume from 1500–3000 vph), and undesirable (weaving volume > 3000 vph).

To develop recommendations for ramp spacing, the researchers studied the relationship between weaving speed and weaving length. The relationship revealed that as weaving length decreased, weaving speed also decreased; however, there were certain ranges of weaving lengths in which the weaving speed decreased more rapidly. These results concluded that it is desirable to have a weaving length greater than 300 meters. If this length is not achievable, the minimum length should be approximately 200 meters.

CHAPTER 1

INTRODUCTION

The effects of weaving vehicles on the operations of a facility can have a heavy influence on the quality of service provided to motorists. The influence can be especially notable when the weaving is occurring in relatively short distances and/or when the weaving section also contains other elements that disturb traffic flow such as driveways, pedestrians, and parking. Techniques for evaluating weaving on arterial streets, however, are limited. Methods reported in the literature are generally based on the weaving procedure presented in the *Highway Capacity Manual*¹ (HCM) for freeways. As noted in most discussions, the speed assumptions in the HCM for freeways make it a poor predictor of quality of service for an arterial street. The development of procedures to evaluate weaving on arterial streets would provide a guide in the selection of alternative solutions.

Similar to arterial streets, the traffic operations on frontage or access roads along freeways can also be heavily affected by weaving. As part of a larger study that is developing a level of service evaluation procedure for freeway frontage roads, researchers examined the issues associated with one-sided weaving on one-way frontage roads. This report documents those efforts. Field data and computer simulation were used to identify relationships and develop procedures that evaluate the operations at one-sided weaving areas. They were also used to identify desirable and minimum weaving lengths.

OBJECTIVES

The efforts documented in this report focus on studying one-sided weaving operations on one-way frontage roads. The objectives of this study were to develop a technique for evaluating one-sided weaving operations, and to develop recommendations on minimum and desirable ramp spacing. The results from this study will be incorporated into the final frontage road analysis package.

ORGANIZATION

This report consists of seven chapters. **Chapter 1** contains some background information concerning weaving operations and defines the problem statement and research objective.

Chapter 2 contains definitions of relevant terms and a review of previous research work involving non-freeway weaving operations. Also included is a review of current design policies regarding recommended ramp spacings. Finally, a summary of previous research concerning weaving on freeways is provided.

Chapter 3 provides a description of the study design. The site selection and data collection procedures, as well as the data reduction strategies for the field data, are included in this chapter. Also included is a summary of the computer simulation techniques and a discussion on the procedures used to combine the data from the field and from computer simulation to develop a procedure for evaluating the level of service at one-sided weaving areas.

Chapter 4 presents the study results. This chapter includes findings from both the field study and computer simulation. **Chapter 5** introduces the proposed level of service analysis procedure for one-sided weaving areas on one-way frontage roads. Also included are recommended ramp spacings. **Chapter 6** contains the techniques used to validate the proposed level of service analysis procedure. Finally, **Chapter 7** presents the conclusions and recommendations for this study.

CHAPTER 2

PREVIOUS STUDIES

A unique aspect of frontage road operations is the weaving turbulence introduced by the vehicles exiting (or entering) a freeway. While significant attention has been devoted to the weaving on freeways, little attention has been directed to arterial street (or non-freeway) weaving. Only three studies were identified on arterial weaving. The Maryland, New Jersey, and Texas Departments of Transportation sponsored these studies. A summary for each study is included below with information on freeway weaving and spacing between an exit and an entrance ramp.

DEFINITIONS

Several terms are used to define weaving. Following are the definitions of relevant terms from the 1994 *Highway Capacity Manual*¹(HCM).

- **Weaving** is the crossing of two or more traffic streams traveling in the same general direction along a significant length of highway without traffic control devices.
- **Weaving length** is the space in which drivers must make all required lane changes. Measured from the merge gore area at a point where the right edge of the freeway shoulder lane and the left edge of the merging lane(s) are 0.6 meters apart to a point at the diverge gore area where the two edges are 3.6 meters apart.
- **One-sided weaving** occurs when all weaving movements take place on one side of the roadway. Occurs on a freeway when an entrance ramp is followed by an exit ramp and is joined by a continuous auxiliary lane.

- **Two-side weaving** occurs when a right-hand entrance ramp is followed by a left-hand exit ramp or vice-versa. Vehicles entering a facility must move across all travel lanes to reach their destination.
- **Configuration** refers to the relative placement and number of entry lanes and exit lanes for the section. The *HCM* Freeway chapter deals with three primary types of weaving configurations—Type A, Type B, and Type C. The types are specific to the minimum number of lane changes that must be achieved by weaving vehicles as they travel through the section.
- **Type A** weaving areas require that each weaving vehicle make one lane change to execute the desired movement.
- **Type B** weaving areas all involve multilane entry and/or exit legs. In Type B weaving areas, one weaving movement may occur without making any lane changes while the other weaving movement requires, at most, one lane change.
- **Type C** weaving areas are similar to Type B in that one or more through lanes are provided for one of the weaving movements. In Type C weaving areas, one weaving movement may be achieved without making a lane change while the other weaving movement requires two or more lane changes.
- **Major weaving sections** are distinguished by three or more entry and exit roadways having multiple lanes, for example, when two two-lane sections join to form a four-lane roadway, only to separate into two two-lane sections at the diverge point.
- **Constrained operations** have weaving vehicles occupying a smaller proportion of the available lanes than desired while non-weaving vehicles occupy a larger proportion of lanes than for balanced operation. This results in non-weaving vehicles operating at a much higher speed than weaving vehicles.

- **Unconstrained operations** occur when configuration does not restrain weaving vehicles from occupying a balanced proportion of available lanes. Average running speed of weaving and non-weaving vehicles generally differ by less than 8 kilometers per hour, except in short Type A sections, where acceleration and deceleration of ramp vehicles limit their average speed regardless of the use of available lanes.

EXAMPLES OF FRONTAGE ROAD WEAVING AREAS

Examples of one-sided and two-sided weaving areas for a frontage road are shown in Figure 2-1. It also illustrates different configurations of weaving, such as weaving between two ramps or weaving between a ramp (or a driveway) and a downstream intersection. A configuration that is not perceived to be a weaving area is an exit ramp followed by an entrance ramp not joined by a continuous auxiliary lane (see Figure 2-2). In this case, the *HCM* states that the ramp areas are to be treated as separate merge and diverge areas and analyzed using the procedures of the Ramps and Ramp Junction chapter. One-sided weaving between an exit ramp and entrance ramp connected by an auxiliary lane (see top portion of Figure 2-1) was the focus of the research efforts documented in this report.

TEXAS STUDY

The objective of the Texas study² was to develop a method for analyzing Type A weaving areas on frontage roads. Type A weaving occurs when each weaving vehicle makes one lane change to execute the desired movement. Data collected at six sites were used to formulate the models, and data from two additional sites were used to test the models. Data collected included traffic volume, vehicle classification, lane changing activity, speed, density, and weaving section geometry. The length of the weaving areas varied between approximately 136 and 341 meters, and the width varied between 11.0 meters (3 lanes) and 14.6 meters (4 lanes).

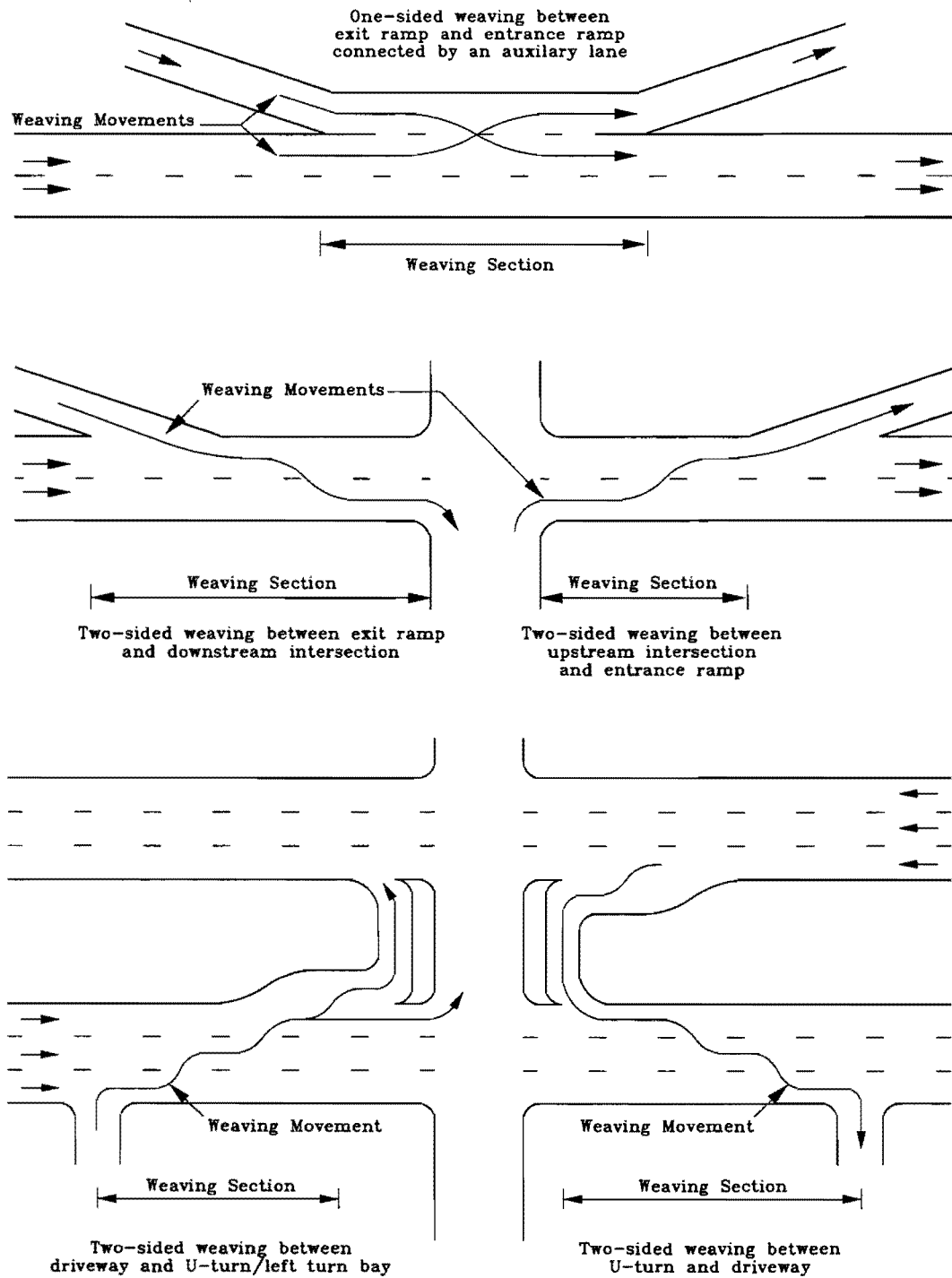


Figure 2-1. Examples of Frontage Road Weaving Areas.

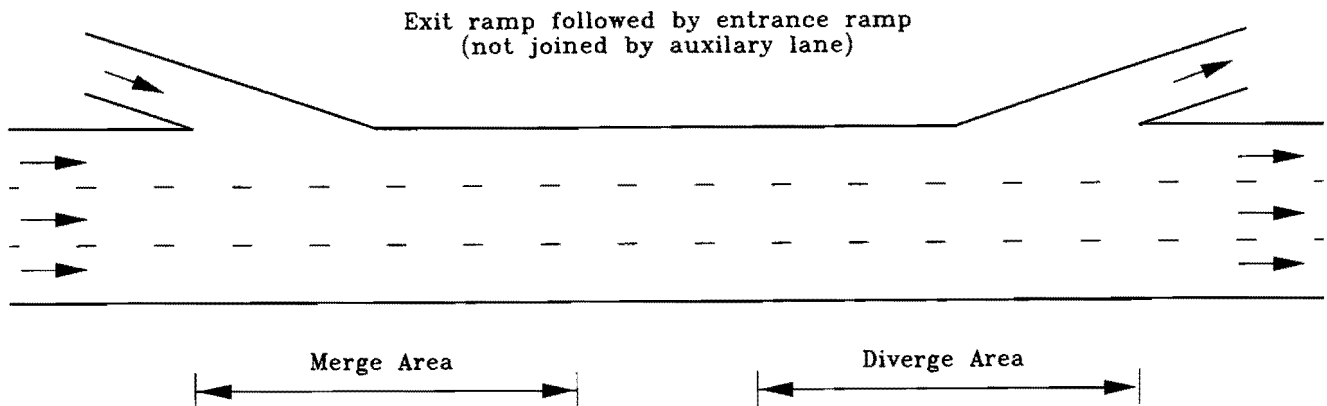


Figure 2-2. Exit Ramp Followed by Entrance Ramp not Connected by Auxiliary Lane.

Lane changing intensity (LCI) was the measure of effectiveness (MOE) selected because it provided a more direct measure of the turbulence experienced within a weaving section than speed. It is defined as the number of lane changes per hour per kilometer per lane. The collected data was separated into three weaving section length groups—122 to 182 meters, 183 to 274 meters, and 275 to 366 meters. A linear model was developed for each weaving section length group using a regression program. These models, listed in Table 2-1, estimate the lane changing intensity in a frontage road weaving section based on the average volume per lane. The adjusted r^2 value for the equations ranged between 0.78 and 0.94 (i.e., 78 to 94 percent of the variability of the dependent variable, LCI, is explained by the variability of the independent variable, volume).

LCI ranges were selected for three levels of service—unconstrained, constrained, and undesirable. Unconstrained conditions represented free flow, while constrained conditions represented stable flow, but with individual behavior being restricted by others. Undesirable level of service represented flow conditions approaching capacity in which comfort and convenience levels are poor and breakdowns in flow occurred. The proposed LOS criteria are shown graphically in Figure 2-3.

Table 2-1. Texas Models².

122 to 182 m weaving length:	$LCI = 6.50 (V/n) + 231$	(2-1)
183 to 274 m weaving length:	$LCI = 5.29 (V/n) + 49$	(2-2)
275 to 366 m weaving length:	$LCI = 243 (V/n) + 367$	(2-3)

where:

LCI = lane changing intensity (lane changes per hour per lane per kilometer)

V = hourly volume entering the weaving section

n = number of lanes in the weaving section

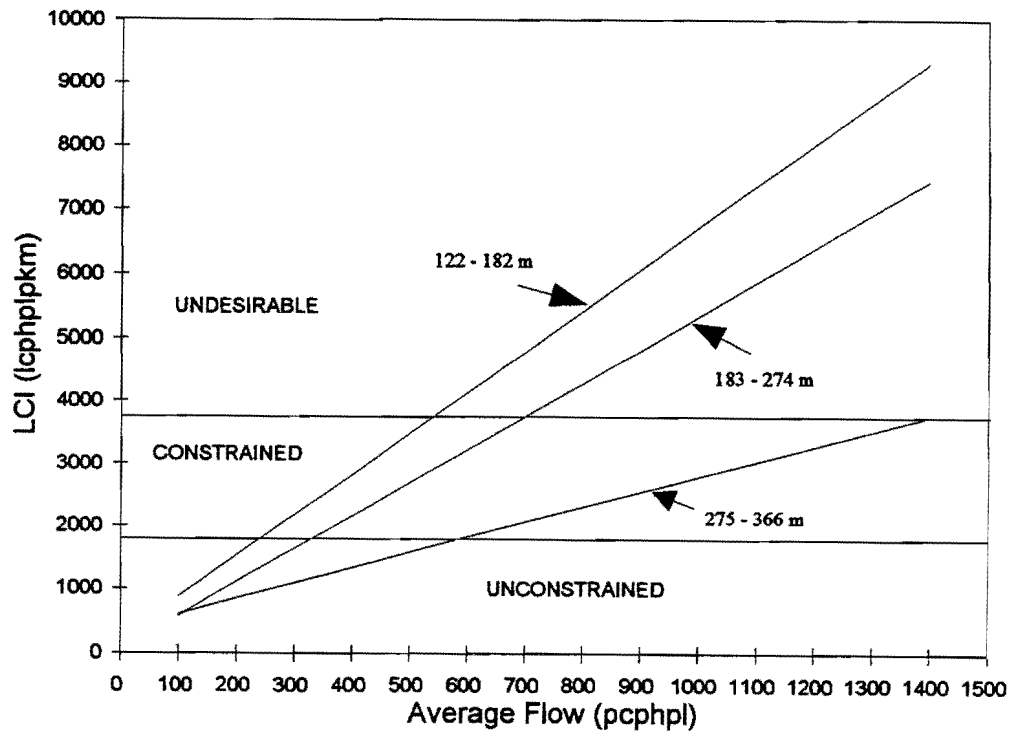


Figure 2-3. Proposed LCI Models from Texas Study.

