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16. Abstract

Existing geometric design guidance related to interchange ramp spacing in the Texas *Roadway Design Manual* and the AASHTO's *A Policy on Geometric Design of Highways and Streets* (*Green Book*) is not speed-dependent even though intuition indicates spacing and speed are related. Understanding the relationship between interchange ramp spacing, speed, and freeway operations is important, especially in developing potential design values for higher speeds (e.g., 85 to 100 mph). The objectives of this project were to: (a) investigate relationships between weaving length, speed, and overall vehicle operations on Texas freeways and (b) propose updates to current Texas Department of Transportation guidance on recommended distances between ramps. Within the research tasks several methods were utilized to assist in developing guidance on ramp spacing lengths. The methods or resources used to generate potential lengths included: guidance provided in *Design Manual for Roads and Bridges* published by the Highways Agency in England, minimum deceleration and acceleration length for freeway conditions, decision sight distance, sign spacing needs, NCHRP project 3-75 findings, findings from field studies at seven study sites, findings from simulation conducted as part of this research, and safety relationships identified in the literature. Suggested ramp spacings were developed for the entrance ramp to exit ramp and exit ramp to exit ramp conditions.

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GUIDELINES FOR SPACING BETWEEN FREEWAY RAMPS

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DISCLAIMER

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- Diana Wallace – Programmer/Analyst
- Tony Voight – Research Engineer

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Page

CHAPTER 1

INTRODUCTION

The minimum acceptable distance between ramps is dependent upon the merge, diverge, and weaving operations that take place between ramps as well as distances required for signing. The Texas *Roadway Design Manual* (*RDM*) (*1*) recommends the use of the *Highway Capacity Manual* (*HCM*) (*2*) for analysis of these requirements. The *RDM* provides a figure to show the minimum distances between ramps for various ramp configurations (reproduced as Figure 1-1 in this report). Key dimensions are:

Entrance Ramp Followed by Exit Ramp (see Figure 1-1 for control points)

- Minimum weaving length without auxiliary lane = 2000 ft (600 m).
- Minimum weaving length with auxiliary lane = 1500 ft (450 m).

Other key reference documents that provide information on ramp spacing, such as the 2004 *A Policy on Geometric Design of Highways and Streets* (commonly known as the *Green Book*) (*3*), also encourage the reader to use the *Highway Capacity Manual* (*2*) to identify appropriate spacing dimensions.

Texas Department of Transportation (TxDOT) Project 0-5544: "Development of High-Speed Roadway Design Criteria and Evaluation of Roadside Safety Features" investigated the effects of design speeds above 80 miles per hour (mph) on various controlling criteria for roadway design. The project also investigated ramp design, specifically the ramp terminal designs for entrance and exit ramps (*4*). One component of ramp design was ramp spacing. Logically, the ramp spacing should be related to the design speed of the roadway, with more distance required when the design speed is higher.

However, the actual design guidance available is not sensitive to the design speed of the roadway. For example, the Texas *Roadway Design Manual* guidance provides for two minimum ramp spacing lengths: one without an auxiliary lane (2000 ft) and one with the auxiliary lane (1500 ft). These distances apply regardless of design speed. The American Association of State Highway and Transportation Officials' (AASHTO's) *Green Book* similarly provides a minimum ramp spacing of 2000 ft between system and service interchanges and 1600 ft between two service interchanges; but again, these values are independent of design speed. A question to ask is should the design speed of the facility determine the minimum spacing? Intuition indicates that spacing and speed are related. If this is true, guidance on this relationship is important.

RESEARCH OBJECTIVES

The objectives of this project were to: (a) investigate relationships between weaving length, speed, and overall vehicle operations on Texas freeways and (b) propose updates to current TxDOT guidance on recommended distances between ramps contained in Chapter 3 of the Texas *Roadway Design Manual* (see Figure 1-1).

A key relationship for the research to define is the relationship between speed and ramp spacing that provides unconstrained operation. The findings from this research will be used to produce recommendations on minimum weaving lengths that TxDOT could incorporate into the Texas *Roadway Design Manual*. Freeway design speeds ranging from 60 mph to 100 mph were considered in this research project.

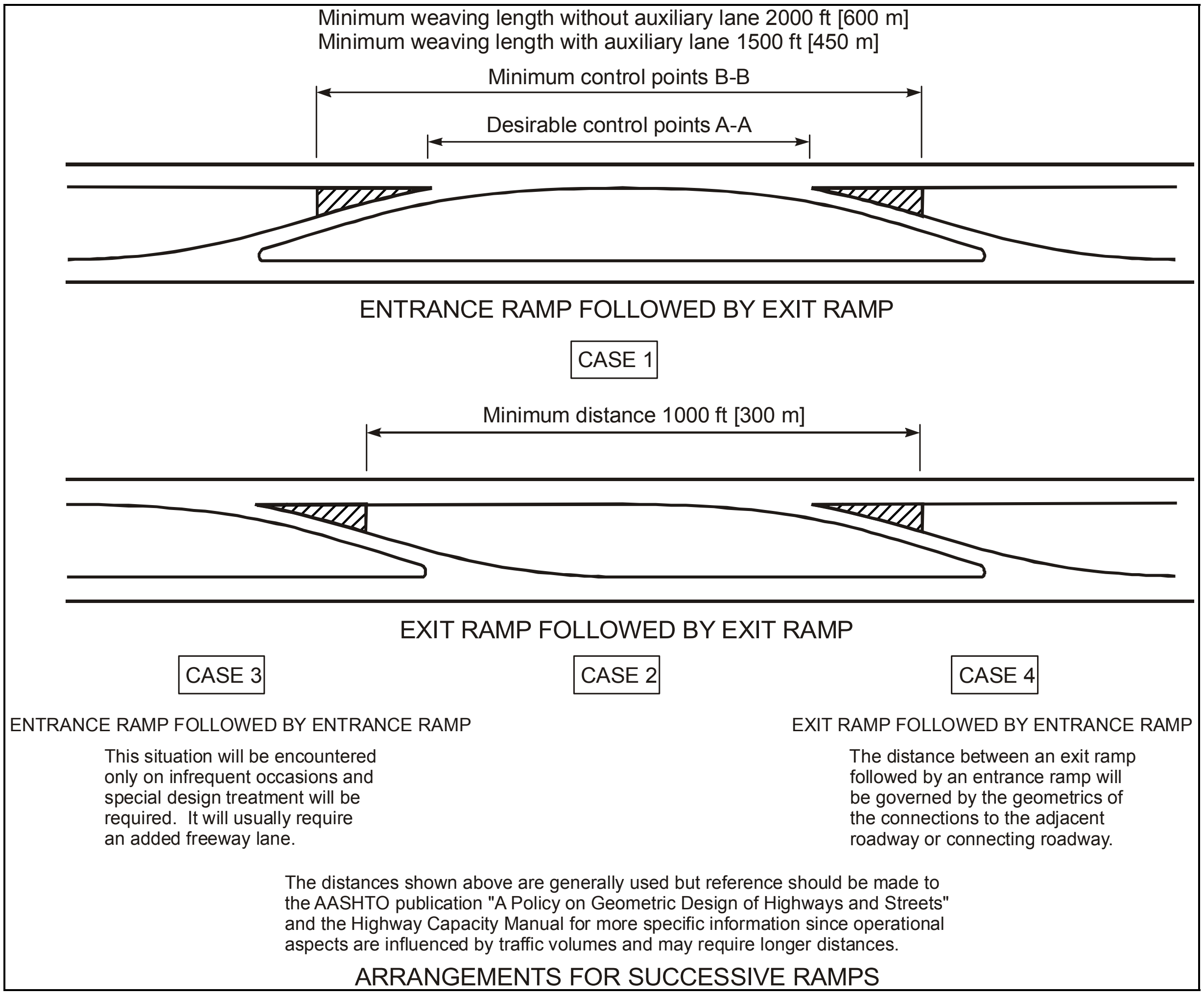


Figure 1-1. Arrangements for Successive Ramps from Texas *Roadway Design Manual* Figure 3-51 (*1*).

RESEARCH APPROACH

The research tools utilized in this project include reviews of the literature and previous research projects, field data, and simulation. Simulation allows for flexible modeling of complex weaving environment. Real-world data were collected to calibrate the simulation. The calibrated simulation was used to investigate a variety of different volumes and speeds. These combinations were used to determine the relationship of ramp spacing to design and operating speed on the freeway. In addition to simulation and field data, investigations included a review of the literature along with developing logical relationships between driving characteristics and weaving length.

REPORT ORGANIZATION

This report has seven chapters. Their topics are:

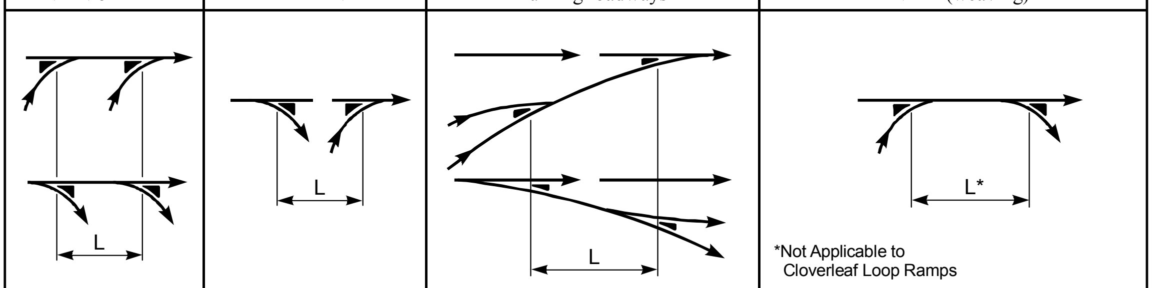
Chapter 1 **Introduction**—includes the objective of the project and the report organization.
Chapter 2 **Literature Review**—includes a summary of previous research relevant to the subject of freeway weaving along with a review of potential methods for calculating the length of an auxiliary lane along with discussion on sign spacing.
Chapter 3 **Field Studies**—includes information on how the speed and volume data were collected in the field.
Chapter 4 **Simulation**—provides a summary of the methodology used to generate the simulation data.
Chapter 5 **Analyze Results**—includes an explanation of the analyses of the field study and simulation data.
Chapter 6 **Develop Recommendations**—includes discussion on the findings from the different procedures investigated by the researchers along with the suggested guidance on minimum ramp spacing lengths.
Chapter 7 **Summary and Conclusions**—provides the summary, key findings from the field and simulation studies, and conclusions of the research.

CHAPTER 2

LITERATURE REVIEW

BACKGROUND

Figure 1-1 shows the guidance on ramp spacing included in the Texas *Roadway Design Manual.* Users of Figure 1-1 are referred to *A Policy on Geometric Design of Highways and Streets* (*Green Book*) for additional information. Figure 2-1 illustrates related *Green Book* guidance.



EN-EN or EX-EX		EX-EN		Turning roadways		EN-EX (weaving)			
						System to Service Interchange		Service to Service Interchange	
Full Freeway	CDR or FDR	Full Freeway	CDR or FDR	System Interchange	Service Interchange	Full Freeway	CDR or FDR	Full Freeway	CDR or FDR
Minimum lengths measured between successive ramp terminals									
300 m [1000 ft]	240 m [800 ft]	150 m [500 ft]	120 m [400 ft]	240 m [800 ft]	180 m [600 ft]	600 m [2000 ft]	480 m [1600 ft]	480 m [1600 ft]	300 m [1000 ft]

NOTES: FDR - Freeway Distributor Road
CDR - Collector Distributor Road
EN - Entrance
EX - Exit

The recommendations are based on operational experience and need for flexibility and adequate signing. They should be checked in accordance with the procedure outlined in the Highway Capacity Manual and the larger of the values is suggested for use. Also a procedure for measuring the length of the weaving section is given in chapter 24 of the 2000 Highway Capacity Manual. The "L" distances noted in the figures above are between like points, not necessarily "physical" gores. A minimum distance of 90 m [270 ft] is recommended between the end of the taper for the first on ramp and the theoretical gore for the succeeding on ramp for the EN-EN (similar for EX-EN).

Figure 2-1. Recommended Minimum Ramp Terminal Spacing, AASHTO 2004 Policy Exhibit 10-68 (*2*).

The dimensions in Figure 1-1 and Figure 2-1 are experienced-based and have "proven to be appropriate to accommodate ramp exit or entrance geometric criteria and for driver operational needs in spreading conflict or decision points. This spacing also results in smoother freeway operations with more uniform operating speed" (*5*). The recommended dimensions are not speed-dependent.

Geometric design guidance has traditionally existed for speeds ranging from 15 to 80 mph. Potential values for geometric elements designed for 85 to 100 mph speeds were included in a recently completed research project conducted for TxDOT (*4*). Design elements that were addressed in the final report included:

- sight distance,
- horizontal and vertical alignment,
- cross section,
- roadside design and hardware, and
- interchange ramps.

Recommendations have been incorporated into Chapter 8 of the *RDM*, "Mobility Corridor (5R) Design Criteria" (*1*). Researchers noted that current guidance on ramp spacing was not speed-dependent even though intuition and results of current analysis techniques indicate that spacing and speed are related (*4*).

This chapter provides a review of published criteria and existing knowledge on relationships between interchange ramp spacing, speed, and overall freeway operations.

PHYSICAL RELATIONSHIPS BETWEEN INTERCHANGE FEATURES

Ramp spacing, defined for the remainder of this project as the longitudinal distance between like points on successive interchange ramps, is interrelated to several design dimensions including the following:

- interchange spacing (crossroad-to-crossroad),
- longitudinal distance from crossroad to entrance and exit ramp gores,
- locations and radii of controlling ramp curves on the entrance and exit ramps, and
- ramp type.

Leisch (2005) provides a logical approach to illustrating these relationships (*5*) (see Figure 2-2). The figure is not directly applicable to all conditions, especially in Texas due to state-specific and unique characteristics (e.g., an extensive freeway frontage road system). However, it is a sensible starting point for later departure.

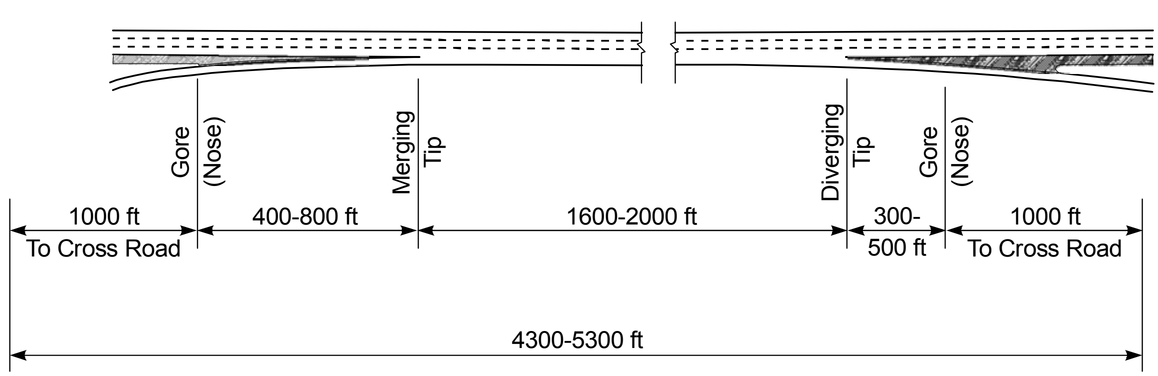


Figure 2-2. Relationship between Longitudinal Interchange and Ramp Dimensions (*5*).

The profile elevation of the freeway mainline and ramp match at the gore. The crossroad-to-gore dimension is an estimate to obtain the elevation change between freeway and crossroad (e.g., an elevation change of 22 ft between freeway and crossroad profiles that takes place over 1000 ft results in an average 2.2 percent grade on the ramp). It is also a reasonable dimension for storage of queued vehicles on the exit ramp or for ramp metered storage on the entrance ramp. The distance from the gore to the merging or diverging tips is related to the type of ramp design (i.e., parallel or taper) and the location and radius of the controlling curve on the ramp. The distance between merging and diverging tips shown in Figure 2-2 is based on existing guidance in the *Green Book* (see Figure 2-1). Similar guidance exists in the *RDM* (see Figure 1-1) and is the focus of this research. Acceleration and deceleration lanes may be oriented to span across all or parts of the labeled dimensions (i.e., crossroad-to-gore, gore-to-tip, and tip-to-tip).

The sum of these dimensions represents a crossroad-to-crossroad interchange spacing, in this case, an approximate 1-mile minimum recommended by many state departments of transportation (DOTs) for urban areas. Several conditions may influence the cited dimensions, including:

- ramp sequence,
- presence and type of frontage roads,
- number of ramp lanes,
- additional vehicle storage requirements at entrance or exit,
- channelized or braided ramps, and
- collector-distributor roads.

Relationships between interchange-related dimensions are important considerations in developing ramp spacing recommendations. For example, the recommended spacing between successive entrance ramps in the *Geometric Design Guide for Canadian Roads* is based on the distance required for vehicles from the first entrance ramp to accelerate and merge with mainline traffic (*6*). Therefore, acceleration lane presence and length may ultimately influence recommended ramp spacing.

A HISTORIC LOOK AT RAMP SPACING DESIGN DIMENSIONS

Ramp spacing has long been recognized and addressed in geometric design policies of AASHO (American Association of State Highway Officials), which is the former name of AASHTO (American Association of State Highway and Transportation Officials). One of the earliest AASHO publications on geometric design policy, the 1944 edition entitled *A Policy on Grade Separations for Intersecting Highways,* addressed the issue for the first time (*7*). This 1944 policy did not suggest any dimensions for ramp spacing; it introduced different ramp sequences and included several examples of ramp combinations. The use of an auxiliary lane to connect an entrance ramp followed by an exit ramp was also suggested in this early AASHO geometric design policy.

In the subsequent AASHO publications, more specific recommendations on ramp spacing were developed. The 1954 AASHO policy, *A Policy on Geometric Design of Rural Highways* (*8*), recommended conducting weaving analyses using the procedures included in the 1950 edition of the *Highway Capacity Manual* to determine the distance between an entrance ramp and an exit ramp. The next AASHO policy, adopted in 1957 entitled *A Policy on Arterial Highways in Urban Areas* (*9*), provided more detailed guidelines on the distance between successive ramp terminals. This edition of AASHO policy suggested that the consecutive ramp terminals should be properly spaced and the ramp maneuver areas should be separated from one another to avoid multiple and complex maneuvers. The policy stated that the required spacing distance between ramps could not be precisely determined. It varied with different conditions such as sufficient sight distance and adequate signing and knowledge of the highway by most drivers through repeat use. The most important improvement of this 1957 edition from the preceding versions was diagrams of various ramp combinations with minimum and desirable spacing distances between ramp terminals. Table 2-1 lists the distances provided in the 1957 AASHO policy. The numbers given as minimum distances between ramp terminals were based on a combined decision and maneuver time of 5 to 6 seconds for operation at average running speeds and the values of desirable spacing lengths were given on the basis of 7 seconds of combined decision and maneuver time and operation at design speed.

