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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 two-sided weaving on one-way frontage roads (between an exit ramp and a downstream signalized intersection). The objectives of this study were to develop a technique for evaluating two-sided weaving operations, and to develop recommendations on minimum and desirable ramp-to-intersection 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 based upon frontage road density between the exit ramp and downstream intersection: unconstrained (density < 40 veh/km/ln), constrained (density from 40 - 100 veh/kn/ln), and undesirable (density > 100 veh/km/ln). Recommended ramp-to-intersection spacings were developed base on frontage road volume, exit ramp volume, and percent exit ramp vehicles making a two-sided weaving maneuver.

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TWO-SIDED WEAVING ANALYSIS ON ONE-WAY FRONTAGE ROADS

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Research Report 1393-2
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 and proposed two-sided weaving sections on one-way frontage roads. The procedures developed can be used to estimate the level of service at these types of sections. This, in turn, will aid engineers in prioritizing frontage road improvement projects and/or predicting future operations. Also provided are recommended desirable and minimum exit ramp-to-intersection spacings. The results from this study will be incorporated into 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 Lewis Nowlin and Kay Fitzpatrick (PA-037730-E).

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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. 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 two-sided weaving operations on one-way frontage roads. The objectives were to develop a technique for evaluating two-sided weaving operations and to develop recommendations on minimum and desirable ramp-to-intersection spacing.

To investigate two-sided weaving operations on frontage roads, both field data and computer simulation (NETSIM 5.0) were used. The field data were used to calibrate a computer simulation model and the results from computer simulation were used to develop a procedure for analyzing two-sided weaving operations. The field data were also used to estimate the distance that drivers use to make a two-sided weaving maneuver in the field. This information was combined with the results from computer simulation to develop recommendations for minimum and desirable ramp-to-intersection spacings.

After an analysis of two-sided weaving areas using NETSIM, it was concluded that the density on the weaving link would be the proposed MOE. Density is a good measure of weaving operations because it measures the proximity of vehicles and is a reflection of drivers' freedom to maneuver.

The criteria for estimating the level of service are based upon frontage road density (veh/km/ln) between the exit ramp and downstream intersection. From the NETSIM results, regression equations were developed to predict density based on frontage road configuration, frontage road volume, exit ramp volume, exit ramp-to-intersection spacing, and percent of exit ramp vehicles making a two-sided weaving maneuver.

Two-sided weaving operations were divided 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. Using the results from computer simulation in combination with field observations, criteria were developed to predict level of service based on density. By calculating the density for a two-sided weaving area, the level of service can be estimated based on the following criteria: unconstrained (density < 40 veh/km/ln), constrained (density from 40 - 100 veh/km/ln), and undesirable (density > 100 veh/km/ln).

To develop recommendations for minimum and desirable spacings, the regression equations developed to predict density were used to back calculate for spacing given frontage road volume, ramp volume, and percent two-sided weaving maneuvers. To estimate minimum and desirable spacings, the density values between constrained and undesirable operations (100 veh/hr/ln) and between unconstrained and constrained operations (40 veh/km/ln) were used, respectively. The recommended minimum and desirable spacings are based upon the following factors: frontage road configuration, frontage road volume, exit ramp volume, and percent of exit ramp vehicles making a two-sided weaving maneuver (less than 50 % or greater than 50 %). Based upon findings from this study and findings from previous research, an absolute minimum exit ramp-to-intersection spacing of 150 meters is recommended.

CHAPTER 1
INTRODUCTION

Weaving along a roadway occurs when drivers traveling in one lane must make one or more lane changes to reach a desired destination. Weaving on freeways typically occurs around ramp junctions, and weaving on arterial streets may occur around intersections or driveways. The effects of weaving vehicles on the operations of a facility can have a heavy influence on the quality of service provided to motorists. As the interference between weaving vehicles (and non-weaving vehicles) increases, the level of service continues to decrease. Procedures to evaluate the operations on weaving sections can help to determine how specific factors, such as traffic volume and weaving length, affect the level of service of a facility.

PROBLEM STATEMENT

To date, techniques to evaluate weaving on arterial streets 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. Procedures are needed to evaluate weaving on arterial streets so as to 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 influenced by weaving. One section of a frontage road which may be influenced by weaving is the area between a freeway exit ramp and a downstream intersection. This type of area is said to have two-sided weaving operations because exit ramp vehicles desiring to make a right turn at the downstream intersection must maneuver from one side of the frontage road to the opposite side. The level of operations in this type of area may be influenced by several factors including traffic volumes, turning percentages, and ramp-to-intersection spacing.

As part of a larger study that is developing a level of service evaluation procedure for freeway frontage roads, the issues associated with two-sided weaving on one-way frontage roads were examined. This report documents those efforts. Field data and computer simulation were used to develop procedures to evaluate the operations on two-sided weaving areas and to develop recommended ramp-to-intersection spacings.

OBJECTIVES

The objectives of this study were to develop techniques for evaluating two-sided weaving sections on one-way frontage roads and to develop recommended ramp-to-intersection spacings. The results from this study will be incorporated into the final frontage road analysis package. To accomplish the objectives of this research, the following tasks were performed:

- Collect data at existing frontage road sites.
- Use the field data to determine the distance drivers use to make a two-sided weaving maneuver.
- Select a traffic simulation program to analyze two-sided weaving operations.
- Use the field data to calibrate the selected traffic simulation program.
- Perform the simulation for various traffic volumes, turning percentages, frontage road configurations, and ramp-to-intersection spacings.
- Analyze the data from the simulation runs.
- Use the results from the field study and from computer simulation to develop a procedure for analyzing the operations on two-sided weaving sections and to develop recommended ramp-to-intersection spacings.

ORGANIZATION

This report is divided into six 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 summary of previous research concerning weaving on freeways. Also included is a review of previous research work addressing issues associated with two-sided weaving on non-freeway roadways.

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 described in this chapter. Also included is a summary of the computer simulation techniques and a discussion on the procedures used to develop procedures for evaluating the level of service at two-sided weaving areas.

Chapter 4 presents the study results. This chapter includes finding from both the field study and computer simulation. **Chapter 5** introduces the proposed level of service analysis procedure for two-sided weaving areas on one-way frontage roads. Also included are procedures for determining minimum and desirable ramp-to-intersection spacings. Finally, the conclusions for this study are presented in **Chapter 6**.

CHAPTER 2
PREVIOUS STUDIES

An unique aspect of frontage roads 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. For those studies that have dealt with non-freeway weaving, the majority only addressed weaving areas that lacked the presence of a traffic signal. Only two studies were identified which addressed two-sided weaving operations on arterial streets with the presence of a signalized intersection. Additional studies were identified which addressed exit ramp-to-intersection spacing needs on frontage roads. The following sections contain definitions of terms associated with weaving, examples of frontage road weaving areas, a brief review of freeway weaving, and summaries of the identified studies associated with two-sided weaving.

DEFINITIONS

Following are the definitions of relevant terms associated with freeway weaving from the 1994 *Highway Capacity Manual* (*HCM*) (1).

- **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.

- **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** is formed 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 defined in terms of the minimum number of lane changes which must be made by weaving vehicles as they travel through the section.

- **Type A** weaving areas require that each weaving vehicle make one lane change in order 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 be accomplished 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 accomplished without making a lane change while the other weaving movement requires two or more lane changes.

- **Major weaving sections** are characterized 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 significantly higher speed than weaving vehicles.

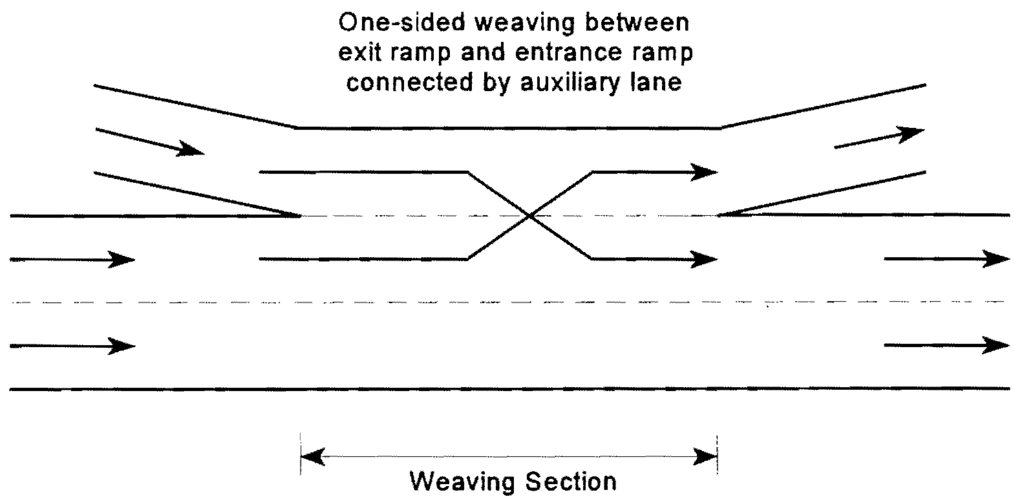
- **Unconstrained operations** occur when configuration does not restrain weaving vehicles from occupying a balanced proportion of available lanes. Average running speed of weaving and non-weaving vehicles generally differ by less than 8 kilometers per hour, except in short Type A sections, where acceleration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

EXAMPLES OF FRONTAGE ROAD WEAVING AREAS

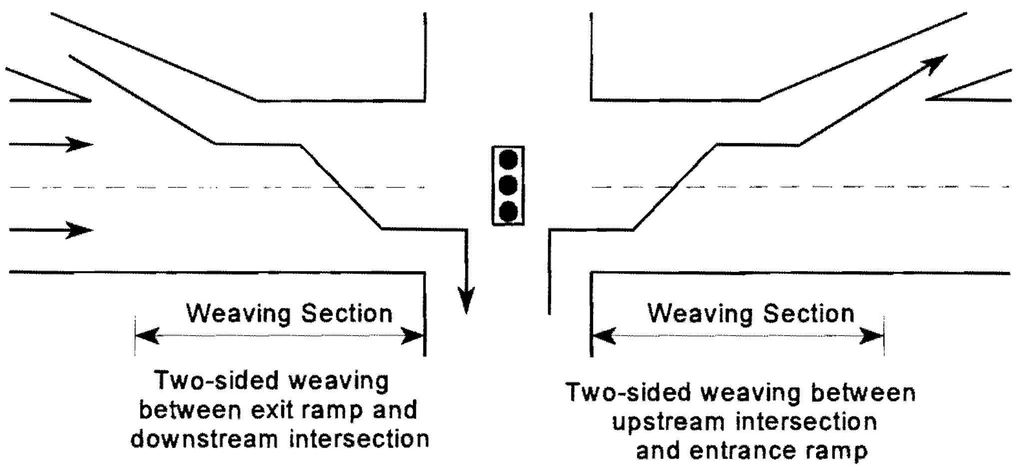
Examples of one-sided and two-sided weaving areas for a frontage road are shown in Figure 2-1. Different configurations of weaving, such as weaving between two ramps or weaving between a ramp (or a driveway) and a downstream intersection are also illustrated. Two-sided weaving between an exit ramp and a downstream intersection (see part (b) of Figure 2-1) was the focus of the research efforts documented in this report.

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 *HCM* (2). This procedure was based on empirical analysis of data collected prior to 1948. The 1965 *HCM* (3) contained a new method based on efforts initiated by the United States Bureau of Public Roads. The Polytechnic Institute of New York (PINY) (4) formulated a new methodology that was published in 1975. Because of its complexity, a modified PINY procedure was included in the TRB Circular 212 (5). Circular 212 also included a method developed by Jack Liesch (6) which 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 which 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* (7). These same procedures were carried over to the 1994 *HCM* (1).



(a) One-Sided Weaving Maneuvers



(b) Two-Sided Weaving Maneuvers

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

Since the publication of the 1985 *HCM*, several major studies at the University of California at Berkeley have examined aspects of freeway weaving. One study (8) examined six existing methods for the design and analysis of freeway weaving sections. It found 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. (9) 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 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 demonstrated that the configuration 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 another MOE rather than speed should be considered. 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.

TWO-SIDED WEAVING STUDIES

Analysis of Weaving Operations

In 1986, Trivedi and Schondfeld (10) conducted a study at the University of Maryland which investigated existing methods for analyzing weaving operations on arterial streets. The objective of the study was to identify an appropriate methodology for analyzing arterial weaving sections. The research approach included the following: survey of literature, survey of current practice, and review of the *HCM*. 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 which cannot be applied directly to arterials due to difference in type of operation on freeways and arterials. Questionnaires in the form of a weaving area problem were sent to traffic engineers in Maryland and traffic engineers and academic researchers in other states were contacted by phone. The results of the survey indicated that there is no acceptable procedure available for analysis of weaving sections on arterials. Most of the methods used were improvisations based on the *HCM* 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 *HCM* while the traffic on the ramp would use the procedure for unsignalized intersections. They indicated that the methods in the freeway chapter could be used for one-sided weaving problems. Because the *HCM* procedures cannot be reliably used for weaving on arterials, they recommended that procedures for arterial weaving be developed.

In 1995, Mike Lloyd (11) published a Master of Science thesis which investigated issues associated with two-sided weaving on arterial streets. The research for the thesis was part of the National Cooperative Highway Research Program (NCHRP) Project 3-47, "Capacity Analysis of Interchange Ramp Terminals." Specifically, Lloyd's research focused on studying weaving operations on an arterial street between an interchange ramp terminal and a downstream cross street. In this situation, two-sided weaving occurs when drivers on the exit ramp make a right turn on the arterial followed by a left turn at the downstream intersection (see Figure 2-2).

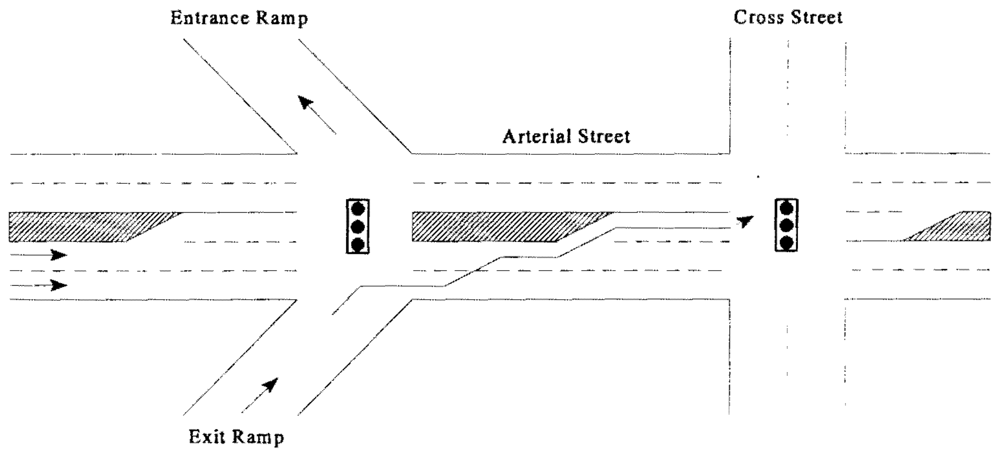


Figure 2-2. Two-Sided Weaving Maneuvers Studied by Lloyd (11).

Lloyd's study involved using computer simulation to study the arterial weaving section between a ramp terminal and a downstream intersection. The objectives of the study were to identify factors which had the greatest impact on the arterial weaving section and to assess TRAF-NETSIM's performance in simulating arterial weaving. The study design involved investigating several scenarios in which the following factors were varied: total volume on weaving section, number of lanes on weaving section, length of weaving section, and signal offset between ramp signal and downstream signal.

Results from the study revealed that the following factors affected traffic operations on the weaving section: total volume, weaving section length, queue length at downstream intersection, delays at downstream intersection, and signal offset. Lloyd also concluded that average travel speed was a potential MOE for predicting the level of service on the weaving section.

Based on regression analyses, equations were developed to predict the speed of weaving vehicles and the speed of non-weaving vehicles on the arterial weaving section. Following are the equations that were generated. The coefficients of determination (R^2) for the weaving speed and non-weaving speed equations were 0.95 and 0.96, respectively.

$$WS = 4.7 + 0.00955(LL) - 0.000242(VPH) - 0.0115(NWD) - 0.0592(WD) \tag{2-1}$$

$$NWS = 20.2 + 0.0106(LL) - 0.491(NWD) - 0.000135(VPH) \tag{2-2}$$

where:

WS = travel speed of weaving vehicles, miles per hour;
NWS = travel speed of non-weaving vehicles, mile per hour;
LL = length of weaving section, feet;
VPH = total through volume on weaving section, vehicles per hour;
NWD = delay of non-weaving vehicles at downstream signal, seconds per vehicle; and
WD = delay of weaving vehicles at downstream signal, seconds per vehicle.

The study also concluded that TRAF-NETSIM was an appropriate tool for evaluating traffic operations on arterial weaving sections. The traffic simulation program provides link specific outputs which allowed for the examination of the effects of changing various inputs in a controlled manner. Also, the graphics simulation package (GTRAF) which accompanies TRAF-NETSIM allowed the researchers to closely examine the operations on the weaving section, which helped them to better understand and explain the outputs.

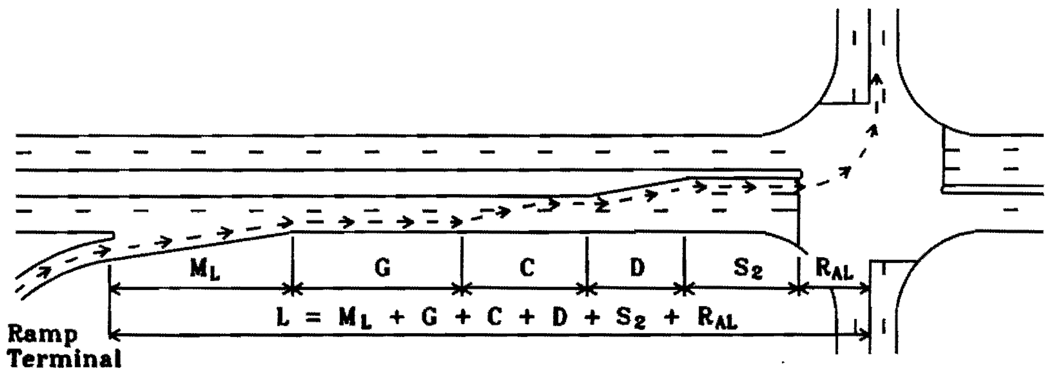
Exit Ramp-To-Intersection Spacing

General guidance on spacing is provided in the 1994 AASHTO *Green Book* (12). The Green Book states that ramps should connect to the frontage road a minimum of 105 meters from the crossroad. It also states that "desirable lengths will be several hundred feet longer to provide adequate weaving length, space for vehicle storage, and turn lanes at the cross road."