Based on their findings, the authors made the following conclusions:

- weaving section lengths in the range of 275 to 366 meters (or greater) are desirable;
- weaving section length of less than 183 meters is not desirable;
- a minimum of three lanes in the weaving area, two through lanes, and one auxiliary lane connecting the two ramps is desirable.

NEW JERSEY STUDY

The New Jersey study³ examined two categories of weaving: 1) on/off ramp connecting an arterial with a highway and 2) weaving caused by merging and diverging of ramps with an arterial (see Figure 2-4). Originally, the study was to include three other categories; however, they were eliminated from the study due to lack of adequate field sites. Three freeway weaving analysis models were selected for evaluation of the arterial weaving configurations. The three selected models were first used in their original format with data from the sites. Next, the models were recalibrated using the statistical analysis package (SAS). The structures of the models remained unchanged; only the coefficients and exponents were recalibrated using the non-freeway data.

The Category 1 analysis included seven sites (on/off ramp connecting arterial or highway with a highway). Five of the seven sites had an auxiliary lane; one was without an auxiliary lane, and one site had a lane added to the through lanes at the entrance of the on-ramp. The data from four of these sites were used in the model development. Each of the sites had three through lanes with widths varying between 10.4 and 14.6 meters. The length of the weaving sections ranged between 66 and 91 meters with the average length being 81 meters.

The category 2 sites (merging and diverging of ramps with an arterial) included seven sites: five in New Jersey and two in New York City. The width of the weaving sections ranged

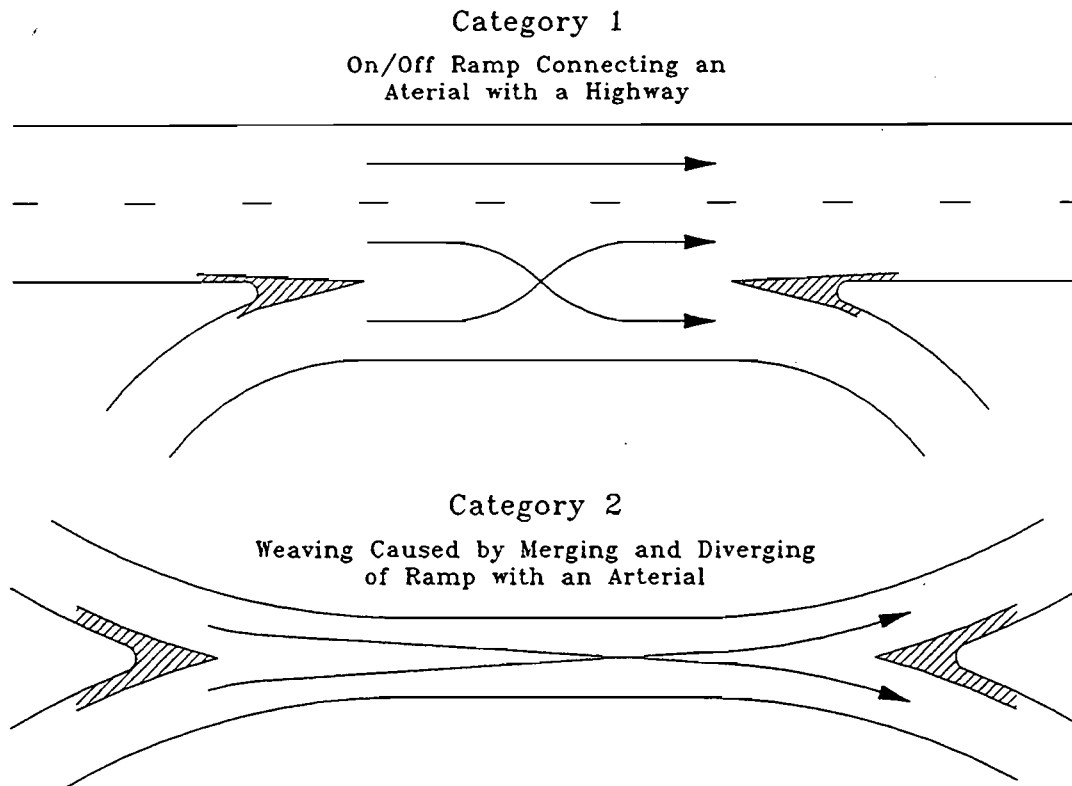


Figure 2-4. New Jersey Study's Ramp Configurations³.

from 7.9 to 14.0 meters, and the length ranged from 64 to 159 meters. Data from five of the sites were used in model development.

The results of the study indicated that the existing freeway models cannot properly represent the non-freeway conditions. The authors then developed new models for predicting the average weaving and non-weaving speeds of traffic on non-freeway weaving areas. Table 2-2 shows the proposed models along with the definition of variables used in the models. Because of higher r^2 values, the authors concluded that the new models are better than the calibrated existing models in predicting the average weaving and non-weaving speeds in non-freeway areas.

MARYLAND STUDY

The objective of the Maryland study⁴ was to identify a methodology for the analysis of weaving sections on arterial highways. This research approach included the following: survey

Table 2-2. New Jersey Models (NJIT)³.

Category 1—On/Off Ramp Connecting an Arterial With a Highway	
$S_w = 15 + \frac{25}{[1 + 16(1 + VR)^{4.82}] / [(W)(L/V)]^{1.47}}$	(2-4)
$S_{NW} = 15 + \frac{40}{[1 + (3.26 \times 10^7)(1 + MR)^{11.96}] / [(1 + VR)^{3.14} W^{5.89}]}$	(2-5)
<p>Where:</p> <p>S_w^* = Weaving speed (mph)</p> <p>S_{NW}^* = Non-weaving speed (mph)</p> <p>V = Total volume</p> <p>VR = (Weaving volume)/(total volume)</p> <p>MR = (Minor approach volume)/(total volume)</p> <p>W = Width of weaving section (ft)</p> <p>L = Length of weaving section (ft)</p>	
Category 2—Weaving Caused by Merging and Diverging of Ramps With an Arterial	
$S_w = 15 + \frac{35}{[1 + (3.6 \times 10^{-4})(1 + MR)^{0.176} (V/N)^{1.67}/L^{0.6}]}$	(2-6)
$S_{NW} = 15 + \frac{35}{[1 + 0.003(1 + VR)^{6.22}(V/N)^{1.79} / W^{2.86}]}$	(2-7)
<p>Where:</p> <p>S_w^* = Weaving speed (mph)</p> <p>S_{NW}^* = Non-weaving speed (mph)</p> <p>V = Total volume</p> <p>N = Number of lanes</p> <p>VR = (Weaving volume)/(total volume)</p> <p>W = Width of weaving section (ft)</p> <p>L = Length of weaving section (ft)</p>	

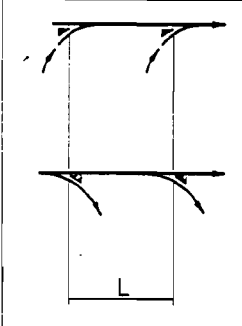
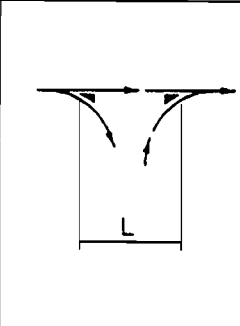
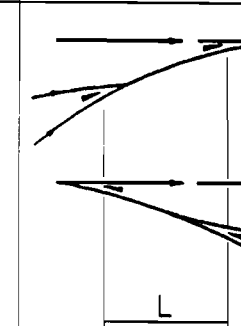
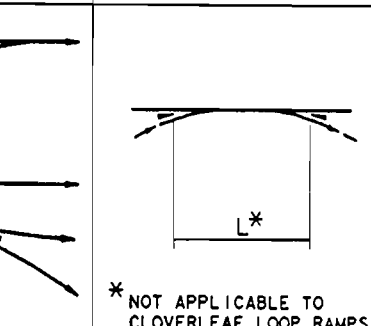
* To convert to km/h, multiply by 1.609.

of literature, survey of current practice, and review of the *Highway Capacity Manual*. After the comprehensive literature survey, the authors concluded that considerable research has been done on the subject of weaving, but most of it pertains to weaving on freeways that cannot be applied directly to arterials due to differences in types of operation on freeways and arterials. Questionnaires including a weaving area problem were sent to traffic engineers in Maryland, and traffic engineers and academic researchers in other states were contacted by phone. Results of the survey showed no acceptable procedures are available for analysis of weaving sections on arterials. Most of the methods used were improvisations based on the *Highway Capacity Manual* freeway weaving procedures with a considerable amount of subjective judgment being used.

The authors presented suggestions for evaluating two classes of weaving—one-sided and two-sided. For two-sided weaving, they suggested a method of separately determining the level of service for the arterial street, signalized intersection, and traffic on the ramp. The evaluation of the arterial street and the signalized intersection would use the appropriate chapters in the *Highway Capacity Manual*, while the traffic on the ramp would use the procedure for unsignalized intersections. They showed that the methods in the freeway chapter could be used for one-sided weaving problems. Because the *Highway Capacity Manual* procedures cannot be reliably used for weaving on arterials, they recommended development of procedures for arterial weaving.

DESIGN MANUALS

Guidance on the spacing between ramp terminals (i.e., length of weaving area) is available in the 1994 publication of *A Policy on Geometric Design of Highways and Streets*⁵ (commonly known as the *Green Book*). Figure 2-5 is a reproduction of the *Green Book* figure. For a freeway or collector distributor road, the minimum spacing between successive entrance or exit ramps is 240 meters, while the minimum spacing between an entrance and an exit ramp is 480 meters. The *Green Book* cautions that “these recommended distances are based on operational experience and the need for flexibility and adequate signing [and] should be checked in accordance with the procedures outlined in the *Highway Capacity Manual* and the larger of the values is suggested for use.”

EN-EN OR EX-EX		EX-EN		TURNING ROADWAYS		EN-EX (WEAVING)			
									
FULL FREEWAY	CDR OR FDR	FULL FREEWAY	CDR OR FDR	SYSTEM INTER- CHANGE	SERVICE INTER- CHANGE	SYSTEM TO SERVICE INTERCHANGE		SERVICE TO SERVICE INTERCHANGE	
						FULL FWY.	CDR OR FDR	FULL FWY.	CDR OR FDR
MINIMUM LENGTHS MEASURED BETWEEN SUCCESSIVE RAMP TERMINALS METERS									
300	240	150	120	240	180	600	480	480	300

* NOT APPLICABLE TO CLOVERLEAF LOOP RAMPS

NOTE: FDR - FREEWAY DISTRIBUTOR ROAD EN - ENTRANCE
CDR - COLLECTOR DISTRIBUTOR ROAD EX - EXIT

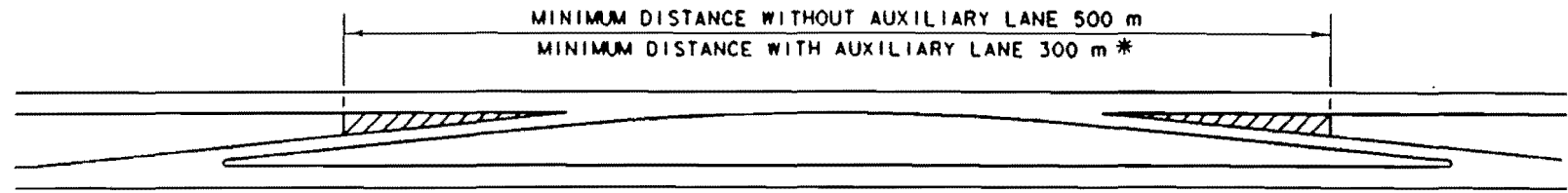
THE RECOMMENDATIONS ARE BASED ON OPERATIONAL EXPERIENCE AND NEED FOR FLEXIBILITY AND ADEQUATE SIGNING. THEY SHOULD BE CHECKED IN ACCORDANCE WITH THE PROCEDURE OUTLINED IN THE HIGHWAY CAPACITY MANUAL (3) AND THE LARGER OF THE VALUES IS SUGGESTED FOR USE. ALSO, A PROCEDURE FOR MEASURING THE LENGTH OF THE WEAVING SECTION IS GIVEN IN CHAPTER 4 OF THE HIGHWAY CAPACITY MANUAL (3).

Figure 2-5. Green Book Ramp Spacing.

The Texas Department of Transportation's (TxDOT) *Operations and Procedures Manual*⁶ also provides guidance on recommended ramp spacing. These guidelines are shown in Figure 2-6. For the case of successive freeway exit ramps, a minimum distance of 300 meters is recommended. For a freeway exit ramp followed by a freeway entrance ramp, the manual states that the spacing should "be governed by the geometrics of the connections to the adjacent roadway or connecting roadway."

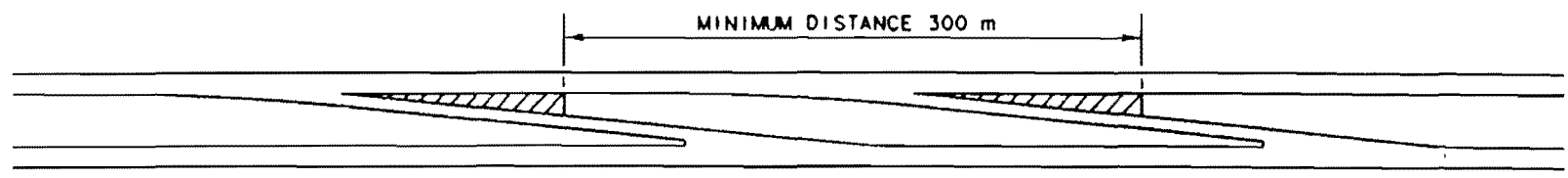
SUMMARY OF FREEWAY WEAVING

One of the first methods for analyzing the operations and design of freeway weaving sections was the 1950 edition of the *Highway Capacity Manual*⁷. This procedure was based on empirical analysis of data collected prior to 1948. The 1965 *HCM*⁸ contained a new method based on efforts initiated by the United States Bureau of Public Roads. The Polytechnic Institute of New



ENTRANCE RAMP FOLLOWED BY EXIT RAMP

CASE 1



EXIT RAMP FOLLOWED BY EXIT RAMP

CASE 2

CASE 3

ENTRANCE RAMP FOLLOWED BY ENTRANCE RAMP

THIS SITUATION WILL BE ENCOUNTERED ONLY ON INFREQUENT OCCASIONS AND SPECIAL DESIGN TREATMENT WILL BE REQUIRED. IT WILL USUALLY REQUIRE AN ADDED FREEWAY LANE.

CASE 4

EXIT RAMP FOLLOWED BY ENTRANCE RAMP

THE DISTANCE BETWEEN AN EXIT RAMP FOLLOWED BY AN ENTRANCE RAMP WILL BE GOVERNED BY THE GEOMETRICS OF THE CONNECTIONS TO THE ADJACENT ROADWAY OR CONNECTING ROADWAY.