Table 2-1. Distance between Successive Ramp Terminals from AASHO 1957 Policy Figure J-5 (*9*).

Design speed (mph)	30 or less	40 to 50	60 or more
Average running speed (mph)	20 to 25	35 to 40	45 to 50
Distance (ft)			
Minimum	175	300	400
Desirable	300	450	600

The next edition of AASHO policy on geometric design published in 1965 entitled *A Policy on Geometric Design of Rural Highways* (*10*) provided similar diagrams. Minimum and desirable distances between ramp terminals suggested in the 1965 AASHO policy were larger than those included in the preceding edition because these values were computed based on longer decision and maneuver time. Time used for calculation of these recommended ramp spacing distances was 5 to 10 seconds instead of 5 to 6 seconds, or 7 seconds as in the 1957 edition. Average running speeds used in this 1965 AASHO policy were also higher than those included in the previous document and a new category of 80 mph design speed was also added to the table. This publication also noted that in most cases, the required lengths of speed-change lanes should be the governing values and greater values than those shown in the table should be preferred, allowing drivers to have adequate signing distances (and time). The minimum for sufficient signing distances were suggested to be 1000 ft for consecutive exits on a freeway and 600 ft for a freeway exit followed by an exit on a collector-distributor road. Figure 2-3 and Table 2-2 show the aforementioned diagrams and suggested spacing distances included in the 1965 AASHO policy.

Table 2-2. Distance between Successive Ramp Terminals from AASHO 1965 Policy Figure IX-11 (*10*).

Design speed (mph)	30 or less	40 to 50	60 to 70	80
Average running speed (mph)	23 to 28	36 to 44	53 to 58	64
Distance (ft)				
Minimum	200	400	500	900
Desirable	400	700	900	1200

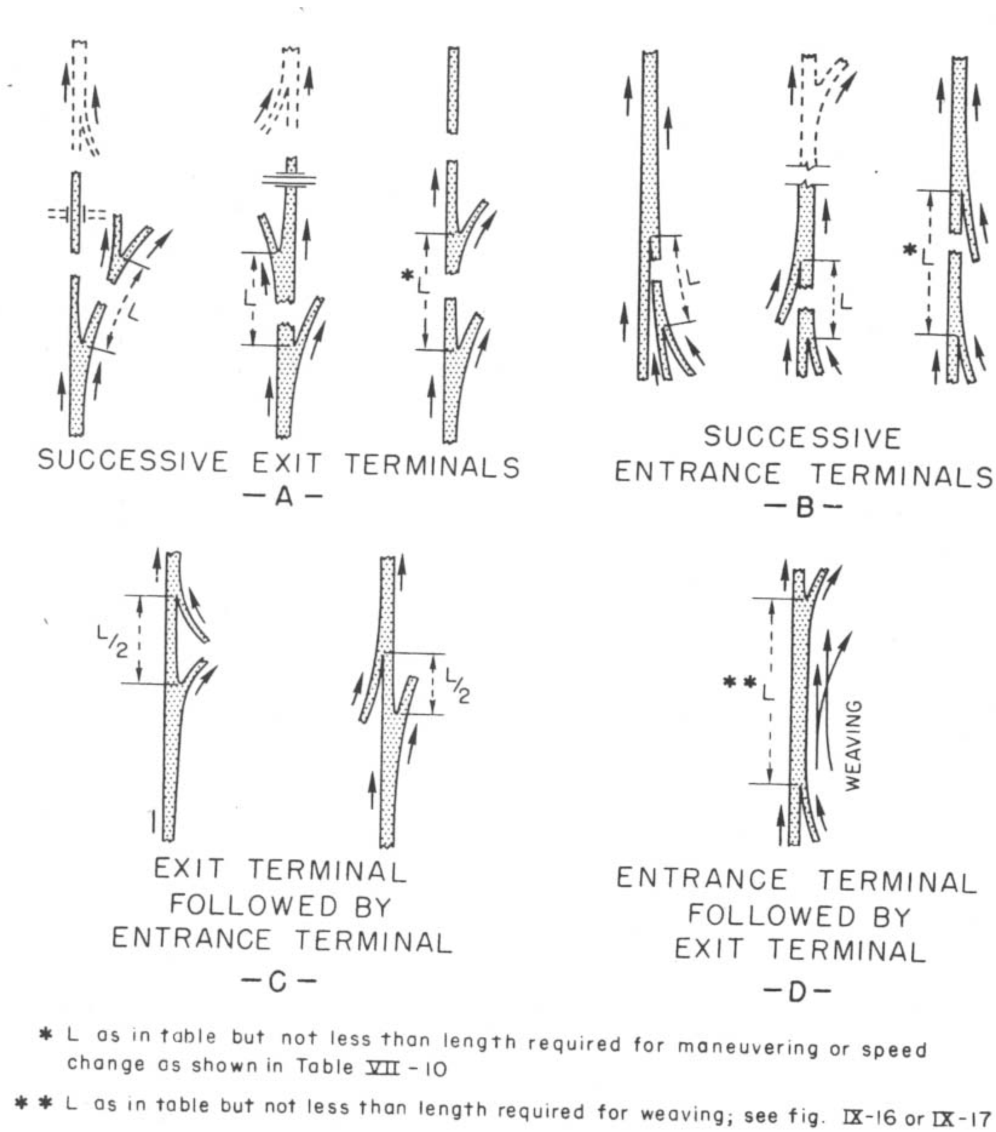


Figure 2-3. Arrangements for Successive Ramp Terminals, AASHO 1965 Policy Figure IX-11 (*10*).

Unlike the AASHO policies published in 1957 and 1965, the new AASHTO policy entitled *A Policy on Design of Urban Highways and Arterial Streets* published in 1973 (also known as the 1973 *Red Book*) (*11*), did not retain the ramp terminal arrangement diagrams from the previous editions. This document provided suggestions for minimum distances between successive exit ramp terminals of 1000 ft and 800 ft for the spacing lengths between exits on a freeway, and between an exit on a freeway and an exit on a collector-distributor road, respectively. Figure 2-4 illustrates these suggestions.

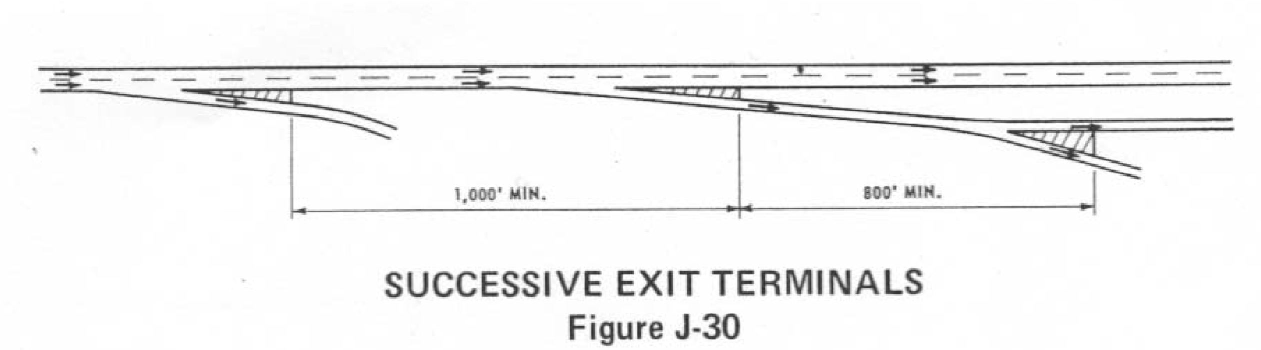
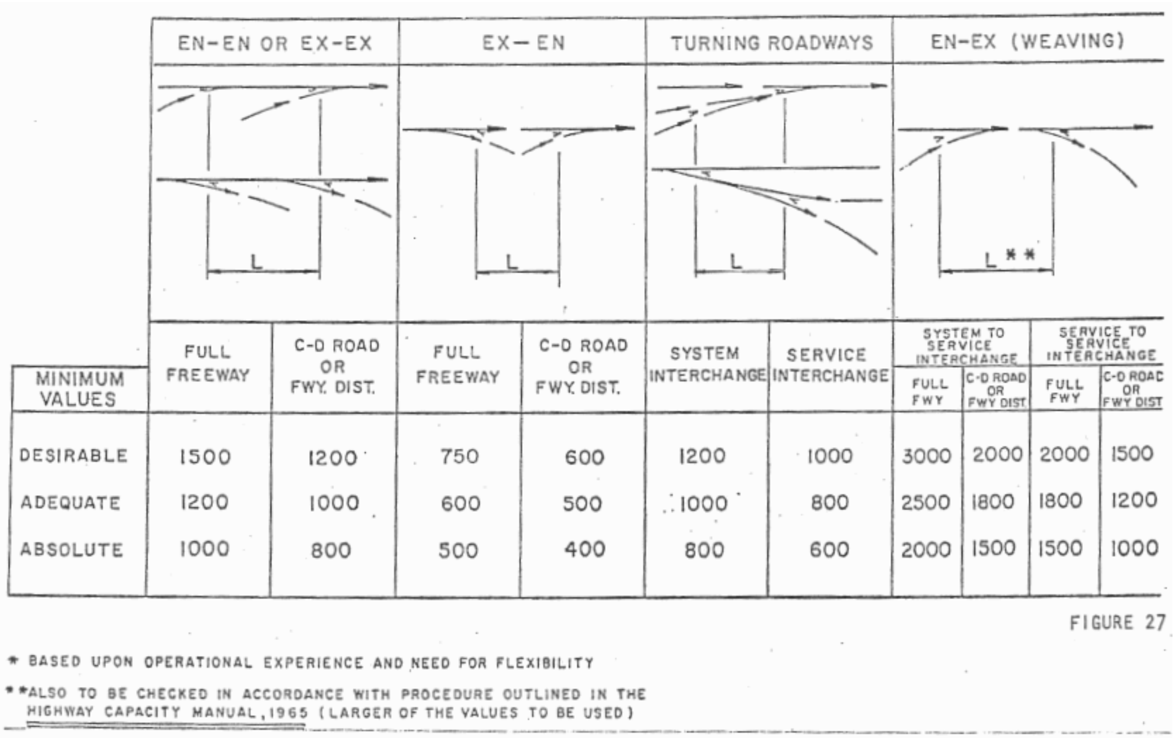


Figure 2-4. Successive Exit Terminals, AASHTO 1973 Policy Figure J-30 (*11*).

The 1973 *Red Book* (*11*) also stated that the distance between an entrance ramp followed by an exit ramp should be governed by weaving requirements and it should not be less than 1000 ft. Where an exit ramp is followed by an entrance ramp, the distance between them should be "reasonable" and should be at least 500 ft. This document also suggested connecting the speed-change lanes to provide a continuous lane where the distance between the end of entrance terminal taper and beginning of exit terminal taper was less than about 1500 to 2000 ft.

Addressing the same issue, in a paper by J. E. Leisch, presented at the Region 2 AASHTO Operating Committee on Design in 1975 entitled *"*Application of Human Factors in Highway Design*"* (*12*), a table with diagrams and recommended minimum distances between ramp terminals for various ramp terminal combinations were introduced. Figure 2-5 shows these diagrams and recommended values.

These diagrams, and the "absolute minimum values" introduced by Leisch were later adopted and included in the 1984 AASHTO policy (see Figure 2-6) (*13*) and have remained in the succeeding editions of the AASHTO *Green Book* published in 1990 (*14*), 1994 (*15*), and 2001 (*16*), as well as the latest and current edition published in 2004 (3). Metric measurements with equivalent values were used in the 1994 edition of the AASHTO *Green Book* (*15*) instead of U.S. standard units. Both measurement systems were included in 2001 and 2004 *Green Books* but the recommendations that appeared in the 1984 AASHTO *Green Book* have been relatively unchanged. The 1984 AASHTO policy also suggested connecting the speed-change lanes to provide an auxiliary lane when the distance between noses of an entrance ramp followed by an exit ramp was less than 1500 ft. This recommendation has also remained in the later editions, including the latest one, the 2004 edition of AASHTO *Green Book* (*3*) (see Figure 2-1).



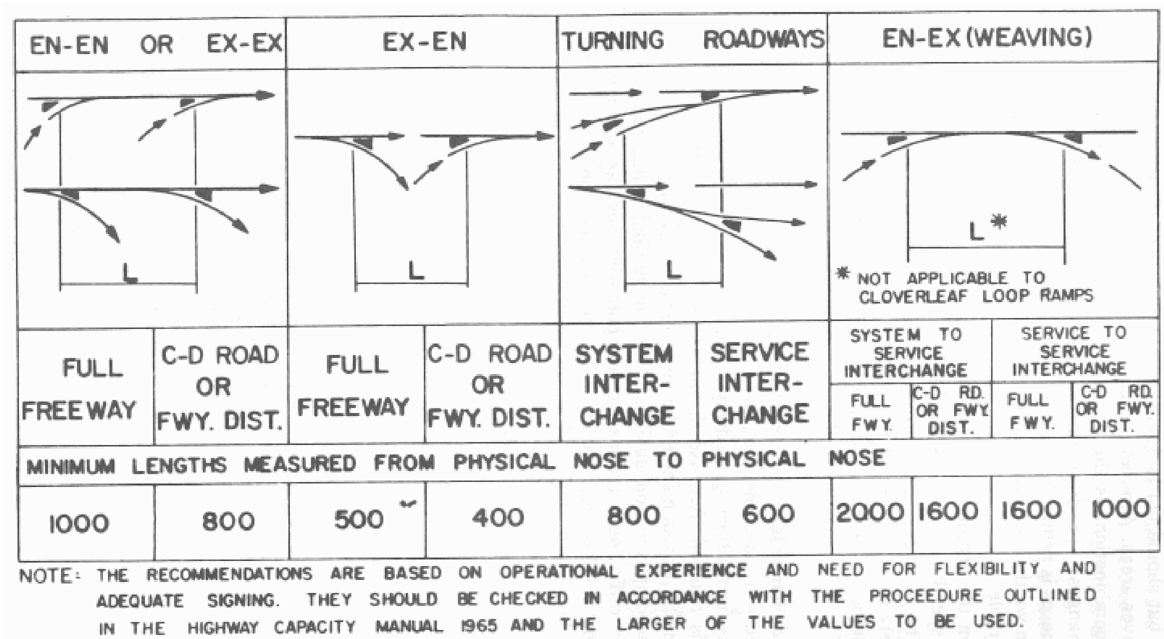
MINIMUM VALUES	EN-EN OR EX-EX		EX-EN		TURNING ROADWAYS		EN-EX (WEAVING)			
							SYSTEM TO SERVICE INTERCHANGE		SERVICE TO SERVICE INTERCHANGE	
	FULL FREEWAY	C-D ROAD OR FWY. DIST.	FULL FREEWAY	C-D ROAD OR FWY. DIST.	SYSTEM INTERCHANGE	SERVICE INTERCHANGE	FULL FWY	C-D ROAD OR FWY DIST	FULL FWY	C-D ROAD OR FWY DIST
DESIRABLE	1500	1200	750	600	1200	1000	3000	2000	2000	1500
ADEQUATE	1200	1000	600	500	1000	800	2500	1800	1800	1200
ABSOLUTE	1000	800	500	400	800	600	2000	1500	1500	1000

FIGURE 27

* BASED UPON OPERATIONAL EXPERIENCE AND NEED FOR FLEXIBILITY

**ALSO TO BE CHECKED IN ACCORDANCE WITH PROCEDURE OUTLINED IN THE HIGHWAY CAPACITY MANUAL, 1965 (LARGER OF THE VALUES TO BE USED)

Figure 2-5. Recommended Minimum Ramp Terminal Spacing, Leisch, 1975 (*12*).



EN-EN OR EX-EX		EX-EN		TURNING ROADWAYS		EN-EX (WEAVING)			
						SYSTEM TO SERVICE INTERCHANGE		SERVICE TO SERVICE INTERCHANGE	
FULL FREEWAY	C-D ROAD OR FWY. DIST.	FULL FREEWAY	C-D ROAD OR FWY. DIST.	SYSTEM INTER-CHANGE	SERVICE INTER-CHANGE	FULL FWY.	C-D RD. OR FWY. DIST.	FULL FWY.	C-D RD. OR FWY. DIST.
MINIMUM LENGTHS MEASURED FROM PHYSICAL NOSE TO PHYSICAL NOSE									
1000	800	500	400	800	600	2000	1600	1600	1000

NOTE: THE RECOMMENDATIONS ARE BASED ON OPERATIONAL EXPERIENCE AND NEED FOR FLEXIBILITY AND ADEQUATE SIGNING. THEY SHOULD BE CHECKED IN ACCORDANCE WITH THE PROCEEDURE OUTLINED IN THE HIGHWAY CAPACITY MANUAL 1965 AND THE LARGER OF THE VALUES TO BE USED.

Figure 2-6. Recommended Minimum Ramp Terminal Spacing, 1984 AASHTO *Green Book* Figure X-67 (*13*).

OPERATIONAL ANALYSIS OF INTERCHANGE RAMPS AND RAMP SPACING

Figure 1-1 and Figure 2-1 (and their predecessors) are guidelines, intended for use in planning and conceptual design. Detailed operational analyses are recommended during final design (*5*). Both the *Green Book* (*3*) and *RDM* (*1*) reference the *Highway Capacity Manual* (*2*) in this regard.

Highway Capacity Manual

The *Highway Capacity Manual* consists of techniques for estimating capacity and quality of service for:

- rural highways,
- urban streets,
- freeways and interchanges,
- intersections, and
- transit, pedestrian, and bicycle facilities.

The first edition of the *HCM* was published by the Bureau of Public Roads (BPR) in 1950 (*17*). Subsequent editions were developed and revised by the Highway Research Board (HRB) (*18*) and the Transportation Research Board (TRB) (*2*, *19, 20, 21*).

The TRB Committee on Highway Capacity and Quality of Service oversees current activities related to the *HCM*. The committee reviews and approves (for inclusion in the *HCM*) research results with a goal of providing practitioners a set of consistent and methodologically sound analysis techniques for a range of facility types. The most recent version of the *HCM* is the 2000 edition (*2*); research and planning for a 2010 edition is currently under way. Methods most relevant to this research are those for analysis of freeway weaving and ramps and ramp junctions.