Chiu et al. (13) reported a survey conducted in the 1980s of state and local agencies on the minimum distance between a ramp terminal and the nearest intersection or driveway. The survey revealed distances between a ramp terminal and the nearest intersection of 30 to 460 meters with the distribution being wide and sparse. The authors attributed the distribution to respondents using subjective judgement based on previous experiences to select minimum distances. The survey also provided information on minimum spacings between driveways and corner clearance distances. The minimum driveway spacing ranged from 2.5 meters for residential driveways to 105 meters for driveways on rural highways with 88 km/h design speed. The corner clearance distances, which is defined as the distance from the nearest edge of a driveway to the nearest edge of an intersection, was from 6 to 90 meters.

A 1976 NCHRP study by Copas et al. (14) reported that general design guidelines for the Interstate Highway System suggest that access control should extend along the crossroad beyond the terminal about 30 meters or more in an urban area and about 90 meters or more in a rural area. A 1960 questionnaire on protection for interchange areas (15) showed that 16 states recommended specific distances between 30 and 300 meters with the majority in the 30 to 75 meter range.

Gern and Joyner (16) in a Highway Research Record discussed a procedure for calculating the desirable distance between a ramp terminal and the nearest access point along the cross route. For a given situation, the controlling design elements were identified, then assumed values for each element were summed to produce the desirable spacing. The paper identified 16 design elements that influence spacing; however, appropriate values for the elements were not provided in the paper. Three examples using their developed procedure were provided. One example of an exiting vehicle making a left turn at a downstream intersection frequently occurs on frontage roads in Texas and therefore could be used for comparison with other procedures. Figure 2-3 shows the equation and the assumed values for each element. In this example the distance used to weave would consist of the merging distance (183 meters), the distance traveled while seeking a gap (157 meters), and the



M_L	=	Merging distance
	=	3.6 m × 50:1 taper = 183 m
G	=	Distance traveled while seeking a gap in adjacent lane
	=	7 sec at frontage road design speed of 50 mph (80 km/h)
	=	7 sec × 80 km/h = 157 m
C	=	Distance traveled while changing lanes
	=	3 sec at frontage road design speed
	=	3 sec × 80 km/h = 67 m
D	=	Deceleration distance to stop condition
	=	122 m
S_2	=	Storage distance for left turn
	=	68 m (based on capacity analysis of left turn bay)
R_{AL}	=	Left turn radius
	=	15 m (assumed)

$$L = M_L + G + C + D + S_2 + R_{AL}$$
$$= 183 + 157 + 67 + 122 + 68 + 15$$
$$= 612 \text{ m}$$

Figure 2-3. Sample Calculation from the Gern and Joyner Procedure (2).

distance traveled while changing lanes (67 meters). The resulting weaving distance was 407 meters. The spacing distance was 612 meters which is significantly larger than the minimum distance listed in the AASHTO *Green Book* and other documents. Summing values for each individual element produces a relatively long distance because of the assumption that a driver is only accomplishing one task at a time.

Turner and Messer (17) developed an approach to determine the spacing needed between an exit ramp and a downstream signalized intersection to prevent blockage of the ramp merge area. The spacing consisted of three components: weaving, braking, and queuing distances. The weaving length was determined using the basic weaving model presented in the 1965 *HCM* (3). The weaving distances assumed by Turner and Messer were divided into three design levels—desirable, usual minimum, and absolute minimum. Table 2-1 presents the weaving distances assumed by Turner and Messer for three design levels.

Table 2-1. Weaving Distances for Different Design Levels (17).

Total Weaving Volume[a] (pcph)	Design Levels		
	Desirable (m)	Usual Minimum (m)	Absolute Minimum (m)
200	15	15	15
400	31	15	15
600	31	15	15
800	76	31	15
1000	107	61	15
1200	137	76	15
1400	168	92	15

[a] Total weaving volume is assumed to be 63 percent of total frontage road approach volume.

Braking was assumed to occur after the weaving movement had been completed. The stopping distance was assumed to be 84 meters for the desirable, 53 meters for usual minimum, and

23 meters for absolute minimum design levels. Field data, including exit ramp volume data collected at 30 ramps, queue counts, and spacing between ramps and interchanges were used to refine and test the developed model. The recommended distances between an exit ramp and a downstream intersection are shown in Table 2-2 and illustrated in Figure 2-4.

Table 2-2. Recommended Ramp-to-Intersection Spacings for Different Design Levels (17).

Total Frontage Road Volume[a] (veh/h)	Approximate Exit Ramp Volume[b] (veh/h)	Desirable (m)	Usual Minimum (m)	Absolute Minimum (m)
200	140	152	116	79
400	275	171	140	110
600	410	192	152	122
800	550	210	165	131
1000	690	232	180	137
1200	830	265	195	146
1400	960	296	210	152
1600	1100	326	235	162
1800	1240	358	262	168
2000	1380	396	296	177

[a] Exit ramp volume plus existing frontage road volume

[b] Exit ramp volume assumed to be 69 percent of total volume

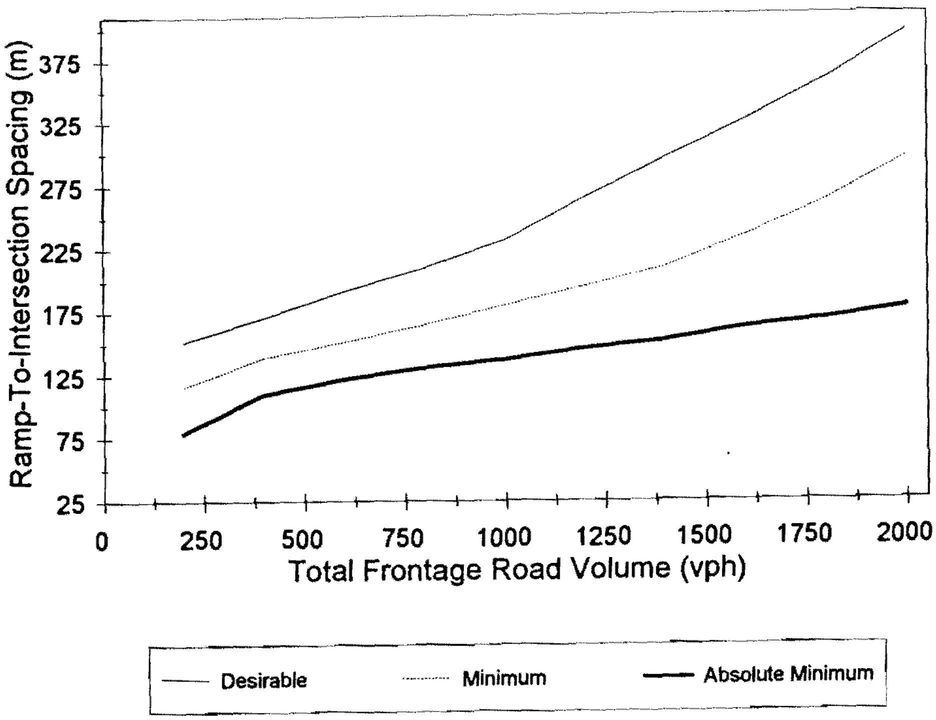


Figure 2-4. Recommended Ramp-to-Intersection Spacings (17).

CHAPTER 3
STUDY DESIGN

To investigate two-sided weaving operations on one-way frontage roads, both field data and computer simulation were used. The intent was to use the field data to calibrate a computer simulation model and use the results from computer simulation to develop a procedure for analyzing two-sided weaving operations on frontage roads. The field data were also used to estimate the distance that drivers use to make a two-sided weaving maneuver in the field. This information was combined with the results from computer simulation to develop recommendations for minimum and desirable ramp-to-intersection spacings. Following is a general overview of the methodology used in this study including information on how the field data were collected and reduced and a summary of the computer simulation process.

FIELD DATA

To observe and quantify actual weaving operations for two-sided weaving sections on frontage roads, data were collected at four field sites. The data collection efforts at these sites served dual roles: they provided information on the distance used by drivers to make a two-sided weaving maneuver from an exit ramp to a downstream intersection, and the data were used to calibrate a computer simulation model. The discussion presented in this section pertains to the efforts to determine two-sided weaving distance. The efforts associated with calibration are discussed in the following section, *Computer Simulation.*

Data Collection

Each field site consisted of a freeway exit ramp followed by a signalized intersection with minimal number of driveways between the ramp and intersection. A description of the study sites is given in Table 3-1. Spacing between the exit ramp gore and the downstream intersection at the sites ranged from 150 to 230 meters. Three of the field sites contained three weaving lanes (i.e., frontage road lanes which an exit ramp vehicle had to cross in making a weaving maneuver to the right-most lane) and one site contained two weaving lanes. Each site was video taped during the morning peak and afternoon peak periods.

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

Site	Location	Ramp-to-Intersection Spacing (m)	Average Volume (vph)		Time	Number of Weaving Lanes
			Exit Ramp	Frontage Road		
1	Houston, IH 610 EB@ T.C.Jester	230	750	750	4:00 pm-5:00 pm	3
2	Dallas, US 75 SB@ Fitzhugh	150	275	250	7:00 am-9:00 am	3
3	San Antonio, IH 410 EB@ Perrin Beitel	190	950	200	1:30 pm-3:30 pm	3
4	San Antonio, IH 410 EB@ Nacogdoches	205	1050	230	7:00 am-9:00 am	2

During the video taping of each site, 30 meter zones were marked on the roadway, beginning at the physical exit ramp gore (i.e., end of curb or grass median, not the painted gore) and proceeding toward the downstream intersection. These zones were used to determine the distance drivers used to weave from the exit ramp to the downstream intersection under various traffic conditions. The location of each zone was recorded on the video tape by having a technician wave an orange flag at the beginning of each zone. Figures 3-1 through 3-4 illustrate the zones used at each of the four sites.

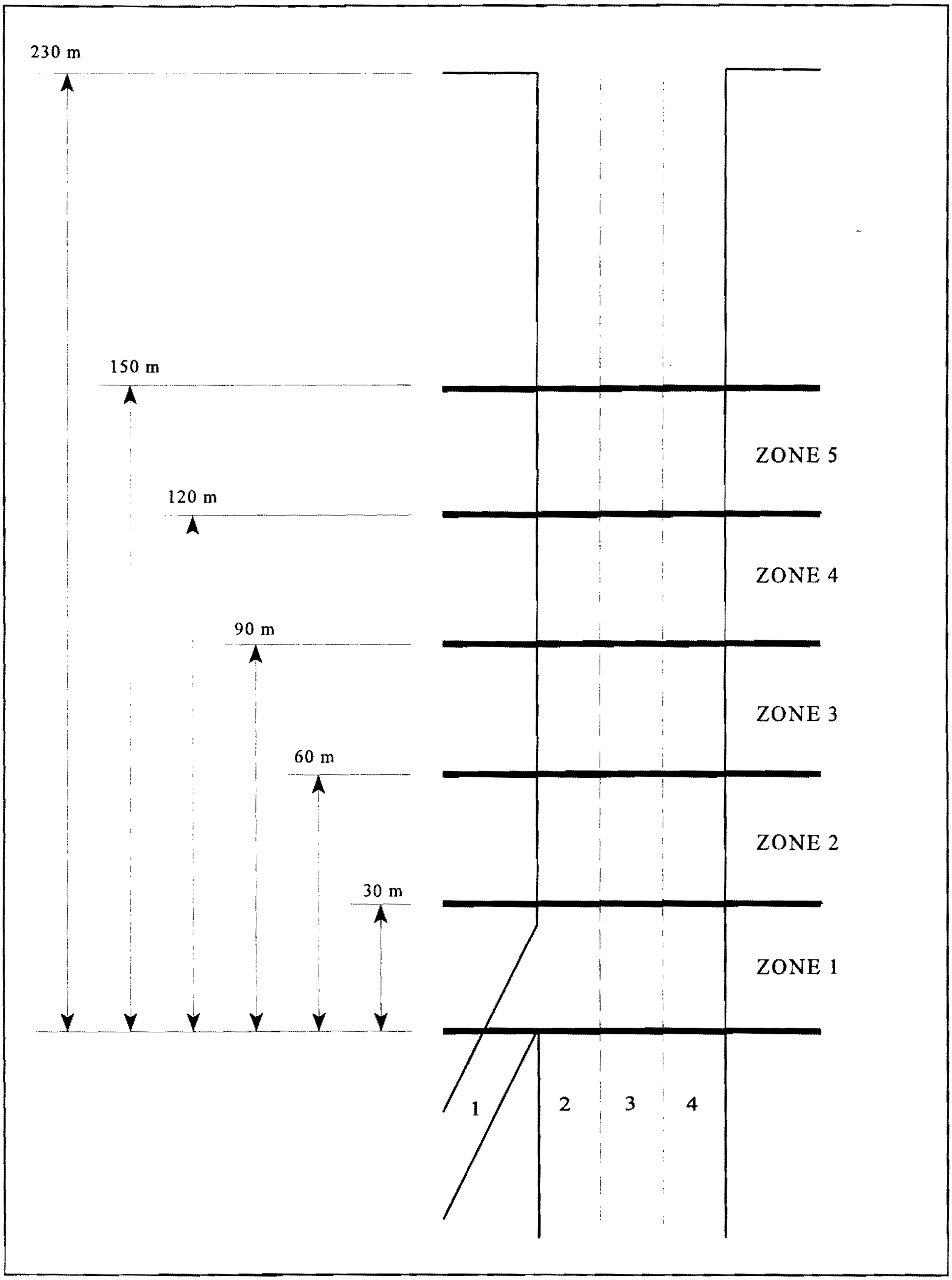


Figure 3-1. Zones Used at Site 1.

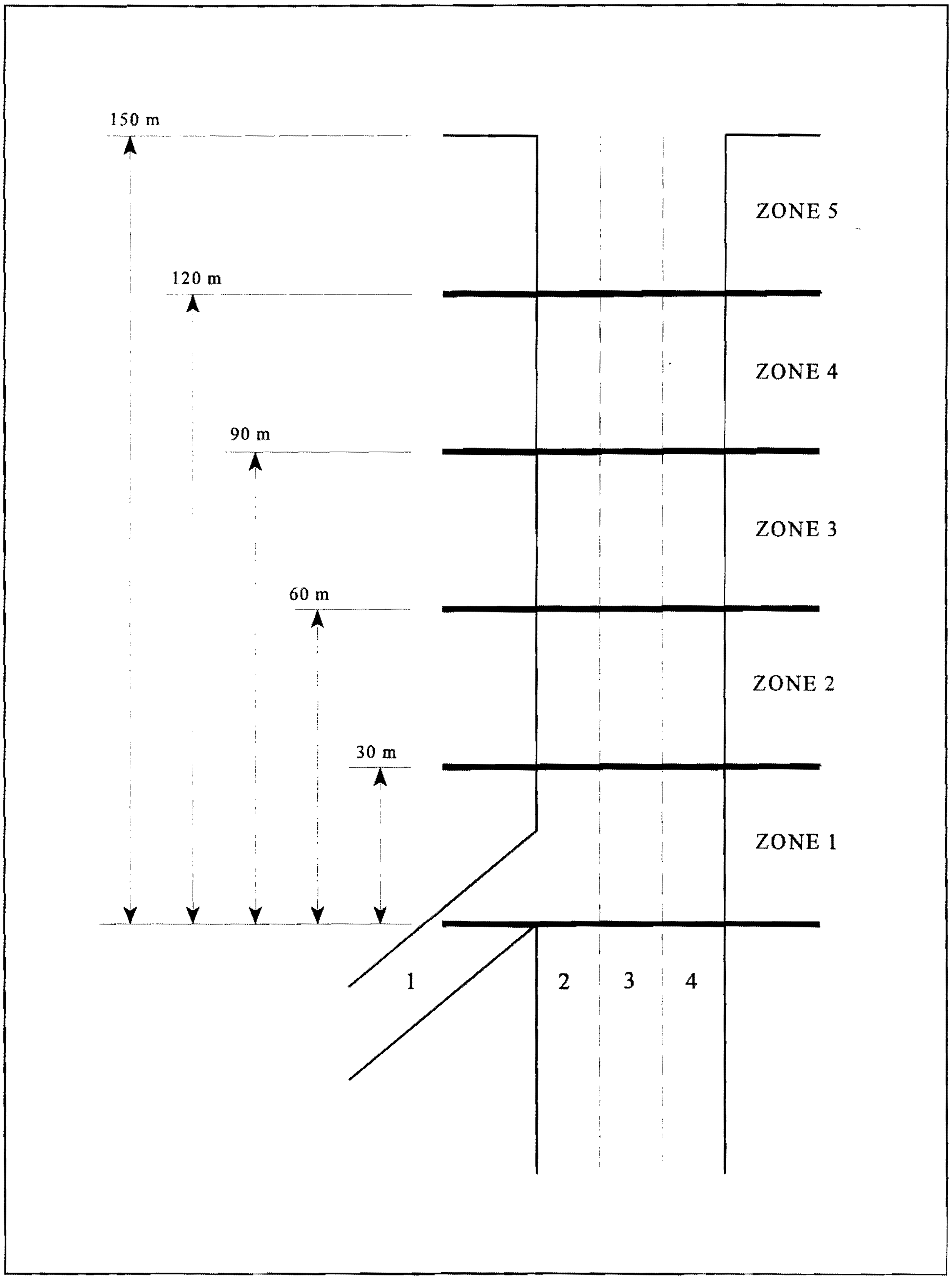


Figure 3-2. Zones Used at Site 2.