* MINIMUM DISTANCE WITH AUXILIARY LANE USUALLY GOVERNED BY TRAFFIC WEAVING REQUIREMENTS.

ARRANGEMENTS FOR SUCCESSIVE RAMPS

Figure 2-6. TxDOT Operations and Procedures Manual Ramp Spacing.

York (PINY)⁹ formulated a new methodology published in 1976. Because of its complexity, a modified PINY procedure was included in the TRB Circular 212¹⁰. Circular 212 also included a method developed by Jack Liesch¹¹ that used two nomographs, one for two-sided configurations, and one for one-sided configurations. A study conducted by JHK for the FHWA examined the two previous methods and produced a new method that consisted of two equations that predicted average speed of weaving and non-weaving vehicles. An NCHRP project in 1984 recalibrated these equations for three types of configurations and for constrained and unconstrained operations. The resulting twelve equations were included in the 1985 *HCM*¹.

Since the publication of the 1985 *HCM*, several major studies at the University of California at Berkeley have examined aspects of freeway weaving. One study¹² examined six existing methods for the design and analysis of freeway weaving sections. Results showed that the models did not accurately predict weaving and non-weaving speeds and that speed was insensitive to changes in geometric and traffic factors over the range of values used. The study suggested that average travel speed is not an ideal measure of effectiveness.

In a later study, Cassidy et al.¹³ proposed a new analytical procedure for the capacity and level of service for freeway weaving sections. The procedure 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 and/or level of service of a weaving area.

While a significant amount of research has been conducted on freeway weaving, these findings cannot be directly applied to weaving on arterial streets or frontage roads. The differences in operations and access control precludes the direct application; however, the insights gained from the freeway weaving research can be used. For example, freeway weaving research has shown that configurations of the weaving area, along with the length and width of the area, are important elements in evaluating the operations. Recent studies have also closely examined different measures of effectiveness available for weaving areas and concluded that rather than speed, consideration should be given to using another MOE. Suggested MOEs include lane

change behavior and vehicle flow rates at critical locations. The methods used to collect and analyze the data in the freeway studies can provide useful direction in developing data collection and analysis techniques for the evaluation of arterial weaving.

CHAPTER 3

STUDY DESIGN

Field data and computer simulation were used to identify relationships and develop procedures to evaluate the operations at one-sided weaving areas, and to identify desirable and minimum weaving lengths. The following general overview provides details of the methodology used and specific information explaining how the field data were collected and reduced and how the findings were generated from the field data and computer simulation.

METHODOLOGY OVERVIEW

Several measures are available to evaluate the operations within a one-sided weaving area. These measures include the traditional measures such as speed, travel time, and delay. Additional measures would include those that are a reflection of the interaction that occurs between weaving (and non-weaving) vehicles. Interaction between vehicles could be measured by the number of lane changes that are occurring within a section. Intuitively, the amount of space for both weaving length and number of lanes should influence the operations within a weaving area.

Because the relationships and procedures identified and developed from this analysis will be used in the larger analysis of frontage roads, a measure of effectiveness that is compatible with the eventual frontage road analysis is desirable. This requirement results in delay and/or speed as the primary measures of effectiveness to be considered in a one-sided weaving analysis. Because speed is used in the current arterial street procedure in the *Highway Capacity Manual*, it was selected as the proposed measure of effectiveness. Speed as a measure of operations is also easy to explain and understand.

Because of the limited amount of studies available on arterial weaving and the desire to have a procedure that reflects actual conditions, the evaluation began with collecting and reducing data from field study sites. The field data provide information on the number of lane changes

expected for different volume levels. Because data are available for different weaving lengths and number of lanes, the effects different lengths and widths have on operations can be shown. Since field data can be limited, for example, only certain weaving lengths or volume ranges are available, computer simulation was used to provide additional information.

FIELD DATA

Data Collection

The investigation of previous studies revealed that the original video recordings of operations at eight one-sided weaving sites were available for this study. These recordings were made during a previous TTI research study by Fredericksen and Ogden². Since previous research used only frontage road and exit ramp volumes, the existing tapes provided information on how entrance ramp volumes may influence operations.

The eight study sites were generally video taped during the morning peak (7:00 to 9:00 am) and afternoon peak (4:00 to 6:00 pm) periods—some periods or parts of a period were not available due to various difficulties. One video camera recorded the weaving area. Data were collected in the Austin, Houston, and Dallas/Fort Worth areas. The criteria used by Fredericksen and Ogden for site selection were as follows:

- Each site must have a basic ramp weave configuration.
- Weaving sections should be less than 457 meters in length from gore point to gore point, preferably less than 305 meters.
- Intermediate disturbances, such as driveways, should be minimal.

Based on a review of each video tape, two of the eight sites were not used for this study. One site had a driveway located within the weaving area that noticeably affected traffic operation. Another site showed that the recording angle would make data reduction extremely difficult, and

therefore, the research team decided that the desired high level of confidence in data reduction efforts would be difficult to achieve.

Table 3-1 lists the six sites used in this project. The weaving sections at the sites ranged from three to four lanes and from approximately 137 to 335 meters in length.

Table 3-1. One-Sided Weaving Study Sites.

Site	City	Location	Number of Lanes	Weaving Length (m)
1	Fort Worth	IH 35W SB @ Felix	3	136
2	Houston	US 59 SB @ Beechnut	3	293
3	Houston	US 59 NB @ Fondren	3	342
4	Fort Worth	IH 820 WB @ Wichita	4	184
5	Dallas	US 75 SB @ Midpark	4	230
6	Austin	IH 35 NB @ Riverside	4	335

Data Reduction

Data reduction involved viewing the video tapes and counting the number of vehicles and the number of lane changes within a five-minute increment. During data reduction, each video tape was viewed by two technicians. One technician would record the following: frontage road volume by lane (prior to exit ramp), exit ramp volume, and entrance ramp volume. The other technician would record the number of lane changes for the following three lane change types: freeway exit ramp to frontage road, frontage road to freeway entrance ramp, and miscellaneous. The miscellaneous category included frontage road vehicles that changed lanes but did not access the freeway. Categories were further separated into one-lane lane change, two-lane lane change, and three-lane lane change categories.

To verify the accuracy of the data extracted from the video, the ramp volumes were compared with the corresponding lane change activity data. For example, the number of frontage road to entrance ramp lane changes were compared with the entrance ramp volume for each five-minute period. If a discrepancy of more than three vehicles appeared in the data, the data were extracted from the video tape a second time. If an unacceptable discrepancy still existed, the data were extracted a third time. After the third extraction, if a discrepancy remained, then the count, (i.e., ramp volume or number of lane changes) which was difficult to obtain, was adjusted to reflect the better count. Approximately 20 percent of the data sets were extracted a second time; 11 data sets were extracted a third time, and only four data sets of 220 were adjusted. Generally, the discrepancies were caused by the coordination at the ending of a five-minute increment. For example, one technician would count lane changes for vehicles that would not enter the entrance ramp until the following five-minute increment. The same two technicians reduced all the field data that resulted in consistent data reduction.

For the study sites that contained four lanes on the weaving link, a total of 108 five-minute data sets were reduced from the video tapes. For the sites that contained three lanes on the weaving link, a total of 112 five-minute data sets were reduced.

Once the data were reduced from the video, they were entered into a spreadsheet program where the data were converted into weaving and total volumes and total lane changes. The frontage road volume was measured prior to the exit ramp and would, therefore, include those vehicles entering the freeway at the downstream entrance ramp. The total volume was calculated as the frontage road volume plus the exit ramp volume. The three- and two-lane lane changes were converted into the equivalent number of one-lane lane changes. All lane changes were then summed to produce total lane changes. All five-minute values were converted into hourly values to allow for easier comprehension of the data.

Lane changes per number of lanes and weaving length were computed because the number of lanes and length of the weaving section present may influence the operations within a weaving section. Previous studies have suggested that the lane changing intensity (LCI) could be a

possible measure of effectiveness. Fredericksen and Ogden² argued that lane change intensity is a more direct measure of the turbulence experienced within the weaving section than speed. Lane change intensity was calculated as follows:

$$LCI = \frac{\text{Number of lane changes per hour}}{(\text{number of lanes}) (\text{length of weaving section})} \quad (3-1)$$

Data Analysis

To illustrate potential relationships, the findings from the field studies were plotted. The following plots were generated:

- lane changes versus weaving volume,
- lane changes versus total volume,
- lane change intensity versus weaving volume, and
- lane change intensity versus total volume.

Answers to several questions were needed from the analyses, such as: Do definable relationships exist between lane changes or lane change intensity, and weaving or total volumes? What effect do weaving length and number of lanes have on the lane changing behavior present? Is lane change behavior the appropriate measure of effectiveness or should another MOE be investigated? Should lane changes be part of the procedure used to evaluate the operations at one-sided weaving areas?

COMPUTER SIMULATION

In an attempt to develop a simulation model that would closely represent field conditions, several computer simulation programs were studied. These programs were investigated as to their inputs, outputs, and general capabilities. From the initial investigation, it was concluded that three computer simulation models (namely, NETSIM, INTRAS, and TEXAS) would be further studied for potential use in analyzing weaving section performance. After further

investigation, it was discovered that NETSIM currently has a Beta Test Version 5.0 available to a select group of institutions willing to use the model and comment on its effectiveness. The Texas Transportation Institute was selected as a Beta Test site for the new version of NETSIM, which contains a significant new change.

Until the latest version of NETSIM, none of the investigated computer simulation models allowed vehicles to change lanes between nodes. (A node is used to code intersections or other significant changes in geometry along a roadway.) Instead, required lane changes would take place at the node. For example, a vehicle traveling in Lane 1 of Link 1 and requiring a lane change would automatically appear in Lane 2 of Link 2 after having traveled over Node 1 (Link 1 is connected to Link 2 by Node 1). This limitation is a serious drawback when investigating weaving between two nodes, for example, the weaving on a frontage road between an exit ramp and an entrance ramp.

NETSIM's latest version allows lane changes between nodes, making simulated weaving sections much more realistic, and allowing for speed fluctuations and delays. As a result, NETSIM was selected as the computer simulation model that would most closely simulate frontage road weaving areas.

Creating and Calibrating a Simulation Model

The geometry of the general model used for this project consisted of a frontage road section with a freeway exit ramp followed by a freeway entrance ramp joined by an auxiliary lane. The general link/node diagram is shown in Figure 3-1 along with a schematic of the section simulated. Table 3-2 lists free flow speeds, link lengths, and number of lanes on each link.

Once a network is created, the next step is to calibrate it. Calibration involves modifying certain variables so that the model produces results similar to those expected in the field. The

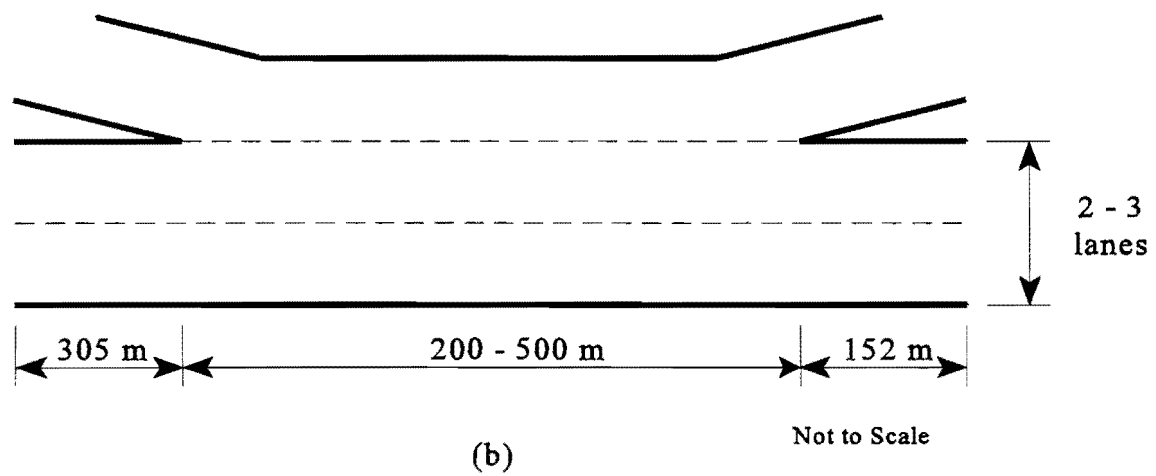
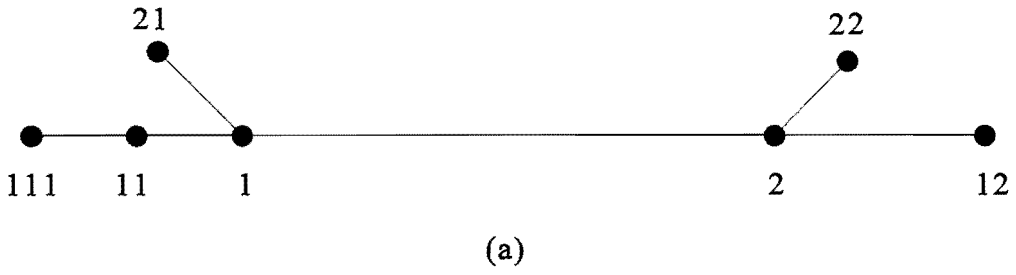


Figure 3-1. (a) General Link/Node Diagram; (b) Schematic of Simulated Section.

Table 3-2. General Model Link Characteristics.

Link (node to node)	Free Flow Speed (km/h)	Weaving Length m	Number of Lanes
111 to 11	72	150	2-3
11 to 1	72	150	2-3
1 to 2	72	200-500	3-4
2 to 12	72	150	2-3
21 to 1	72	150	1
2 to 22	72	150	1

lane changing logic of NETSIM is based on a series of lane changing characteristics. These characteristics include time for a lane change to take place, threshold speed below which any vehicle behind a slower vehicle will automatically change lanes, driver aggressiveness factor, and many others. All characteristics have a default value used by NETSIM, unless the user changes the value. One characteristic, known as the "scanning distance," was believed to be a likely candidate for calibrating the general model. The scanning distance is the distance a driver can scan ahead and determine what action to take. A large scanning distance in a weaving area will result in vehicles moving into the appropriate lane before necessary, while a short scanning distance will result in vehicles making lane changes at the "last minute." In other words, by changing the scanning distance appropriately, lane changes can be moved from one link to another. The same number of total lane changes will be made; however, where they are made will change. Two scanning distances were researched regarding calibration of the model: 46 meters and 137 meters. Short incremental changes in scanning distance did alter results dramatically.

Besides scanning distance, volume lane distribution was also used to calibrate the model. At an input node on a three-lane section of roadway, NETSIM distributes the input volume evenly over the three lanes. In the field, however, researchers witnessed that volume distribution

over the frontage road lanes was not evenly distributed. In addition, vehicles exiting the freeway can make a one-, two-, or three-lane lane change maneuver on the frontage road, depending on the number of lanes in the weaving section. NETSIM automatically requires each vehicle on the exit ramp to make one lane change; however, any subsequent lane changes are based on the predetermined destination of that vehicle and/or lane changing logic used by the program. Therefore, to more closely match field observations, two more models were developed. One model distributed input volumes across existing lanes as they were in the field. The other model also distributed input volumes across the lanes as they were in the field, as well as forcing freeway exiting vehicles to change lanes. As a result, four models were used for calibration. Table 3-3 lists a description of each model.

Table 3-3. NETSIM Model Descriptions.

Model	Description
1	<ul style="list-style-type: none"> • 137 meter scanning distance • Input volumes evenly distributed across existing lanes • Freeway exiting vehicles not forced to change lanes
2	<ul style="list-style-type: none"> • 46 meter scanning distance • Input volumes evenly distributed across existing lanes • Freeway exiting vehicles not forced to change lanes
3	<ul style="list-style-type: none"> • 46 meter scanning distance • Input volumes distributed across existing lanes according to field data • Freeway exiting vehicles not forced to change lanes
4	<ul style="list-style-type: none"> • 46 meter scanning distance • Input volumes distributed across existing lanes according to field data • Freeway exiting vehicles forced to change lanes

A portion of the field data was used in the calibration. Lane changes and volume data were recorded for seven five-minute periods at three sites. Descriptions of the three sites are given in Table 3-4.