Freeway Weaving

Weaving is defined as "the crossing of two or more traffic streams traveling in the same general direction along a significant length of highway without the aid of traffic control devices" (*2*). Weaving may be present at several geometric configurations; the configuration most relevant to this research is when an entrance ramp of one interchange is followed by an exit ramp of an adjacent, downstream interchange. The *HCM* further narrows the scope of weaving by including only successive ramps that are connected with an auxiliary lane. The *RDM* and *Green Book* do not make this exact distinction, but *RDM* spacing recommendations for the entry-exit sequence are dependent on auxiliary lane presence (see Figure 1-1 and Figure 2-1). Weaving is also present within single interchanges with successive loop ramps (e.g., a cloverleaf interchange). However, guidelines in Figure 1-1 and Figure 2-1 are not applicable to this case.

As the length of a freeway weaving segment increases, lane changes from entrance and exit maneuvers are spread across additional space and operational characteristics become more like those of a basic freeway segment. The maximum length of a weaving segment when it should be treated as a weaving section rather than an isolated entrance ramp followed by an exit ramp varies. Methods of the *HCM* generally apply to weaving segments up to 2500 ft in length. Other procedures are applicable up to 8000 ft (depending on total weaving volume) (*22*). A general rule-of-thumb, first offered in *Highway Research Board Bulletin 167* (*23*), is that a weaving segment should be treated as weaving if the number of lane changes per unit length is greater than on similar sections of freeway outside the influence of entrance or exit ramps. Sections that do not meet this criterion are considered "out of the realm of weaving" (e.g., see [*22*]) and can be treated as three distinct features: (a) an entrance ramp, (b) a basic freeway segment, and (c) an exit ramp.

Since the first edition of the *HCM*, analytical methods, discussions, and supporting data have pointed toward two basic weaving premises:

- Vehicles that weave and vehicles that do not weave "separate themselves from each other (in practice) almost as positively as they do in theory" (*17*).
- As the number of weaving vehicles increases and/or the length available for weaving decreases, the weaving maneuver becomes more difficult and drivers will decrease speeds while they search for available gaps and make the weaving maneuver.

Figure 2-7 illustrates these operating characteristics, which is a 1957 update to an original figure provided in the 1950 *HCM*.

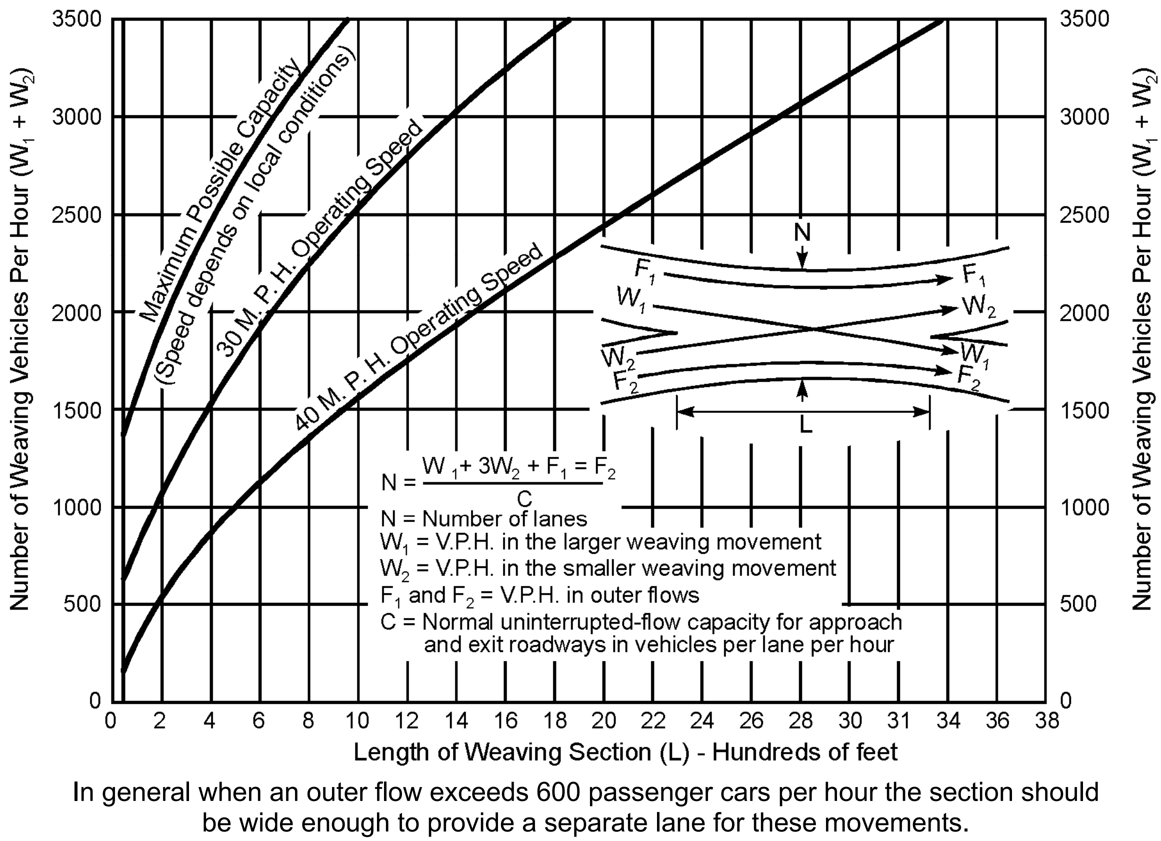


Figure 2-7. Operating Characteristics of Weaving Sections (*23*).

The *HCM* methodology for analyzing weaving segments has been updated on several occasions as additional field data and evaluations of prediction capabilities became available. A modern and comprehensive database of sufficient size for a complete calibration of the weaving methodology does not exist; the *Committee on Highway Capacity and Quality of Service* has incorporated necessary judgments to compensate for the data deficiencies (*24*). The product (to date) is a useable analysis technique with results that are generally consistent with intuitive relationships between weaving length, weaving volume, and speed expressed by the following model (*2*):

$$S_i = 15 + \left[\frac{FFS - 10}{1 + W_i} \right] \tag{1}$$

$$W_i = \frac{a(1 + VR)^b (v/N)^c}{L^d} \tag{2}$$

where:

S_i = average speed of weaving ($i = w$) and non-weaving ($i = nw$) vehicle (mph);

FFS = average free-flow speed of freeway segments entering and leaving the weaving segment (mph);

W_i = weaving intensity factor for weaving ($i = w$) and non-weaving ($i = nw$) flows;

VR = volume ratio, the ratio of weaving flow rate to total flow rate in the weaving segment;

v = total flow rate in weaving segment (passenger car/hour, pc/h);

N = total number of lanes in weaving segment;

L = length of weaving segment (ft); and

a, b, c, d = calibration constants.

Figure 2-8 and Figure 2-9 illustrate examples of these relationships. Both figures were developed using the methodology in *HCM 2000* (*2*) for Type A weaving segments. A large number of volume-weaving length combinations were tested within the boundaries shown on the graph axes. Free-flow freeway mainline speeds of 60 mph and 80 mph were assumed. The weaving segments consisted of two through lanes plus an auxiliary lane connecting single-lane entrance and exit ramps. The figures show that for a given weaving length, speeds of weaving and non-weaving vehicles decrease as the weaving volume increases. Similarly, speeds increase as weaving length increases for a given weaving volume. The speed differential between a weaving segment and its approach roadway has been suggested as a possible performance measure for operational quality (*2*). Information presented in the format of Figure 2-8 and Figure 2-9 would be useful in this regard.

A separate procedure for design and analysis of weaving sections was developed by Jack E. Leisch in the late 1970s, independent from parallel efforts to develop materials for what would be included in the 1985 edition of the *HCM* . Information from several sources was used by Leisch (*18, 25, 26*), along with analytical modeling and rational formulations based on his considerable experience designing and analyzing weaving areas. The procedure was presented in a user-friendly format and is still referenced by several state DOTs (e.g., see [*27*]). Figure 2-10 illustrates Leisch's technique for analysis of one-sided weaving configurations. A recalibrated version of the nomographs using level of service density thresholds from *HCM 2000* is provided in the *Freeway and Interchange Geometric Design Handbook* (5).

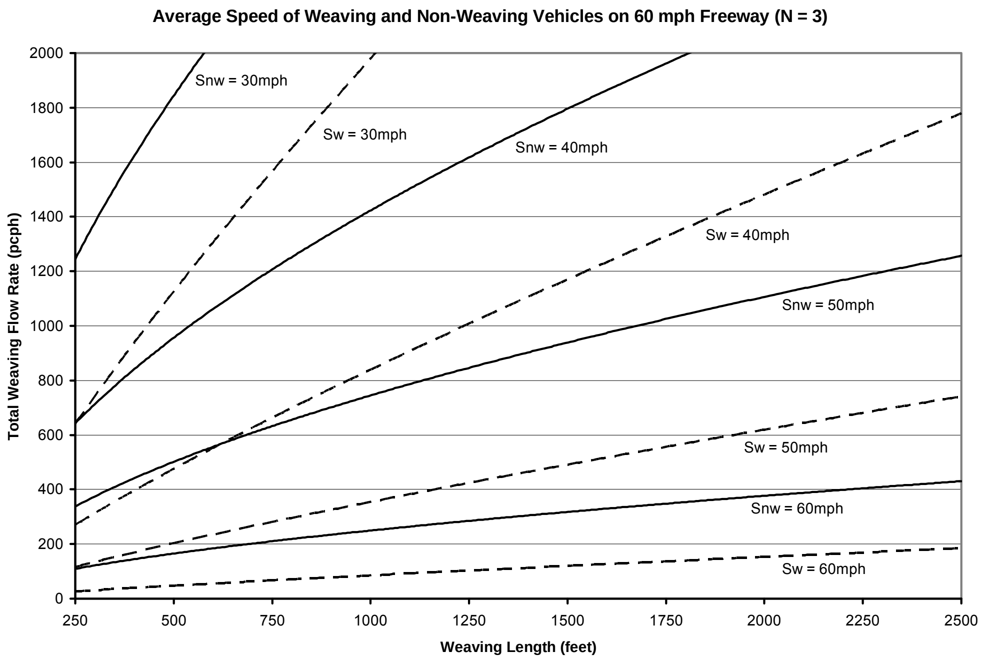


Figure 2-8. Relationships between Weaving Length, Weaving Flow Rate, and Speed on a 55 mph Freeway.

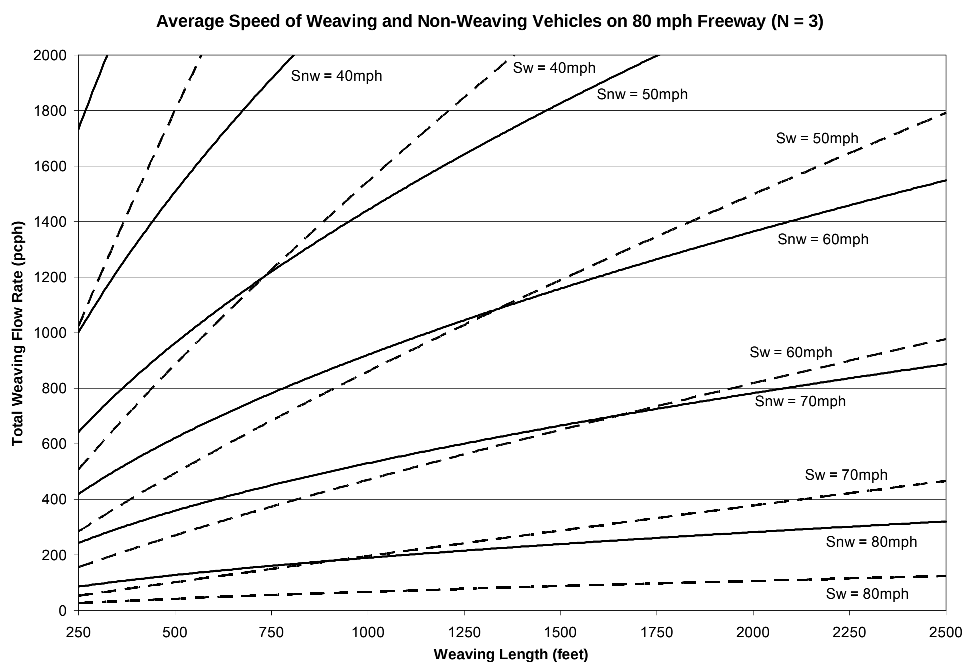
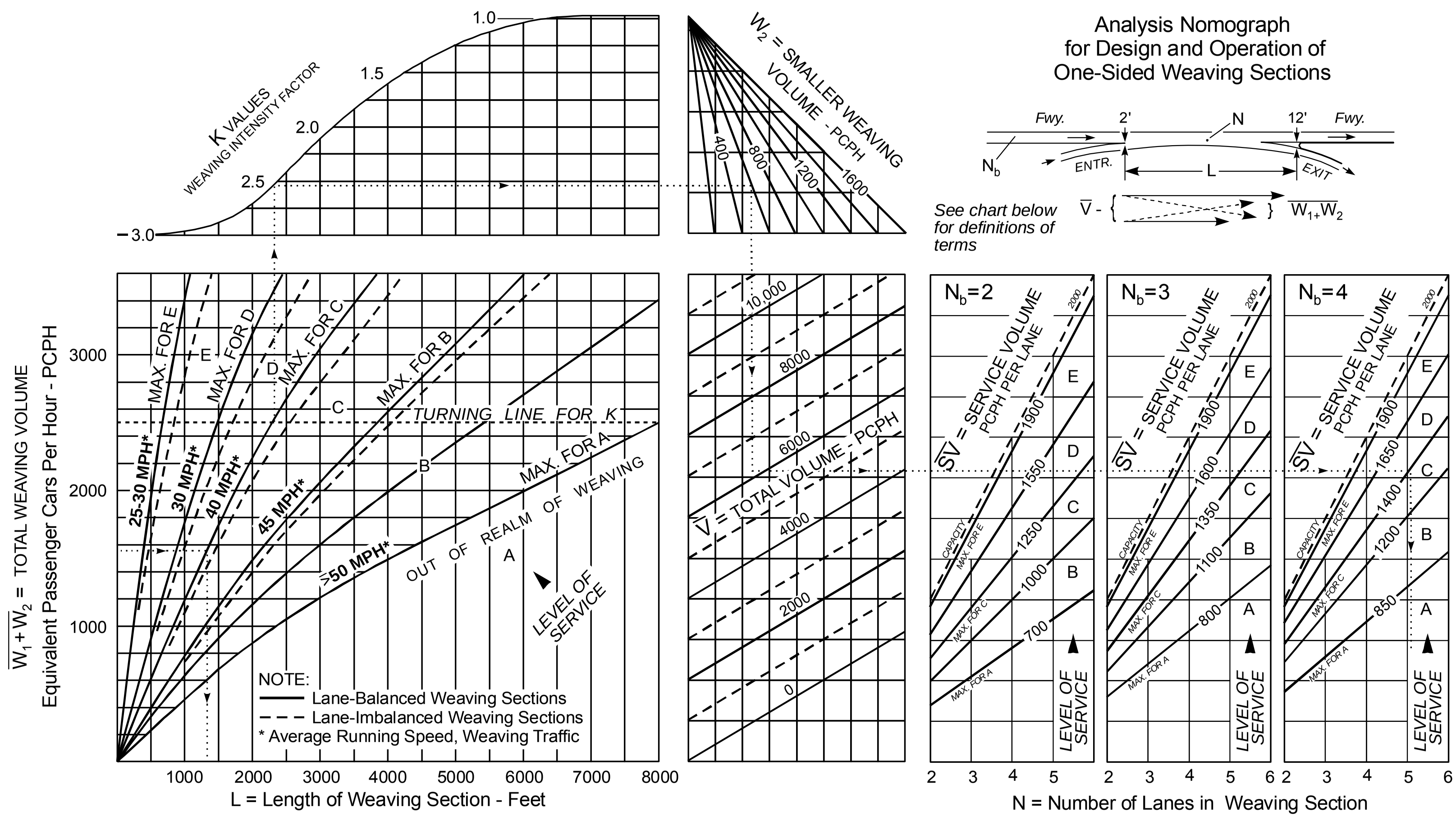


Figure 2-9. Relationships between Weaving Length, Weaving Flow Rate, and Speed on an 75 mph Freeway.



Nomograph for Design and Analysis of Weaving Sections – One-Sided Configurations

Figure 2-10. Nomograph for Design and Analysis of Weaving Sections – One-Sided Configurations (*22*).

Ramps and Ramp Junctions

Ramp-freeway junctions take two general forms: (a) merge areas where vehicles from an entrance ramp enter freeway mainline traffic to form a single traffic stream and (b) diverge areas where the freeway traffic stream separates into two traffic streams at an exit ramp. Merge and diverge areas are places of potential operational turbulence; vehicles wishing to merge or diverge compete for space with through moving vehicles. The amount of turbulence generally depends on:

- freeway and ramp volumes,
- distribution of traffic across available lanes (i.e., lane usage),
- gap acceptance behavior, and
- speed differentials between through and merging or diverging vehicles.

Increased turbulence coincides with higher traffic densities and slower speeds.

Capacities of merge and diverge areas are not influenced by the intensity of traffic turbulence, but by capacities of the roadways themselves. The capacity of a merge area is normally limited by the capacity of the downstream freeway segment (*2*). The capacity of a diverge area may be limited by:

- the freeway capacity upstream or downstream of the diverge,
- the capacity of the ramp proper, or
- the capacity of the ramp-crossroad terminal (*2*).

Discussions and data in early *HCM* editions primarily focused on ramp capacities and lane usage (*17, 18, 19*). Analysis techniques in the *HCM* from 1994 onward are based on results of National Cooperative Highway Research Program (NCHRP) Project 3-37. The current techniques account for influences of adjacent upstream and downstream ramps on vehicle density for six-lane freeway cross sections (*2*). Effects are seen through increased lane usage on the side of the freeway with the ramp (normally the right-hand side). The magnitude of the effect depends on the distance to the adjacent ramps (i.e., ramp spacing); the effect does not appear as elastic to overall freeway operations as weaving length.

The presence and length of an acceleration lane influence lane usage, density, and speed estimates at merge areas in the *HCM 2000* methodology. Presence and length of a deceleration lane influence density estimates in diverge areas (*2*).

Microscopic Simulation

Microscopic simulation models are increasingly becoming operational analysis alternatives, especially for complex highway networks and geometric conditions including closely spaced interchange ramps (*5*). While the *HCM* is macroscopic, based primarily on relationships between average measures of speed, density, and flow, microscopic simulation models are based on vehicle-to-vehicle car-following phenomena and individual driver and vehicle characteristics. The models are still in relatively early stages of development and use; their algorithms are commonly evaluated on whether the simulated results match user-intuition and conform to relationships consistent with those in the *HCM* (e.g., see [*24*]).