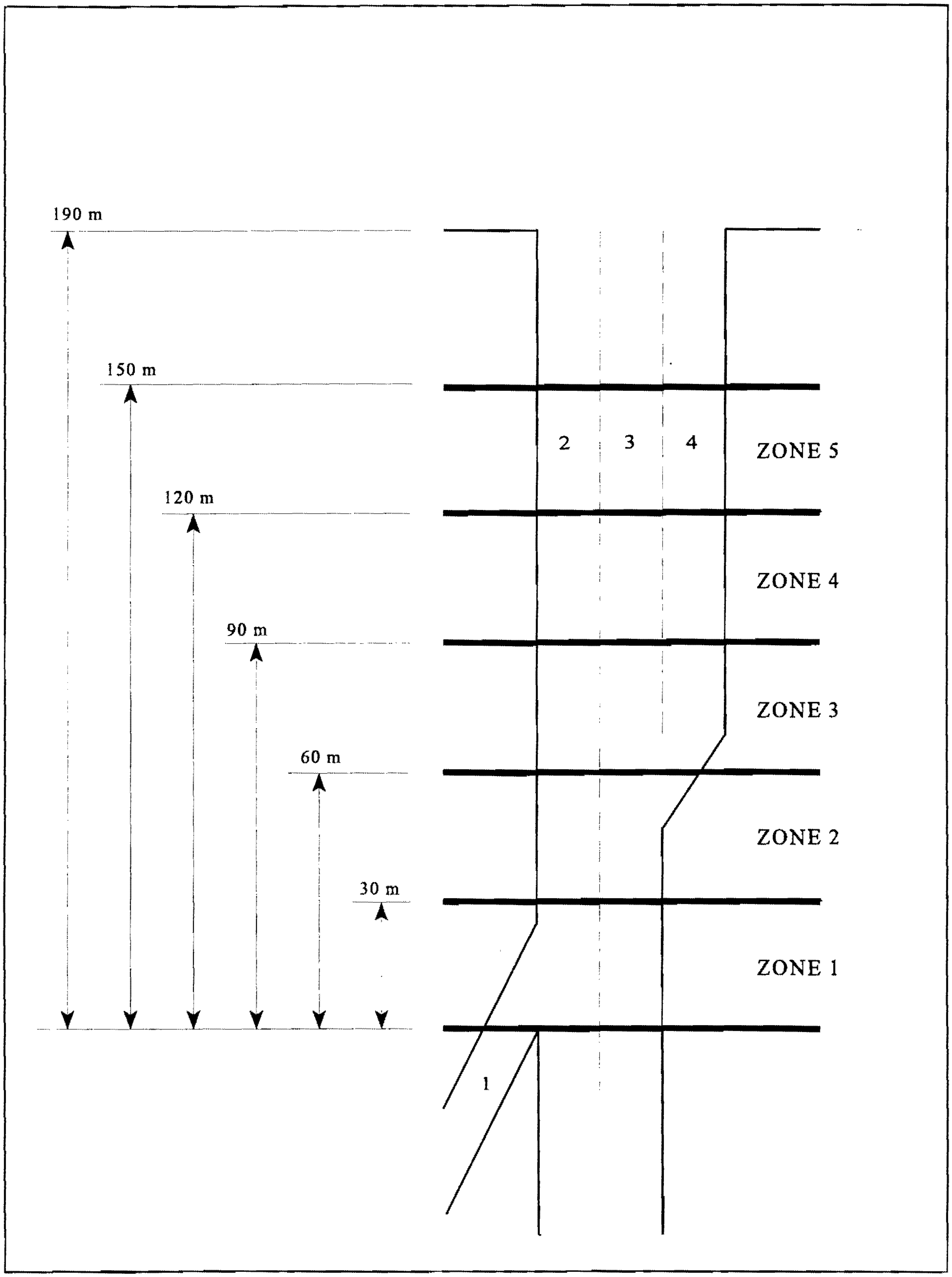


Figure 3-3. Zones Used at Site 3.

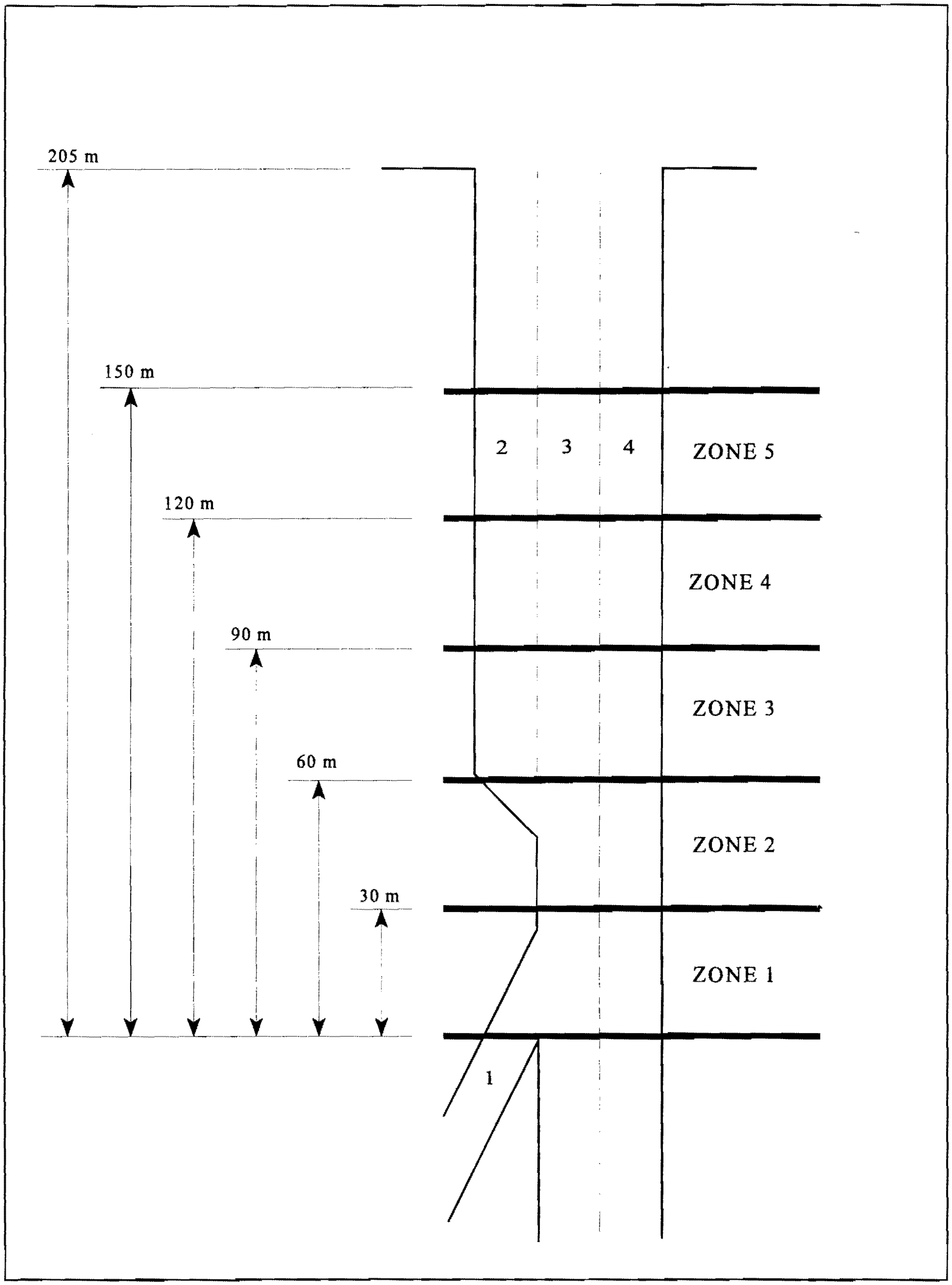


Figure 3-4. Zones Used at Site 4.

Data Reduction

Data reduction efforts began by locating the point on the video tape where the technician marked the zones with an orange flag. The locations of each zone were marked on a clear sheet of plastic that covered the video monitor. Additional reference points such as signs or driveways were also marked so that technicians would be able to determine if the camera was moved during the filming efforts. For each ramp vehicle which made a right turn at the downstream intersection, the time the vehicle arrived at the gore, the zone in which the vehicle made its last lane change, and a comment on the driver's action(s) during the weave were recorded. The categories used to describe the driver action(s) during the weave from the exit ramp to the right-most lane are listed in Table 3-2.

Table 3-2. Driver Actions During Two-Sided Weaving Maneuver.

Category	Driver Action
1	Moved directly from exit ramp to right-most lane with no difficulty.
2	Adjusted speed while on exit ramp.
3	Stopped for an adequate gap in frontage road traffic.
4	Adjusted speed for adequate gaps in interior lanes on frontage road.
5	Adjusted speed for an adequate gap in right-most lane on frontage road.

The *moved directly from exit ramp to right-most lane with no difficulty* category reflects the situation when the exit ramp drivers did not appear to modify their behavior as a result of any other vehicular influence. This category reflects a desirable weaving condition where drivers were able to choose the weaving distance that was comfortable to them. Categories 2 through 5 reflect conditions when the exit ramp driver's behavior was influenced by other vehicles. These drivers were having to slow, stop, or increase their speed to complete the desired weaving maneuver.

The data reduction efforts began with Site 1. Based on experience obtained from reducing the data from this site, data concerning the queue length at the intersection was collected for the remaining three sites. This was accomplished by recording the zone in which the queue at the intersection extended into during each weaving maneuver. One hour of data was reduced from Site 1, producing 156 data points. Two hours of data were reduced from each of the Sites 2, 3, and 4, producing 431, 366, and 418 data points, respectively.

Data Analysis

After reducing the data from the four field sites, the data were divided into two groups—exiting vehicles *unaffected* by the frontage road vehicles and exiting vehicles *affected*, i.e., vehicles that adjusted their speed in response to the presence of frontage road vehicles. The *unaffected* group contained those exiting vehicles with a driver action category of 1 while the *affected* group contained those exiting vehicle with driver action categories 2 through 5 (see Table 3-2). To determine the distance used by drivers to make a two-sided weaving maneuver, the data for each field site was plotted, showing the percent of drivers completing the maneuver within a given distance. The effects of queue length on weaving vehicles were also investigated by plotting queue length versus number of drivers which were unaffected and affected.

COMPUTER SIMULATION

In an attempt to select a simulation model which would closely represent field conditions, several computer simulation models were studied. These models 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 the latest version of NETSIM, Version 5.0, contained a significant new change. Until the NETSIM 5.0, 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 intersection. NETSIM's latest version allows lane changes between nodes, making simulated weaving sections much more realistic.

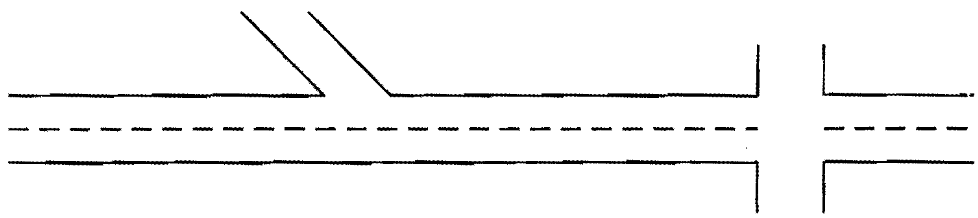
In addition, NETSIM allows users to code conditional turning movements. For example, the percent of exit ramp vehicles making left, through, and right movements at the downstream intersection can be specified. Other simulation models investigated only allowed users to code intersection turning percentages that were independent of the origin (i.e., exit ramp or frontage road). Using this feature of NETSIM, the researchers could vary the percentage of vehicles making a two-sided weaving maneuver and investigate the effects that this had on traffic operations. Because of these features, NETSIM was selected as the computer simulation model that would most closely simulate frontage road weaving areas.

Creating and Calibrating a Simulation Model

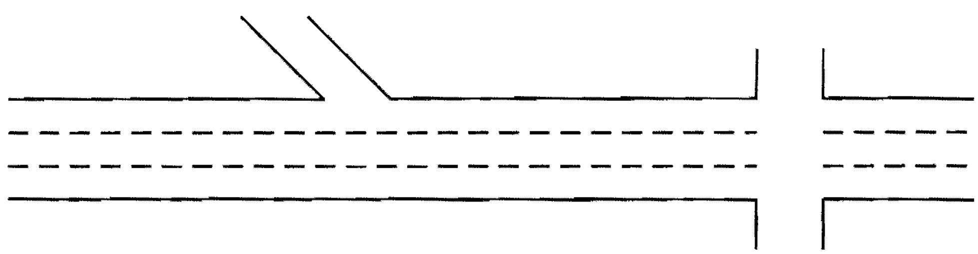
The geometry of the general model used for this project consisted of a frontage road section with a freeway exit ramp followed by an intersection. Three frontage road configurations were investigated: two-lane frontage road, three lane frontage road, and two-lane frontage road with an auxiliary lane connecting the exit ramp to the downstream intersection. Sections of roadway under investigation are coded into NETSIM using a link-node configuration. The general link-node diagram used in this study is shown in Figure 3-5 along with schematics of the three frontage road configurations simulated. Free flow speeds, link lengths, and number of lanes on each link are listed in Table 3-3.

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

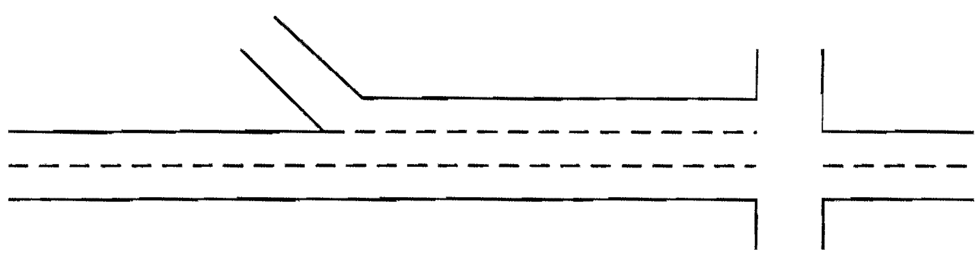
(a) General Link-Node Diagram



(b) Two-Lane Frontage Road (2LFR)



(c) Three-Lane Frontage Road (3LFR)



(d) Two-Lane Frontage Road with Auxiliary Lane (2LFR+Aux)

Figure 3-5. General Link-Node Diagram and Schematics of Simulated Sections.

Table 3-3. General Model Link Characteristics.

Link (node to node)	Free Flow Speed (km/h)	Weaving Length m	Number of Lanes
13 to 3	72	500	2-3
23 to 3	72	300	1
3 to 1	72	100-400	2-3
1 to 5	72	150	2
4 to 1	72	150	1
2 to 1	72	150	1

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.

The calibration process involved comparing travel times predicted by NETSIM to observations made in the field. The field site selected for calibration was Site 2 (see Table 3-1). This site was selected because the traffic signal at the intersection operated on fixed time (i.e., the cycle length and phasing remained constant over the study period). The traffic signals at Sites 1, 3, and 4 were all semi-actuated. Even though NETSIM can simulate traffic actuated controllers, detailed information about the signal timing and detectors is required, and this information was not obtained during the data collection process. Because the traffic signal timing has a large effect on the travel time, it was important to have the signal timings used in NETSIM very close to those observed in the field.

For calibration purposes, data at Site 2 were reduced in five-minute increments over a 30 minute period (7:00 a.m. to 7:30 a.m.). The data included the following: exit ramp volume, frontage road volume, intersection turning percentages for exit ramp volume, intersection turning percentages for frontage road volume, and travel times for both exit ramp and frontage road vehicles. The travel times were measured on the frontage road from the exit ramp gore to the intersection. In addition, the cross street volume (from left to right) was obtained to control permitted right-turn-on-red. The volume data observed at Site 2 are shown in Table 3-4.

Table 3-4. Volume Data Observed at Site 2.

Time	Exit Ramp		Frontage Road		Cross Street Volume, Left to Right (vph)
	Volume (vph)	Turning Percentage (L, T, R)	Volume (vph)	Turning Percentage (L, T, R)	
7:00-7:05 a.m.	252	30, 5, 65	120	30, 30, 40	864
7:05-7:10 a.m.	288	15, 4, 79	276	26, 35, 39	672
7:10-7:15 a.m.	276	21, 4, 75	144	17, 33, 50	552
7:15-7:20 a.m.	275	40, 5, 55	228	11, 47, 42	960
7:20-7:25 a.m.	264	25, 9, 66	276	17, 26, 57	912
7:25-7:30 a.m.	192	20, 20, 60	300	16, 28, 56	1008

To collect the data, technicians monitored the video tapes and recorded the following information for each vehicle: origin of vehicle (frontage road or exit ramp), time that vehicle entered system (passed exit ramp gore), destination of vehicle (left turn, through, or right turn), and time that vehicle left system (passed stop bar at intersection). The travel time was computed by subtracting the time that the vehicle entered the system from the time that the vehicle left the system.

After the field data were collected and reduced, a NETSIM model was developed to represent Site 2. This model consisted of a three-lane frontage road section with a exit ramp-to-intersection spacing of 150 meters. The free-flow speed was set at 72 km/h for all links.

To represent actual field conditions, NETSIM was coded so that vehicles on the frontage road yielded to vehicles on the exit ramp. In an attempt to give priority to the exit ramp vehicles, the frontage vehicles were given a yield control at the exit ramp merge point and the exit ramp vehicles were given no control. However, after further investigation, it was discovered that the frontage road vehicles still had priority over the exit ramp vehicles. Inspection of the model and the results revealed that the type of movement (i.e., left, through, and right) at the merge point of the exit ramp and frontage road had a greater influence on the yielding behavior seen at the junction than the traffic control code (i.e., yield versus no control). Initially, the vehicles on the frontage road link prior to the weaving section (link 13-3) were given a through movement at Node 3 (see Figure 3-5). Vehicles on the exit ramp (link 23-3) were given a left-turn movement at Node 3. Node 3 was coded so that vehicles on link 13-3 should yield to vehicles on link 23-3. 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.

In an attempt to correct this problem, exit ramp vehicles and frontage road vehicles were assigned different movements at Node 3. To give exit ramp vehicles priority, the vehicles on link 23-3 were given a through movement at Node 3, and vehicles on link 13-3 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.

After an appropriate model for Site 2 was developed, the five-minute volumes and turning percentages observed in the field were coded into NETSIM along with the traffic signal timing. For each five-minute increment, a separate NETSIM run was made for a total of six runs. Each run was simulated for one hour. To begin simulation, all of NETSIM's default values were used.

The next step was to compare the travel times predicted by NETSIM to those observed in the field. Since the travel times in the field were measured from the exit ramp to the intersection, the travel times from NETSIM were obtained for link 3-1 (see Figure 3-5). The results are shown in Table 3-5. A two-sided t-test was performed on the field data and NETSIM data to determine if there was a significant difference in the average travel times. At a 95 percent confidence level, the test revealed that the average travel times were statistically equal. Based on these results, it was concluded the NETSIM model provided a good representation of the field data.

Table 3-5. Comparison of Travel Times from Field and NETSIM.

Time Period	Total Volume (vph)	Travel Time (sec)	
		Field	NETSIM
7:00 - 7:05 a.m.	370	34.9	32.9
7:05 - 7:10 a.m.	565	35.8	31.3
7:10 - 7:15 a.m.	420	27.9	31.4
7:15 - 7:20 a.m.	505	38.7	42.5
7:20 - 7:25 a.m.	540	40.3	39.0
7:25 - 7:30 a.m.	490	35.0	37.1
Average Travel Time:		**35.4**	**35.7**

Performing the Simulation

Before performing the simulation, the variables that would be modified along with the size of the increment for each variable had to be selected. The variables that were modified included the following: ramp-to-intersection spacing, number of lanes, frontage road volume, and exit ramp volume. In addition, the intersection turning percentages for the exit ramp vehicles were varied. The percent of exit ramp vehicles making a right turn (i.e., a two-sided weaving maneuver) ranged from 25 to 75 percent. The intersection turning movements for the frontage road vehicles were held constant. Table 3-6 shows the values and increments used for each variable. The ranges for the variables were selected based on observation of the field data and engineering judgement. Optimum signal timings were computed using the signal optimization program PASSER II.