Table 3-4. NETSIM Model Calibration Sites.

Field Site	Weaving Section Length (m)	Number of Lanes in Weaving Area	Average Volume (vph)		
			Exit	Entrance	Frontage Road
Site 1	136	3	245	250	555
Site 2	293	3	785	310	1260
Site 4	184	4	350	225	340

Each combination of model and geometric/volume data situation was run seven times so that input volumes matched those of the seven five-minute periods reduced from the field data. Each model variation was simulated for one hour, with output given every five minutes. Lane changes for each five minute period were then averaged and compared with the five-minute number of lane changes witnessed in the field. Average five-minute lane changes produced from each NETSIM model were then compared with the five-minute lane change frequencies observed in the field. A two-sided t-test was done on each model to decide which model was producing statistically similar results to the field data. At a 95 percent confidence level, a t-statistic less than 2.645 meant the model was producing statistically the same number of lane changes as was witnessed in the field. Table 3-5 lists the t-statistics produced from the t-test, while noting those that were determined to be statistically the same. Only one model—Model 2—produced similar results for all three field sites.

Table 3-5. T-Statistics for NETSIM Models and Field Sites.

Field Site	Model 1	Model 2	Model 3	Model 4
Site 1	7.578	1.925*	6.725	-3.935
Site 2	2.105*	2.271*	6.040	-4.200
Site 4	15.428	1.201*	11.78	-2.07*

* Results from NETSIM Model and field data are statistically similar.

Based upon the findings from the calibration efforts, Model 2 was selected as the best model. After several runs, however, it was discovered that Model 2 produced questionable results at high traffic volumes. At higher traffic volumes, long queues formed on the exit ramp. These long queues most likely would not have formed in the field, because in Texas, ramp vehicles have priority over frontage road vehicles. The codes used in the NETSIM model did state that vehicles on the frontage road are to yield to vehicles on the exit ramp. Inspection of the model and the results revealed that the type of movement (i.e., left, through, and right) at the junction for the different approaches (i.e., frontage road and ramp) had a greater influence on the yielding behavior observed at the junction than the traffic control code (i.e., yield versus no control). In Model 2, the vehicles on the frontage road link prior to the weaving section (link 11-1) were given a through movement at Node 1 (see Figure 3-1). Vehicles on the exit ramp (link 21-1) were given a left-turn movement at Node 1. Node 1 was then coded so that vehicles on link 11-1 should yield to vehicles on link 21-1. A review of the results showed that NETSIM was giving priority to the through movement in this situation. Therefore, with this configuration, vehicles on the exit ramp were yielding to vehicles on the frontage road, and a queue was forming on the exit ramp.

In an attempt to correct this problem, exit ramp vehicles and frontage road vehicles were assigned different movements at Node 1. To give exit ramp vehicles priority, the vehicles on link 21-1 were given a through movement at Node 1, and vehicles on link 11-1 were given a right-turn movement. Since NETSIM gives priority to through movements, this new configuration resulted in frontage road vehicles correctly yielding to exit ramp vehicles.

To check the accuracy of the results of the revised NETSIM model, field data from Site 2 (see Table 3-1) were used. This field site was selected because it contained the widest range of traffic volumes. From the field data, 10 data points (reduced in five-minute increments) were randomly selected and simulated using the revised NETSIM model. The model was simulated for one hour, with output given every five minutes. Lane changes for each five-minute period were then averaged and compared with the five-minute number of lane changes observed in the field.

Variables affecting the lane changing characteristics in NETSIM (used in the initial calibration process) were adjusted to recalibrate the model. Again, these variables included time for a lane change to take place, driver aggressiveness factor, scanning distance, and others. The variables were adjusted until the number of lane changes predicted by NETSIM were closest to those observed in the field. After completion of the recalibration, it was determined that the values of the variables used in Model 2 still produced the best results. Therefore, the revised Model 2 was used for the analysis of traffic operations on one-sided weaving sections.

Performing the Simulation

In performing the simulation, variables that would be modified along with the size of the increment for each variable had to be selected. Because the lane distribution for input volumes and freeway exiting volumes were not a factor for Model 2, these values did have to be varied. However, weaving length, number of lanes in the weaving area, exit ramp volume, entrance ramp volume, and frontage road volume were all varied. In selecting the range and increment size of the variables, a trade-off between the desire to have a large quantity of data and in having a manageable number of NETSIM runs was made.

In NETSIM, entrance ramp volume is expressed as a percentage of frontage road vehicles that will enter the freeway. At the six sites listed in Table 3-1, the percentage of frontage road vehicles entering the freeway ranged from approximately 50 to 80 percent. For this evaluation, the entrance ramp volume was expressed as 67 percent of the frontage road volume. Additional

reviews of the field sites also revealed that the entrance ramp volume to exit ramp volume ratio did not exceed 1:4. Therefore, the entrance ramp volume to exit ramp volume ratios used for the NETSIM runs were within a 4:1 to 1:4 range.

Tables 3-6 and 3-7 list the variables and values used in the NETSIM runs for three-lane weaving sections and four-lane weaving sections, respectively. Some combinations were not used (shown as NU), because the entrance ramp volume to exit ramp volume ratio was not within the 4:1 to 1:4 range. The number of runs made for the three-lane and four-lane sites were 60 and 92, respectively.

Combinations of weaving length, number of lanes in the weaving area, frontage road volume, and exit ramp volume and entrance ramp volumes were run using Model 2. Subsequently, each run produced a different output from which the delay, average speed, number of lane changes, and travel time were recorded for the weaving link. Average speeds were also recorded for the ramp link and for the link just prior to the weaving link. This was done to determine the speeds of vehicles before entering the weaving link.

Data Analysis

Upon obtaining the results from the NETSIM runs, the next step was to find any potential relationships. To illustrate potential relationships, the following plots were generated:

- lane changes versus weaving volume,
- lane changes versus total volume,
- weaving speed versus weaving volume,
- weaving speed versus total volume,
- weaving speed versus average lane changes,
- weaving delay versus weaving volume, and
- speed prior to weaving section versus weaving volume.

Table 3-6. NETSIM Model Variables for Three-Lane Weaving Sections.*

Frontage Road Volume (vph)	Entrance Ramp Volume (vph)	Exit Ramp Volume (vph)				
		100	500	1000	1500	2000
500	335				NU	NU
1000	670	NU				
1500	1005	NU				
2000	1340	NU				

* Weaving Length (m): 100, 200, 300, 400, 500

NU= Combination not used because the entrance ramp volume to exit ramp volume ratio was not within the 4:1 to 1:4 range

Table 3-7. NETSIM Model Variables for Four-Lane Weaving Sections.*

Frontage Road Volume (vph)	Entrance Ramp Volume (vph)	Exit Ramp Volume (vph)				
		100	500	1000	1500	2000
500	335				NU	NU
1000	670	NU				
1500	1005	NU				
2000	1340	NU				
2500	1675	NU				
3000	2010	NU				

* Weaving Length (m): 100, 200, 300, 400, 500

NU= Combination not used because the entrance ramp volume to exit ramp volume ratio was not within the 4:1 to 1:4 range

The analysis of these plots helped to answer several questions, such as: How well does the NETSIM model simulate existing field conditions? What limitations does the NETSIM model have? What are some potential relationships between various MOEs? Which MOE(s) should be used to determine the level-of-service at one-sided weaving sections?

COMPARISON OF FIELD DATA WITH SIMULATION DATA

An attempt at validating the NETSIM model was made using the reduced data from the field sites listed in Table 3-1. The process of validation included developing a linear regression model from the field data to predict the average number of lane changes per hour, given weaving volume. The results from NETSIM were then plotted to show the relationship between the predicted average number of lane changes per hour and weaving volume. The regression line developed from the field data could then be compared with the NETSIM results to learn whether any significant differences existed. These differences could then be used to detect any limitations that might exist from the simulation results.

DEVELOP ONE-SIDED WEAVING PROCEDURE

To define the level of operations on a one-sided weaving section, the results from the field studies and from computer simulation were used to study the relationships between various MOEs. The goal was to select a MOE that could be used for measuring the level of service on a one-sided weaving section, and to define boundaries to distinguish between different levels of service. After defining the level of service, the final task was to develop a step-by-step procedure for determining the level of service on one-sided weaving sections.

VALIDATION OF ONE-SIDED WEAVING PROCEDURE

To validate the proposed level of service analysis procedure for one-sided weaving sections, additional field data were collected. Specifically, researchers studied a field site with

a wide range of traffic volumes. This type of site allowed further investigation of how traffic volumes affect weaving behaviors.

The purpose of the validation process was to learn whether recommended level of service criteria could be applied to existing field conditions. The testing procedure involved comparing output from NETSIM (i.e., speed) with measurements taken in the field. To test the average speeds on the weaving link predicted by NETSIM, researchers measured speeds in the field and compared with those predicted by NETSIM.

CHAPTER 4

RESULTS

The results from field studies and from computer simulation (NETSIM) were used to identify relationships between the average number of lane changes per hour on a weaving link and other variables. The intent was to use the results from the field study to develop a NETSIM model and use the NETSIM model to predict various MOEs (e.g., speed and delay) under different conditions. By studying the relationships of the MOEs predicted by NETSIM, a procedure could be developed for determining the level-of-service within a weaving area. Following is a discussion on the results from the analysis for four-lane and three-lane, one-sided weaving areas.

FIELD DATA

Data reduced from the video tapes of the six field sites (see Table 3-1) included traffic volumes (exit ramp, entrance ramp, and total volume) and the number of lane changes. Generally, the sites were recorded from 7:00 to 9:00 am and from 4:00 to 6:00 pm. The data were summarized in five-minute increments to allow for more data points, and were later converted to units of one hour. Results from the video tapes were then used to develop a regression model to predict the average number of lane changes.

As shown in Figure 4-1, and as suspected, the number of lane changes shows a strong linear relationship with weaving volume. A regression model was developed to predict lane changes given weaving volume for the six field sites. The r-square value, which provides an appreciation of the amount of the data variability explained by the regression equation, was 0.97. Following is the resulting regression model:

$$LC = 1.33(W) \tag{4-1}$$

where:

LC = average number of lane changes per hour (lc/hr)

W = weaving volume (entrance ramp + exit ramp) (vph)

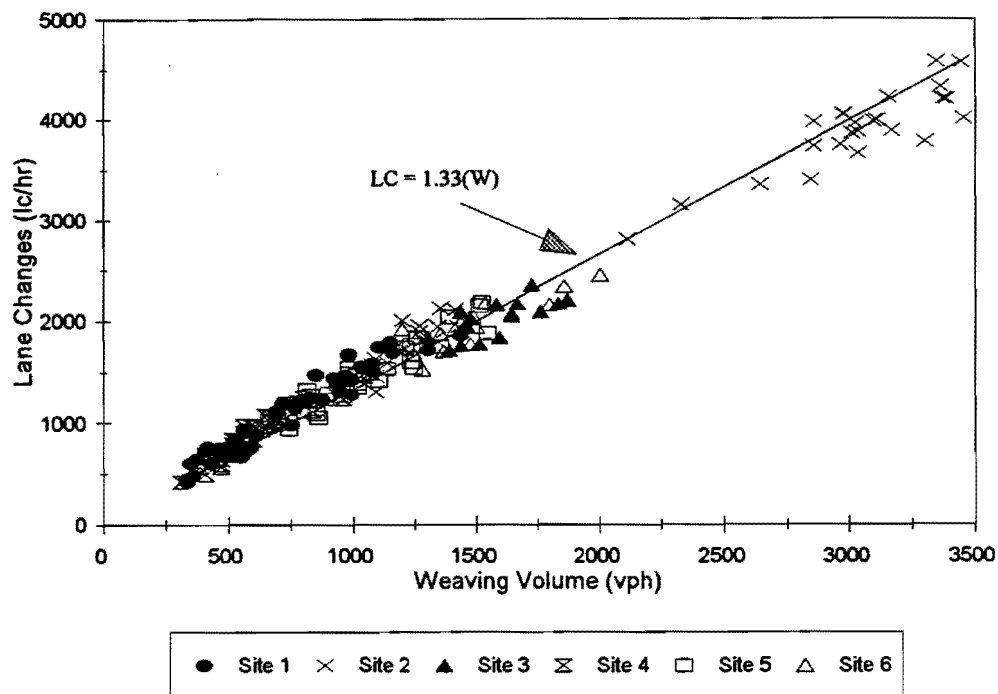


Figure 4-1. Lane Change and Weaving Volume Relationship for Field Data.

As demonstrated by the high r-square value and the plot in Figure 4-1, the number of lanes and the weaving length have minimal influence on the number of lane changes, even at very high weaving volumes. For example, some of the data from Site 2 is in the 2000 to 3500 vph range, yet these data points also fit well with the calculated regression line. Figure 4-2 illustrates that the relationship between lane changes and total volume is noticeably weaker than the relationship between lane changes and weaving volume (as to be expected).

Lane change intensity has been used or suggested in previous studies as a measure of effectiveness of the operations at one-sided weaving areas. The relationship between weaving volume and lane change intensity for the six field sites is shown in Figure 4-3. If the data is split into three distance groups (say less than 150 meters, between 180 and 300 meters, and greater than 335 meters), then reasonable relationships can be developed (as shown on Figure 4-3). Splitting the data into groups by weaving length, however, appears to be nonproductive since the calculation of lane change intensity was performed to remove or minimize the effects of weaving

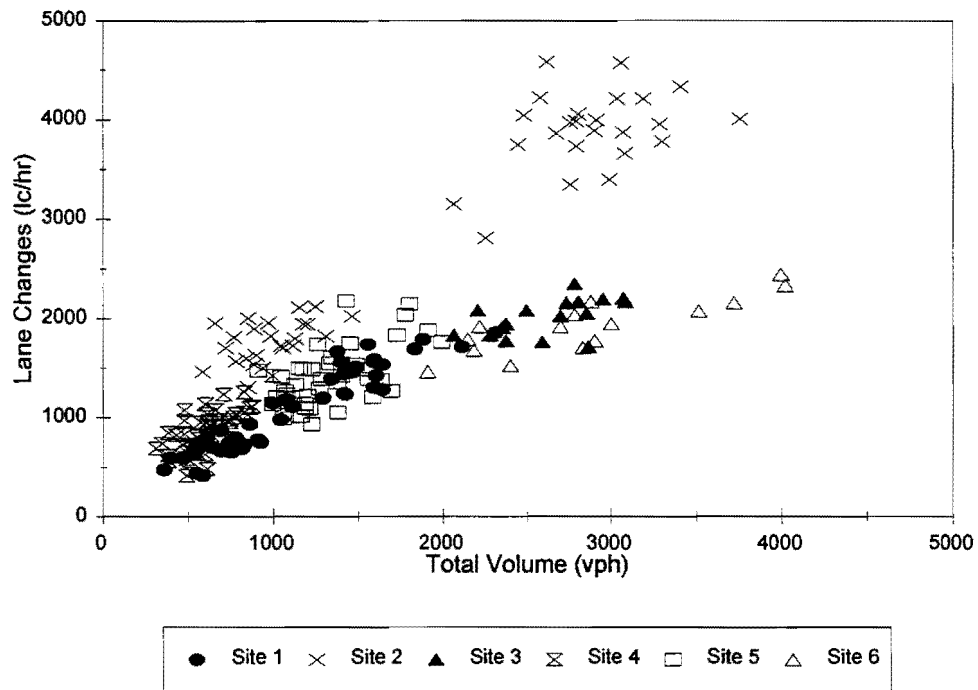


Figure 4-2. Lane Change and Total Volume Relationship for Field Data.