Microscopic simulation has been applied to modeling weaving, merge, and diverge areas (e.g., *28, 29*). The most important step during the application of microscopic simulation is calibration, where the ability of the simulation model to replicate real-world conditions is tested. Roess and Ulerio provided the following recommendations for a definitive study on weaving sections that uses a combination of field data and simulation (*24*):

- Collect enough data to be able to calibrate and test a simulator over a range of configurations, lengths, widths, flow levels, and proportions of weaving vehicles.
- Calibrate an existing simulator or develop and calibrate a new simulator to more accurately duplicate lane-changing behavior and other microscopic characteristics of weaving operations within weaving areas.
- Use a simulator to produce a wide range of results for all important variables to supplement field data and for use in calibrating a new, more comprehensive procedure (than in the *HCM*).

NCHRP Project 3-75

A new model to analyze performance in freeway weaving sections, developed as part of NCHRP Project 3-75, is currently being evaluated by the TRB *Committee on Highway Capacity and Quality of Service* for possible inclusion in the 2010 *HCM* (*30, 31*). The proposed model has one notable difference from the *HCM 2000* methods that is of particular importance to this research project:

> "Speed-prediction algorithms are not separated by weaving configuration (i.e., Type A, B or C) or by relative operational quality of weaving and non-weaving vehicles (i.e., constrained or unconstrained). There is a single algorithm for predicting weaving speeds and a single algorithm for predicting non-weaving speeds, both of which require the output of new algorithms that predict lane-changing activity. The lane changing algorithm is intended to capture the impact of weaving configuration and type of operations on resulting speeds and densities."

NCHRP Project 3-75 researchers also revisited and redefined the measurement of weaving length, historically defined as "the length from a point at the merge gore where the right edge of the freeway shoulder lane and the left edge of the merging lane(s) are 2 ft apart to a point at the diverge gore where the two edges are 12 ft apart" (*2*). Chapter 3 discusses their proposed weaving length measurements: *short length*, *base length,* and *long length*.

Within their methodology they discussed the concept of "maximum length" of a weaving section. Maximum length is the length at which weaving turbulence no longer has an impact on the operations within the section or, alternatively, on the capacity of the weaving section. They noted that the definition selected will impact the value. Weaving turbulence can have an impact on operations (i.e., weaving and non-weaving vehicle speeds) for distances far in excess of those defined by when the capacity of the section is no longer affected by weaving. The methodology proposed for the 2010 *HCM* uses the latter definition because if longer lengths were treated as weaving sections, the methodology would produce a capacity for the weaving section that exceeds that of a basic freeway section with the same number of lanes and conditions. The following equation is to be used to determine the length at which the capacity of the weaving section is the same as a basic freeway section with the same number of lanes:

$$L_{max} = [5728(1+VR)1.6]-[1566*N_{WL}] \quad (3)$$

where:

L_{max} = the maximum weaving section length (using the short-length definition);
VR = volume ratio: $VR = v_W/v$;
v = total demand flow rate in the weaving section (pc/h);
v_W = weaving demand flow rate in the weaving section (pc/h): $v_W = v_{RF} + v_{FR}$;
v_{RF} = ramp-to-freeway demand flow rate in the weaving section (pc/h);
v_{FR} = freeway-to-ramp demand flow in the weaving section (pc/h); and
N_{WL} = number of lanes from which a weaving maneuver may be made with one or no lane changes (for a section with an auxiliary lane, $N_{WL} = 2$).

The equation was derived by setting the per-lane capacity of a weaving section (with the prevailing conditions that exist) equal to the per-lane capacity of a basic freeway section (with the same prevailing conditions).

The equation is not a function of the design speed of the facility; therefore, it can be implied that the proposed procedure assumes that design speed does not impact the operations of a weaving area. The equation is sensitive to the volume ratio, as shown in Figure 2-11. As VR increases the impact of weaving turbulence would extend further. If the weaving demand is about 30 percent of the total demand, a length of approximately 5600 ft would be needed to have all the weaving influenced area be between the two ramps.

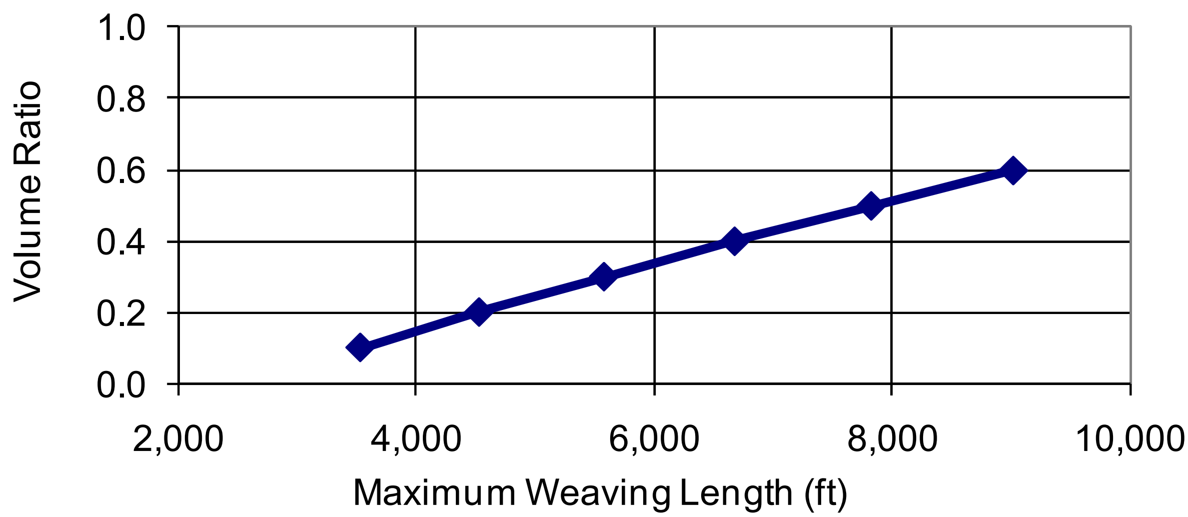


Figure 2-11. Maximum Weaving Length for Volume Ratio Based on Proposed Equation for the 2010 *HCM*.

INTERNATIONAL GUIDANCE

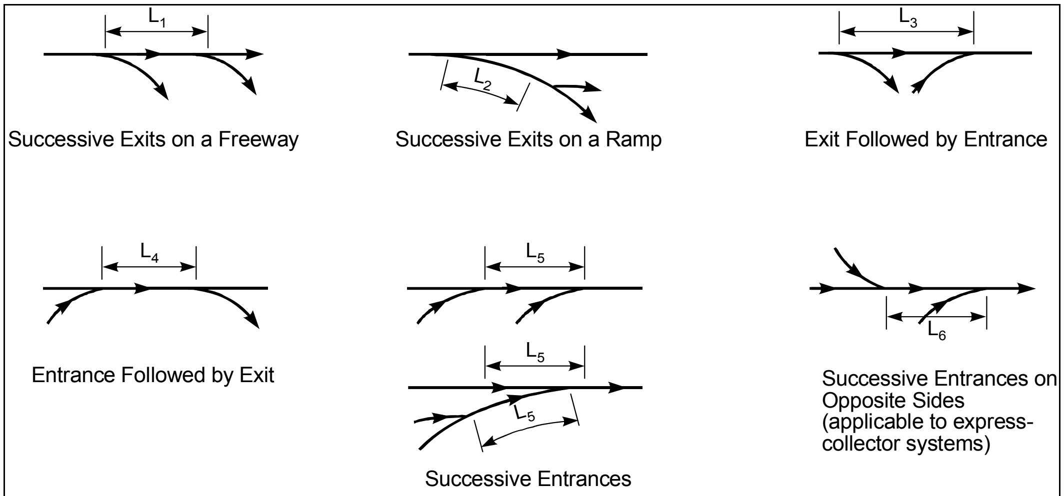
Geometric design guidance documents from Canada and England include speed-dependent ramp spacing criteria (6, *32*). Personal correspondence with design and research colleagues from both countries indicated the guidance has been around for some time; its origin and the existence of supporting research results were unknown. General freeway, interchange, and ramp design considerations and principles in Canada and England are similar to United States practice. A review of their procedures is therefore well within this project scope.

The Transportation Association of Canada (TAC) bases its ramp terminal spacing guidance contained in the *Geometric Design Guide for Canadian Roads* on the principle that drivers must be able to "make decisions in sufficient time to make safe maneuvers" (*6*). Table 2-3 summarizes specific considerations for alternative scenarios. Accompanying design values are illustrated in Figure 2-12. Values are not provided for successive entrance ramps; however, consideration of acceleration and merging indicate that spacing will generally increase as mainline design speeds increase due to the presence of longer acceleration lanes. Weaving lengths of 2600 to 3300 ft for freeway-to-arterial interchanges and 1800 to 2300 ft for arterial-to-arterial interchanges are generally recommended for efficient operations (*6*). However, the need for shorter lengths imposed by site-specific constraints is recognized. Weaving lengths longer than 3300 ft are considered "out of the realm of weaving" (*6*).

Ramp spacing guidance contained in the *Design Manual for Roads and Bridges* published by the Highways Agency in England is based on effective signing and signaling and the specific characteristics of different roadway types (*32*). It is summarized in Table 2-4 and Figure 2-13. Recommended spacing is dependent only on design speed for all ramp sequence combinations except an entrance followed by exit (i.e., weaving). Recommended weaving lengths range from 3300 to 6600 ft for rural roadways and are speed and volume dependent for urban roadways. The maximum possible weaving length, interpreted as meaning the boundary between weaving sections and sections out of the realm of weaving, is 9800 ft on rural motorways and 6600 ft on all-purpose rural roads.

Table 2-3. Considerations for Ramp Terminal Spacing in the *Geometric Design Guide for Canadian Roads* (*6*).

Ramp Sequence	Spacing Consideration
Exit followed by exit	Provision of adequate signing
Exit followed by entrance	Allow vehicle on a through lane to prepare for the merge ahead after passing the exit nose
Entrance followed by entrance	Required length for acceleration and merging
Entrance followed by exit	*HCM* weaving analysis



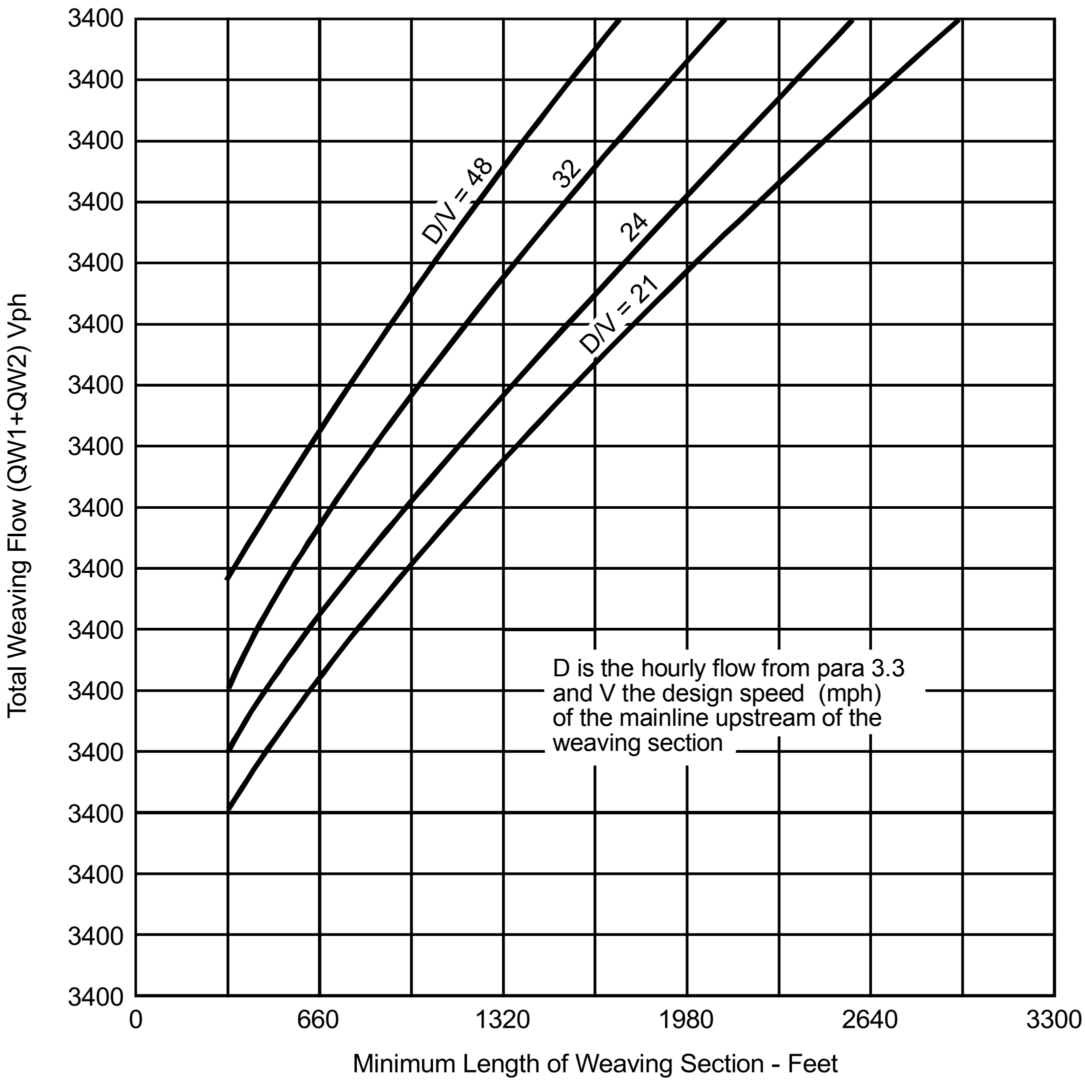
Spacing[1] (ft)	Main line design speed (mph) 50	55	60	70	75	80
L_1	980	1070	1150	1230	1230	1390
L_2	660	740	820	1230	980	1070
L_3	490	490	570	570	660	660
L_4	Based on weaving requirements Subsection 2.1.7.3					
L_5	Sufficient to allow for acceleration and merging length before second entrance					
L_6	60% of L_5					

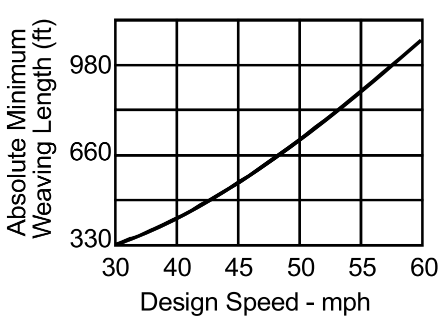
[1] Minimum lengths from bullnose to bullnose

Figure 2-12. Ramp Terminal Spacing (*6*) (Figure Converted to U.S. Customary Units).

Table 2-4. Guidance for Ramp Terminal Spacing in the *Design Manual for Roads and Bridges* (*32*).

Ramp Sequence	**Recommended Spacing and Weaving Length**
Exit followed by exit	19.8*V ft (with V in mph)
Exit followed by entrance	19.8*V ft (with V in mph)
Entrance followed by entrance	19.8*V ft (with V in mph)
Entrance followed by exit	Rural motorways: 6600 ft
	Rural all-purpose roads: 3300 ft
	Urban roads: greater of two lengths from Figure 2-13





To determine the minium length of weaving section (Lmin) for insertion within the formula of Paragraph 2.71

1. For known total weaving flow and chosen D/V value read off the minimum length of weaving section from the graph above
2. Check the absolute minimum weaving length allowable for chosen design speed from the graph on the left
3. Select the greater of the two lengths

Figure 2-13. Weaving Length Diagram for Urban Roads (*32*) (*Figure Converted to U.S. Customary Units*).

MINIMUM LENGTH FROM DECELERATION AND ACCELERATION

Exit ramp design is based on the assumption that vehicles exiting from a freeway have the space to decelerate to the ramp's limiting design speed feature (typically a horizontal curve) after clearing the through-traffic lane. The length provided between the freeway departure point and the ramp's limiting design speed feature should be at least as great as the distance needed to accomplish the appropriate deceleration, which is governed by the speed of traffic on the through lane and the speed to be attained on the ramp. The deceleration length values in the 2004 *Green Book* are based upon assumed running speed for the limited-access highway and the ramp along with deceleration rates based on 1930s studies. The need to update the speed assumption for the highway and the ramp curve is clear, although determining appropriate deceleration rates is not as simple (*4, 33*). Previous research demonstrates that drivers select speeds at or above the design speed on horizontal curves, rather than the much lower average running speed that had been previously assumed for several design elements including exit ramps.

For entrance ramp design, the AASHTO *Green Book* (*3*) notes that drivers entering a highway from a turning roadway accelerate until the desired highway speed is reached. Because the change in speed is usually substantial, provision is made for accomplishing acceleration on an auxiliary lane, called an acceleration lane, to minimize interference with through traffic and to reduce crash potential. The 2004 *Green Book* (*3*) contains acceleration lane lengths. The procedure identified to reproduce these values used assumed running speed for the limited-access highway and the ramp along with acceleration rates from 1930s studies (*4, 34*). Potential acceleration length values were then calculated by (a) updating the assumptions within the identified procedure and (b) using spreadsheets that can generate second-to-second acceleration. A recent TxDOT study (*4*) suggested lengths that are based upon more realistic speed assumptions and more current acceleration lengths along with findings from recent research.

The intent of an auxiliary weaving area is to provide room for drivers to weave onto or off of the freeway. In theory, the length required to accelerate (for an entrance) or decelerate (for an exit) occurs on the ramp and not in the auxiliary weaving area. A method of determining the desired length of the auxiliary weaving area, however, could be the length needed for a driver to come to a complete stop at the start of the auxiliary area followed by the length needed for a driver to accelerate from the complete stop to the freeway speed.

Table 2-5 lists potential distances along with the assumptions used to generate the values. Potential acceleration lengths and deceleration lengths were calculated as part of the TxDOT 0-5544 project for speeds up to 100 mph (*4*). These lengths could be used as the deceleration and acceleration values. As documented in the 0-5544 report (*4*) and elsewhere (*33*, *34*), there are concerns with the methodology and assumptions in the existing acceleration and deceleration length calculations.

Table 2-5 also lists the potential distances if the assumptions in the acceleration and deceleration procedures are updated. For deceleration two sets of assumptions were used. The first set assumed the initial speed is the freeway design speed rather than the lower running speed and the deceleration rates were extrapolated into the higher design speeds. The second set of assumptions assumed a constant deceleration rate for the entire deceleration equal to the deceleration rate used in stopping sight distance. For acceleration, the revised assumptions included using the design speed of the freeway for the final speed and using an acceleration rate of 3.5 ft/sec^2 based on previous research (*34*).