Performing the NETSIM runs for each combination of variables shown in Table 3-6 resulted in a total of 360 runs. Each of these runs were made for the three frontage road configurations studied (see Figure 3-5) resulting in a total of 1080 NETSIM runs.

Table 3-6. Variables Used in Simulation.

Variable	Values
Ramp-to-Intersection Spacing	100, 200, 300, 400 m
Number of Weaving Lanes	2, 3
Frontage Road Volume	500, 1000, 1500, 2000 vph
Exit Ramp Volume	250, 500, 750, 1000, 1250 vph
Frontage Road Turning Percentages (L, T, R)	35, 30, 35 %
Exit Ramp Turning Percentges (L, T, R)	60, 15, 25 % 35, 15, 50 % 22, 15, 63 % 19, 15, 75 %

After each run, specific output generated by NETSIM were reduced. This output included speed on the frontage road from the exit ramp to the intersection, speed on the frontage road prior to the exit ramp, and speed on the exit ramp.

Data Analysis

Measures of Effectiveness

The objective of the analysis was to determine how specific variables (i.e., frontage road configuration, frontage road volume, exit ramp volume, percent of exit ramp vehicles making a two-sided weaving maneuver, and exit ramp-to-intersection spacing) affected the operations on two-sided weaving sections. The researchers investigated speed and density as potential measures of effectiveness for evaluating the operations on this type of section. The speed investigated was average travel speed. Computation of average travel speed includes the time that the vehicles are in motion and the time that they are stopped. The average travel speed was computed by NETSIM using the following formula: *speed = total vehicle kilometers of travel / total vehicle hours of travel.*

Density is a measure of the proximity of vehicles. It is an important measure of the quality of traffic flow because it is directly related to traffic demand. Density affects the freedom to maneuver and psychological comfort of drivers (18). For this analysis, density was computed by dividing the average flow (vehicles per hour) by the average travel speed.

Statistical Analysis

Statistical analyses were performed on the data to determine which factors had significant effects on traffic operations (i.e., speed and density). This was accomplished by first entering the data into a database and then using the statistical analysis package SAS to perform stepwise regression.

Linear regression models can be used to express a dependent variable as a function of a single independent variable. Linear regression models are expressed as $y = b + m(x)$, where y = dependent variable, x = independent variable, b = y-intercept, and m = slope. Multiple regression models are used to express a dependent variable as a function of two or more independent variables and are expressed as $y = b + m_1(x_1) + m_2(x_2) + \ldots$ Stepwise regression is a procedure that can be used to select the best multiple regression model (19). In other words, stepwise regression helps to identify those independent variables ($x_1, x_2, \ldots$) that have the greatest affect on the dependent variable (y).

Stepwise regression works by starting with one independent variable and adding variables one at a time until a certain criteria is met (19). The criteria used in this analysis was the coefficient of determination, R^2. The coefficient of determination is the portion of variability in the dependent variable that is explained by the independent variables. For each step in the stepwise regression procedure, the R^2 value is computed. The procedure is continued until there is no longer a significant increase in R^2, and the resulting model is assumed to be the best-fitting regression equation. Stepwise regression was performed on the three configurations studied to develop equations to predict speed and density for a given configuration and for given traffic volumes, two-sided weaving maneuvers, and ramp-to-intersection spacing.

Validation of Regression Equations

The purpose of the validation process was to determine whether the developed regression equations could be applied to existing field conditions. The testing procedure involved comparing output from the developed equations with measurements taken in the field. This was accomplished by first reducing data (i.e., traffic volumes, turning movements, travel times, etc.) from video tapes of an existing field site. Next, the developed equations were used to predict certain MOEs for the given field conditions. Finally, the predictions from the equations were compared to the operations measured in the field.

DEVELOP TWO-SIDED WEAVING PROCEDURE

To define the level of operations on a two-sided weaving section, the study results were used to investigate the relationships between various factors influencing traffic operations, and to develop equations to predict certain MOEs (i.e., speed and/or density) under various conditions. The goal was to select an MOE which could be used for measuring the level of service on a two-sided weaving section and to define boundaries to distinguish between different levels of service. After the level of service was defined, the final task was to develop a step-by-step procedure for determining the level of service on two-sided weaving sections.

To develop recommended exit ramp-to-intersection spacings, results from the field data and from computer simulation were used. The results from the field data were used in conjunction with findings from previous research studies to define an absolute minimum ramp-to-intersection spacing. Results from the regression analysis of the computer simulation data were then used to define minimum and desirable spacings for various traffic volumes and frontage road configurations.

CHAPTER 4
RESULTS

Results from field studies and from computer simulation (NETSIM) were used to develop a procedure for estimating the level of service on two-sided weaving sections along one-way frontage roads, and to develop recommended exit ramp-to-intersection spacings. Results from the field studies were used to estimate the distance drivers need to make a two-sided weaving maneuver. Field data were then used to develop and calibrate the NETSIM model for different frontage road configurations. The computer simulation model was used to study traffic operations on two-sided weaving sections under various conditions. By studying the output predicted by NETSIM, a procedure could be developed for estimating the level of service within a weaving area and to determine spacing needs. Following is a discussion on the results from the field study and from computer simulation.

FIELD DATA

Traffic operations at four existing frontage road sites (see Table 3-1) were observed to determine the distance that drivers used to make a two-sided weaving maneuver from an exit ramp to a downstream intersection. The data collection effort involved video taping operations at each site either during the morning or afternoon peak period. During the video taping of each site, 30 meter zones were marked on the roadway, beginning at the physical exit ramp gore and proceeding toward the downstream intersection. These zones were used to determine the distance drivers used to weave from the exit ramp to the downstream intersection under various traffic conditions.

While reducing the data from the video tapes, technicians recorded the zone in which each ramp vehicle making a two-sided weaving maneuver completed the last lane change. For each vehicle making a two-sided weaving maneuver, the driver's action(s) during the weave were recorded. The five categories used to describe the driver action(s) are listed below:

1. Moved directly from exit ramp to right-most lane with no difficulty.
2. Adjusted speed while on exit ramp.
3. Stopped for an adequate gap in frontage road traffic.
4. Adjusted speed for adequate gaps in interior lanes on frontage road.
5. Adjusted speed for an adequate gap in right-most lane on frontage road.

The data for the sites were divided into two groups—exiting vehicles *unaffected* by the frontage road vehicles and exiting vehicles *affected*, i.e., vehicles that adjusted their speed in response to the presence of frontage road vehicles. The *unaffected* group included those exiting vehicles with a driver action code of 1 while the *affected* group included those exiting vehicle with driver action codes 2 through 5. Because the zones were divided into 30 meter increments, weaving distances could only be estimated to the nearest 30 meters.

Distance to Weave

Figures 4-1 through 4-4 show the results for each of the four sites. Observing these figures, it is noted that for all four sites, the majority of weaving vehicles completed their maneuvers in either Zone 3 or Zone 4 (60 meters to 120 meters from exit ramp). For each site, the percent of unaffected weaving vehicles that completed the maneuver in Zones 3 or 4 ranged from 82 percent at Site 4 to 94 percent at Site 2. For affected vehicles, the percentages ranged from 67 percent at Site 4 to 90 percent at Site 3.

Although the majority of drivers at the observed sites had completed the weaving maneuver by Zone 4, Figures 4-1 and 4-4 indicate that a significant portion (at least 25 percent) of the affected drivers did not complete the maneuver until Zone 5. Observing the video tapes for these two sites, it was determined that most vehicles completing their maneuver in Zone 5 did so when the frontage road volumes were relatively higher. The increase in traffic on the frontage road created more conflicts between through frontage road vehicles and weaving exit ramp vehicles. Because of the increase in conflicts, the exit ramp vehicles required a longer distance to weave.

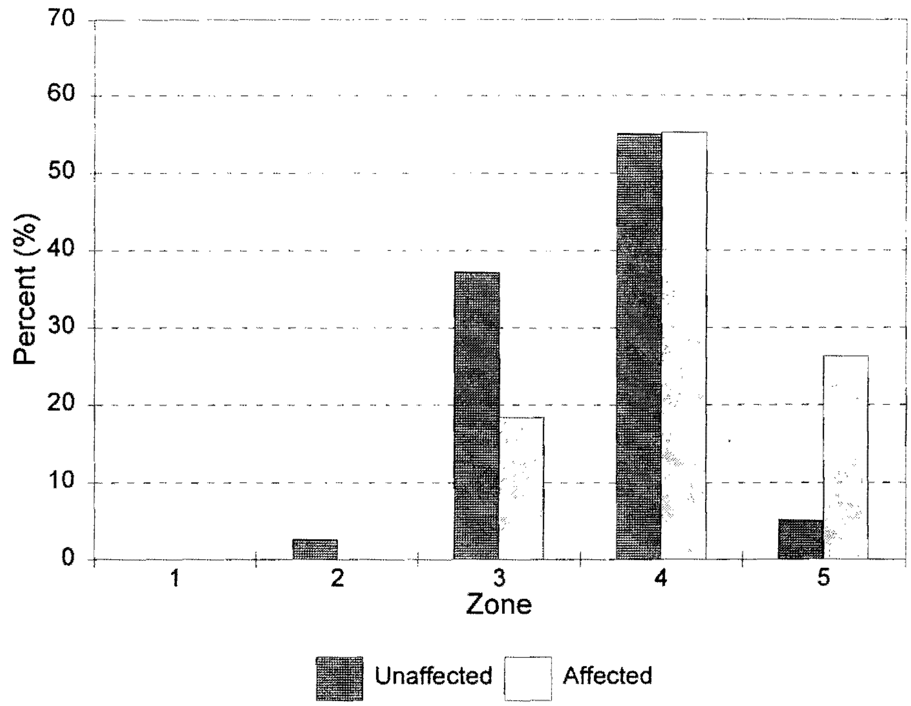


Figure 4-1. Zonal Distribution of Weaving Vehicles at Site 1.

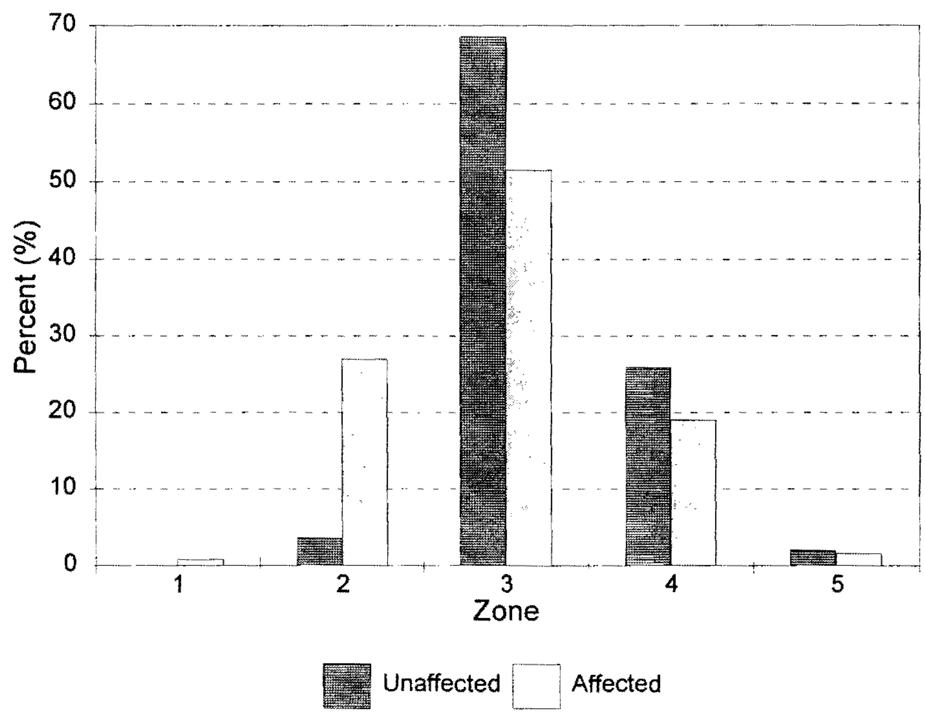


Figure 4-2. Zonal Distribution of Weaving Vehicles at Site 2.

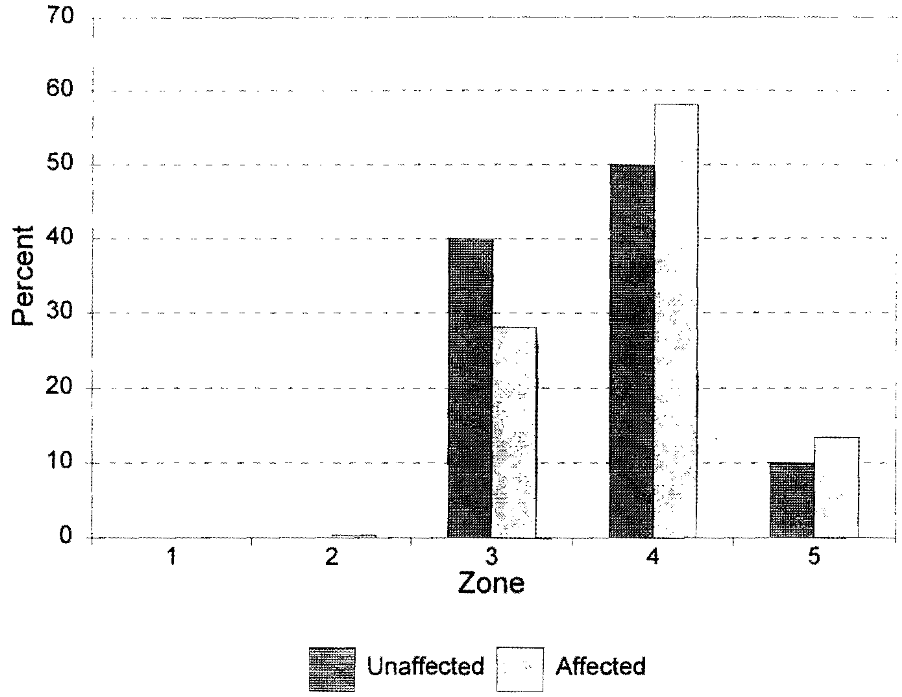


Figure 4-3. Zonal Distribution of Weaving Vehicles at Site 3.

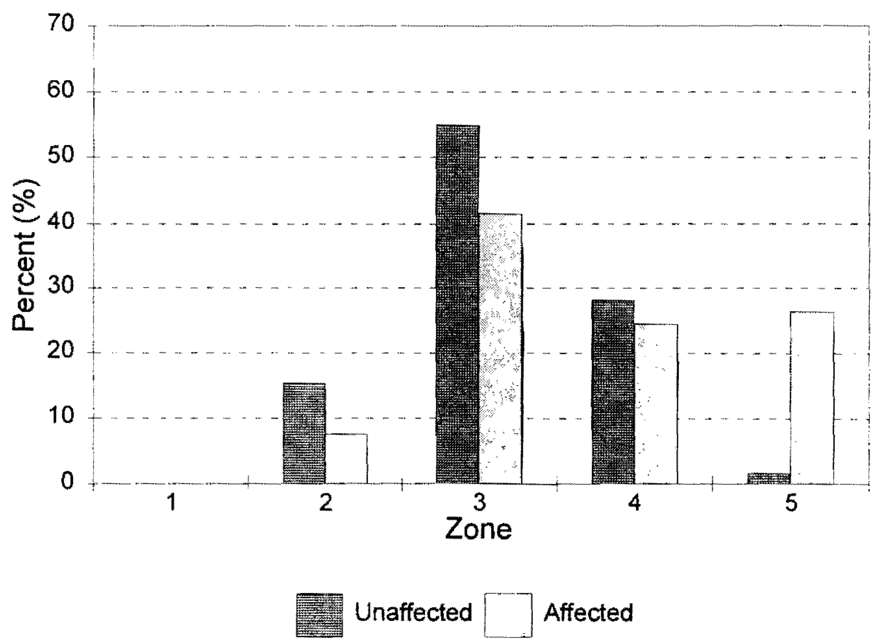


Figure 4-4. Zonal Distribution of Weaving Vehicles at Site 4.

Figures 4-1 through 4-4 also indicate that most drivers at Sites 2 and 4 used shorter weaving distances than drivers at Sites 1 and 3. At Sites 2 and 4, greater percentages of drivers completed the weaving maneuver in Zone 3, while the majority of drivers at Sites 1 and 3 completed the weaving maneuver in Zone 4.

The primary reason for the shorter weaving distances at Site 2 is most likely due to the geometric configuration of the exit ramp. The angle of approach for the exit ramp at this site is greater than that for the other three sites; therefore, the exiting vehicles at Site 2 approach the frontage road at a greater angle. Approaching the frontage road at a greater angle can result in a shorter weaving distance because of the natural path of the exiting vehicle.

At Site 4, the shorter weaving distances can be attributed to the number of weaving lanes that the exit ramp vehicles were required to cross to reach the right-most lane—Site 4 had two weaving lanes on the frontage road while the other sites had three weaving lanes. Due to the smaller number of weaving lanes, the exit ramp vehicles at Site 4 required less distance to weave to the right-most lane.

Effects of Queue Lengths

Other factors that could have affected the weaving distances include the queue length at the downstream intersection, the available spacing between the exit ramp and the downstream intersection, and the frontage road traffic volumes. Although queue length was seldom a problem, there were some instances in which queues extended into the zones used by the exiting vehicles weaving to the right-most lane. When this occurred, exiting drivers wanting to change lanes either slowed or stopped to wait for an adequate gap before making the lane changes.

To study the effects that queue length had on weaving vehicles, the zone into which the queue extended was recorded during each weaving maneuver. This procedure was carried out for Sites 2, 3, and 4, and the results are shown in Figures 4-5, 4-6, and 4-7, respectively. These figures illustrate the number of affected vehicles and the number of unaffected vehicles present when queues

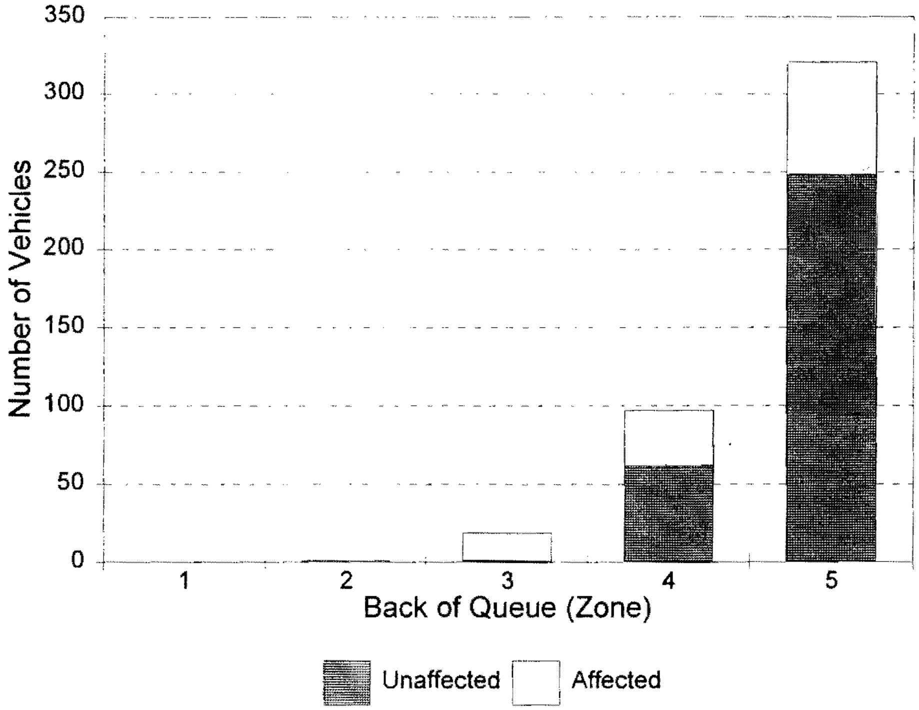


Figure 4-5. Effects of Queue at Site 2.