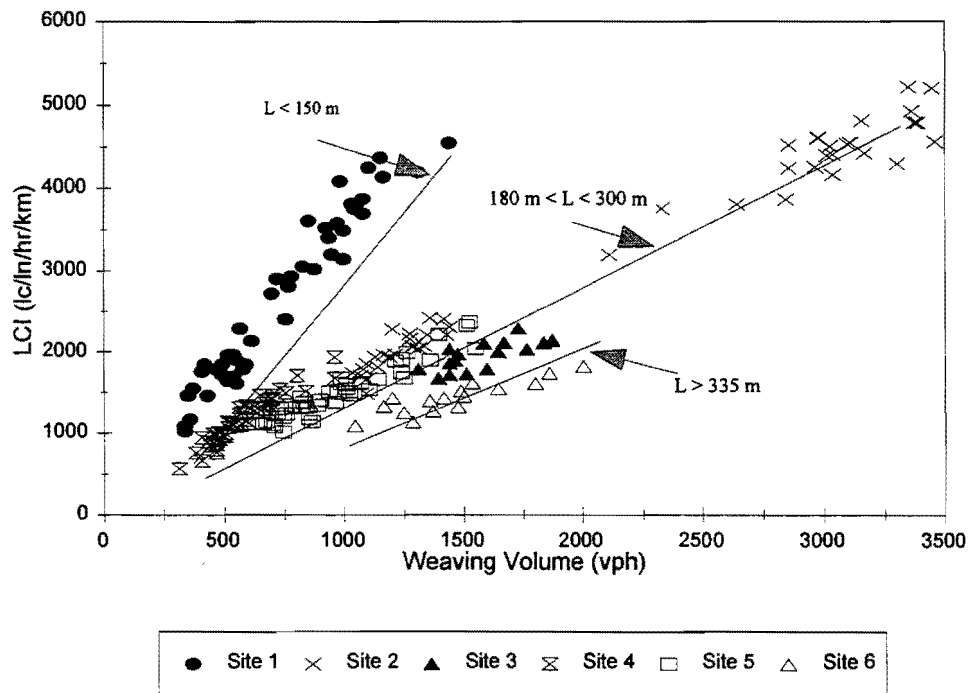


Figure 4-3. Lane Change Intensity and Weaving Volume Relationship for Field Data.

distance. As illustrated in Figure 4-4, the relationships of total volume to lane change intensity have similar weaknesses.

The findings from the field studies clearly indicate that the number of lane changes can be accurately predicted from the exit and entrance ramp volumes. A level of service scale can be developed based upon viewing the video data and using engineering judgement on the operational performance present during different volumes and lane changes level. Using the findings from the field studies to verify the findings from computer simulation, which can provide additional information such as delay and speed, can result in a better level of service scale.

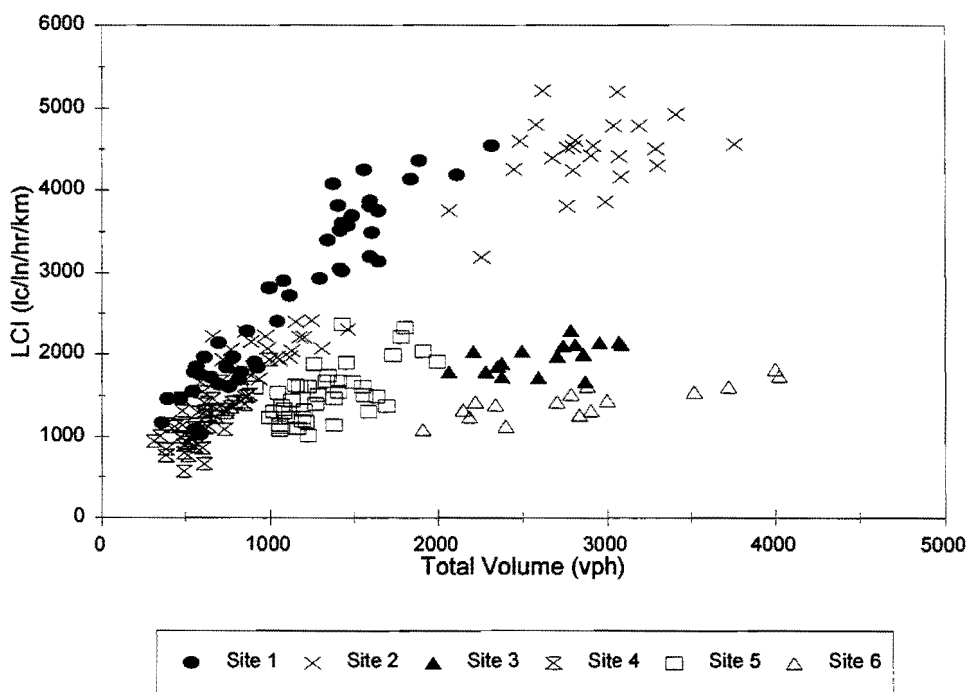


Figure 4-4. Lane Change Intensity and Total Volume Relationship for Field Data.

COMPUTER SIMULATION (NETSIM)

The calibrated NETSIM model for three- and four-lane, one-sided weaving areas were run using various combinations of traffic volumes and weaving lengths (see Tables 3-7 and 3-8). After each run, the following were recorded for the weaving link: average speed, average delay, average travel time, and average number of lane changes. Average speeds were also recorded for the exit ramp and link prior to the weaving link. Several graphs were plotted to study the relationships between the various findings.

Figure 4-5 shows the average number of lane changes per hour versus weaving volume for the three-lane and four-lane sites. The relationships between lane changes and weaving volume showed a linear trend (similar to the field data) for weaving sections between 200 meters and 500 meters in length; however, for a weaving length of 100 meters, the relationship was different. Observing Figure 4-5 for the 100 meter sections, there appears to be a critical weaving volume where the number of lane changes becomes relatively constant (i.e., the number of lane changes does not increase with increasing weaving volume). For example, for the four-lane, 100 meter section, the average number of lane changes increases linearly with increasing weaving volume to a weaving volume of approximately 3000 vph. After this point, the number of lane changes becomes relatively constant at approximately 5200 lc/hr. This critical weaving volume is most likely due to drivers wanting to change lanes but cannot because of the high volumes and inadequate weaving length. Therefore, results show that weaving sections below approximately 200 meters in length will begin to break down at relatively lower traffic volumes as compared to weaving sections with lengths above 200 meters.

Similar to the results from the field data, Figure 4-5 shows that the number of lane changes do not appear dependent upon the length of the weaving section. The number of lanes in the weaving section, however, does affect the number of lane changes predicted by NETSIM, which is contradictive to the findings from the field data. A plot of the regression line for the field data is also shown on Figure 4-5. The actual number of lane changes observed in the field are lower than the number of lane changes predicted by NETSIM.

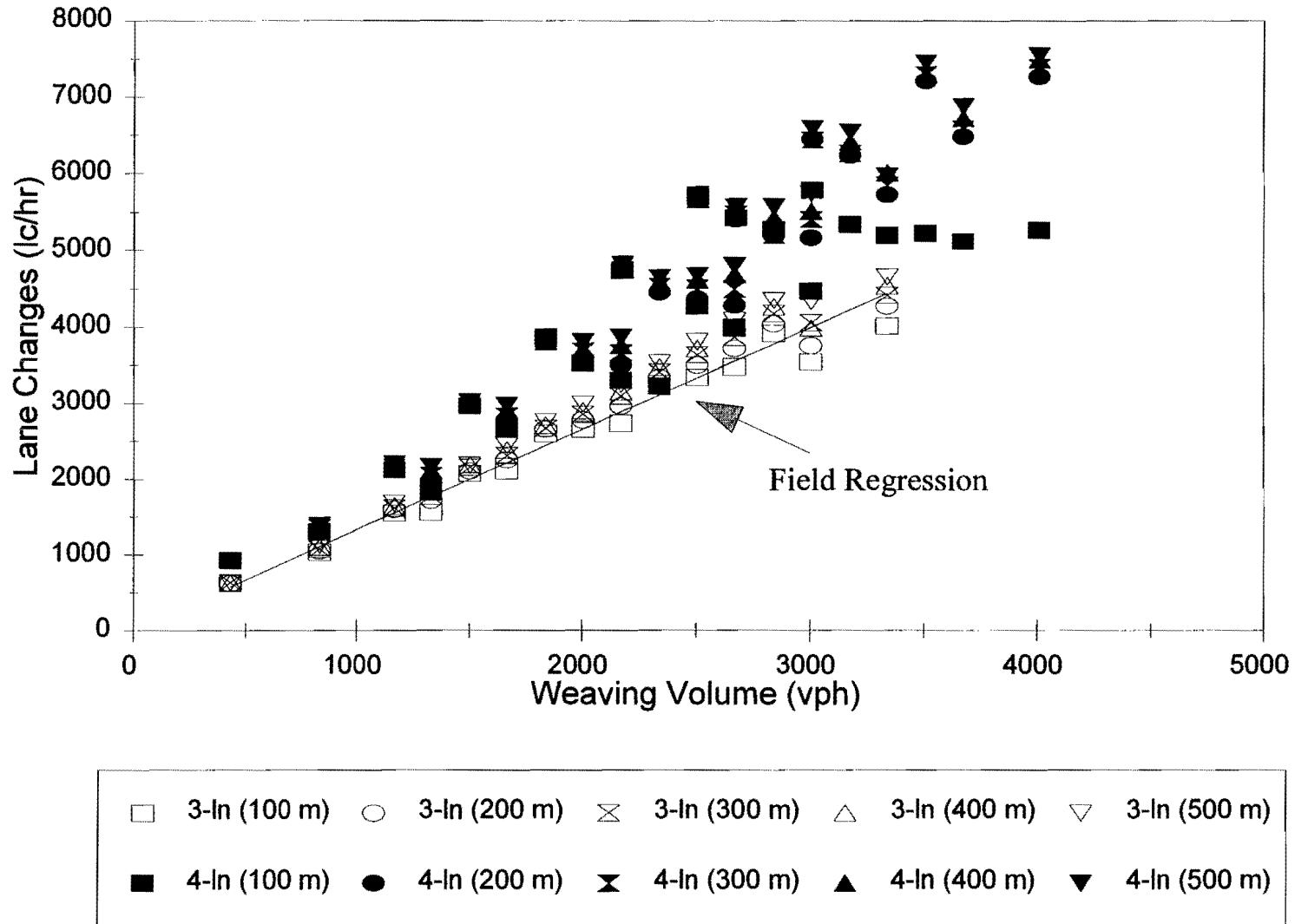


Figure 4-5. Lane Change and Weaving Volume Relationship for NETSIM Data.

These differences can be attributed to the way frontage road vehicles maneuver to the entrance ramp in NETSIM, as opposed to the maneuvers observed in the field. When coding a NETSIM model, the number of vehicles entering the freeway is expressed as a percent of the frontage road vehicles on the weaving link. NETSIM then randomly selects frontage road vehicles on the weaving link (independent of lane assignment) which will enter the freeway, based upon the coded percentage. In other words, vehicles wanting to maneuver from the frontage road to the entrance ramp do not begin their weaving maneuver until they reach the weaving link. Observation of the existing field sites, however, revealed that vehicles entering the freeway begin to make their maneuver before the weaving section. Therefore, the actual number of lane changes on the weaving section observed in the field are somewhat lower than those predicted by NETSIM. Also, in this situation, one would expect a higher number of lane changes in the four-lane sections than the three-lane sections because of the opportunity for a higher number of lane changes for each individual maneuver (i.e., when a vehicle in the right-most lane weaves across all lanes to access the entrance ramp in the four-lane situation it has three lane changes while only two lane changes would be counted in the three-lane situation). A simple procedure to reduce this limitation within the NETSIM model is not present.

By observing Figure 4-5, it is seen that the NETSIM results for the three-lane weaving sections more closely represent the field data than do the NETSIM results for the four-lane weaving sections. In other words, the NETSIM results for the three-lane weaving sections best represent the actual lane change activity observed in the field. Since the three-lane data from NETSIM best represented actual field conditions, it was decided that only the three-lane NETSIM model would be used for analyzing the level of operations on one-sided weaving sections. Thus, from this point forward, only the results from the three-lane NETSIM model were studied. Again, results from the field studies revealed that the number of lane changes within a one-sided weaving section is independent of the number of lanes; therefore, it was believed that the results from the three-lane NETSIM model could be applied to both three-lane and four-lane field sites.

Figure 4-6 illustrates the relationships between weaving speed and weaving volume. This figure illustrates that, as suspected, the speeds of weaving vehicles decrease as the weaving

volumes increase. The figure also shows that the weaving speeds for the 100 meter weaving section are relatively lower and decrease faster than the weaving speeds for the other weaving sections. Again, this indicates that weaving sections below approximately 200 meters in length may begin to break down at relatively lower traffic volumes as compared to weaving sections with lengths above 200 meters.

Observing Figure 4-6, there appears to be some variability in the relationship between weaving speed and weaving volume. This variability reveals that weaving speed may be dependent upon more than just weaving volume. For instance, the speed of weaving vehicles may be dependent upon the number of vehicles exiting the freeway relative to the number of vehicles entering the freeway.

To further investigate this concept, researchers conducted a study to determine the relationship between weaving speed and the ratio of entrance/exit ramp volume. Figure 4-7 reveals the results from this effort. This figure illustrates the relationship between weaving speed

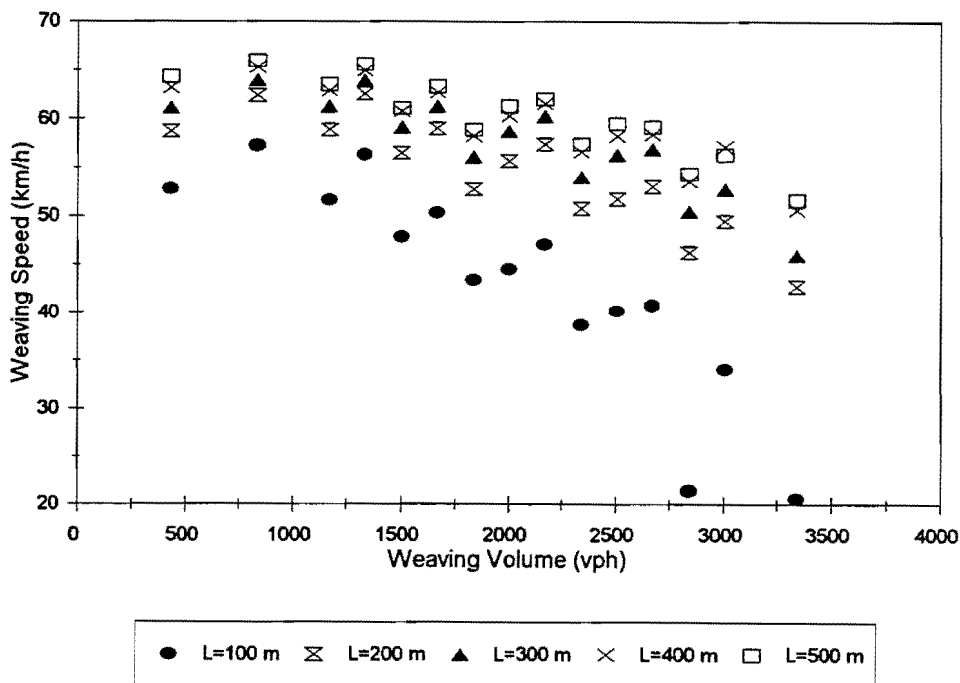


Figure 4-6. Weaving Speed and Weaving Volume Relationship for NETSIM Data.