When using design speed for the freeway speed (rather than the lower assumed running speed) and deceleration and acceleration values identified from research, the rounded suggested weaving length would be:

- 60 mph = 1500 ft,
- 70 mph = 2000 ft,
- 80 mph = 2600 ft,
- 90 mph = 3300 ft, and
- 100 mph = 4100 ft.

Table 2-5. Potential Weaving Lengths Based on Deceleration and Acceleration.

Variable	**Lengths (ft) for Freeway Design Speed (mph) of**				
	60	**70**	**80**	**90**	**100**
Extrapolating existing *Green Book* values: Values from extrapolating criteria in the *Green Book* (see TxDOT 0-5544-1 (*4*) report) Speed = running speed Deceleration without brakes and with brakes = extrapolated from *Green Book* values (without brakes range from 4.0 to 6.2 ft/sec^2, with brakes range from 7.3 to 8.8 ft/sec^2) Acceleration = value used in *Green Book* for 70 mph also assumed for 80 to 100 mph (1.9 ft/sec^2)					
Deceleration	530	615	605	695	900
Acceleration	1199	1597	1979	2403	3372
Weaving Length	**1729**	**2212**	**2584**	**3098**	**4272**
Updating freeway speed assumption: Speed = design speed Deceleration without brakes and with brakes = extrapolated from *Green Book* values (without brakes range from 4.0 to 6.2 ft/sec^2, with brakes range from 7.3 to 8.8 ft/sec^2) Acceleration = value used in *Green Book* for 70 mph also assumed for 80 to 100 mph (1.9 ft/sec^2)					
Deceleration	643	836	1042	1259	1485
Acceleration	1955	2786	3639	4606	5687
Weaving Length	**2598**	**3622**	**4681**	**5865**	**7172**
Updating freeway speed and deceleration/acceleration rate assumptions: Speed = design speed Deceleration with brakes = values assumed for stopping sight distance (11.2 ft/sec^2) (*3*, *35*) Acceleration = value identified in Canadian study (3.5 ft/sec^2) (*36*)					
Deceleration	348	473	617	781	965
Acceleration	1111	1512	1976	2501	3087
Weaving Length	**1459**	**1985**	**2593**	**3282**	**4052**

DECISION SIGHT DISTANCE

Decision sight distance, as defined by the AASHTO *Green Book* (*2*), is "the distance required for a driver to detect an unexpected or otherwise difficult-to-perceive information source or hazard in a roadway environment that may be visually cluttered, recognize the hazard or its threat potential, select an appropriate speed and path, and initiate and complete the required maneuver safely and efficiently." According to AASHTO the decision sight distance requires about 6 to 10 seconds to detect and understand the situation and 4 to 4.5 seconds to perform the appropriate maneuver. Table 2-6 lists the suggested decision sight distance resulting if one assumes the 11.2 to 14.5 seconds is applicable for the higher design speeds. These distances could serve as the minimum weaving lengths.

Table 2-6. Decision Sight Distance (*2*).

Speed (mph)	Time (sec)	Decision Sight Distance	
		Calculated Distance (ft)	Distance in *Green Book* Exhibit 3-3 for Avoidance Maneuver C and E (ft)
60	11.2 to 14.5	988 to 1279	990 to 1280
70	11.2 to 14.5	1152 to 1492	1105 to 1445
80	11.2 to 14.5	1317 to 1705	1260 to 1650
90	11.2 to 14.5	1482 to 1918	Not provided
100	11.2 to 14.5	1646 to 2132	Not provided

Baker and Stebbins (*37*) originally developed a model for decision sight distance to quantify sufficient distances based on the principle of hazard avoidance. This hazard-avoidance model was later modified by Leisch (*38*) and Pfefer (*39*). In a study published in 1979, McGee expanded this concept and conducted field tests to validate the model (*40*). In his study, McGee outlined a sequence of events to avoid a hazardous situation, starting from sighting the hazard, detection and then recognition of the hazard, to decision, response to the hazard, and completion of required maneuver. A field validation procedure was designed and conducted with 19 test subjects driving through a course and responding to certain geometrics. The study results reinforced the analytical assessments of the preceding studies. However, the study also revealed that not all previously recommended values were supported by the field test results. Based on the field test, a table of decision sight distance values was recommended, as shown in Table 2-7. In the McGee study, the use of decision sight distance was recommended in highway design in general, especially at locations with special features including interchanges, toll plazas, and any other location requiring unexpected or unusual maneuvers. The use of decision sight distance at interchanges was again restated and recommended in 1993 by Lunenfeld (*41*), Leisch (*42*), and Keller (*43*).

In a study conducted by Lerner et al. (*44*) for the Federal Highway Administration, published in 1995, the total time for decision sight distance was measured in heavily traveled urban freeway conditions and found to be longer than the value of 14.5 seconds that was recommended by McGee (*40*) and included in the AASHTO *Green Book* (*3*). The decision sight distance measurements were conducted for three age groups; 20 to 40, 65 to 69, and 70 and older at six freeway lane-drop locations. The recommended times are as follows:

- 16.5 sec for the 20 to 40 year old group,
- 17.6 sec for the 65 to 69 year old group, and
- 18.8 seconds for the 70 and older group.

The researchers of the FHWA study (*44*) discussed the difference between their results and the values currently in the *Green Book,* noting that their study was conducted under heavy traffic conditions in which drivers were required to wait for acceptable gaps for lane-changing maneuvers. The AASHTO recommended value, by comparison, was likely to be the result of a study conducted in free-flow conditions where no driver was required to wait for a gap before performing lane-changing maneuvers. Table 2-8 provides the suggested decision sight distance values if using the results of Lerner et al. (*44*).

Table 2-7. Recommended Decision Sight Distance Values from McGee (*40*).

Design Speed (mph)	Time (sec)				Decision Sight Distance (ft)	
	Before Maneuver		Maneuver (Lane Change)	Total	Computed	Rounded for Design
	Detection and Recognition	Decision and Initiation of Response				
25	1.5-3.0	4.2-6.5	4.5	10.2-14.0	372-510	375-525
37	1.5-3.0	4.2-6.5	4.5	10.2-14.0	558-766	575-775
50	1.5-3.0	4.2-6.5	4.5	10.2-14.0	744-1021	750-1025
62	2.0-3.0	4.7-7.0	4.3	11.2-14.5	1021-1322	1025-1325
74	2.0-3.0	4.7-7.0	4.0	10.7-14.0	1170-1531	1175-1525
87	2.0-3.0	4.7-7.0	4.0	10.7-14.0	1365-1786	1350-1800

Note:
Values converted from metric
Rounded up to the nearest 25 ft for the low value and up or down to the nearest 25 ft for the upper value

Table 2-8. Decision Sight Distance Values if Total Times Found in Lerner et al. (*44*) Study is Used.

Speed (mph)	Time (sec)	Distance (ft)		Time (sec)	Distance (ft)		Time (sec)	Distance (ft)	
		Calc	Rounded		Calc	Rounded		Calc	Rounded
60	16.5	1455	1500	17.6	1552	1600	18.8	1658	1700
70	16.5	1698	1700	17.6	1811	1800	18.8	1935	1900
80	16.5	1940	1900	17.6	2070	2100	18.8	2211	2200
90	16.5	2183	2200	17.6	2328	2300	18.8	2487	2500
100	16.5	2426	2400	17.6	2587	2600	18.8	2764	2800

The total times found by Lerner et al. by age group:
16.5 sec for the 20 to 40 year old group,
17.6 sec for the 65 to 69 year old group, and
18.8 seconds for the 70 and older group.

SAFETY

A review of the literature regarding the safety relationships between weaving length and crashes revealed few studies. Even within the few studies available, researchers identified contrary results.

Cirillo *(45)* examined the relationship between accident rates and weaving area lengths using Interstate data from 20 states. Approximately 700 urban weaving segments were included in the data set. New analyses of the accident rates, measured as accidents per million vehicle miles (accidents per MVM), were conducted and are summarized in Figure 2-14. Trends show that, for a given level of traffic volume, accident rates tend to increase as weaving area lengths decrease. Results also show that, for a given weaving area length, accident rates decrease as volume decreases. Cirillo aggregated accident rates by five levels of one way mainline average daily traffic (ADT) in the original work (ADT < 10,000; 10,000 ≥ ADT < 20,000; 20,000 ≥ ADT < 30,000; 30,000 ≥ ADT < 40,000; 40,000 ≥ ADT), but reported a limited sample size in the lowest volume area category. More consistent general trends were found by this research team when the three lowest volume categories were combined into one (ADT < 30,000). Figure 2-14 reflects this change.

Results from a later study showed opposite trends; accident rates decreased as weaving length decreased *(46)*. The sample size was limited to 21 locations. The locations were not selected randomly, but were included due to poor accident histories (a possible selection bias problem). Traffic volumes were not considered in the analysis other than their use in accident rate calculations. Non-linear trends between accidents and volumes are well established. Segregating accident rates by level of traffic volume is desirable if accident rates are the safety measure of choice. The results reported by Cirillo *(45)*, while older, are likely more reliable.

Bared et al. *(47)* modeled the safety effects of interchange spacing using California freeway data (1998–2002). Interchange spacing was defined as the smallest distance between gore points of ramps from consecutive interchanges (the authors define gore point and ramp nose synonymously). Negative binomial regression models for total accidents and fatal plus injury accidents were estimated using data from 58.5 miles of California Interstates; number of lanes varied from 6 to 14. Reported models had the following functional form:

$$N = a \times ADT^{b1} \times SL^{b2} \times \left(\sum RampADT\right)^{b3} \tag{4}$$

where:

N = expected number of accidents per year;
ADT = average daily traffic on the freeway mainline (veh/day);
SL = segment length, defined as interchange spacing (mi);
$\sum RampADT$ = the sum of ADT for the two entrance ramps and two exit ramps associated with a defined interchange spacing segment (veh/day); and
$a, b1, b2, b3$ = parameters estimated using available data.

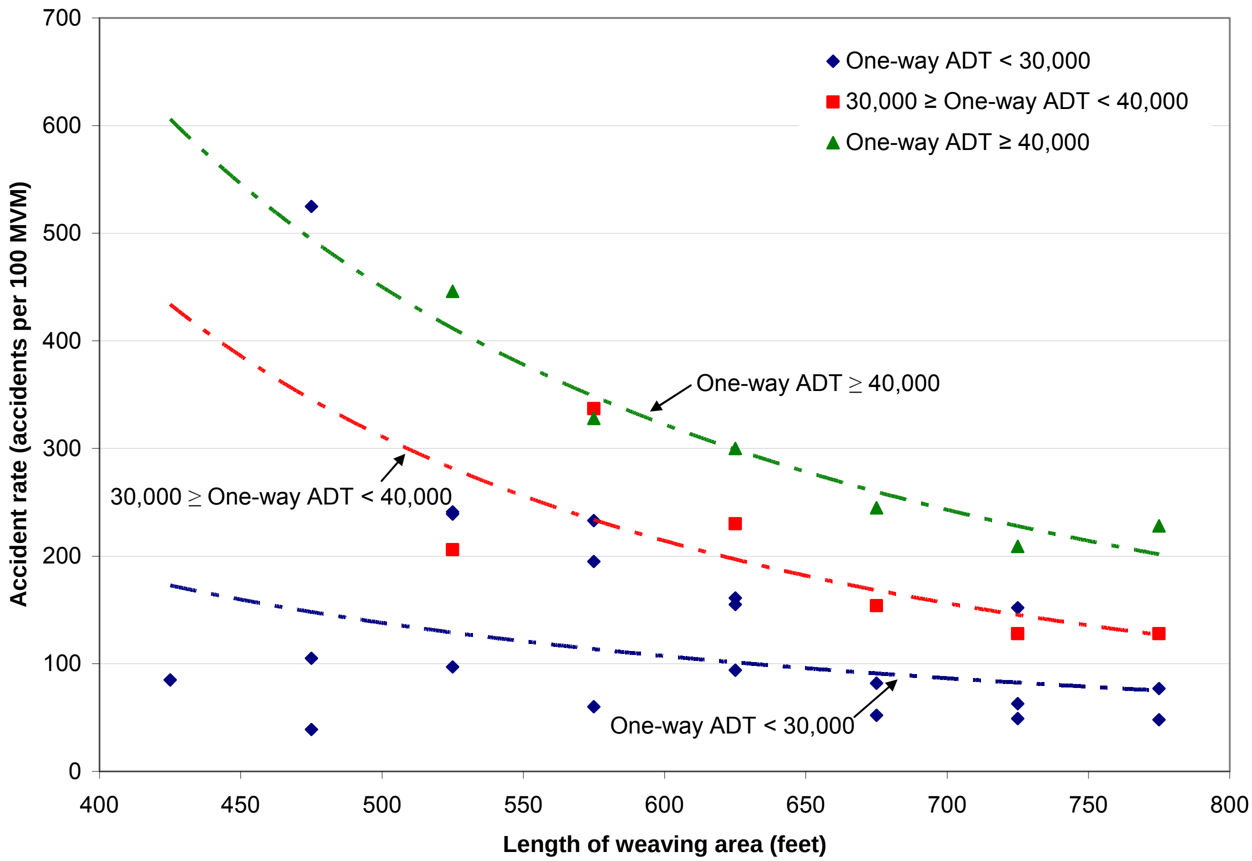
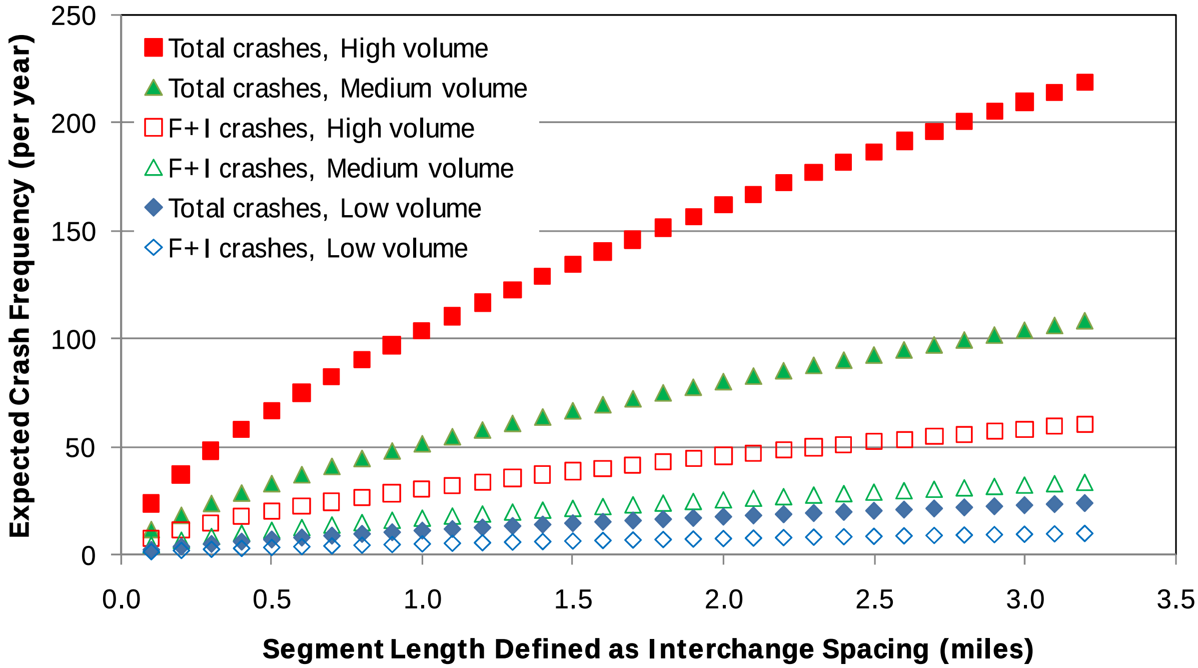


Figure 2-14. Analysis of Accident Rates by Weaving Areas Length Reported by Cirillo (*45*).

Figure 2-15 summarizes and illustrates model results by length of weaving area. The model parameters generally make intuitive sense. However, a closer look at the segment length variable reveals potential challenges associated with their study objective: determining the safety effect of interchange spacing.

The traffic and segment length components of an accident frequency model represent measures of exposure; respective regression parameters generally have a value around one. The parameter for ADT may be slightly greater than or less than one, depending on the crash type of interest. The parameter for segment length is sometimes constrained to equal one. In the model reported by Bared et al. (*47*), the parameter associated with segment length represented the net effect of several potential confounding factors. Exposure was the most predominant, resulting in an overall positive effect of segment length. However, the interchange spacing effect is confounded with the exposure effect because every segment in the database is defined with an entrance gore on one side and an exit gore on the other side. Shorter segment lengths represent reduced exposure, but with increased ramp interaction, these two factors are expected to have opposite effects on accident frequency. The segment length, as defined by Bared et al., may also be correlated with additional interchange related features that influence safety. For example, shorter segment lengths are likely associated with an increased presence of auxiliary lanes between the entrance and exit ramps of two consecutive crossroads, a feature not captured in the data.



Low volume: ADT = 66,600 veh/day; ΣRampADT = 6,900 veh/day
Medium volume: ADT = 188,000 veh/day; ΣRampADT = 34,100 veh/day
High volume: ADT = 274,000 veh/day; ΣRampADT = 120,700 veh/day
Total crashes = $6.18\times10^{-6}ADT^{1.122} \times$ Segment Length$^{0.6394} \times \Sigma RampADT^{0.2213}$
F+I crashes = $5.44\times10^{-5}ADT^{0.8618} \times$ Segment Length$^{0.5918} \times \Sigma RampADT^{0.2088}$

Figure 2-15. Summary of Freeway Models from Bared et al. (*47*).