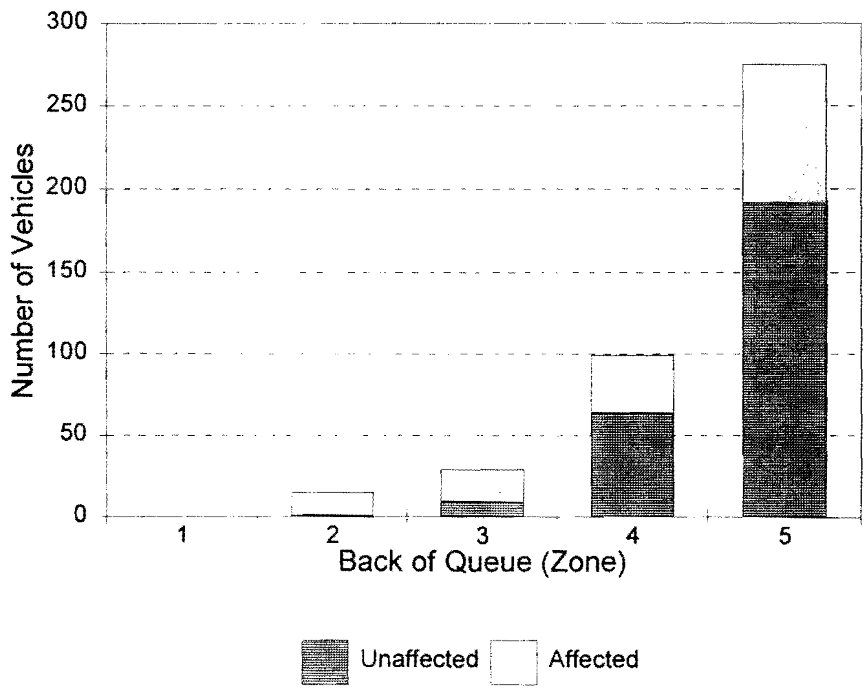


Figure 4-6. Effects of Queue at Site 3.

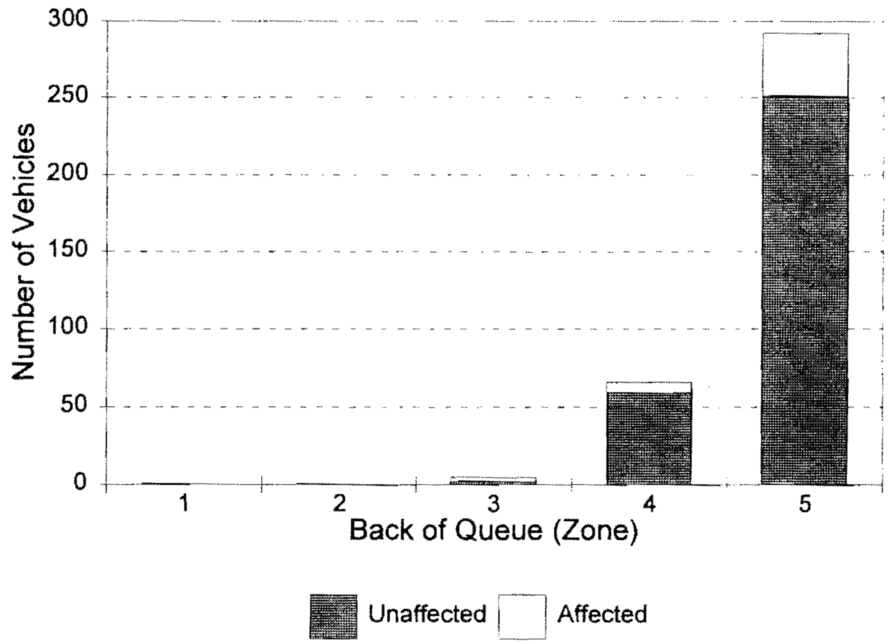


Figure 4-7. Effects of Queue at Site 4.

extended into a particular zone. As shown in these figures, when the queues were in Zones 5 or 4, the majority of the vehicles were unaffected; however, when the queues reached Zones 3 or 2, the majority of the vehicles were affected. Therefore, these results reveal that the queue at the intersection begins to have a significant effect on weaving vehicles when the queue length is within approximately 90 meters of the exit ramp.

Actions of Exiting Drivers

Table 4-1 summarizes the actions of the exiting drivers for the four sites. The majority of drivers at each site had no difficulty in weaving directly from the exit ramp to the right-most lane. Also, very few drivers actually stopped to wait for an adequate gap in the traffic stream before weaving. These results were probably due to traffic volumes which were too low to cause significant interaction between the exiting vehicles and the frontage road vehicles. At Site 1, a relatively higher percentage of drivers adjusted their speeds for an adequate gap in the interior lanes on the frontage

Table 4-1. Actions Taken While Weaving.

Action	Percent (Number) Drivers Taking Action*			
	Site 1	Site 2	Site 3	Site 4
Exiting vehicles *unaffected* by the frontage road vehicles				
Moved directly from exit to right-most lane with no difficulty	74 (119)	69 (311)	73 (266)	86 (313)
Exiting vehicles *affected* by the frontage road vehicles				
Adjusted speed for an adequate gap in right-most lane on frontage road	8 (12)	20 (92)	3 (10)	8 (31)
Adjusted speed for adequate gaps in interior lanes on frontage road	14 (23)	4 (21)	2 (6)	3 (10)
Adjusted speed while on exit ramp	4 (6)	4 (16)	37 (136)	2 (9)
Stopped for an adequate gap in frontage road traffic	0 (0)	3 (12)	0 (0)	1 (3)
TOTAL	100 (160)	100 (452)	100 (418)	100 (366)

* Number of actions do not sum to number of exiting vehicles because more than one action comment can be assigned to a driver.

road, and at Site 3, a relatively higher percentage of drivers adjusted speed while on the exit ramp. These actions were primarily due to a higher demand for left-turns at the downstream intersection. At Site 2, due to a higher demand for right-turns at the downstream intersection, a relatively higher percentage of drivers adjusted their speed for an adequate gap in the right-most lane.

COMPARISON OF FIELD STUDY FINDINGS WITH LITERATURE FINDINGS

There have been few previous studies which have evaluated the spacing needs between ramps and intersections on frontage roads. The most noteworthy study was conducted by Turner and Messer (16) in 1978. A summary of this study is presented in *Chapter 2*.

Comparisons of the findings from the field studies with results produced by the methods developed by Turner and Messer need to be made with caution. For example, Turner and Messer's method developed a recommended spacing based upon desirable conditions. While the findings from a field study may indicate that less distance is used, other issues, such as whether providing less distance will result in an unsafe condition or what effects reasonable traffic growth may have on the operations, need to be examined.

In the Turner and Messer procedure, distances are determined based on design levels (which are a surrogate for quality of flow) and weaving volume. For the usual minimum design level, the weaving length determined is between 15 meters and 92 meters depending upon the approach volume. From the field study, the majority of drivers observed used between 60 meters and 120 meters to complete the weaving maneuver, with some drivers using up to 150 meters. Therefore, a portion of the actual weaving distances observed in the field were longer than those recommended by Turner and Messer.

In unrestricted conditions, drivers are using more distance to weave than the values assumed for the usual minimum design level. Because some of the weaving vehicles observed at the field sites were decelerating during the weaving maneuver, the 60 meters to 150 meters weaving distance observed in the field includes some consideration of deceleration. When the stopping distance is included in the Turner and Messer procedure, "weaving" distances of 69 to 145 meters result. These distances are comparable to the field findings.

COMPUTER SIMULATION

For the analysis involving computer simulation, the following three frontage road configurations were investigated (see Figure 3-5): two-lane frontage road (2LFR); three-lane frontage road (3LFR); two-lane frontage road with an auxiliary lane extending from the exit ramp to the downstream intersection (3LFR+Aux). The calibrated NETSIM model for the three different frontage road configurations was run using various combinations of traffic volumes, turning percentages, and ramp-to-intersection spacings (see Table 3-5). After each run, average speeds were recorded for the frontage road section between the exit ramp gore and the downstream intersection. Average speeds were also recorded for the exit ramp and frontage road link prior to the exit ramp gore. Several graphs were plotted to study the relationships between the various findings.

The MOEs investigated for use in determining the level of service on two-sided weaving sections included average travel speed and density. The average speeds were obtained from the NETSIM output. Density was computed by dividing the average flow (vehicles per hour) by the average travel speed. Following are the results of the efforts to investigate speed and density as measures for evaluating two-sided weaving operations.

Speed

Several plots were generated to investigate the relationships between speed and other factors for the three frontage road configurations studied. The first speeds investigated were those on the weaving link (i.e., the frontage road section between the exit ramp gore and the downstream intersection). Figures 4-8 through 4-10 illustrate the relationship between speed on the weaving link and total volume (exit ramp volume + frontage road volume) for the three frontage road configurations studied. The data in each plot is separated only by ramp-to-intersection spacing.

Observing Figures 4-8 through 4-10, the relationships between speed and total volume are similar for all three configurations. Speed on the weaving link decreases as volume increases, with a significant decrease in speed at a volume of 1500 vph. For 2LFR and 3LFR, there is a high

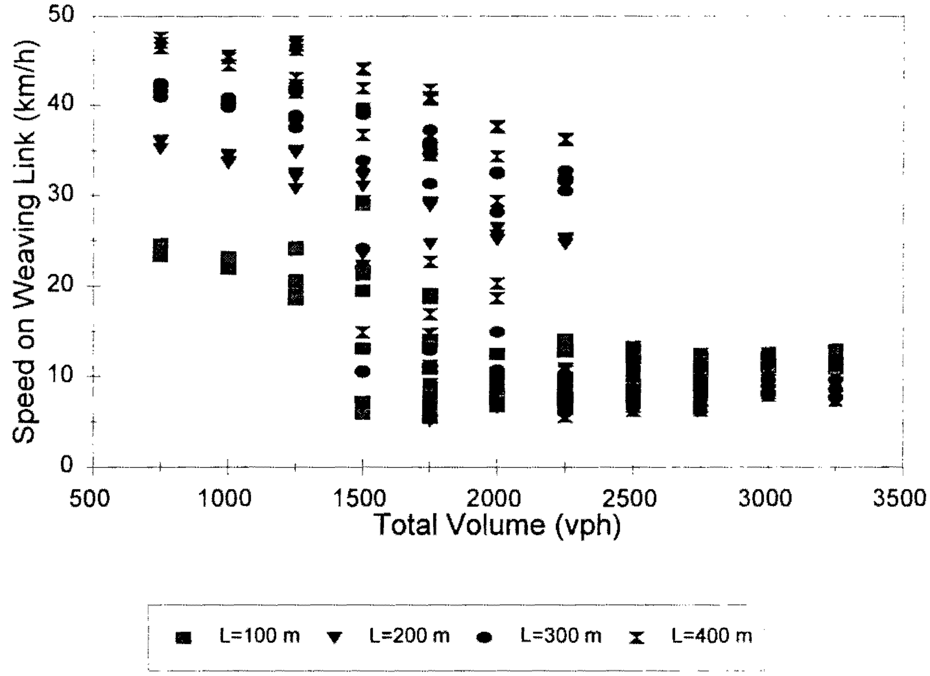


Figure 4-8. Weaving Speed and Total Volume Relationship for 2LFR.

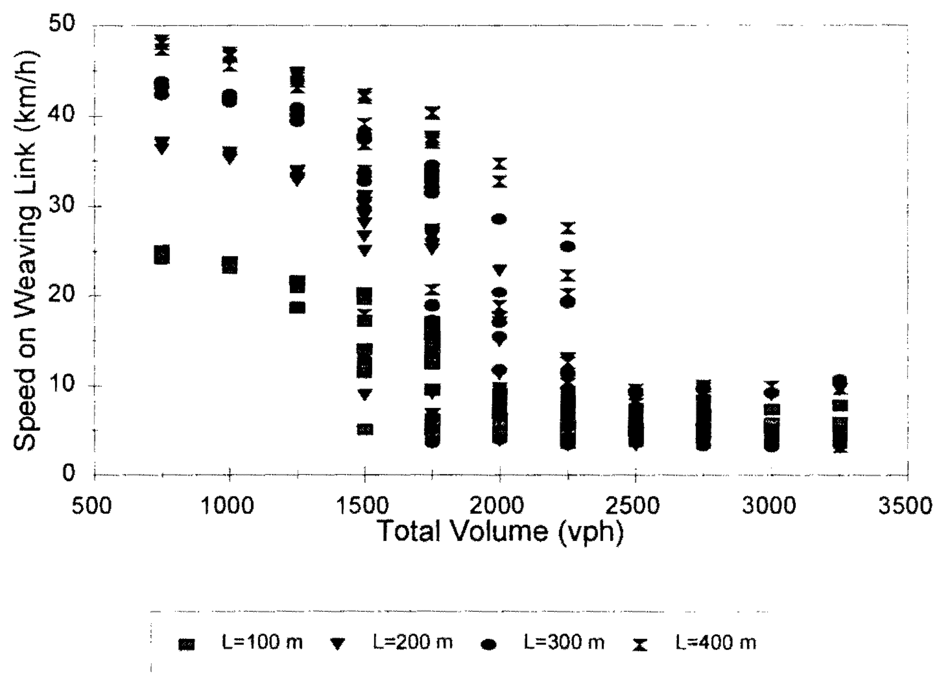


Figure 4-9. Weaving Speed and Total Volume Relationship for 3LFR.

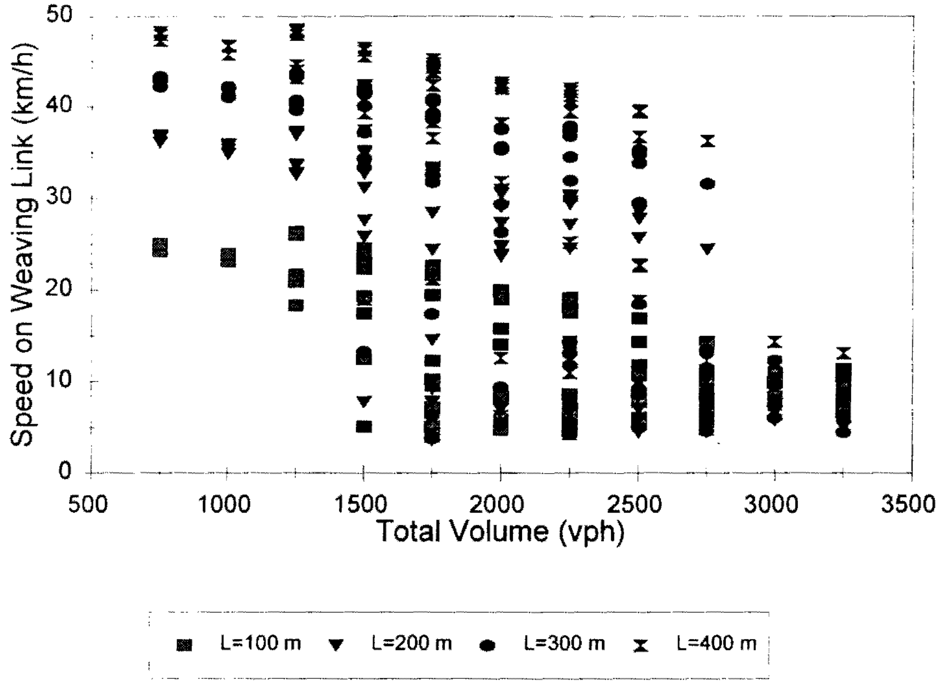


Figure 4-10. Weaving Speed and Total Volume Relationship for 2LFR+Aux.

variation in speed between 1500 vph and 2250 vph. A similar variation in speed exists for 2LFR+Aux between 1500 vph and 2750 vph. This high variation reveals that speed is being influenced by other factors besides total volume. These other factors might include the ratio between frontage road volume and ramp volume and/or the percent of ramp vehicles making a two-sided weaving maneuver.

For 2LFR and 3LFR, the speeds reach the minimum level at volumes above 2250 vph and remain relatively constant. For 2LFR+Aux, the speeds do no reach minimum until 2750 vph. This reveals that 2LFR+Aux operates at a better level of service at high volumes than do 2LFR or 3LFR. This is primarily due to the auxiliary lane included with 2LFR+Aux. The auxiliary lane removes the direct merge point between exit ramp vehicles and frontage road vehicles, allowing the ramp vehicles and frontage road vehicles to merge more smoothly.

Figures 4-8 through 4-10 also illustrate that ramp-to-intersection spacing influences the maximum speed (i.e., speed at the lowest volume). This was expected because the speeds investigated were average travel speeds, which included the time that the vehicles were in motion and the time that the vehicles were stopped at the intersection. Therefore, speeds on shorter links would include a relatively higher percentage of vehicles that are queued at the intersection when compared to links with longer ramp-to-intersection spacings. This results in lower average travel speeds for the ramp-to-intersection links with shorter lengths.

Additional plots were generated to investigate other speeds and other factors influencing speed. Because the relationships investigated were similar for all three frontage road configurations, only the plots for 3LFR will be shown.

Figure 4-11 illustrates the relationship between the speed on the frontage road prior to the exit ramp and total volume. The relationship between exit ramp speed and total volume is shown in Figure 4-12. Observing these two figures, the speeds are relatively constant and independent of ramp-to-intersection spacing below volumes of 1500 vph. At approximately 1750 vph, the speeds on both the frontage road and the ramp break down and become highly variable. Comparing these relationships to the relationship shown in Figure 4-9 (for speed on the weaving link) reveals that operations on the weaving link begin to break down at lower volumes (i.e., 1500 vph) than operations on either the exit ramp or frontage road link prior to the exit ramp. Therefore, since traffic operations on the weaving link begin to break down first, the researchers decided to base the criteria for evaluating two-sided weaving operations only on the traffic operations on the weaving link.