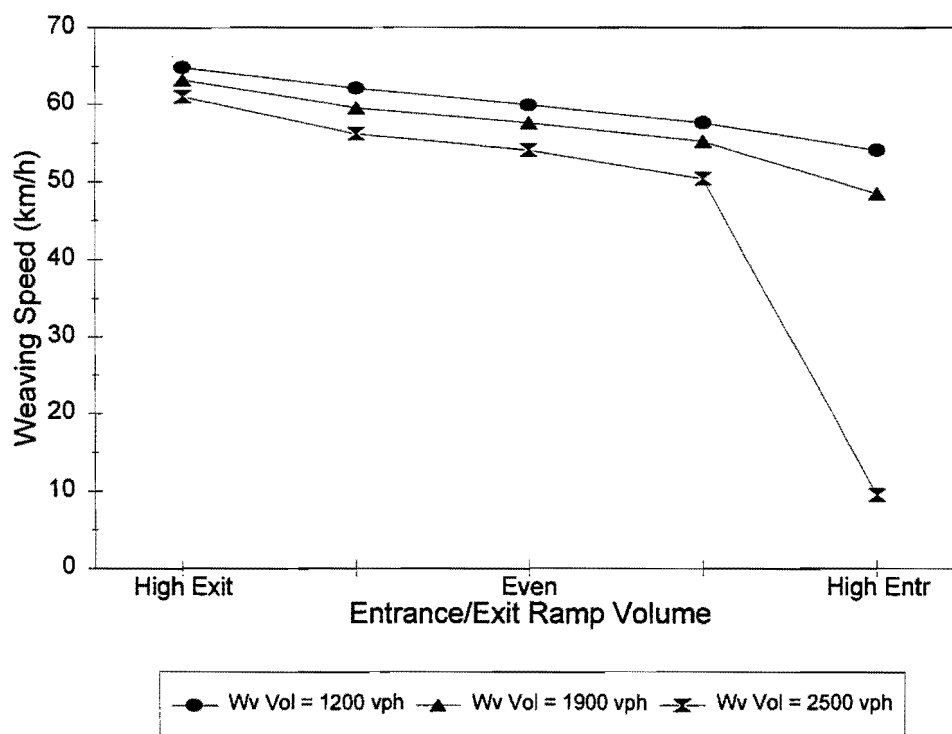


Figure 4-7. Weaving Speed and Entrance/Exit Ramp Volume Relationship.

and entrance/exit ramp volume for three weaving volume levels (1200, 1900, and 2500 vph). As suspected, the weaving speeds decrease as the entrance/exit ramp ratio increases. In other words, for a constant weaving volume (exit ramp + entrance ramp), the weaving speeds will be expected to be lower when the entrance ramp volumes are high relative to the exit ramp volumes, and higher weaving speeds will be expected when the entrance ramp volumes are low relative to the exit ramp. The change in weaving speeds becomes more significant as the weaving volumes increase.

As discussed in Chapter 3, when coding, NETSIM entrance ramp volume is coded as a percentage of frontage road vehicles that will enter the freeway. Initially, this value was expressed as 67 percent. To determine if this value had any affect on the weaving speeds, additional NETSIM runs were made in which the entrance ramp volume was expressed as 50 percent and 80 percent of the frontage road volume. This increased the total number of NETSIM runs from 60 to 180 (for the three-lane weaving sections). Figure 4-8 demonstrates the

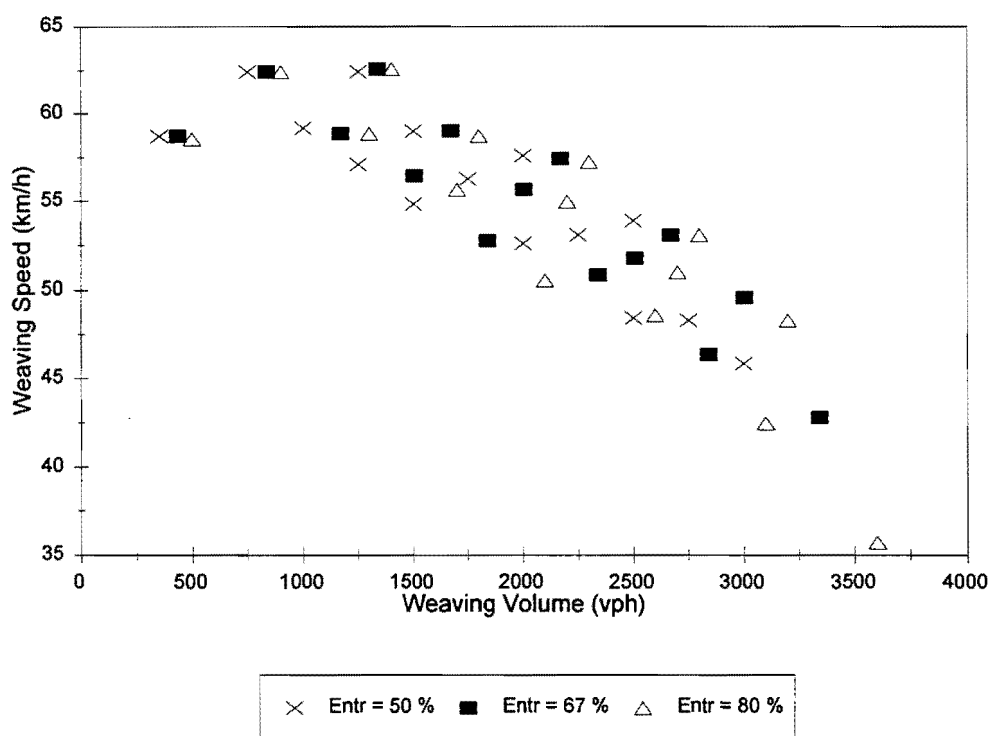


Figure 4-8. Weaving Speed and Entrance Ramp Percentage Relationship (L=200 m).

relationship between weaving speed and weaving volume for three entrance ramp percentages (50, 67, and 80 percent) for a weaving length of 200 meters. As shown in this figure, the value of the percentage of frontage road vehicles entering the freeway has little effect on the weaving speed. This indicates that the weaving speed is more dependent upon the weaving volume (i.e., exit ramp volume + entrance ramp volume) than the frontage road volume.

Figure 4-9 illustrates the relationship between weaving speed and lane changes. (For this plot, the entrance ramp volume was expressed as 50, 67, and 80 percent of the frontage road volume.) As discussed earlier, a linear relationship exists between lane changes and weaving volume. Therefore, similar relationships should exist between weaving speed versus lane changes and weaving speed versus weaving volume. Comparing Figure 4-9 to Figure 4-6, the relationships are similar; however, there appear to be less variability in the weaving speed when it is plotted against lane changes. These results show that the weaving speed is more closely related to the amount of lane change activity than to weaving volume.

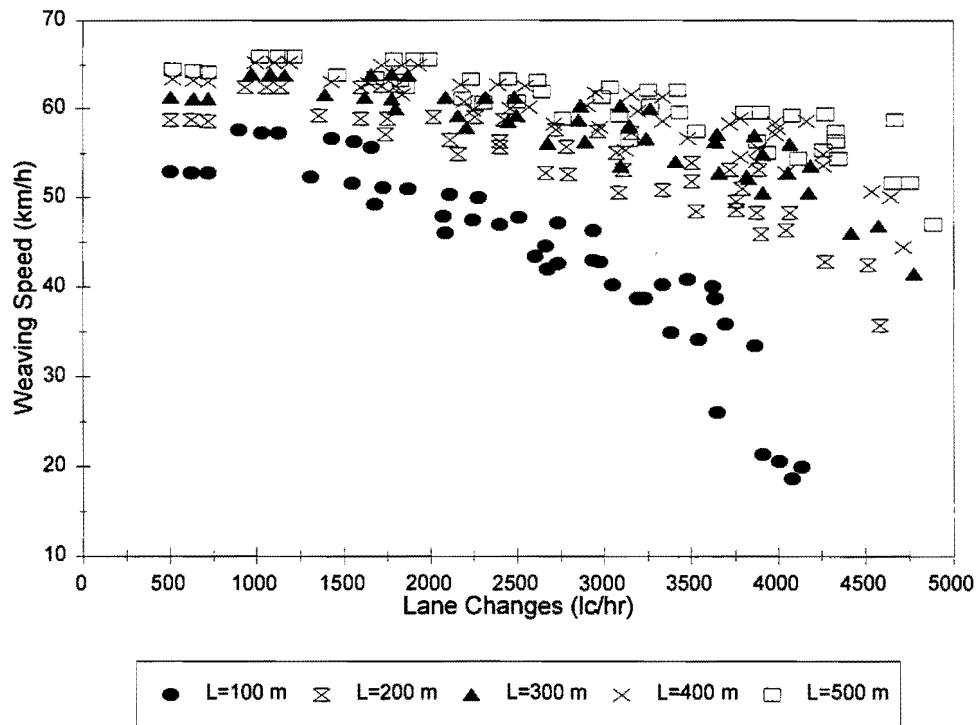


Figure 4-9. Weaving Speed and Lane Change Relationship for NETSIM Data.

Figure 4-10 illustrates the relationship between weaving speed and total volume. Total volume includes the weaving volume and the non-weaving volume. This figure illustrates an increase in variability in the weaving speed as total volume increases. Again, this indicates that the weaving speed may be influenced by the actual values of the exit ramp, entrance ramp, and frontage road volumes rather than just the sum of the three values.

The speeds on the frontage road link prior to the weaving link were inspected to identify if after a certain volume level, the yielding of the frontage road vehicles would result in a noticeable decrease in speed for the frontage road vehicles. Observing Figure 4-11, speeds were relatively constant at approximately 57 km/h between weaving volumes of 500 and 4000 vph. After approximately 4000 vph, the speeds became noticeably lower and highly variable. Again, Figure 4-11 indicates that the 100 m weaving sections began to break down sooner than weaving sections with lengths of 200 meters and above. The approximate volume location where speeds are affected can provide an appreciation of how the system is operating.

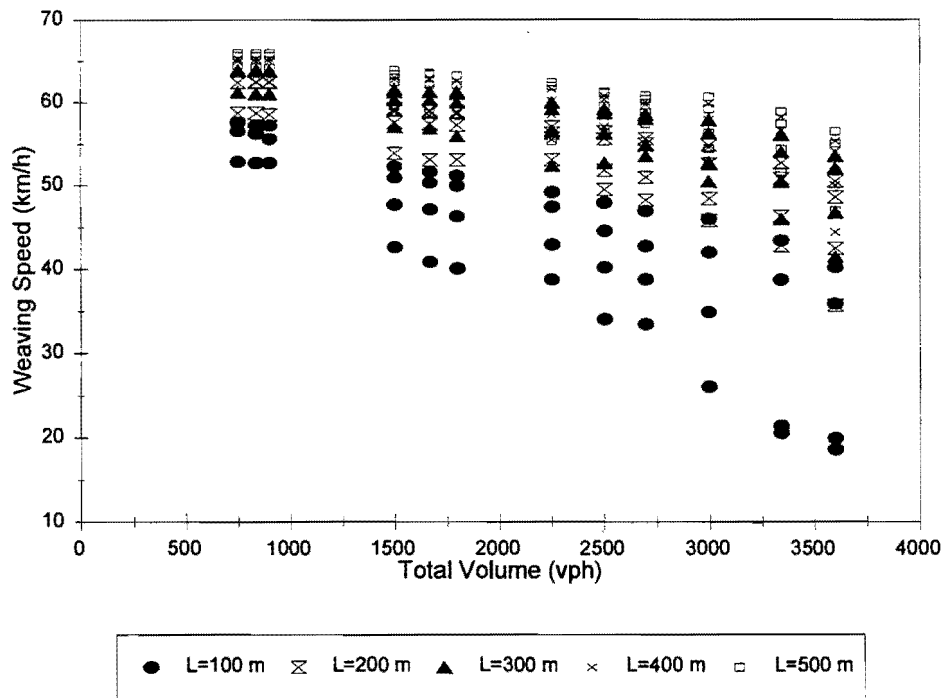


Figure 4-10. Speed and Total Volume Relationship for NETSIM Data.

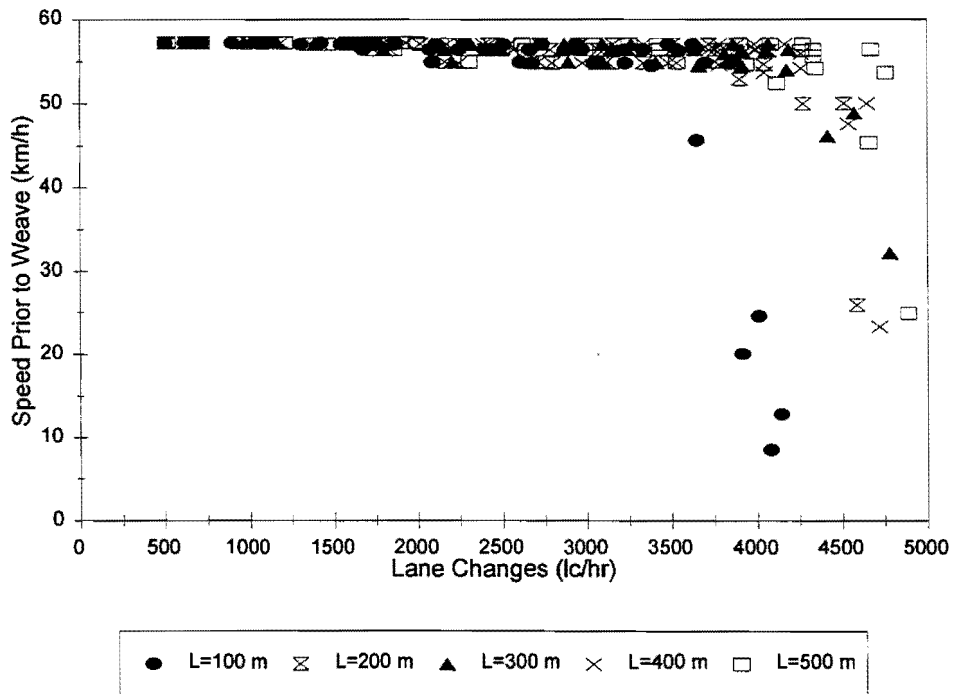


Figure 4-11. Prior Speed and Lane Change Relationship for NETSIM Data.

Figure 4-12 illustrates the relationship between delay on the weaving link and weaving volume. This relationship is very similar to the relationship between weaving speed and weaving volume (see Figure 4-6), revealing that the delays predicted by NETSIM are highly correlated with the corresponding speeds. Therefore, since speed is easier to measure than delay in the field, and speed is the MOE currently used in the arterial street analysis procedure in the *HCM*, the research team selected speed as the MOE for determining the level of operations for one-sided weaving areas.

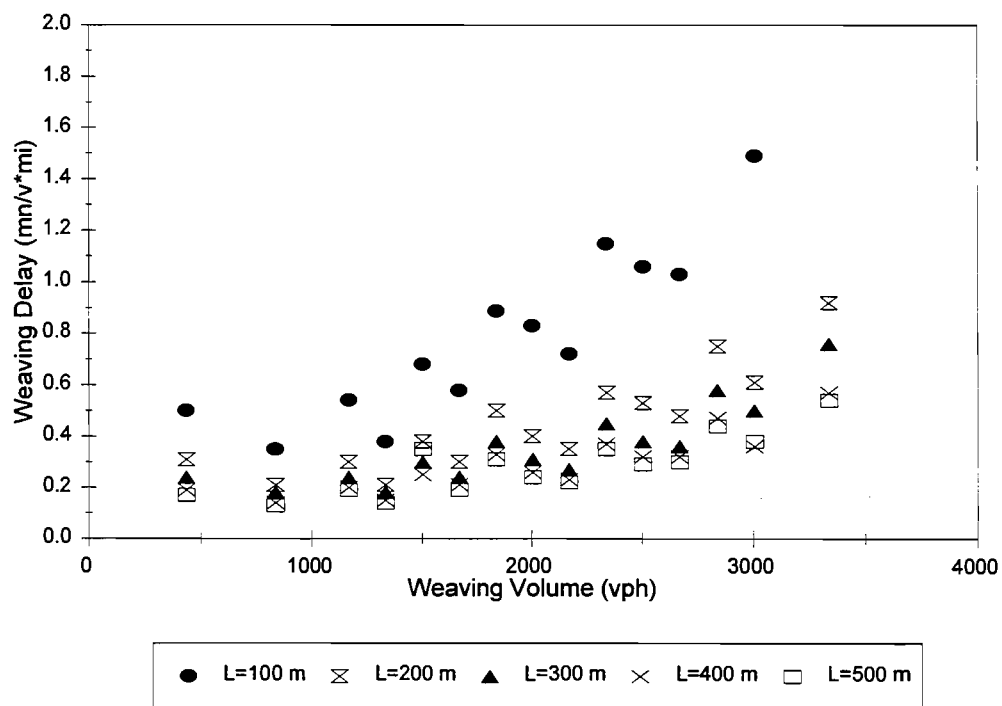


Figure 4-12. Delay and Weaving Volume Relationship for NETSIM Data.