One possible solution was explored by Bared et al. and is recreated in Figure 2-16. The expected number of accidents predicted from the regression models in Figure 2-15 are normalized (i.e., divided by) the segment length. The resulting rate, with units of accidents per mile per year, follows an intuitive trend: the expected number of accidents per unit length increases as interchange spacing decreases. The procedure assumes the segment length parameter associated with exposure is equal to one and that the difference between the originally estimated segment length parameter and one is attributable to the interchange spacing effect. This concept is illustrated by:

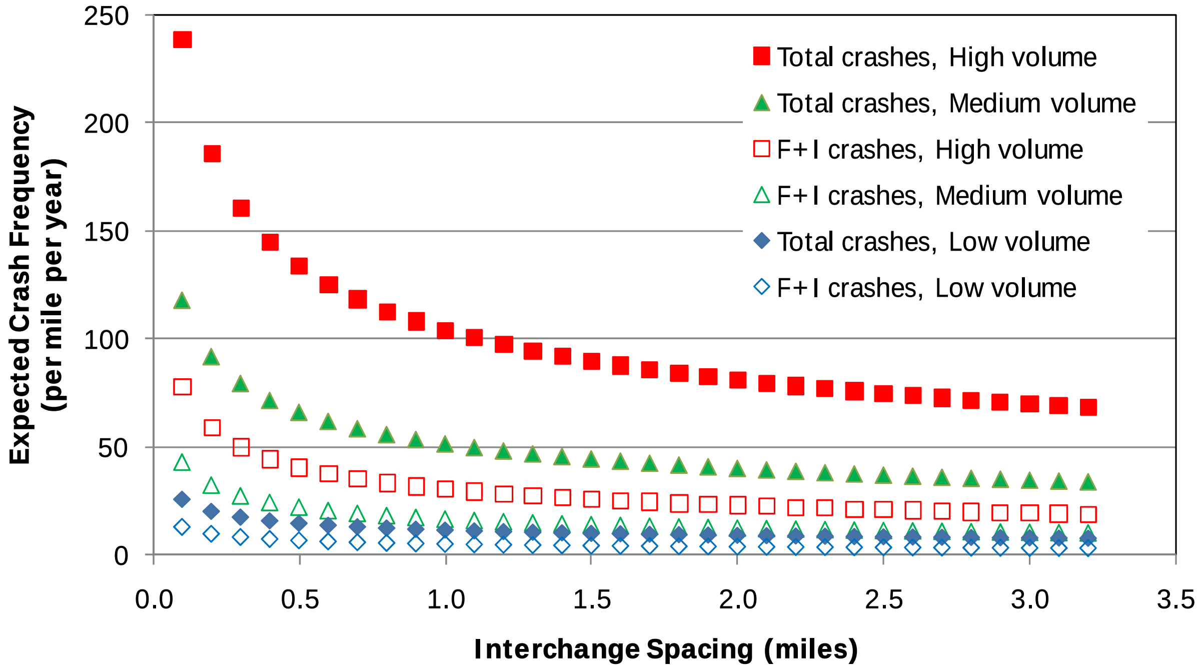
$$\frac{N}{SL} = a \times ADT^{b1} \times SL^{(b2-1.0)} \times \left(\sum RampADT\right)^{b3} \tag{5}$$

where:

$\frac{N}{SL}$ = expected number of accidents per mile per year;

SL= interchange spacing (miles); and

$ADT, \sum RampADT, a, b1, b2, b3 =$ same as previously defined.



Low volume: ADT = 66,600 veh/day; ΣRampADT = 6,900 veh/day
Medium volume: ADT = 188,000 veh/day; ΣRampADT = 34,100 veh/day
High volume: ADT = 274,000 veh/day; ΣRampADT = 120,700 veh/day
Total crashes = $6.18 \times 10^{-6} ADT^{1.122} \times Spacing^{-0.3606} \times \Sigma RampADT^{0.2213}$
F+I crashes = $5.44 \times 10^{-5} ADT^{0.8618} \times Spacing^{-0.4082} \times \Sigma RampADT^{0.2088}$

Figure 2-16. Summary of Freeway Models from Bared et al. with Results Normalized for Segment Length.

The slope of the line representing the expected accident frequency versus interchange spacing relationship approaches zero as interchange spacing increases, indicating minimal safety influence from the ramps at the segment termini (i.e., from a safety perspective, the segment operates as a normal freeway segment without deleterious interchange or ramp effects). The interchange spacing at which this occurs becomes longer as mainline and ramp volumes increase. The normalizing technique is promising if one can be fairly certain that effects other than exposure and interchange spacing are not fully or partially captured in the segment length definition.

Pilko et al. *(48)* conducted a follow-up effort to the study by Bared et al. *(47)* with some notable changes:

- The size of the California data set was increased to include 95 spacing observations representing 134 freeway miles (compared to 53 observations representing 58.5 miles).
- A Washington freeway data set consisting of 100 spacing observations representing 144 freeway miles was added and used for model estimation and validation.
- Mainline traffic was specified as vehicles per lane per day.
- Ramp volumes were expressed at the ratio of ramp ADT to mainline ADT for the California models.

- Cross-section variables representing median width, median type, and high-occupancy vehicle (HOV) lane presence were included in some models.
- The definition for interchange spacing was changed to represent the distance between crossroads of consecutive interchanges.

Model estimation results are summarized in Table 2-9. The graphical displays in Figure 2-16 represent general trends that are also seen when the models in Table 2-9 are plotted. Discussion and analysis associated with Figure 2-16 are also applicable. Therefore, the figures and analysis are not repeated here.

Table 2-9. Summary of Reported Models in Pilko et al. (*48*).

Data and Specification	Accident Types	Expected accident frequency per year
CA only	TOTAL	$=4.97\times10^{-5}\left(\frac{ADT}{LN}\right)^{1.39} SL^{0.57}\exp(1.50*RRatio+0.37*HOV-0.01*MW+0.27*MT)$
	F+I	$=1.81\times10^{-5}\left(\frac{ADT}{LN}\right)^{1.37} SL^{0.57}\exp(1.42*RRatio+0.34*HOV-0.01*MW+0.35*MT)$
CA for WA validation	TOTAL	$=3.61\times10^{-5}\left(\frac{ADT}{LN}\right)^{1.11} SL^{0.52}\sum RampADT^{0.34}\exp(0.0072*MW)$
	F+I	$=1.64\times10^{-5}\left(\frac{ADT}{LN}\right)^{1.07} SL^{0.51}\sum RampADT^{0.35}\exp(0.0051*MW)$
Joint CA and WA	F+I	$=1.63\times10^{-6}\left(\frac{ADT}{LN}\right)^{1.37} SL^{0.62}\sum RampADT^{0.26}\exp(0.0032*MW)$

ADT = average daily traffic on freeway mainline (veh/day);
LN = number of lanes at the segment midpoint (includes through lanes, HOV lanes, and auxiliary lanes greater than 0.2 mile long);
SL = segment length, defined as interchange spacing (mi);
$RRatio$ = the sum of ADT for the two entrance ramps and two exit ramps associated with a defined interchange spacing segment divided by average daily traffic on the freeway mainline;
HOV = indicator for presence of an HOV lane (1 = present);
MW = median width (ft);
MT = indicator for median type (1 = unpaved, 0 = paved); and
$\sum RampADT$ = the sum of ADT for the two entrance ramps and two exit ramps associated with a defined interchange spacing segment.

SIGN SPACING FOR AN EXIT RAMP

The *Texas Manual on Uniform Traffic Control Devices TMUTCD* (*49*) and the TxDOT *Freeway Signing Handbook* (*50*) provide information on freeway signing. Included in those discussions is a table on desirable and maximum units of information per freeway guide sign structure (see Table 2-10). In section 2E.30 of the *TMUTCD*, the guidance is to place advance guide signs at 0.5 and 1 mile in advance of the exit with a third advance guide sign placed at 2 miles in advance of the exit if spacing permits.

Hawkins et al. (*51*) examined guide sign characteristics for a 90 mph freeway. They identified typical design parameters such as a maximum sign width of 24 ft, height of center of sign (20 ft above driver eye height), a city name that would represent approximately the 85th percentile value for number of characters, and other parameters. The recommendation for the letter height of an overhead guide sign was based on both the sign width and legibility height analyses. The sign width analysis showed that the maximum letter height for the word "San Antonio" is 22 inches. The legibility height analysis was used to determine the minimum letter height required for an overhead guide sign. Historically, signs have been designed using a 50 ft/inch legibility index but the MUTCD now recommends using a 40 ft/inch index, and suggests that 33 ft/inch can be beneficial. Using a 40 ft/inch legibility index and two methods for determining required reading time found that the letter height of 22 inches would satisfy legibility requirements for:

- 10 units of information or less and
- 12 units of information using two panel signs.

Based on their findings, the researchers recommended that the legend on guide signs be a minimum of 22 inches and that additional guide sign installations be provided in advance of the exit. Furthermore, sign sheeting for overhead signs should be limited to sheeting types that will provide adequate luminance.

The amount of information on a guide sign is the key limiting factor for maintaining the legibility of longer names for destinations. Therefore, the authors recommended using more redundancy of signs for the high speed facilities. The redundancy will allow the use of fewer units of information per sign so that a driver can read the sign. The tradeoff is that more signs and probably a greater distance will be needed in advance of the ramp to adequately sign for the exit.

Table 2-10. Desirable and Maximum Units of Information per Freeway Guide Sign Structure (*50*).

Number of Sign Panels	Units of Information per Structure	
	Desirable	Maximum
2	12	16
3	16	18
4	18	20
5	Undesirable Design	20
Source: McNees, R. W. and C. J. Messer. Reading Time and Accuracy of Response to Simulated Urban Freeway Guide Signs in *Transportation Research Record 844*, Transportation Research Board, Washington, D.C., 1982.		

CHAPTER 3

FIELD STUDIES

OPERATIONAL MEASURES

Highway Capacity Manual algorithms for entrance ramps followed by exit ramps with an auxiliary lane (i.e., weaving) have traditionally included speed estimation as the primary predictive step. Conversions to density, and subsequently level of service, are made for consistency with basic freeway segment and ramp junction analysis. The capacity of a weaving segment is defined as any combination of flows that cause density to reach 43 passenger cars per mile per lane (pc/mi/ln). A direct solution is not possible so trial and error is used.

Recently proposed weaving algorithms that are currently being considered for future *HCM* editions include predictive steps for lane changing, as well as new predictive structures for speed and capacity. Conversions to density are still made for level of service estimates. In the supporting research, the number and longitudinal positions of lane changes as well as average speeds were used to calibrate microscopic simulation models (*52*). The simulation results ultimately complemented field data and supported the new algorithm development (*52*).

HCM algorithms for entrance ramps followed by exit ramps without an auxiliary lane treat each ramp separately. Flow rates in the merge and diverge influence areas are compared to respective capacity values to determine the likelihood of congestion. The capacities of merge and diverge areas are limited by the capacities of the upstream, downstream, and ramp facilities themselves and are not influenced by the intensity of traffic turbulence from lane changing maneuvers. Densities are directly computed and used to determine level of service. Average speeds in ramp influence areas are estimated as a secondary performance measure, most often when the computations are part of a larger, multi-facility analysis.

Unrelated research aimed at real-time freeway monitoring and incident response has begun to link operational measures to accident occurrence (*53*). Relationships between speed variance and the likelihood of a downstream accident have been reported (*53*).

All of the aforementioned performance measures are inextricably linked to traffic volumes and the distributions of origins and destinations (e.g., freeway through movement, freeway to exit ramp, entrance ramp to freeway, entrance ramp to exit ramp).

Given these discussions, the target operational measures for the field data collection efforts were:

- volumes by lane and location;
- speed magnitudes by lane, location, and movement;
- speed variability by lane, location, and movement; and
- number, direction, and location of lane changes.

The level of detail and disaggregation for these measures were limited by practicality and safety issues associated with field data collection.

DATA COLLECTION EQUIPMENT

The 0-5860 proposal identified camera trailers, supplemental camcorders, and traffic management cameras as alternatives to collect lane changing and volume data. Traffic sensors and light detection and ranging (lidar) guns were identified as options for speed data acquisition. Some technologies were field tested on SH 6 (Earl Rudder Freeway) southbound between SH 30 (Harvey Road) and Southwest Parkway East, a low-volume weaving segment in College Station, Texas. Other options were evaluated subjectively based on prior data collection experience combined with observed behavior at weaving segments. The following conclusions were reached:

- Ideal positioning for the camera trailer was upstream of the painted entrance gore or downstream of the painted exit gore (depending on the direction of the vertical grade). The trailer presented a possible safety hazard at these locations, potentially blocking sight lines and occupying emergency recovery areas.
- Winds affected the stability of the camera trailer arm. Although this is not an issue for most trailer applications, the desire to identify lane change locations made constant camera movement undesirable, even if it was minimal.
- Collecting speeds with lidar was difficult and impractical. Individual vehicles could not be tracked through the entire entrance-exit segment, as sight lines to those vehicles were often blocked by other vehicles as a result of lane changing. In addition, the positions needed by lidar gun operators to capture speeds of entering, exiting, and through vehicles were very conspicuous to drivers.

A decision was made to use traffic management center (TMC) cameras combined with pneumatic tubes as the first data collection alternative. Closed circuit television (CCTV) cameras are located along major roadways in Houston, Dallas, and San Antonio and are operated through TranStar, DalTrans, and TransGuide, respectively. TTI researchers have used TMC cameras for data collection on previous studies through coordination with TxDOT and appropriate TMC staff. The use of these cameras offers several advantages, including height, stability, and ease of video recording. There are also disadvantages associated with their use. Site selection is controlled more by available camera views than by the originally identified site selection factors in the 0-5860 proposal. Camera views at each location are likely to vary, requiring flexibility in data reduction techniques. Finally, cameras are used for traffic and incident management. TxDOT may take control of camera operation at anytime during data collection. Extended time periods with the camera aimed away from weaving areas during the specified data collection period was expected. Figure 3-1 and Figure 3-2 show two examples of weaving areas as viewed from TranStar cameras in Houston, Texas.

Figure 3-3 (entrance-exit with auxiliary lane) and Figure 3-4 (entrance-exit without auxiliary lane) illustrate the general pneumatic tube layouts used for data collection. The tube layouts are a compromise between collecting all desired data (i.e., speeds and volumes in every lane) and issues regarding safety and practicality of installation, durability, and removal on a multi-lane freeway. Two pairs of tubes were placed in the rightmost through travel lane to capture speeds and volumes immediately upstream and downstream of the entrance and exit movements for both ramp configurations. A single tube was placed on the entrance and exit ramps to collect entering and exiting volumes for both ramp configurations.

Figure 3-1. View of SH 288 SB between Reed Road and Airport Boulevard (Viewed from Camera 810 at Reed Road).

Figure 3-2. View of SH 288 NB between Airport Boulevard and Reed Road (Viewed from Camera 811 at Airport Boulevard).

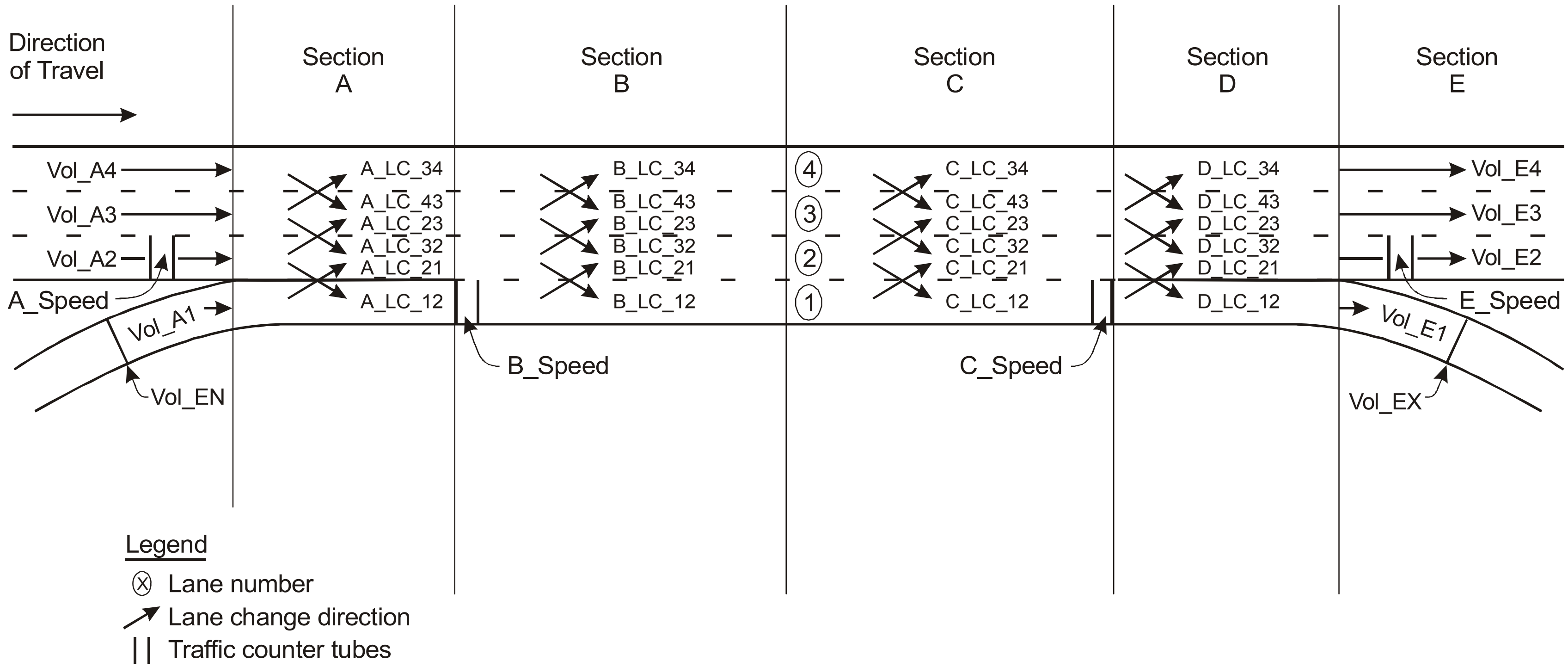


Figure 3-3. Layout of Pneumatic Tubes for Entrance Ramp Followed by Exit Ramp with Auxiliary Lane.