To investigate other factors influencing speed on the weaving link, Figure 4-13 was generated. This figure illustrates the relationship between speed on the weaving link (shown on the y-axis), ramp volume (shown on the x-axis), and frontage road volume (shown as different symbols) for a ramp-to-intersection spacing of 200 m. For each ramp volume level, there are four data points representing frontage road volume. These four points represent the four percentages (i.e., 25%, 50%,

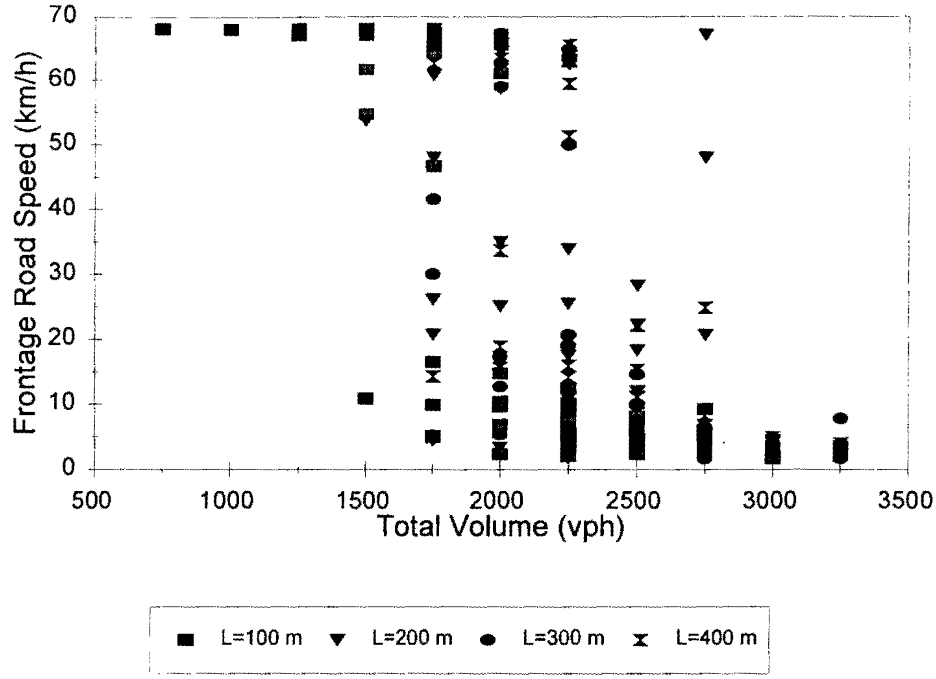


Figure 4-11. Frontage Road Speed Prior to Weaving Link and Total Volume Relationship for 3LFR.

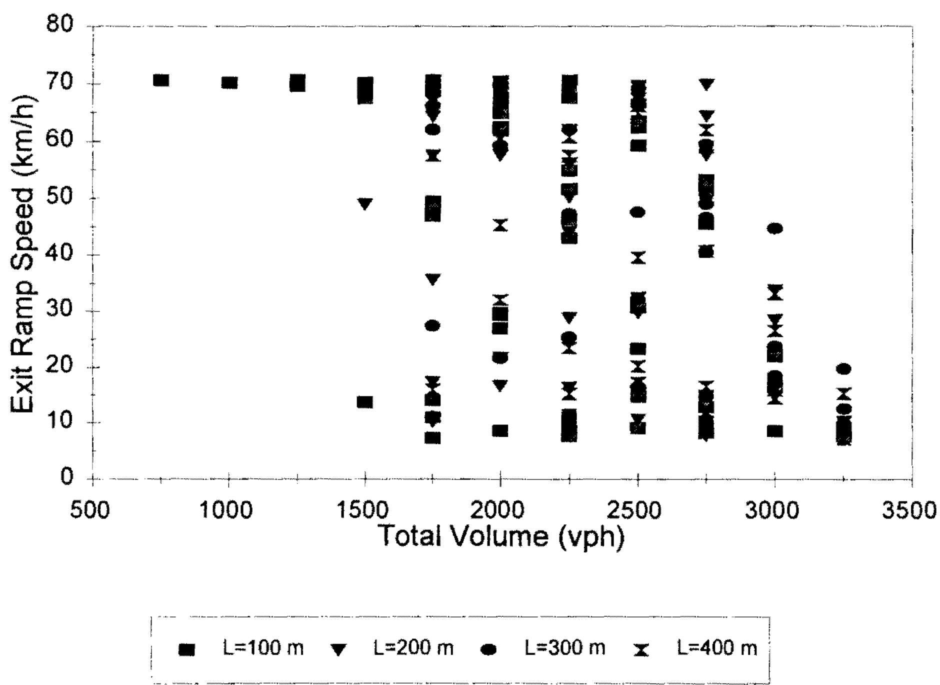
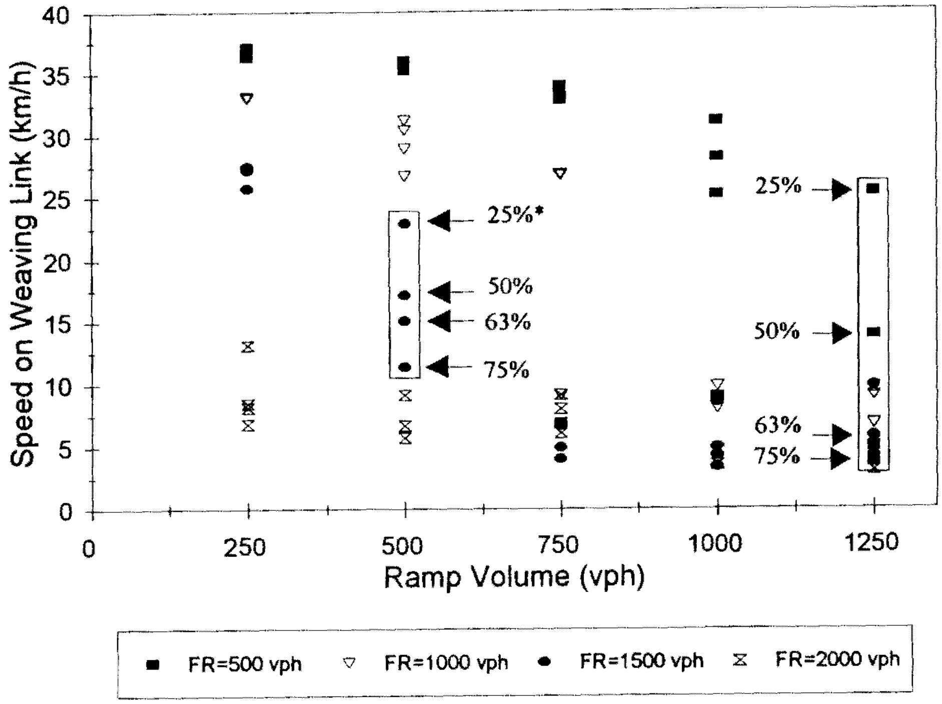


Figure 4-12. Exit Ramp Speed and Total Volume Relationship for 3LFR.



* Percent two-sided weaving maneuvers

Figure 4-13. Weaving Speed and Exit Ramp Volume Relationship for 3LFR (L = 200 m).

63%, and 75%) of exit ramp vehicles making a two-sided weaving maneuver. The proportion of two sided weaving maneuvers had significant effects on traffic operations when frontage road volumes were high and ramp volumes were low or when frontage road volumes were low and ramp volumes were high. For example, at a ramp volume of 500 vph and a frontage road volume of 1500 vph, the speeds range from approximately 23 km/h (low proportion of two-sided weaving maneuvers, 25%) to 11 km/h (high proportion of two-sided weaving maneuvers, 75%). At a ramp volume of 1250 vph and a frontage road volume of 500 vph, the speeds range from approximately 27 km/h to 5 km/h. At low frontage road volumes and low ramp volumes, the speeds were relatively high and varied little with increasing two-sided weaving maneuvers. For high frontage road volumes and high ramp volumes, the speeds were relatively low and still varied little with increasing two-sided weaving maneuvers. These relationships were also evident for the other ramp-to-intersection spacings studied.

Figure 4-14 demonstrates that speed on the weaving link is dependent on the frontage volume to exit ramp volume ratio. This figure shows the relationship between average speed on the weaving link and total volume (ramp volume + frontage road volume). For each data point, the frontage road volume and exit ramp volume are shown in parenthesis (frontage road volume/exit ramp volume). This figure reveals that weaving speed is more dependent on the ramp volume than frontage road volume. For example, using a total volume of 1750 vph, with a frontage road volume of 1500 vph and a ramp volume of 250 vph the average speed is approximately 44 km/h. However, for a frontage road volume of 500 vph and an exit ramp volume of 1250 vph, the average speed is approximately 19 km/h (a difference of 25 km/h). Therefore, for a constant total volume, the average speed on the weaving link decreases with decreasing frontage road volume to exit ramp volume ratio (i.e., keeping total volume constant, speed decreases with increasing ramp volume and decreasing frontage road volume). The variation in speed is lowest when the total volume is very high or very low.

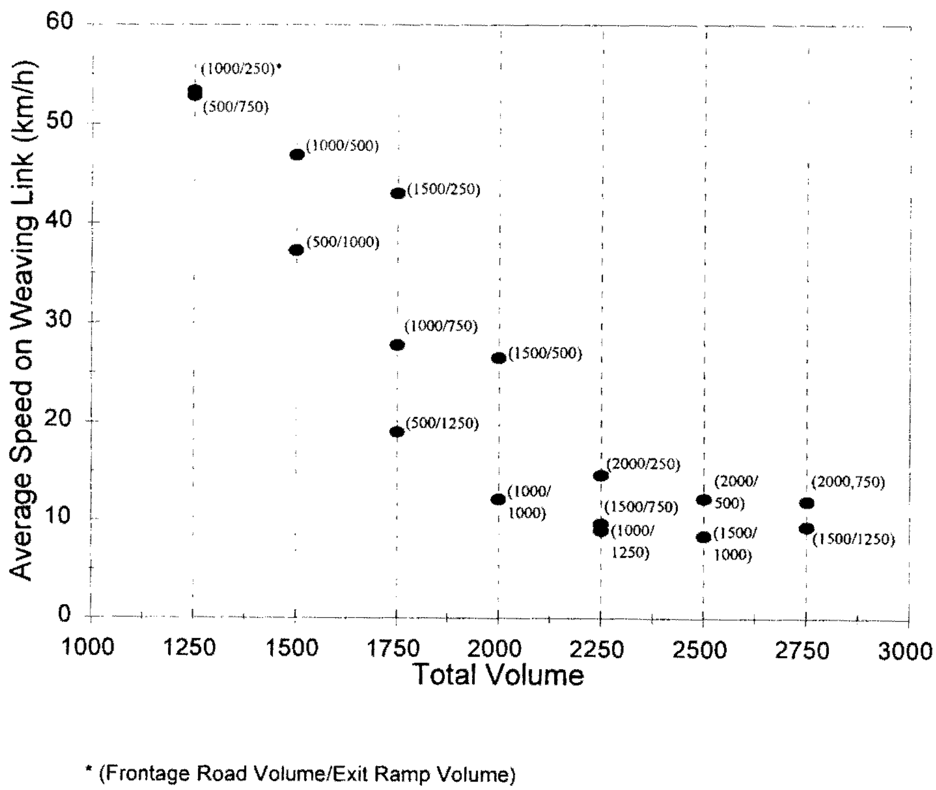


Figure 4-14. Effects of Ramp Volume on Weaving Speed for 3LFR (L=200m).

Regression Equations

To develop equations for predicting the average travel speed on the weaving link, three databases were built for each frontage road configuration under investigation. Next, the statistical analysis package SAS was used to perform stepwise regression. Several variables were investigated to determine the factors affecting speed on the weaving link. These variables included the following: frontage road volume, exit ramp volume, percent of exit ramp vehicles making a two-sided weaving maneuver, ramp-to-intersection spacing, and green to cycle time ratio of the signal at the intersection.

To simplify the procedure, the percent of two-sided weaving vehicles was separated into the following: less than or equal to 50% and greater than 50%. The researchers felt that this separation would not affect the results because traffic operations were only significantly affected when the percent of two sided weaving maneuvers was high (i.e., above approximately 50%). Making this separation in two-sided weaving percentages would also make this information easier to collect in the field in preparation of conducting an evaluation.

The stepwise regression procedures were performed for each of the three frontage road configurations studied. The procedures involved starting with one independent variable and adding variables one at a time until there was no longer a significant increase in the coefficient of determination, R^2. The resulting model was assumed to be the best-fitting regression equation. The resulting equations and R^2 values are shown below:

<u>Two-Lane Frontage Road</u>

$$WS = 48.1 - 0.017(FR) - 0.019(R) + 0.047(L) - 0.727(T) \quad [R^2 = 0.77] \qquad \textbf{(4-1)}$$

<u>Three-Lane Frontage Road</u>

$$WS = 46.5 - 0.015(FR) - 0.022(R) + 0.039(L) - 5.01(T) \quad [R^2 = 0.75] \qquad \textbf{(4-2)}$$

Two-Lane Frontage Road with Auxiliary Lane

$$WS = 45.9 - 0.008(FR) - 0.030(R) + 0.056(L) - 6.12(T) \qquad [R^2 = 0.80] \qquad \textbf{(4-3)}$$

Where:

WS = speed on weaving link, km/h

FR = frontage road volume, vph

R = exit ramp volume, vph

L = ramp-to-intersection spacing, m

T = factor based on percent of exit ramp vehicles turning right at downstream intersection

($T = 0$, Percent $\leq$ 50; $T = 1$, Percent > 50)

Using Speed for Predicting Traffic Operations

After developing equations to predict the average travel speed on the weaving link of a two-sided weaving section, the next step was to determine if speed could be used to estimate the level of service. In an effort to perform this task, the researchers investigated two approaches. The first was to use only the actual speed on the weaving link and compare this to some optimum value. The optimum speed would ideally be the maximum speed observed (at low traffic volumes). This approach proved to be difficult because the maximum speeds on the weaving link were dependent on the ramp-to-intersection spacing (see Figures 4-8 through 4-10). Again, average travel speed includes the time that the vehicles are in motion and the time that the vehicles are stopped at the intersection; therefore, speeds on shorter links include a relatively higher percentage of vehicles that are queued at the intersection when compared to links with longer ramp-to-intersection spacings. Using this procedure, it would be difficult to compare operations on a short two-sided weaving section (e.g. 100 meters) to operations on a longer two-sided weaving section (e.g. 400 meters).

The second approach was to calculate the reduction in speed from the exit ramp to the weaving link and/or from the frontage road to the weaving link. This would involve developing more equations to predict the speeds on the exit ramp and on the frontage road section prior to the exit ramp. The equations could be used to predict the speed reductions, and these values could be compared to a set criteria. For example, a speed reduction of less than 10 km/h might be satisfactory while a speed reduction greater than 10 km/h would be undesirable.

The second approach, nevertheless, had the same drawbacks as the first approach. The speeds on the exit ramp and on the frontage road prior to the exit ramp are only dependent upon traffic volume and not ramp-to-intersection spacing. However, the speed on the weaving link is dependent on spacing, therefore, affecting the calculated speed reduction. For example, for low traffic volumes, the speed on the exit ramp might be 50 km/h. For a weaving link with a ramp-to-intersection spacing of 400 meters, the speed in this situation might be 45 km/h compared to an average speed of 25 km/h for a weaving link with a spacing of 100 meters. Even though the traffic volumes are low and the two weaving sections are operating at similar levels of service, the reduction in speed would be 5 km/h for the 400 meter section and 25 km/h for the 100 meter section.

From these results, it was concluded that it would be very difficult to use average travel speed to predict the level of service on two-sided weaving sections. The next step was to investigate density as a possible measure for predicting traffic operations.

Density

Density is a measure of how close vehicles are to one another over a given length. The units used for density in this study were number of vehicles per length of roadway per lane (e.g. veh/km/ln). Since density is normalized by length, the problems associated with using average travel speed, discussed above, should be alleviated. Since the results from the speed study revealed that operations on the weaving link began to break down sooner than operations on the exit ramp and operations on the frontage road prior to the exit ramp, the researchers investigated using the density of vehicles on the weaving link as a measure for estimating traffic operations.

Figures 4-15 through 4-17 illustrate the relationships between density and total volume on the weaving link for the three frontage road configurations. Comparing these figures to Figures 4-8

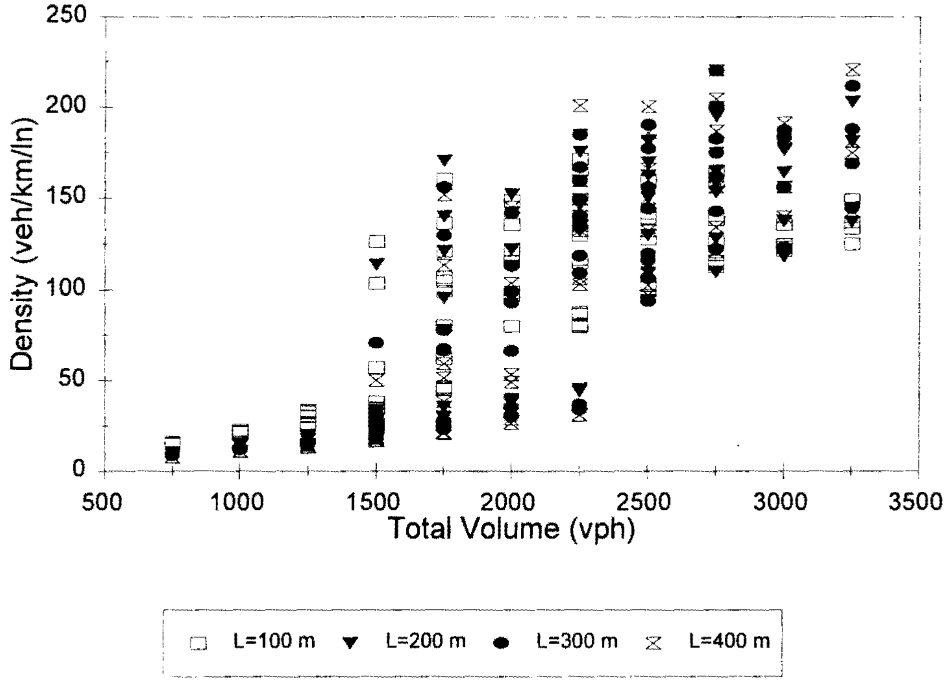


Figure 4-15. Density and Total Volume Relationship for 2LFR.