CHAPTER 5

ONE-SIDED WEAVING EVALUATION TECHNIQUE

PROPOSED LEVEL OF SERVICE CRITERIA

To develop a procedure for determining the LOS within a one-sided weaving area, researchers investigated several MOEs. After an analysis of one-sided weaving areas using NETSIM, it was concluded that the average speed on the weaving link would be the proposed MOE. Speed is currently used in the *HCM* for evaluating arterial streets; measuring it in the field is easy, and it is easy to explain and understand.

In an attempt to use weaving speed to determine the LOS on a weaving section, the relationships between weaving speed and several other variables were studied using NETSIM. These variables included weaving volume, total volume, and number of lane changes. From the analysis, it was concluded that weaving speed is most closely related to lane changes.

Figure 5-1 illustrates the relationship between weaving speed and lane changes for one-sided weaving areas. Observing this figure, there appear to be certain critical points (or break points) in which the weaving speed begins to drop more rapidly. For instance, there is a critical lane change value (approximately 2000 lane changes per hour) in which the weaving speed begins to drop more rapidly. Also, as the number of lane changes increase, there is another point (approximately 4000 lane changes per hour) in which speeds drop significantly and become more variable. The latter critical point was also evident in the relationship between the speed prior to the weaving link and lane changes (see Figure 5-2). Observing Figure 5-2, the speeds prior to the weaving link are relatively stable up to an average number of lane changes per hour of approximately 4000. After the number of lane changes per hour exceeds 4000, the speeds drop and become more variable. For both Figures 5-1 and 5-2, the 100 m weaving sections began to break down sooner than weaving sections with lengths of 200 meters and above.

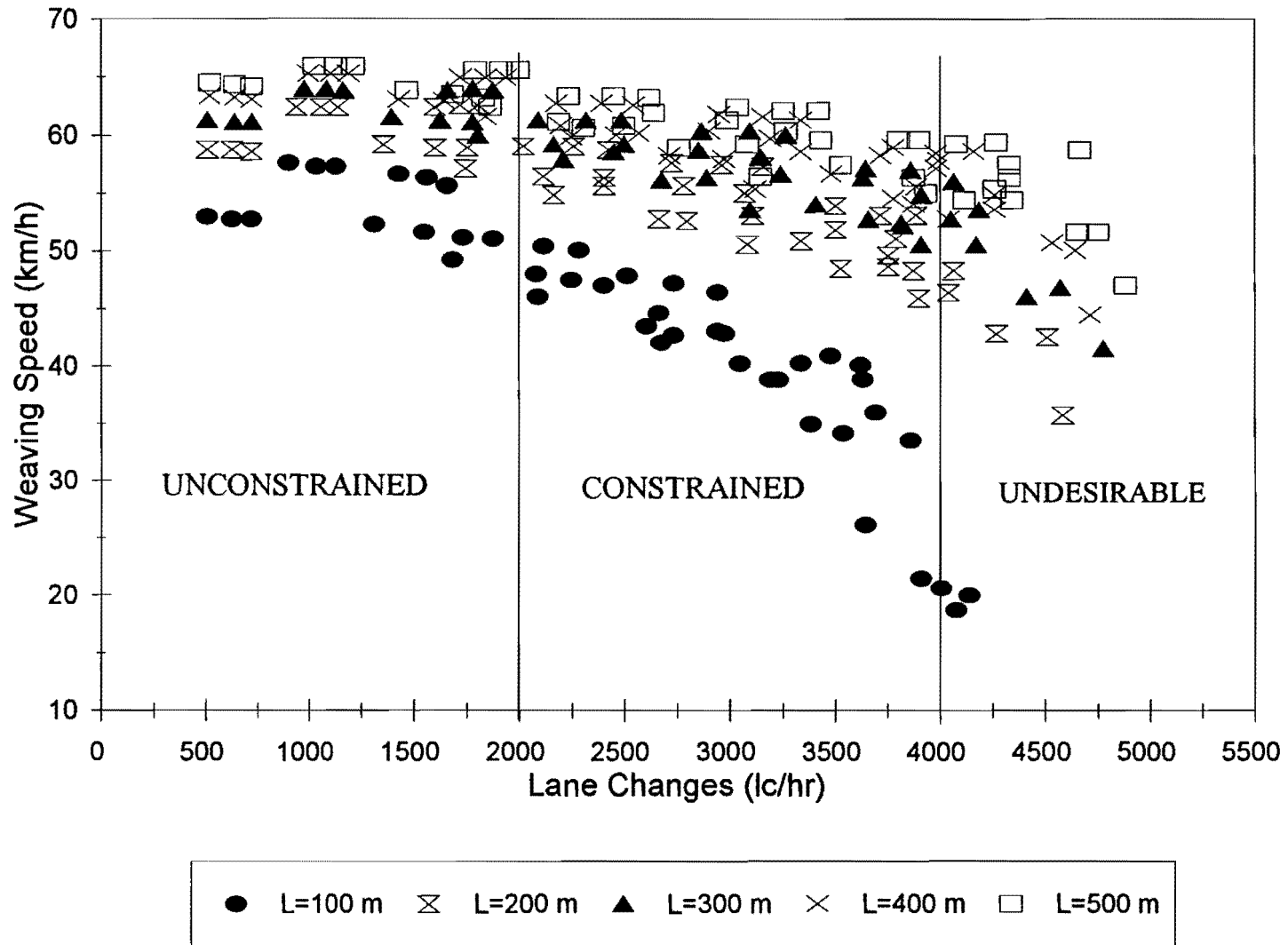


Figure 5-1. Breaking Points for Weaving Speed and Lane Change Relationship.

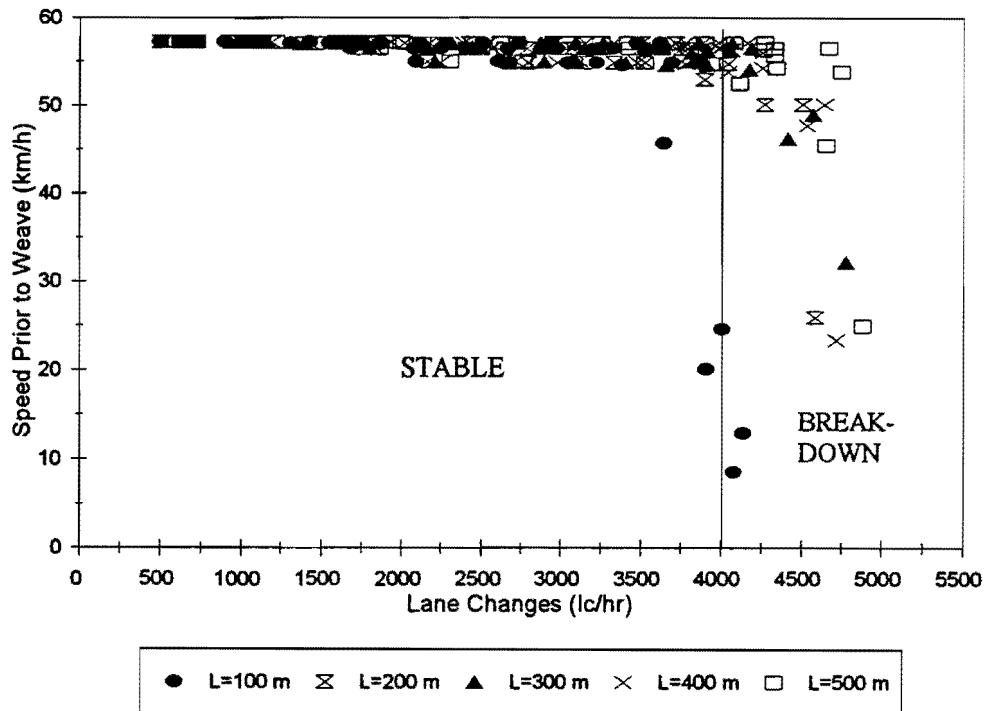


Figure 5-2. Breaking Point for Prior Speed and Lane Change Relationship.

Using these critical points, each weaving section was divided into three levels of operation: unconstrained, constrained, and undesirable. These three levels of operation correspond to the following levels of service defined by the *HCM*: unconstrained = LOS A-B, constrained = LOS C-D, and undesirable = LOS E-F. Unconstrained operations represent free flow to stable operations in which drivers can maneuver with relatively little impedance from other traffic. Constrained operations represent stable operations in which drivers' ability to maneuver becomes more restricted due to other traffic. Undesirable operations represent unstable operations in which flows are approaching capacity and drivers' ability to maneuver are highly restricted.

Technique for Determining Level of Service

The proposed LOS criteria are shown in Table 5-1. These criteria apply to one-sided weaving areas on one-way frontage roads with the following characteristics:

Table 5-1. Proposed Level of Service Criteria.

Level of Service	Average Lane Changes (lcph)	Weaving Volume* (vph)
Unconstrained	< 2000	< 1500
Constrained	2000-4000	1500-3000
Undesirable	> 4000	> 3000

* weaving volume = average lane changes / 1.33

- frontage road section containing a freeway exit ramp followed by an entrance ramp connected by an auxiliary lane,
- either two or three frontage road through lanes, and
- spacing between exit ramp and entrance ramp from 100 to 500 meters.

To estimate the level of service for an existing one-sided weaving area, the following procedures should be followed:

- (1) Collect exit ramp and entrance ramp volumes for the one-sided weaving section.
- (2) Calculate weaving volume: weaving volume = exit ramp volume + entrance ramp volume.
- (3) Compare the calculated weaving volume with the values listed in Table 5-1 to estimate the LOS.

The values presented in Table 5-1 are not meant to represent exact divisions in LOS. The values are intended to provide a general idea of the LOS which might be expected for a particular weaving area; therefore, engineering judgement should be used when applying these criteria.

WEAVING LENGTH

The spacing between an exit ramp and a downstream entrance ramp can greatly affect the operations of a weaving section. The effect of weaving length on traffic operations becomes more

evident as traffic volumes increase. To illustrate this point, the results from NETSIM were used to examine the speeds of weaving vehicles on weaving sections with different lengths at high traffic volumes. In particular, the weaving speeds were examined at the boundary between unconstrained and constrained operations (2000 lc/hr) and at the boundary between constrained and undesirable operations (4000 lc/hr).

Figure 5-3 shows the relationships between weaving speed and weaving length. This figure illustrates that weaving speed decreases at a relatively low rate as weaving length decreases for lengths above 300 meters. The rate in which the speeds decrease becomes greater for weaving lengths between 200 and 300 meters, and the rate of decrease is greatest for weaving lengths below 200 meters. These findings correspond to the findings in Chapter 4 which showed that the weaving sections with a length of 100 meters began to break down sooner than those weaving sections with lengths of 200 meters and above. From these results, it was concluded that it is desirable to have a weaving length greater than 300 meters. If this length is not achievable, then the absolute minimum length should be approximately 200 meters.

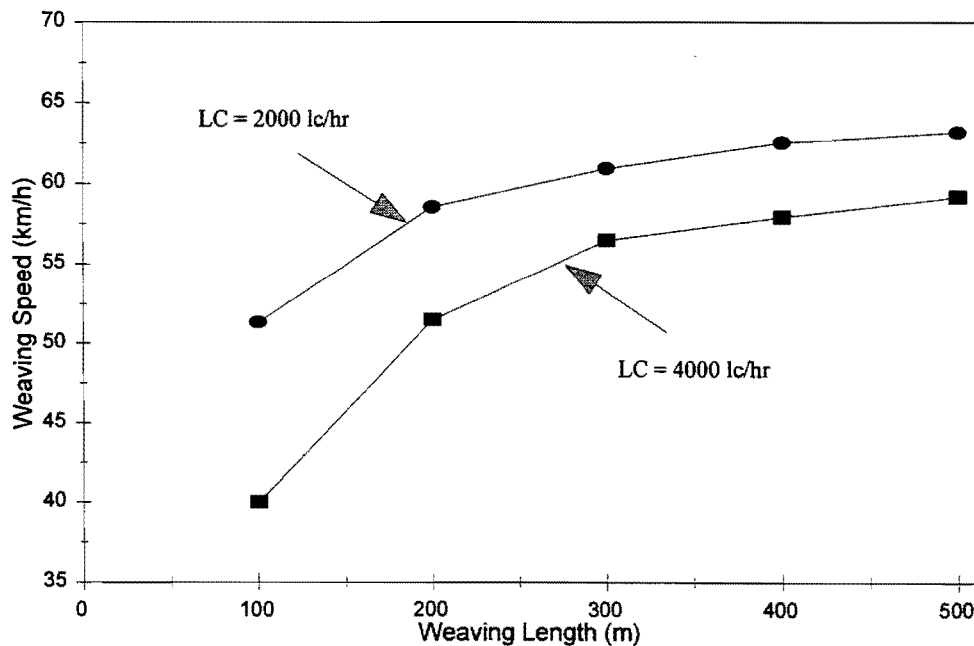


Figure 5-3. Weaving Speed and Weaving Length Relationship.

CHAPTER 6

VALIDATING PROPOSED LEVEL OF SERVICE CRITERIA

The objective of the validation procedure was to test the proposed level of service criteria. To accomplish this task, additional field data were collected at a selected field site. From the field data, weaving maneuvers and speeds were measured to determine when the traffic operations became unstable. These observations were then compared with the NETSIM results and the level of service recommendations.

FIELD DATA

Site Selection

In an attempt to select a validation site, researchers investigated several one-sided weaving frontage road sections in Austin, Dallas, Fort Worth, and Houston. Since the proposed level of service criteria were based on weaving volume, it was very important that the selected field site have a high traffic volume during the peak period. The criteria used for site selection were as follows:

- frontage road section with one-sided weaving configuration,
- high traffic volumes,
- weaving area from 200 to 500 m in length,
- relatively straight horizontal and vertical alignment, and
- no intermediate disturbances in the weaving area (such as a major driveway).

Based on the above criteria, a site in Houston was chosen. The site was located north of Houston on the IH 45 northbound frontage road between Gulf Bank and SH 249. The weaving section was approximately 242 m in length and contained three lanes (two frontage road lanes and one auxiliary lane).

Data Collection

Volume estimates were obtained before visiting the field site in Houston. These volumes not only helped with the site selection process but also revealed the time of day in which the highest volumes were present (i.e., the time in which the weaving section would most likely begin to become unstable). Based on this information, the research team decided to collect field data during the pm peak. To study a range of traffic volumes, data at the Houston site were collected from 12:00 pm to 6:00 pm.

To record the traffic operations at the field site, two video cameras were used. Both cameras were located in the exit ramp gore area upstream of the weaving area. One camera was “zoomed out” to get a wide view of the entire weaving section, and the other camera was “zoomed in” toward the downstream entrance ramp to get a clear view of the traffic operations in that area.