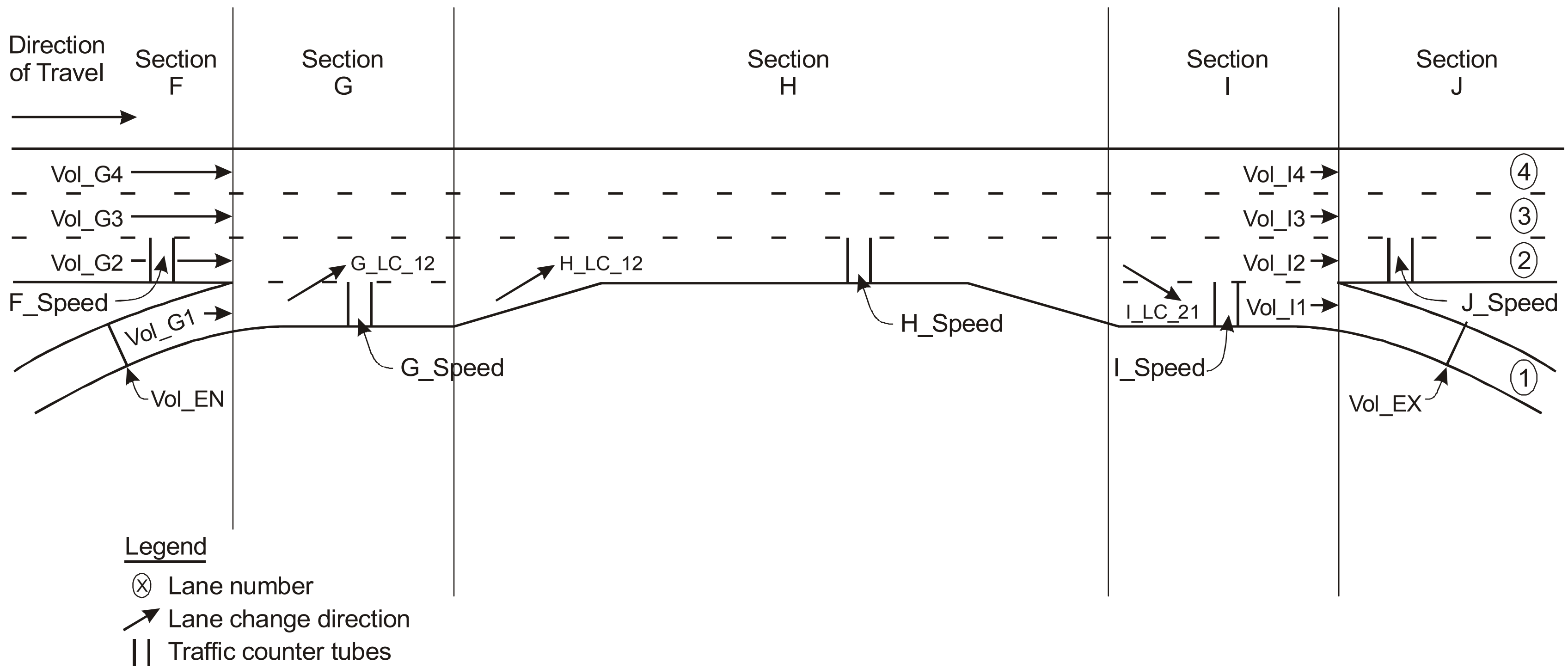


Figure 3-4. Layout of Pneumatic Tubes for Entrance Ramp Followed by Exit Ramp without Auxiliary Lane.

The two pairs of tubes located at the ends of the painted solid lines in Figure 3-3 were primarily for speeds, but could also be used for volumes. The tubes at the end of the solid line near the merge tip were meant to capture entering speeds, but they also captured some vehicles that exited the freeway mainline early or that entered the segment from the entrance ramp, remained in the auxiliary lane, and exited. Similarly, the tubes at the end of the solid line near the diverge tip were meant to capture exiting speeds, but they also captured some vehicles that entered the freeway mainline late or that entered the segment from the entrance ramp, remained in the auxiliary lane, and exited. Similarly, two pairs of tubes located near the entrance taper and exit taper in Figure 3-4 were primarily for speeds, but could also be used for volumes. The tubes on the entrance ramp near the entrance taper were meant to capture speeds of most entering vehicles. The tubes on the exit ramp near the exit taper were meant to capture speeds of most exiting vehicles. The pair of tubes between the entrance and exit tapers in Figure 3-4 captured right lane volumes and speeds on the freeway mainline between the ramps.

Freeway volumes in the outer through lanes as well as the numbers and locations of lane changes were counted manually using the recorded video. A subsequent section on data collection and reduction provides additional detail.

SITE IDENTIFICATION

The 0-5860 proposal included a list of potential factors to consider during the site selection process including

- ramp spacing,
- volume,
- posted speed limit,
- number of through lanes,
- area type, and
- truck restrictions.

The process was modified when the decision was made to use TMC cameras; selection was controlled more by available camera views than by the originally identified factors. Sites with a range in the key variable of interest, ramp spacing, were still desired. Desired volume ranges were observed by collecting data at each site during peak periods as well as during hours with lower demand (e.g., mid-morning, mid-afternoon).

Table 3-1 lists their characteristics. The table includes:

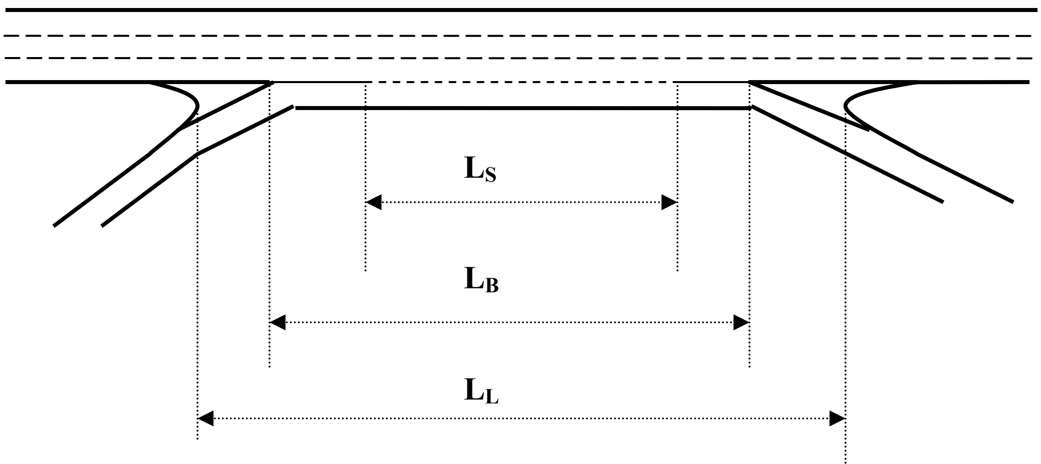
- the route designation and direction of the freeway mainline where the segment was located,
- adjacent cross streets and their proximity,
- number of lanes on the mainline,
- number of lanes on the entrance and exit ramps, and
- three different measures of ramp spacing.

Table 3-1. Site Characteristics of Data Collection Locations.

Site # - Freeway Route	Entrance ramp from:		Exit Ramp to:		Posted Speed[3]	Number of lanes				Spacing[5] (ft)		
	Road	Dis[1] (ft)	Road	Dis[2] (ft)		Thru	Aux[4]	En	Ex	L_S	L_B	L_L
1 - SH 288 SB Houston	Reed Rd	1700	Airport Blvd	2300	60	3	Yes	1	1	490	1100	1600
2 - SH 288 NB Houston	Airport Blvd	1700	Reed Rd	1700	60	3	Yes	1	1	980	1600	2550
3 - IH 45 NB Houston	FM 2351	1500	FM 1959	2700	65	3	Yes	1	1	3150	3800	4300
4 - US 67 SB Dallas	W Kiest Blvd	1500	S Polk St	1100	60	3[6]	Yes	1	1	500	600	1600
5 - US 67 SB Dallas	W Red Bird Ln	1200	W Camp Wisdom Rd	1700	60	2[7]	Yes	1	1	530	1150	1800
6 - IH 635 EB Dallas	Forest Ln	1000	Josey Ln	1100	60	4[8]	Yes	1	1	760	880	1350
7 - IH 30 WB Dallas	Motley Dr	1700	Big Town Blvd	1800	60	3/2[9]	No	1	1	200	1400	2300

[1] Distance from the upstream cross street to the painted entrance gore where the left edge of the ramp travel lanes and the right edge of the freeway travel lanes meet
[2] Distance from the painted exit gore where the left edge of the ramp travel lanes and the right edge of the freeway travel lanes meet to the downstream cross street
[3] No truck or night speed limits were posted
[4] Presence of a continuous auxiliary lane between the entrance and exit ramps
[5] See Figure 3-5 and Figure 3-6 for definitions
[6] Does not include adjacent HOV lane in median separated from the traveled way by a barrier
[7] Does not include adjacent HOV lane in median separated from the traveled way by painted solid lines and rumble strips
[8] Does not include adjacent HOV lane in median separated from the traveled way by a painted skip line
[9] A moveable barrier was present; the segment had three through lanes from morning through early afternoon and two through lanes in the afternoon and evening

The three definitions of ramp spacing, illustrated in Figure 3-5 and Figure 3-6, are based on newer definitions of weaving lengths that are currently being considered for incorporation into the 2010 edition of the *HCM*. Video of lane-changing maneuvers collected in the supporting research study suggested that L_B (base length) is the most logical measure of weaving length *(52)*. Results of statistical analysis did not give the same impression; the use of L_S as the measure of weaving length provided superior statistical fit compared to the other length measures when developing the weaving algorithms *(52)*.

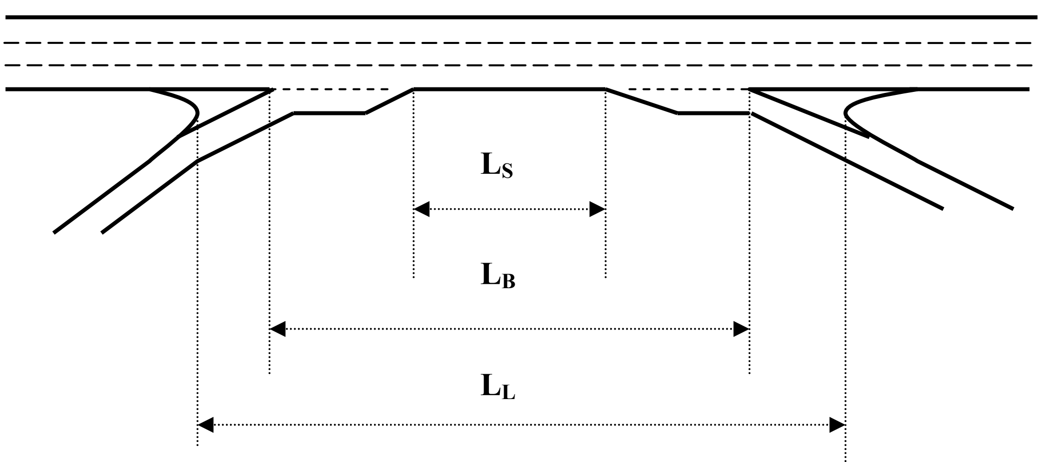


L_S = short length; the distance between the end points of any barrier markings that prohibit or discourage lane changing

L_B = base length; the distance between points in the respective gore areas where the left edge of the ramp travel lanes and the right edge of the freeway travel lanes meet

L_L = long length; the distance between physical barriers marking the ends of the merge and diverge gore areas

Figure 3-5. Measurement of Weaving Length (from NCHRP Project 3-75).



L_S = short length; the distance between the end of the merge taper and the beginning of the diverge taper

L_B = base length; the distance between points in the respective gore areas where the left edge of the ramp travel lanes and the right edge of the freeway travel lanes meet

L_L = long length; the distance between physical barriers marking the ends of the merge and diverge gore areas

Figure 3-6. Weaving Length Definitions (from NCHRP Project 3-75) Adapted to Entrance Ramp followed by Exit Ramp without Auxiliary Lane.

DATA COLLECTION AND REDUCTION

Data were collected for at least three consecutive days at each location. A calendar period of approximately one work week per site was needed. Pneumatic tubes were normally placed by TTI researchers on a Monday with temporary traffic control help from TxDOT courtesy vehicles. The tubes collected volume and speed data continuously until they were removed on Friday. The tubes were monitored regularly throughout the week for possible malfunction or removal.

The TMC camera was aimed to capture the freeway segment of interest on Monday evening of the data collection week. The camera view was then recorded in digital video format from Tuesday through Thursday, from dawn to dusk. These cameras are used for traffic and incident management. In several instances, TxDOT changed the camera views to monitor traffic congestion or incidents. The objective for each week was to get at least one full day, spanning peak periods and lower volume conditions, with the desired camera view and functioning pneumatic tubes.

The video files were saved either directly onto a computer hard drive in a format compatible to most commonly used players, or directly onto the hard drive of a digital video recorder. Tube data were saved in a comma-separated value format compatible with most spreadsheet-based data management and statistical analysis programs. Time stamps on the video and tube data were either synchronized prior to data collection or adjusted during data reduction, in which case the time stamps on the tube data were adjusted to match the video time stamp. The following general data reduction steps were followed:

1. Video and tube data were scanned to identify day and time periods when the TMC camera was set at the desired view and the pneumatic tubes were functioning.
2. Lane changes were counted and aggregated for 5-minute intervals during selected time periods.
3. Volumes in the outer lanes (i.e., where there were no tubes) were manually counted using the video for the same time periods that lane changes were counted and aggregated for 5-minute intervals.
4. Volumes collected with the pneumatic tubes were aggregated for 5-minute intervals for all hours of data collection.
5. Speed data were aggregated into 5-minute and 15-minute speed bins, and mean speed and standard deviation of speed were computed for all hours of data collection.
6. Volume, speed, and lane change data were merged into one file using the date and time as linking variables.

The result of these six steps was two comprehensive data sets spanning several days at each site. One data set, called the Counter Data, included tube volumes and speeds. It included the hours that the tubes were operational, usually between 48 and 72 hours per site. The other data set, called the Video Data, included lane changes and counted volumes. It included approximately two or more hours per site. The research team attempted to span at least one hour of fairly high volume flow and one hour of lower volume flow with the lane change and volume counts. Selected time intervals where the tube and count data overlapped were used for calibration of the microscopic simulation models as discussed in Chapter 4, *Simulation*. The evaluation of the data sets is discussed in Chapter 5, *Analyze Results*, and Chapter 6, *Develop Recommendations*.

Passenger cars and trucks can be separated for tube data. No distinctions between passenger cars and trucks were made for the video data (i.e., lane changes and outer lane volumes). The percentages of trucks observed were fairly low, ranging from 2 to 8 percent of all traffic.

Organization of such a large amount of data at such a high level of disaggregation required development of a formal numbering and labeling scheme, illustrated in Figure 3-3 (entrance-exit with auxiliary lane) and Figure 3-4 (entrance-exit without auxiliary lane).

Each freeway segment spanning an entrance ramp followed by an exit ramp with a continuous auxiliary lane was divided into five sections (illustrated in Figure 3-3):

- Section A: from painted entrance gore to the downstream end of the solid painted line extending from the painted entrance gore.
- Section B: from the downstream end of solid painted line extending from the painted entrance gore to the midpoint of the short weaving section.
- Section C: from the midpoint of the short weaving section to the upstream end of the solid painted line extending from the painted exit gore.
- Section D: from the upstream end of the solid painted line extending from the painted exit gore to the painted exit gore.
- Section E: downstream of the painted exit gore.

Lanes were numbered, beginning with the auxiliary lane as *1* and increasing in a direction toward the freeway median or HOV lane (if present). The following measures were then defined using this referencing system:

- Vol_ij = volume entering section *i,* lane *j*;
- MnSp_ij = mean speed from tube data in section *i*, lane *j*;
- StSp_ij = standard deviation of speed from tube data in section *i*, lane *j*; and
- i_LC_jk = number of lane changes from lane *j* to lane *k* in section *i*.

Camera views and pavement markings (i.e., the presence and length of painted solid lines) at each location varied, requiring flexibility in data reduction techniques. Counts of all volumes and lane changes were desired, but not always possible or practical. At a minimum, the following measures were counted at most locations:

- Vol_Ai for all *i*;
- Vol_Ei for all *i*; and
- i_LC_12 and i_LC_21 for different combinations of *i* = A, *i* = B, *i* = C, and/or *i* = D.

Vol_A1, Vol_A2, Vol_B1, Vol_C1, Vol_E1, Vol_E2, MnSp_A2, StSp_A2, MnSp_B1, StSp_B1, MnSp_C1, StSp_C1, MnSp_E2, and StSp_E2 were computed from the pneumatic tube data. MnSp_A2 and StSp_A2 are labeled 'A' even though their locations are slightly upstream of Section A (see Figure 3-3) in order to simplify the complexity of the notation. Speeds and volumes for passenger cars and trucks were separated for the data coming from four pairs of tubes, two located at the end of solid lines, in the auxiliary lane, near entrance and exit ramps, and the other two located in the rightmost through travel lane.

The one freeway segment spanning an entrance ramp followed by an exit ramp without a continuous auxiliary lane was also divided into five sections (illustrated in Figure 3-4):

- Section F: upstream of the painted exit gore.
- Section G: from painted entrance gore to the downstream end of the painted skip line extending from the painted entrance gore.
- Section H: from the downstream end of the painted skip line extending from the painted entrance gore to the upstream end of the taper for the exit ramp.
- Section I: from the upstream end of the taper for the exit ramp to the painted exit gore.
- Section J: downstream of the painted exit gore.

Lanes were numbered, beginning with the entrance and exit ramps and the respective acceleration and deceleration lanes as *1* and increasing in the direction toward the freeway median or HOV lane. Efforts were made to create sections and labels that were generally consistent with those for the entrance-exit with auxiliary lane combination. Small modifications were ultimately necessary to accommodate the unique geometrics and tube layout for each case.

The following measures were defined for the entrance-exit without auxiliary lane:

- Vol_ij = volume entering section *i,* lane *j*;
- MnSp_ij = mean speed from tube data in section *i*, lane *j*;
- StSp_ij = standard deviation of speed from tube data in section *i*, lane *j*; and
- i_LC_jk = number of lane changes from lane *j* to lane *k* in section *i*.

Vol_F1, Vol_F2, Vol_G1, Vol_I1, Vol_J1, Vol_J2, Vol_H2, MnSp_F2, StSp_F2, MnSp_G1, StSp_G1, MnSp_H2, StSp_H2, MnSp_I1, StSp_I1, MnSp_J2, and StSp_J2 were computed from the pneumatic tube data. H_LC_12 was computed by subtracting G_LC_12 from entrance ramp volume, which was Vol_F1. I_LC_21 equaled exit ramp volume that was Vol_J1.

CHAPTER 4

SIMULATION

All possible combinations of geometric and operational factors that may affect desired ramp spacing cannot be studied in the field. Roadways with certain traffic characteristics, such as 100 mph 85th percentile speed, simply do not exist. In addition, field studies typically cannot provide sufficient control over most of the key variables affecting weaving traffic between entrance and exit ramps. Systematic variations in ramp spacing and other key variables affecting traffic operations within a weaving section are not possible under field conditions. However, they can be done using properly calibrated traffic simulation models.

In this study traffic simulation was used for studying a range of ramp spacing scenarios under various traffic conditions and to provide data for developing relationships between desired ramp spacing and the key variables identified previously. The simulation task involved the following four steps:

- select simulation model,
- run initial simulations to assess model capabilities,
- calibrate model parameters, and
- simulate ramp spacing scenarios.

The following sections of this chapter discuss these steps.