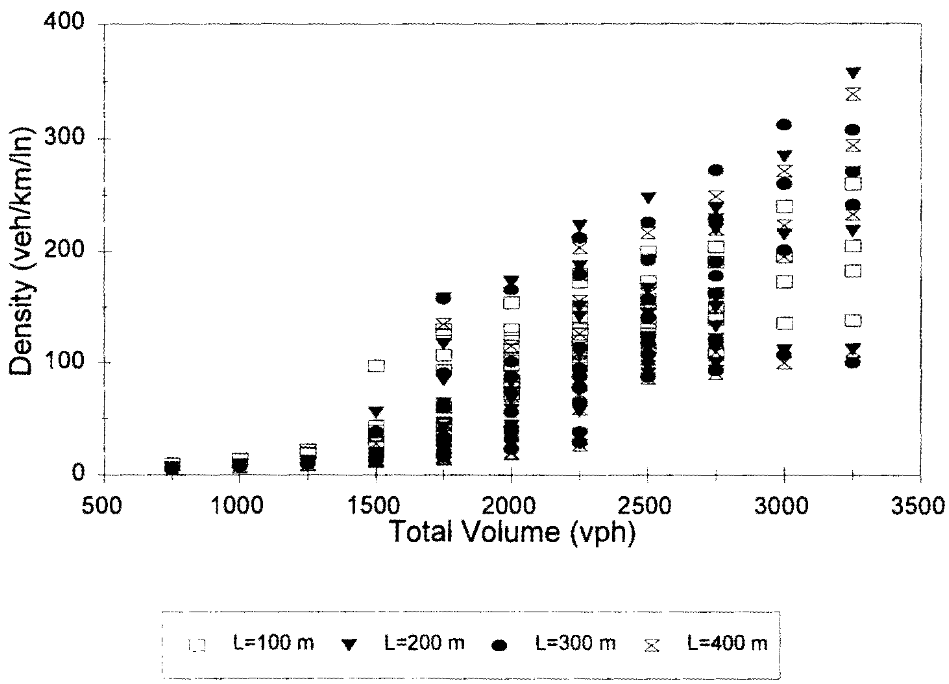


Figure 4-16. Density and Total Volume Relationship for 3LFR.

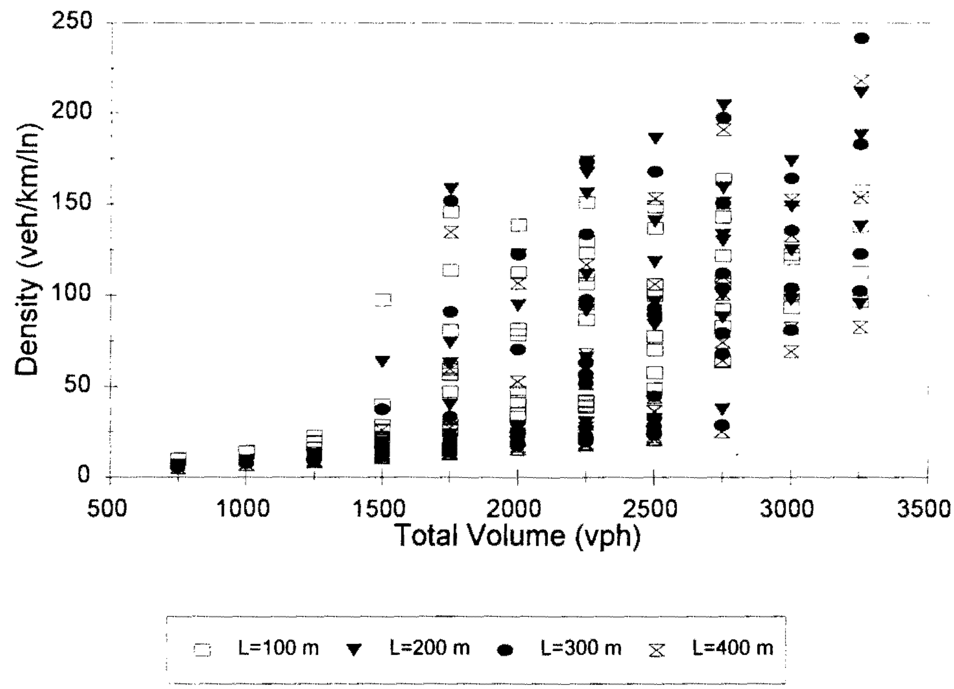


Figure 4-17. Density and Total Volume Relationship for 2LFR+Aux.

through 4-10 reveals that the relationships between density and total volume are similar to the relationships between speed and total volume in some areas. For 2LFR and 3LFR, there are critical breaks in speed and density at total volumes of 1500 vph and 2250 vph. For 2LFR+Aux, these breaks occur at 1500 vph and 2750 vph. However, even though the critical breaks for each configuration occur at the same volume level, there is still a major difference between speed and density. As mentioned above in the discussion on speed, for each configuration there is a high variation in speed below a total volume of 1500 vph (implying that the maximum average travel speed for the weaving link is dependent upon ramp-to-intersection spacing). For the relationship between density and total volume, this high variation does not exist. Below a total volume of 1500 vph, the density is dependent upon volume and relatively independent of ramp-to-intersection spacing.

The next step that the researchers took was to develop regression equations for predicting density. SAS was again used to perform stepwise regression to determine which factors had a significant effect on density. The variables included in the analysis were frontage road volume, exit ramp volume, percent of exit ramp vehicles making a two-sided weaving maneuver ($\leq$ 50 % or > 50 %), ramp-to-intersection spacing, and green to cycle time ratio of the traffic signal.

Regression Equations

Three databases were developed for each frontage road configuration and SAS was used to develop regression equations for each. The first equations developed contained large negative y-intercept values. This resulted in a prediction of negative densities at low volume levels. In an attempt to solve this problem, the y-intercepts were set to zero and the regression analysis was performed again. This procedure minimized negative density predictions and increased the resulting R^2-values. Following are the equations that were developed to predict density:

<u>Two-Lane Frontage Road</u>

$$D = 0.022(FR) + 0.066(R) - 0.088(L) + 6.34(T) \qquad [R^2 = 0.90] \qquad \textbf{(4-4)}$$

<u>Three-Lane Frontage Road</u>

$$D = 0.055(FR) + 0.080(R) - 0.200(L) + 27.4(T) \qquad [R^2 = 0.84] \qquad \textbf{(4-5)}$$

<u>Two-Lane Frontage Road with Auxiliary Lane</u>

$$D = 0.021(FR) + 0.077(R) - 0.150(L) + 23.4(T) \qquad [R^2 = 0.83] \qquad \textbf{(4-6)}$$

Where:

D = density on weaving link, veh/km/ln

FR = frontage road volume, vph

R = exit ramp volume, vph

L = ramp-to-intersection spacing, m

T = factor based on percent of exit ramp vehicles turning right at downstream intersection ($T = 0$, Percent ≤ 50; $T = 1$, Percent > 50)

Validation of Regression Equations

The purpose of the validation process was to determine how well the regression equations could predict existing field conditions. The procedures involved comparing the density measured at an existing field site to that predicted by the regression equation. To measure density in the field, selected video recordings made during the field study were viewed. The density was computed by dividing the average flow by the average travel speed. The average travel speed was computed by first measuring the total travel time of vehicles on the weaving link (i.e., from exit ramp gore to stop bar at intersection). Average travel speed was computed by dividing the distance between the ramp and the intersection by the average travel time on the weaving link.

The field site selected for the validation procedures was Site 3 from the field study (see Table 3-1). Site 3 consists of a two-lane frontage road with a right turn bay and a ramp-to-intersection spacing of approximately 190 meters (see Figure 3-3). This site was selected because the video recordings made at the site were clear, making it relatively easy to track vehicles from the exit ramp to the downstream intersection. For the remaining field sites, several factors, such as long ramp-to-intersection spacings or poor video recordings, made it difficult to track vehicles through the intersection.

At Site 3, densities were computed in five-minute increments over three time periods. The five minute traffic volumes observed were converted to vehicles per hour. The percent of exit ramp vehicles making a two-sided weaving maneuver ranged from approximately 33 to 44 percent. To estimate densities using the regression equation, the exit ramp and frontage road volumes for each five minute period were used in the regression equation for a two-lane frontage road (Equation 4-4).

Table 4-2 shows the densities measured in the field and the densities predicted by the regression equation. As shown in this table, the densities observed in the field are consistently lower

Table 4-2. Comparison of Field Data to Regression Equation.

Frtg Road Volume (vph)	Exit Ramp Volume (vph)	Field Data			Regression Equation
		Trvl Time (sec)	Speed (km/h)	Density (vh/km/ln)	Density (vh/km/ln)
144	876	51	13.3	38.5	43.4
108	948	59	11.4	46.2	47.3
324	1044	56	12.0	56.8	58.4
			Average:	47.2	49.7

than the densities predicted by the regression equation, with the average density measured in the field being 2.5 veh/km/ln less that the average density predicted by the regression equation. This was expected because the field site included a right turn bay which was not accounted for in the regression equation. The inclusion of a right turn bay helps relieve congestion and results in less density (veh/km/ln). Because the densities measured in the field and predicted by the regression equation were close, the researchers concluded that the regression equations can adequately predict existing field conditions; however, when using the regression equations, the effects of turn bays should be taken into consideration (i.e., turn bays typically relieve congestion and may decrease traffic density somewhat).

Using Density for Predicting Traffic Operations

After developing equations to predict density for given situations, the next step was to select criteria for evaluating the level of service. In an attempt to complete this task, the relationships between speed, density, and flow were investigated.

Figure 4-18 illustrates the relationships between flow and density for the three frontage road configurations. This figure demonstrates that as density and flow increase, the variability increases. In addition, the relationship between flow and density becomes more dependent on frontage road configuration as density and flow increase. At high flow rates, the density is highest for

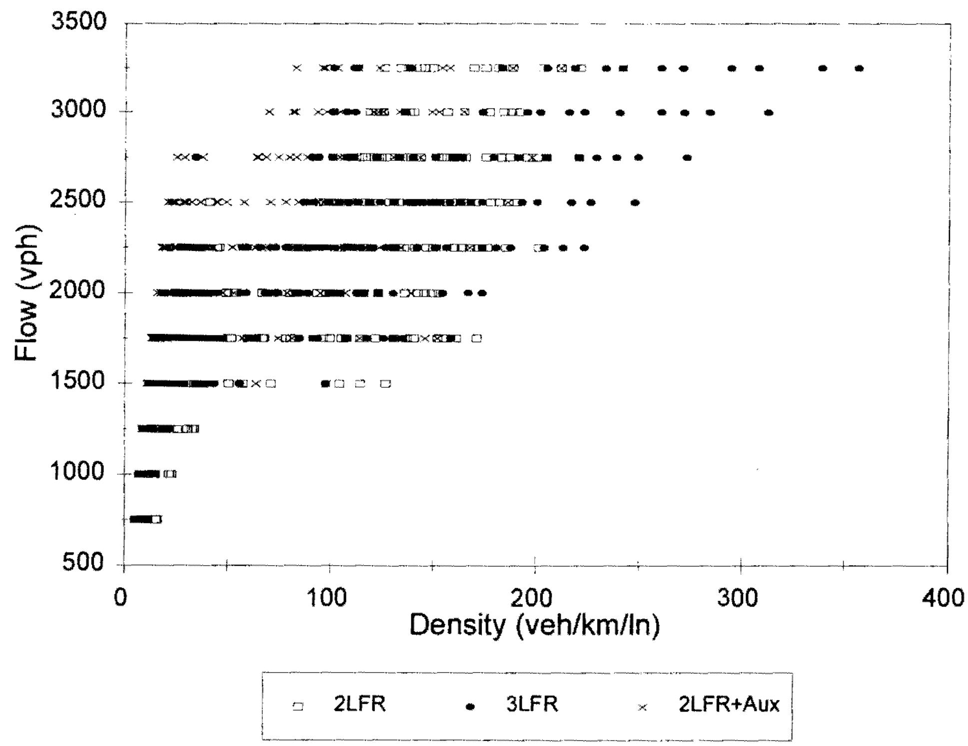


Figure 4-18. Flow and Density Relationship.

3LFR and lowest for 2LFR. 3LFR also contains the highest variability at high flow rates. By observing the database for 3LFR, it was determined that high densities occurred at high flow rates when there was a high percent (i.e., larger than 50 %) of exit ramp vehicles making two-sided

Figure 4-19 illustrates the relationships between speed and density for the three frontage road configurations. For each frontage road configuration, the speed decreases significantly as density increases for densities below approximately 40 veh/km/ln. This signifies that at lower densities, the operations on the weaving link diminish with relatively small increases in density. In this range, traffic operations may vary from free-flow to unstable. From 40 veh/km/ln to 100 veh/km/ln, the rate of decrease in speed becomes less. In this density range, traffic operations are beginning to break down and become predominately unstable. Above 100 veh/km/ln, the rate of decrease begins to level off and become relatively constant, signifying that traffic operations are at their lowest level. Using this relationship between speed and density can help determine level of service criteria for two-sided weaving operations.

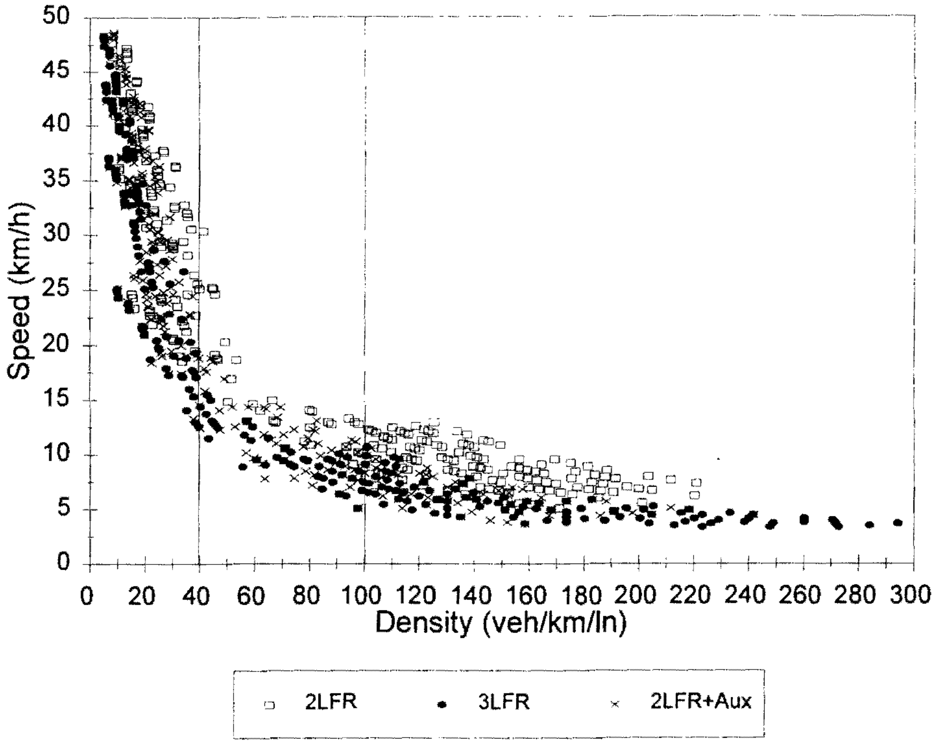


Figure 4-19. Speed and Density Relationship.

CHAPTER 5

TWO-SIDED WEAVING EVALUATION TECHNIQUE

LEVEL OF SERVICE ANALYSIS

To develop a procedure for determining the level of service within a two-sided weaving area, several MOEs were investigated. After an analysis of two-sided weaving areas using NETSIM, it was concluded that the density on the weaving link would be the proposed MOE. Density is a good measure of weaving operations because it measures the proximity of vehicles and is a reflection of drivers' freedom to maneuver.

From the NETSIM results, regression equations were developed to predict density based on frontage road volume, exit ramp volume, exit ramp-to-intersection spacing, and percent of exit ramp vehicles making a two-sided weaving maneuver. Density equations were derived for each of the three frontage road configurations included in the study (i.e., two-lane frontage road, three-lane frontage road, and two-lane frontage road with auxiliary lane). After equations were developed to predict density, the next step was to select criteria for estimating the level of service based on density.

Level of Service Criteria

To develop level of service criteria for two-sided weaving sections, traffic operations were divided into three levels: unconstrained, constrained, and undesirable. These three levels of operation correspond to the following levels of service defined by the 1994 *HCM*: unconstrained = LOS A-B, constrained = LOS C-D, and undesirable = LOS E-F. Unconstrained operations represents predominantly free-flow operations in which drivers can maneuver with relatively little impedance from other traffic and delay is minimal. Constrained operations represents situations in which drivers ability to maneuver becomes more restricted due to other traffic and delay is moderate.

Undesirable operations represents situations in which flows are approaching capacity, drivers ability to maneuver are highly restricted, and delay is high.

To determine the ranges of density which represent each of the defined levels of service, operations at existing field sites were observed to supplement the findings from computer simulation. The objective of studying field data was to view actual two-sided weaving operations and use engineering judgement to estimate the critical densities in which there was a change in the level of service. This was accomplished by viewing the video tapes collected during the field study (four field sites) and viewing existing operations at selected frontage road sites in Houston, Texas (nine field sites). At each of the 13 field sites investigated, densities were computed by determining the exit ramp volume, frontage road volume, percent two-sided weaving maneuvers ($\leq$ 50% or > 50%), and ramp-to-intersection spacing and using the appropriate regression equation to estimate density.

After viewing traffic operations in the field, it was determined that the division between unconstrained and constrained operations occurred at a density of approximately 40 veh/km/ln, and the divisions between constrained and undesirable operations occurred at approximately 100 veh/km/ln. These results correspond to the findings derived from the relationship between speed and density for the NETSIM data (see Figure 4-18 and discussion).

The proposed level of service criteria are shown in Table 5-1. The ranges shown in this table are not meant to represent exact divisions in level of service; they are only to be used as estimates.

Table 5-1. Level of Service Criteria.

Level of Service	Density (veh/km/ln)
Unconstrained	< 40
Constrained	40 - 100
Undesirable	> 100

To estimate the level of service for a particular frontage road configuration, Tables 5-2, 5-3, and 5-4 were generated. These tables contain densities based on the developed regression equations for each frontage road configuration. Calculated densities are given for various frontage road volumes, exit ramp volumes, ramp-to-intersection spacings, and percents of exit ramp vehicles turning right at downstream intersection (< 50% or > 50%). The estimated levels of service are shown using various shades: white (unconstrained), light grey (constrained), and dark grey (undesirable). The levels of service are based on the criteria shown in Table 5-1.

For an example, consider a two-lane frontage road with a ramp-to-intersection spacing of approximately 200 meters, a frontage road volume of 1000 vph, a ramp volume of 500 vph, and an exit ramp right turn percentage less than 50%. Using Table 5-2, the estimated density would be approximately 56 veh/km/ln. This results in a level of service in the constrained region (40 - 100 veh/km/ln).