To record speeds at the field site, three radar guns were used. Technicians measured speeds for the following maneuvers: exit ramp to frontage road, frontage road to entrance ramp, and frontage road through. Vehicle speed of every vehicle could not be measured due to high volumes, therefore, technicians measured the speeds of vehicles believed to be traveling at a representative speed compared with the other traffic.

Data Reduction

As discussed in Chapter 5, the level of service can be estimated using weaving volume. To reiterate, the recommended criteria were divided into the following three levels of operation: unconstrained (weaving volume < 1500 vph), constrained (weaving volume from 1500 to 3000 vph), and undesirable (weaving volume > 3000 vph). After the data had been collected, it was discovered that the weaving volumes observed at the study site ranged from approximately 1000 vph to 2000 vph; therefore, the collected field data could only be used to test the operations in the unconstrained and constrained regions.

From the video tapes, selected operational data were extracted. As mentioned above, data were collected from 12:00 pm to 6:00 pm. However, data were only reduced for the 4:00 pm to 6:00 pm period since the data collected from 12:00 pm to 4:00 pm contained relatively low traffic volumes and would contribute little to the validation efforts. The traffic operational data reduced from the video tapes included traffic volumes (i.e., exit ramp, entrance ramp, and frontage road) and weaving maneuvers (i.e., exit ramp to frontage road, frontage road to entrance ramp, and miscellaneous). To provide a larger sample size, data were reduced in five-minute increments. The procedures used in this effort followed the data reduction procedures discussed in Chapter 3.

The speeds measured in the field were also summarized in five-minute increments. Since the recommended level of service criteria was based on weaving speeds, the speeds measured in the field were divided into weaving and non-weaving speeds. The weaving speeds included vehicles maneuvering from the exit ramp to the frontage road and vehicles maneuvering from the frontage road to the entrance ramp. Speeds from these two maneuvers were combined and averaged to estimate an average weaving speed per five-minute period.

Once the data were reduced from the video, they were entered into a spreadsheet program where weaving volume and total lane changes were computed. The weaving volume consisted of the exit ramp to frontage road volume plus the frontage road to entrance ramp volume. The total lane changes were the sum of all the lane changes made on the weaving section. To allow for easier comprehension of the data, all five-minute values were converted into hourly values. Finally, the average weaving speeds corresponding to each weaving volume and number of lane changes were added to the spreadsheet.

COMPARISON OF FIELD DATA TO RECOMMENDED PROCEDURES

The proposed level of service criteria developed in this study were based upon weaving speeds estimated using computer simulation (NETSIM); therefore, to validate these findings, weaving speeds measured in the field were compared with those predicted by NETSIM. As discussed in Chapter 4, to study the behavior of weaving speed, the results from NETSIM were used

to study the relationship between weaving speed versus weaving volume and weaving speed versus lane changes. From these results, it was concluded that weaving speeds were more closely related to lane change activity than weaving volume (i.e., a higher variability existed in the relationship between weaving speed and lane changes, see Figures 4-6 and 4-9).

To compare the weaving speeds measured in the field to those predicted by NETSIM, researchers examined the effects of weaving volume and lane changes on weaving speed. Figures 6-1 and 6-2 show the relationships between weaving speed and weaving volume and weaving speed and lane changes, respectively. In comparing Figure 6-1 with Figure 6-2, less variability in weaving speed is present when it is plotted against lane changes. Similar to the results from NETSIM, these figures illustrate that weaving speed is more closely related to lane change activity.

Observing Figure 6-2, weaving speed becomes more variable as lane changes increase. As illustrated, weaving speed is relatively stable below approximately 2000 lc/hr and becomes more variable above 2000 lc/hr. Lower weaving speeds are also present above 2000 lc/hr. The 2000 lc/hr

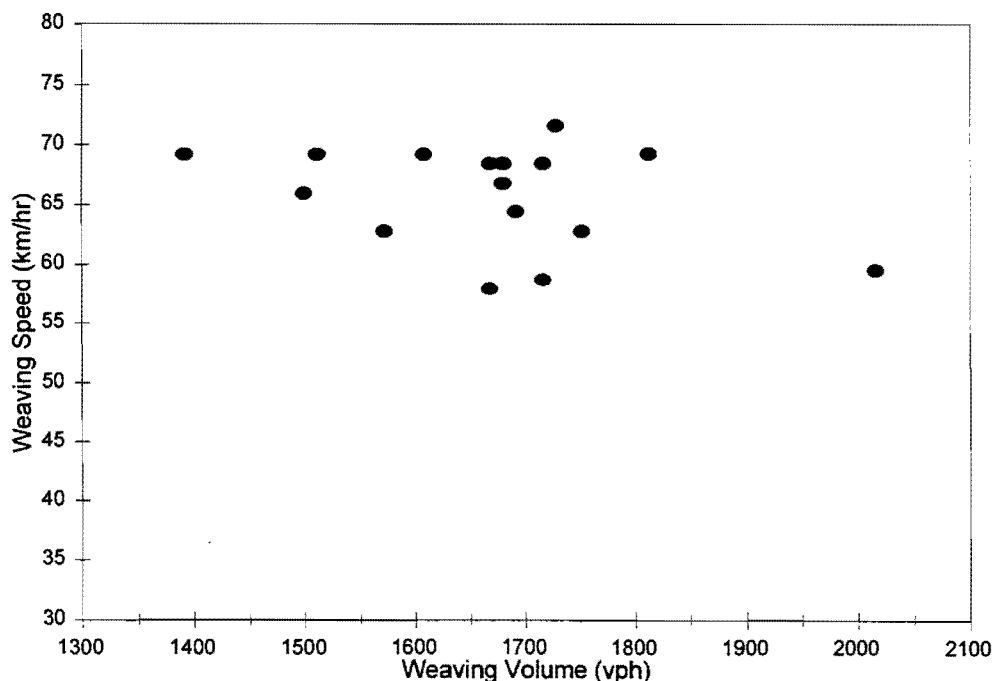


Figure 6-1. Weaving Speed and Weaving Volume Relationship for Validation Data.

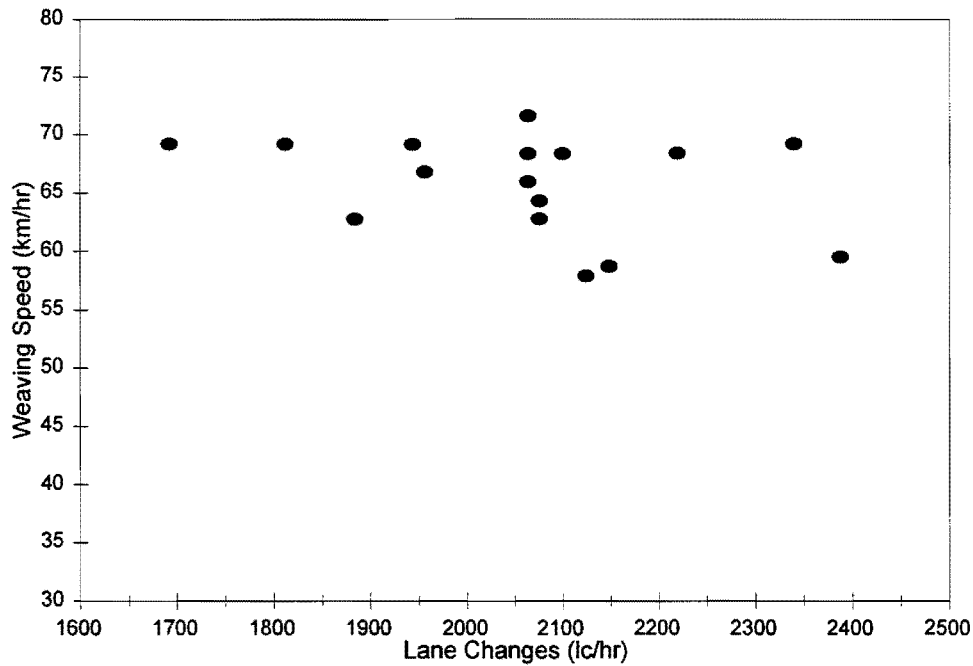


Figure 6-2. Weaving Speed and Lane Change Relationship for Validation Data.

value corresponds to the boundary between unconstrained and constrained operations derived from the NETSIM results.

To provide a closer comparison between the field data and the NETSIM data, results from both the field and from NETSIM were plotted on the same figure (see Figure 6-3). Since the weaving section length of the field site was approximately 242 m, the NETSIM results for the 200 m and 300 m sections were included in Figure 6-3.

Observing this figure, the overall weaving speeds predicted by NETSIM were slightly lower than those observed in the field. This is most likely due to the way that NETSIM was coded. As discussed in Chapter 3 in the section *Creating and Calibrating a Simulation Model*, to give exit ramp vehicles priority over frontage road vehicles at the exit ramp-frontage road merge point, vehicles on the exit ramp were assigned a through movement and vehicles on the frontage road were assigned a right turn movement. Although this solved the issue of priority, it resulted in relatively

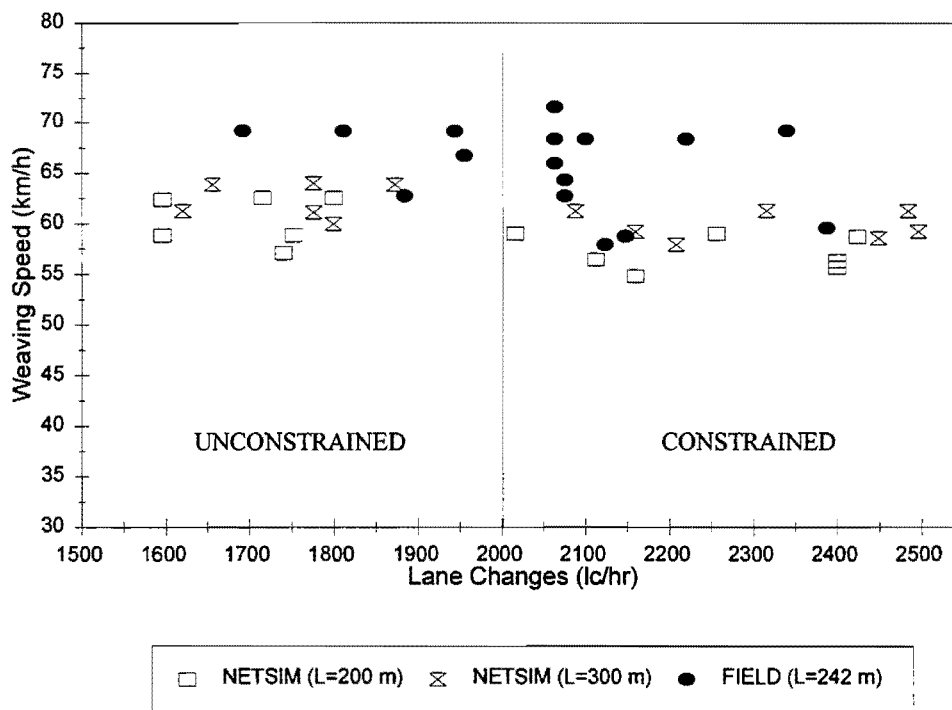


Figure 6-3. Weaving Speed and Lane Change Relationship for Combined Data.

lower speeds of frontage road vehicles because the frontage road vehicles were assigned a right turn movement before entering the weaving section.

Even though the speeds predicted by NETSIM were slightly lower than those observed in the field, the relationships between weaving speed and lane changes were similar. As illustrated in Figure 6-3, a breaking point in weaving speeds occurs at approximately 2000 lc/hr for both the field data and the NETSIM data. For the NETSIM data, the weaving speeds experience a slight drop and begin to decrease at approximately 2000 lc/hr. For the field data, above 2000 lc/hr weaving speeds drop and become more variable.

Observing Figure 6-3 again, it is noted that above 2000 lc/hr, the speeds measured in the field are more variable than the speeds predicted by NETSIM. The spacing between the weaving section and the downstream intersection contributed to the high variability of speeds observed in the field. During the peak period, queues from the downstream intersection approached the one-sided weaving section, interfering with traffic operations in this area. Therefore, during high traffic

volumes, the variability of the speeds observed in the field was not only caused by the weaving maneuvers, but also by queues from the downstream intersection.

FURTHER VALIDATION

In an attempt to further validate the recommended level of service criteria, the video tapes of Site 2 (see Table 3-1) were used to observe the traffic operations over a wide range of volumes. This site was selected because it contained the highest weaving volumes and, therefore, the greatest lane change activity. During the morning peak period (7:00 am to 9:00 am), weaving volumes ranged from approximately 1000 to 1400 vehicles per hour. During the afternoon peak period (4:00 pm to 6:00 pm), weaving volumes ranged from approximately 2500 to 3400 vehicles per hour. Therefore, this high range of weaving volumes would allow testing for all three proposed levels of operation.

To compare the traffic operations at Site 2 to the proposed level of service criteria, engineering judgement was used to determine when the level of operations at the site changed significantly. Signs that showed a decline in the level of traffic operations included the following: an increase in the number of brake lights observed, a decrease in the relative speeds, and an increase in erratic maneuvers (i.e., drivers using more aggression, changing lanes at the “last minute,” etc.).

After viewing the video tapes, it was determined that no significant operational problems existed during the morning peak period. The traffic operations were relatively free flow for most of that period. Since the weaving volume did not exceed 2000 vehicles per hour during the morning peak, the observed traffic operations corresponded to the recommended level of service criteria.

The traffic operations were much more restricted during the afternoon peak period. Drivers had more difficulty in making their maneuvers because of the interaction with other traffic. The traffic operations ranged from constrained to undesirable, and the border between

these two levels of operations ranged from 2700 to 3000 weaving vehicles per hour. Therefore, these field observations also corresponded to the recommended level of service criteria.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

The research documented in this report focused on investigating one-sided weaving operations on one-way frontage roads. The study objectives were to develop a technique for evaluating one-sided weaving operations, and to develop recommendations on minimum and desirable ramp spacing. Objectives were met with the use of both field data and computer simulation. The conclusions and recommendations drawn from this study are as follows.

CONCLUSIONS

- Evaluate the performance of a one-sided weaving area using the technique presented in Chapter 5. The technique provides the user with a LOS based upon the weaving volume present.
- Divide one-sided weaving operations into the following three levels of operation: unconstrained, constrained and undesirable. These three levels of operation correspond to the following levels of service defined by the *HCM*: unconstrained = LOS A-B, constrained = LOS C-D, and undesirable = LOS E-F.
- Estimate the level of service by calculating the weaving volume (exit ramp volume + entrance ramp volume) for a one-sided weaving area, based on the following criteria: unconstrained (weaving volume < 1500 vph), constrained (weaving volume from 1500 - 3000 vph), and undesirable (weaving volume > 3000 vph).
- For one-sided weaving areas, having a weaving length greater than 300 meters is desirable. If this is not achievable, the minimum weaving length should be 200 meters.

RECOMMENDATIONS

- Concerning one-sided weaving operations, the NETSIM model used in this study predicted a relatively high percent of frontage road-to-entrance ramp vehicles weaving from the right-most lane when compared with the field observations. In NETSIM, the frontage road vehicles wanting to access the entrance ramp did not begin the required weaving maneuvers until they reached the weaving link. According to field observations, many of the frontage road vehicles desiring to access the entrance ramp began making the required weaving maneuvers before reaching the weaving link. Therefore, improvements are recommended for NETSIM so that weaving vehicles may begin the required maneuvers before reaching the weaving link.
- Further research is recommended on one-way frontage operations between exit ramps and entrance ramps. The research should focus on lane configurations differing from that addressed in this report. Configurations identified for future study include the following: exit ramp followed by an entrance ramp with no auxiliary lane, and exit ramp followed by an entrance ramp with a lane addition beginning at the exit ramp and terminating at the downstream intersection.

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