The criteria developed in this study did not take into account the effects of turn bays. Turn bays can relieve congestion resulting in less density and improved level of service. When evaluating frontage road configurations with turn bays, use engineering judgement in applying the criteria developed in this study, especially when predicted densities are close to the density boundaries defining level of service (i.e., 40 or 100 veh/km/ln). For example, if a two-lane frontage road with a turn bay is predicted to have a density of approximately 105 veh/km/ln, traffic operations may be within the constrained region. If, however, the density is predicted to be 150 veh/km/ln, the traffic operations are most likely in the undesirable region.

In addition, two-sided weaving operations were analyzed in this study assuming that the cross street traffic at the intersection was moderate and the traffic signal was optimally timed to minimize overall intersection delay. Frontage road operations can be significantly impacted by poor signal timing, especially when volumes are high. Therefore, for situations in which the traffic signal is causing high delays for the frontage road approach, engineering judgement should again be used when applying the criteria developed in this study.

Table 5-2. Exit Ramp-to-Intersection Levels of Service for Two-Lane Frontage Roads.

Density (veh/km/ln)*

Ramp-to-Intrsctn Spacing (m)	Ramp Volume (vph)	FR Volume (vph) 250		FR Volume (vph) 500		FR Volume (vph) 750		FR Volume (vph) 1000	
		Ramp RT Percent		Ramp RT Percent		Ramp RT Percent		Ramp RT Percent	
		< 50%	> 50%	< 50%	> 50%	< 50%	> 50%	< 50%	> 50%
100	250	20	29	28	38	37	46	45	55
	500	44	54	53	62	61	71	70	79
	750	69	78	77	87	86	95	94	104
	1000	94	103	102	111	110	120	119	128
	1250	118	128	126	136	135	144	143	153
200	250	7	16	15	25	24	33	32	41
	500	31	41	40	49	48	58	56	66
	750	56	65	64	74	73	82	81	91
	1000	80	90	89	98	97	107	106	115
	1250	105	114	113	123	122	131	130	140
300	250	NA**	3	2	11	10	20	19	28
	500	18	28	26	36	35	44	43	53
	750	43	52	51	61	59	69	68	77
	1000	67	77	76	85	84	94	92	102
	1250	92	101	100	110	109	118	117	127
400	250	NA	NA	NA	NA	NA	7	6	15
	500	5	14	13	23	22	31	30	40
	750	29	39	38	47	46	56	55	64
	1000	54	64	62	72	71	80	79	89
	1250	79	88	87	97	95	105	104	113

Ramp-to-Intrsctn Spacing (m)	Ramp Volume (vph)	FR Volume (vph) 1250		FR Volume (vph) 1500		FR Volume (vph) 1750		FR Volume (vph) 2000	
		Ramp RT Percent		Ramp RT Percent		Ramp RT Percent		Ramp RT Percent	
		< 50%	> 50%	< 50%	> 50%	< 50%	> 50%	< 50%	> 50%
100	250	54	63	62	71	70	80	79	88
	500	78	88	87	96	95	104	103	113
	750	103	112	111	121	119	129	128	137
	1000	127	137	136	145	144	154	152	162
	1250	152	161	160	170	169	178	177	187
200	250	40	50	49	58	57	67	66	75
	500	65	74	73	83	82	91	90	100
	750	89	99	98	107	106	116	115	124
	1000	114	124	122	132	131	140	139	149
	1250	139	148	147	157	155	165	164	173
300	250	27	37	36	45	44	54	52	62
	500	52	61	60	70	69	78	77	87
	750	76	86	85	94	93	103	102	111
	1000	101	110	109	119	118	127	126	136
	1250	125	135	134	143	142	152	151	160
400	250	14	24	22	32	31	40	39	49
	500	39	48	47	57	55	65	64	73
	750	63	73	72	81	80	90	88	98
	1000	88	97	96	106	105	114	113	123
	1250	112	122	121	130	129	139	138	147

*Density (veh/km/ln)=0.034(FR Vol, vph)+0.098(Ramp Vol, vph)-0.132(Ramp-to-Inters Spcg, m)+9.51(Ramp RT %, 0 for <50%, 1 for >50%)

** NA - Regression equation resulted in negative density value

Unconstrained (< 40 veh/km/ln)

Constrained (40 - 100 veh/km/ln)

Undesirable (> 100 veh/km/ln)

Table 5-3. Exit Ramp-to-Intersection Levels of Service for Three-Lane Frontage Roads.

Density (veh/km/ln)*

Ramp-to-Intrsctn Spacing (m)	Ramp Volume (vph)	FR Volume (vph) 250		FR Volume (vph) 500		FR Volume (vph) 750		FR Volume (vph) 1000	
		Ramp RT Percent		Ramp RT Percent		Ramp RT Percent		Ramp RT Percent	
		< 50%	> 50%	< 50%	> 50%	< 50%	> 50%	< 50%	> 50%
100	250	14	41	27	55	41	68	55	82
	500	34	61	47	75	61	88	75	102
	750	53	81	67	95	81	108	94	122
	1000	73	101	87	114	101	128	114	142
	1250	93	121	107	134	121	148	134	162
200	250	NA**	21	7	35	21	48	35	62
	500	14	41	27	55	41	68	55	82
	750	33	61	47	75	61	88	74	102
	1000	53	81	67	94	81	108	94	122
	1250	73	101	87	114	101	128	114	142
300	250	NA	1	NA	15	1	28	15	42
	500	NA	21	7	35	21	48	35	62
	750	14	41	27	55	41	68	55	82
	1000	33	61	47	75	61	88	74	102
	1250	53	81	67	94	81	108	94	122
400	250	NA	NA	NA	NA	NA	8	NA	22
	500	NA	1	NA	15	1	28	15	42
	750	NA	21	7	35	21	48	35	62
	1000	13	41	27	55	41	68	54	82
	1250	33	61	47	74	61	88	74	102

Ramp-to-Intrsctn Spacing (m)	Ramp Volume (vph)	FR Volume (vph) 1250		FR Volume (vph) 1500		FR Volume (vph) 1750		FR Volume (vph) 2000	
		Ramp RT Percent		Ramp RT Percent		Ramp RT Percent		Ramp RT Percent	
		< 50%	> 50%	< 50%	> 50%	< 50%	> 50%	< 50%	> 50%
100	250	68	96	82	109	96	123	109	137
	500	88	116	102	129	116	143	129	157
	750	108	136	122	149	135	163	149	177
	1000	128	155	142	169	155	183	169	196
	1250	148	175	162	189	175	203	189	216
200	250	48	76	62	89	76	103	89	117
	500	68	96	82	109	96	123	109	137
	750	88	116	102	129	115	143	129	157
	1000	108	135	122	149	135	163	149	176
	1250	128	155	142	169	155	183	169	196
300	250	28	56	42	69	56	83	69	97
	500	48	76	62	89	76	103	89	117
	750	68	96	82	109	96	123	109	137
	1000	88	116	102	129	115	143	129	157
	1250	108	135	122	149	135	163	149	176
400	250	8	36	22	49	36	63	49	77
	500	28	56	42	69	56	83	69	97
	750	48	76	62	89	76	103	89	117
	1000	68	96	82	109	95	123	109	137
	1250	88	115	102	129	115	143	129	156

* Density (veh/km/ln)=0.055(FR Vol, vph)+0.080(Ramp Vol, vph)-0.200(Ramp-to-Inters Spcg, m)+27.4(Ramp RT %, 0 for <50%, 1 for >50%)

** NA - Regression equation resulted in negative density value

Unconstrained (< 40 veh/km/ln)

Constrained (40 - 100 veh/km/ln)

Undesirable (> 100 veh/km/ln)

Table 5-4. Exit Ramp-to-Intersection Levels of Service for Two-Lane Frontage Roads with Auxilary Lane.

Density (veh/km/ln)*

Ramp-to-Intrsctn Spacing (m)	Ramp Volume (vph)	FR Volume (vph) 250		FR Volume (vph) 500		FR Volume (vph) 750		FR Volume (vph) 1000	
		Ramp RT Percent		Ramp RT Percent		Ramp RT Percent		Ramp RT Percent	
		< 50%	> 50%	< 50%	> 50%	< 50%	> 50%	< 50%	> 50%
100	250	9	33	15	38	20	43	25	48
	500	29	52	34	57	39	62	44	68
	750	48	72	53	77	58	82	63	87
	1000	67	91	73	96	78	101	83	106
	1250	87	110	92	115	97	120	102	126
200	250	NA**	18	NA	23	5	28	10	33
	500	14	37	19	42	24	47	29	53
	750	33	57	38	62	43	67	48	72
	1000	52	76	58	81	63	86	68	91
	1250	72	95	77	100	82	105	87	111
300	250	NA	3	NA	8	NA	13	NA	18
	500	NA	22	4	27	9	32	14	38
	750	18	42	23	47	28	52	33	57
	1000	37	61	43	66	48	71	53	76
	1250	57	80	62	85	67	90	72	96
400	250	NA	NA	NA	NA	NA	NA	NA	3
	500	NA	7	NA	12	NA	17	NA	23
	750	3	27	8	32	13	37	18	42
	1000	22	46	28	51	33	56	38	61
	1250	42	65	47	70	52	75	57	81

Ramp-to-Intrsctn Spacing (m)	Ramp Volume (vph)	FR Volume (vph) 1250		FR Volume (vph) 1500		FR Volume (vph) 1750		FR Volume (vph) 2000	
		Ramp RT Percent		Ramp RT Percent		Ramp RT Percent		Ramp RT Percent	
		< 50%	> 50%	< 50%	> 50%	< 50%	> 50%	< 50%	> 50%
100	250	30	53	35	58	40	64	45	69
	500	49	73	54	78	59	83	65	88
	750	69	92	74	97	79	102	84	107
	1000	88	111	93	116	98	122	103	127
	1250	107	131	112	136	117	141	123	146
200	250	15	38	20	43	25	49	30	54
	500	34	58	39	63	44	68	50	73
	750	54	77	59	82	64	87	69	92
	1000	73	96	78	101	83	107	88	112
	1250	92	116	97	121	102	126	108	131
300	250	NA	23	5	28	10	34	15	39
	500	19	43	24	48	29	53	35	58
	750	39	62	44	67	49	72	54	77
	1000	58	81	63	86	68	92	73	97
	1250	77	101	82	106	87	111	93	116
400	250	NA	8	NA	13	NA	19	NA	24
	500	4	28	9	33	14	38	20	43
	750	24	47	29	52	34	57	39	62
	1000	43	66	48	71	53	77	58	82
	1250	62	86	67	91	72	96	78	101

* Density (veh/km/ln)=0.021(FR Vol, vph)+0.077(Ramp Vol, vph)-0.150(Ramp-to-Inters Spcg, m)+23.4(Ramp RT %, 0 for <50%, 1 for >50%)

** NA - Regression equation resulted in negative density value

Unconstrained (< 40 veh/km/ln)

Constrained (40 - 100 veh/km/ln)

Undesirable (> 100 veh/km/ln)

Technique for Determining Level of Service

To estimate the level of service between an exit ramp and an intersection on a one-way frontage road, the following procedures should be followed:

(1) From the field, collect exit ramp and frontage road volumes and determine the exit ramp-to-intersection spacing. In addition, estimate the percent of exit ramp vehicles making a right turn at the downstream intersection as either less than 50 percent or greater than 50 percent.

(2) Based on the frontage road configuration, use Table 5-2 (two-lane frontage road), Table 5-3 (three-lane frontage road), or Table 5-4 (two-lane frontage road with an auxiliary lane) to estimate the level of service.

(3) For volumes and ramp-to-intersection spacings that fall between the increments shown in the tables, one should either interpolate between the columns and rows to predict density or calculate the density using the appropriate regression equation (given at the bottom of each table).

The criteria developed in this study are not meant to represent exact divisions in level of service. The values are intended to provide a general idea of the level of service which might by expected for a particular two-sided weaving area; therefore, engineering judgement should be used when applying these criteria. Special considerations should be given to frontage road configurations with turn bays and situations in which a signalized intersection is causing high delays for the frontage road approach.

EXIT RAMP-TO-INTERSECTION SPACING

The spacing between an exit ramp and a downstream intersection can have a great effect on the operations of a weaving section. In an effort to develop recommendations for minimum and desirable spacings, the regression equations developed to predict density were used. Since spacing was a variable in the equations, the equations could be used to back calculate for spacing given frontage road volume, ramp volume, and percent two-sided weaving maneuvers. To estimate minimum spacing, the density value between constrained and undesirable operations (100 veh/hr/ln) was used in the equations. To estimate desirable spacings, the density value between unconstrained and constrained operations (40 veh/km/ln) was used.

Using the density equations to predict minimum and desirable ramp-to-intersection spacings, small spacings (near zero) were computed for low traffic volumes. Therefore, an absolute minimum spacing had to be selected. The 1994 AASHTO *Green Book* (12) states that ramps should connect to the frontage road a minimum of 105 meters upstream of the crossroad. It also states that desirable lengths should be several meters longer to provide adequate weaving length, space for vehicle storage, and turn lanes at the cross road. From the field studies, it was determined that the majority of drivers used between 60 and 120 meters to weave from the exit ramp to the right-most lane when frontage road traffic and/or queues from the downstream intersection did not significantly influence exit ramp driver behavior. In a study by Turner and Messer (17), a rule-of-thumb ramp-to-intersection spacing of 150 meters was recommended. This spacing corresponds to recommendations from the *Green Book* and findings from the field. Therefore, based upon findings from this study and findings from previous research, an absolute minimum exit ramp-to-intersection spacing of 150 meters is recommended. Using this minimum spacing value and the results from the regression equations, Table 5-5 through 5-7 were generated to estimate minimum and desirable spacings for the three frontage road configurations.

Table 5-5. Minimum and Desirable Ramp-to-Intersection Spacings (m) for Two-Lane Frontage Roads.

Exit Ramp Volume (vph)	Exit Ramp Right Turn Percent	Frontage Road Volume (vph)							
		500		1000		1500		2000	
		Min	Desr	Min	Desir	Min	Desir	Min	Desir
250	< 50%	150	150	150	150	150	150	150	235
	> 50%	150	150	150	150	150	180	150	305
500	< 50%	150	150	150	170	150	295	150	420
	> 50%	150	150	150	240	150	370	150	490
750	< 50%	150	235	150	360	150	485	150	610
	> 50%	150	305	150	430	150	555	150	680
1000	< 50%	150	420	150	545	150	670	150	795
	> 50%	150	490	150	620	150	740	185	865
1250	< 50%	150	610	150	735	175	860	300	985
	> 50%	150	680	150	805	250	930	375	1055

Table 5-6. Minimum and Desirable Ramp-to-Intersection Spacings (m) for Three-Lane Frontage Roads.

Exit Ramp Volume (vph)	Exit Ramp Right Turn Percent	Frontage Road Volume (vph)							
		500		1000		1500		2000	
		Min	Desr	Min	Desir	Min	Desir	Min	Desir
250	< 50%	150	150	150	175	150	310	150	450
	> 50%	150	175	150	310	150	450	290	585
500	< 50%	150	150	150	275	150	410	250	550
	> 50%	150	275	150	410	250	550	390	685
750	< 50%	150	235	150	375	210	510	350	650
	> 50%	150	375	210	510	350	650	490	785
1000	< 50%	150	335	175	475	310	610	450	750
	> 50%	175	475	310	610	450	750	590	885
1250	< 50%	150	445	275	575	410	710	550	850
	> 50%	275	575	410	710	550	850	690	985

Table 5-7. Minimum and Desirable Ramp-to-Intersection Spacings (m) for Two-Lane Frontage Roads with Auxiliary Lane.

Exit Ramp Volume (vph)	Exit Ramp Right Turn Percent	Frontage Road Volume (vph) 500		1000		1500		2000	
		Min	Desr	Min	Desir	Min	Desir	Min	Desir
250	< 50%	150	150	150	150	150	150	150	150
	> 50%	150	150	150	155	150	230	150	295
500	< 50%	150	150	150	150	150	200	150	270
	> 50%	150	215	150	285	150	355	150	425
750	< 50%	150	185	150	255	150	325	150	400
	> 50%	150	345	150	415	150	480	150	555
1000	< 50%	150	315	150	385	150	455	150	525
	> 50%	150	470	150	540	210	615	280	680
1250	< 50%	150	445	150	515	185	585	255	655
	> 50%	200	600	270	670	340	740	410	810

CHAPTER 6
CONCLUSIONS

The research documented in this report focused on investigating two-sided weaving operations on one-way frontage roads. The study objectives were to develop a technique for evaluating two-sided weaving operations and to develop recommendations on minimum and desirable ramp-to-intersection spacings. To meet these objectives, both field data and computer simulation were used. Three types of frontage road configurations were included in the study: two-lane frontage road, three-lane frontage road, and two-lane frontage road with an auxiliary lane connecting the exit ramp to the downstream intersection. The conclusions drawn from this study were as follows.

TWO-SIDED WEAVING OPERATIONS

- The performance of a two-sided weaving area can be evaluated using the techniques presented in Chapter 5. The techniques provide the user with an estimated level of service based upon the following factors: frontage road configuration, frontage road volume, exit ramp volume, percent exit ramp vehicles making a two-sided weaving maneuver (less than or greater than 50 %), and ramp-to-intersection spacing.

- The criteria for estimating the level of service are based upon frontage road density (veh/km/ln) between the exit ramp and downstream intersection. To calculate density, regression equations were developed for each frontage road configuration.

- Two-sided weaving operations can be divided 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.

- By calculating the density for a two-sided weaving area, the level of service can be estimated based on the following criteria: unconstrained (density < 40 veh/km/ln), constrained (density from 40 - 100 veh/km/ln), and undesirable (density > 100 veh/km/ln).

EXIT RAMP-TO-INTERSECTION SPACING

- Results from the field study revealed that the majority of drivers observed used from approximately 60 to 120 meters to weave from the exit ramp to the right-most lane on the frontage road.

- In addition, the field study showed that queue from the downstream intersection began to have significant effects on drivers making a two-sided weaving maneuver when the queue length was within approximately 90 meters of the exit ramp.

- To develop recommendations for minimum and desirable spacings, the regression equations developed to predict density were used to back calculate for spacing given frontage road volume, ramp volume, and percent two-sided weaving maneuvers. To estimate minimum and desirable spacings, the density values between constrained and undesirable operations (100 veh/hr/ln) and between unconstrained and constrained operations (40 veh/km/ln) were used, respectively.

- Techniques for estimating the minimum and desirable ramp-to-intersection spacing are presented in Chapter 5. The recommended spacings are based upon the following factors: frontage road configuration, frontage road volume, exit ramp volume, and percent of exit ramp vehicles making a two-sided weaving maneuver (less than or greater than 50 %).

- Based upon findings from this study and findings from previous research, an absolute minimum exit ramp-to-intersection spacing of 150 meters is recommended.

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