MODEL SELECTION

A simulation model with capability to replicate traffic operations under a range of geometric and operational scenarios and help determining the effect of ramp spacing on freeway operation was needed. An appropriate model is expected to meet the following selection criteria:

- Models driver behavior realistically, including car-following and lane-changing maneuvers, as well as merging and weaving operations between entrance and exit ramps.
- Has the ability to track individual vehicles and record their locations, speeds, and accelerations as they travel through the roadway system.
- Provides model output data that are sufficiently detailed for determining all required measures of effectiveness (MOEs) (e.g., vehicle throughput, average speed, number and direction of lane changes for any lane in any roadway segments).

These criteria require a detailed simulation model that updates and stores the physical coordinates, speed, and acceleration of all vehicles in each simulation time step.
Only microscopic traffic simulation models can provide this level of detail. Three of the most widely used simulation models were considered in this project: VISSIM, CORSIM, and PARAMICS. The three candidate models were compared based on model features and characteristics that may be relevant to this project. Table 4-1 summarizes the main features of the three candidate models.

Table 4-1. Features and Characteristics of Candidate Models.

Features	VISSIM	CORSIM	PARAMICS
Graphical User Interface	Yes	Yes	Yes
Text Editor	Yes	Yes	Yes
Developing Tool	Yes – Vehicle Actuated Programming	Yes – Run Time Extension	Yes – Application Programming Interface
Batch Mode	Yes	Yes	Yes
Traffic Control	Yield, stop, ramp metering, etc.	Yield, stop, ramp metering, etc.	Yield, stop, ramp metering, etc.
Origin-Destination Matrix	Yes	Yes	Yes
MOE	Point/Link-based	Link-based	Point/Link-based
Animation	2-D & 3-D	2-D	2-D & 3-D

For this project, the model feature of having point-based MOEs is critical to replicate weaving traffic operations and assess the impact of different ramp spacing. Therefore, VISSIM and PARAMICS are the preferable models because they provide both point- and link-based MOEs, while CORSIM can only collect link-based MOEs.

Based on model feature comparisons, findings of previous studies, and recent reviews of existing microscopic simulation models VISSIM appeared to be the most appropriate simulation package for the purpose of this project. VISSIM is capable of modeling traffic operations in freeway weaving sections, and determining the required MOEs. Therefore, VISSIM was the strongest candidate among the available models, and it was the one selected.

SIMULATION TEST BEDS

For the purpose of this project a simulation test bed is defined as a coded network of a roadway system in which the roadway geometry (e.g., ramp spacing and lane configuration) and model parameters are fixed, while the model input (e.g., volume, speed) and routing decisions (origin-destination [O-D] percentages) may vary. Three sets of simulation test beds were developed: one set for initial runs, a second set for model calibration, and a third one for the final simulation runs of all scenarios. A simulation test bed was developed in four main steps:

- coding the network,
- defining model input and routing decisions,
- specifying data collection points, and
- setting model parameters that were constant for all simulation scenarios.

Different ramp spacing required different network configuration, and therefore a separate test bed was developed for each ramp spacing scenario. A roadway network was coded for each simulation test bed by defining links and connectors with appropriate geometry and lane configurations to ensure a realistic representation of the freeway segment as well as the connecting entrance and exit ramps. The input data required for the model included freeway and ramp volumes at network boundaries where vehicles may enter the system, desired speed distributions, and routing decisions. Vehicle input was defined as hourly volume per lane at the upstream boundaries of the links representing the freeway segment and entrance ramp. Desired speed distribution was the probability distribution of vehicles under free-flow conditions. For the initial and final simulations it was determined from the 85th percentile speed (v_{85}) assuming 5 mph standard deviation and normal speed distribution, as illustrated in Figure 4-1. These assumptions were based on previous studies and were also supported by the speed data collected in this research project and engineering judgment.

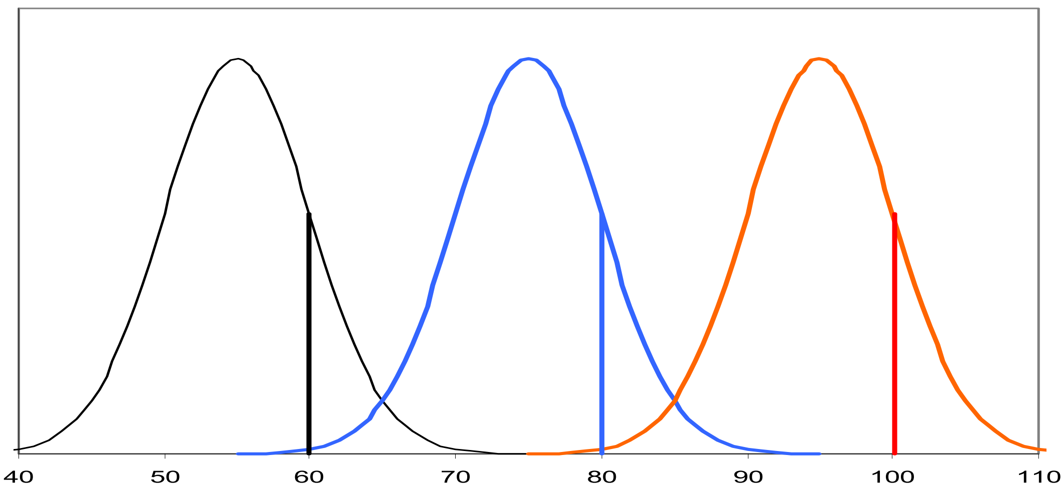


Figure 4-1. Desired Speed Distributions for v_{85} = 60, 80 and 100 mph.

Routing decisions were defined for vehicles entering the system from the freeway and the entrance ramp. They were essentially origin-destination data. For example, for freeway traffic they specified the percentage of vehicles exiting and the percentage of vehicles staying on the freeway.

It was decided that the MOEs to characterize freeway operations would be vehicle speeds, number and location of lane changes within the weaving section, and vehicle throughput. In VISSIM these data can be collected at specific locations using a data collection point object. To determine the desired MOEs, data collection points were defined at certain intervals in each freeway lane upstream, within, and downstream of the weaving section. The spacing between data collection points was not the same for the initial simulations, model calibration, and final simulation runs. For example, data collection points at 250-ft spacing were defined for the simulation test beds used for the initial simulations, as illustrated in Figure 4-2. Data collection points were similarly defined, but with 500-ft spacing, for the final simulations. Data collection points for simulation test beds for model calibration were not uniformly spaced; they were defined at the same locations where tube data were collected in the field.

Model parameters, particularly driver behavior parameters, were different for the initial and final simulation runs. It is because the purpose of the initial runs was to determine the applicability of the VISSIM model to this project; therefore, VISSIM's default parameter values were retained. For the final simulations a parameter set calibrated using field data collected at five Texas freeway segments was used.

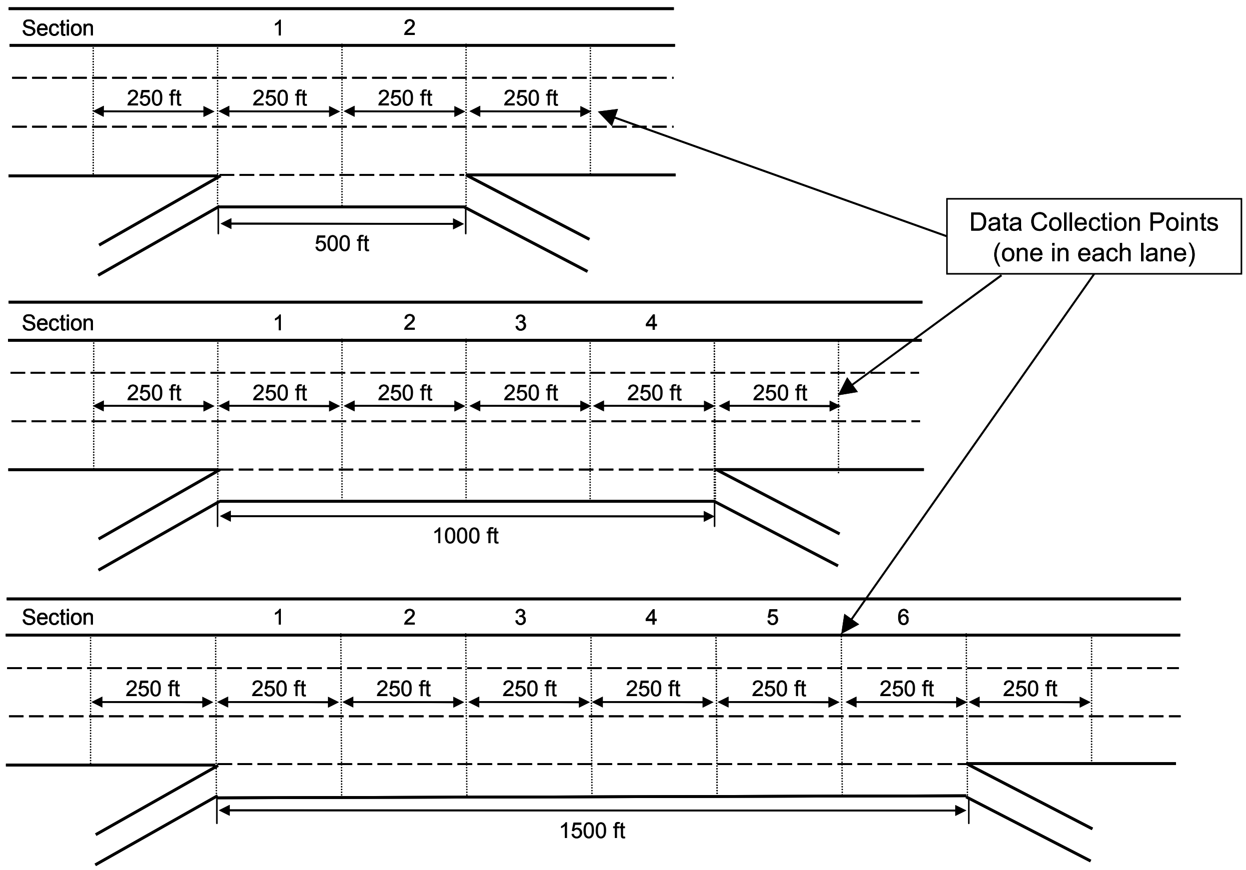


Figure 4-2. Simulation Test Beds for Initial Simulations.

INITIAL SIMULATION RUNS

Before beginning the time-consuming task of simulating all ramp spacing and traffic scenarios, initial simulations were run to assess the appropriateness and capabilities of VISSIM to model weaving traffic operations between freeway ramps. The initial runs involved the simulation of three hypothetical freeway segments with an auxiliary lane between an entrance and exit ramps spaced at 500, 1000, and 1500 ft. The combinations of volume, speed, and ramp spacing used in the initial simulations are summarized in Table 4-2. Table 4-3 gives the O-D percentages used.

Table 4-2. Volume, Speed, and Ramp Spacing Combinations for Initial Simulations.

Ramp Spacing (ft)								
500 ft			1000 ft			1500 ft		
v_{85} (mph)	$V_{Freeway}$ (vphpl)	V_{Ramp} (vph)	v_{85} (mph)	$V_{Freeway}$ (vphpl)	V_{Ramp} (vph)	v_{85} (mph)	$V_{Freeway}$ (vphpl)	V_{Ramp} (vph)
60	1000	600	60	1000	600	60	1000	600
	1400	600 900		1400	600 900		1400	600 900
	1800	600 1200		1800	600 1200		1800	600 1200
80	1000	600	80	1000	600	80	1000	600
	1400	600 900		1400	600 900		1400	600 900
	1800	600 1200		1800	600 1200		1800	600 1200
100	1000	600	100	1000	600	100	1000	600
	1400	600 900		1400	600 900		1400	600 900
	1800	600 1200		1800	600 1200		1800	600 1200

Table 4-3. O-D Percentages Used for Initial Simulations.

From	To	
	Freeway	Exit Ramp
Freeway	90%	10%
Entrance Ramp	95%	5%

Three simulation test beds were coded for the initial runs, one for each ramp spacing configuration, as shown in Figure 4-2. As stated earlier, data collection points were defined at 250-ft intervals in each freeway lane upstream, within, and downstream of the weaving section. The primary purpose of setting up these data collection points was to gather detailed information on vehicle speed and lane changing and weaving maneuvers in multiple points along the freeway. Data collection points in VISSIM can provide two types of output: compiled and raw data. Compiled data are aggregated values over user-defined time intervals. They are useful to characterize traffic conditions (e.g., speed, flow rate) in a cross section of the roadway, but not appropriate to determine weaving-related MOEs (e.g., speed and number of weaving vehicles) and their spatial distribution. This information can be obtained by tracking of individual vehicles as they travel through a weaving area. The raw data listed in Table 4-4 make vehicle tracking possible.

Post-processing of these raw data was required to extract data for vehicle tracking and calculate the speed and the number of lane changes for weaving and through vehicles in each lane of each 250-ft segment. For example, Figure 4-3 illustrates some post-processed speed and lane-change data determined from a one-hour simulation of a three-lane freeway segment with an auxiliary lane between two consecutive ramps with 1000-ft spacing, 80 mph design speed, 1400 vphpl freeway, and 600 vph ramp volume. A program was developed to partially automate the data extraction and post-processing.

Findings from the initial simulations confirmed that VISSIM can provide all required data necessary for the analyses of weaving traffic between freeway entrance and exit ramps. The next task was to calibrate the model to match field conditions observed on selected Texas freeways.

Table 4-4. Raw Data Output.

Variable	Description
T(enter)	Time when the vehicle's front has passed the cross section
T(leave)	Time when the vehicle's end has passed the cross section
Veh No	Internal number of the vehicle
Type	Vehicle type (e.g., 100 = car)
V	Speed (in m/s)
a	Acceleration (in m/s²)

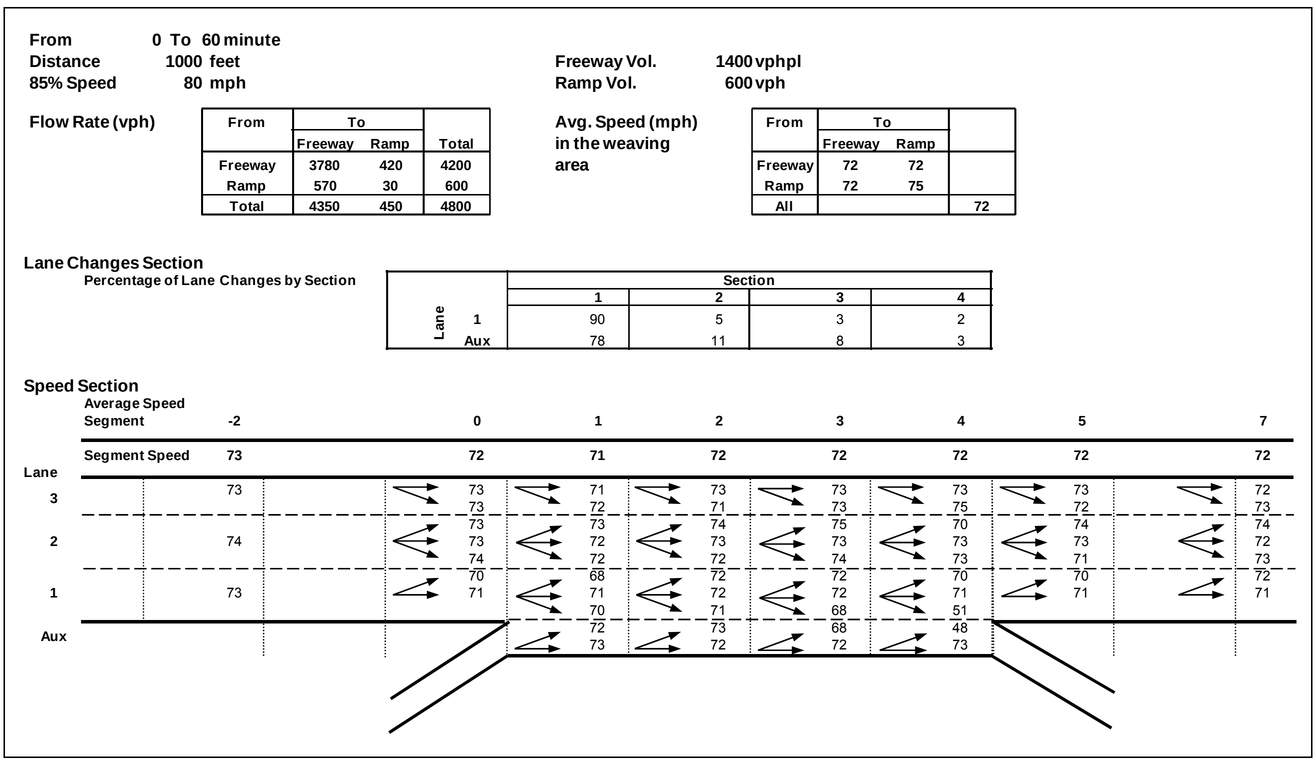


Figure 4-3. Post-Processed Speed and Lane-Change Data.

MODEL CALIBRATION

A calibration of the traffic simulation model is needed to ensure that it replicates field conditions as accurately as possible. As part of the calibration process, certain model parameters are adjusted and fine-tuned to minimize the difference between observed and modeled data.

In this project, field data from several freeway segments were collected. Model input (e.g., freeway and ramp volumes, speed distributions, and O-D patterns) for each calibration test bed was determined from the field data observed at the corresponding study site. Data collection points in the simulation network were specified at the same locations where tube data (speed and vehicle count) were collected in the field. Adequate positioning of the data collection locations was necessary to be able to match model-predicted and observed data (i.e., speed, volume, and lane-changing data). In the calibration process critical model parameters were adjusted to match the model output with field data observed at the study sites.

The objective of model calibration was to find the best parameter combination ($p_1, p_2, \ldots, p_n$) that minimizes the sum of differences between modeled and observed data at all data collection points.

$$Min \left\{ \sum_{\forall i} \left[x_i^{\mathrm{mod}} \left(p_1, p_2, \cdots p_n \right) - x_i^{obs} \right]^2 \right\} \tag{6}$$

where:

x_i^{mod} = data predicted by the model in data collection point *i* and
x_i^{obs} = field data observed in data collection point *i*.

The calibration data *x* included vehicle speeds and number of lane changes observed at the study site. The model parameters that may significantly affect these data are primarily related to driver behavior, such as car-following and lane-changing parameters, and desired speed distributions. The terms $x_i^{\mathrm{mod}}(p_1,..,p_n)$ in the objective function in equation (6) is non-linear, and depending on the number of parameters, finding the best parameter combination (i.e., global minimum) may be a computationally intensive hard-to-solve optimization problem. Therefore instead of trying to find the exact solution to equation (6), which may often not even be possible, the model calibration problem was formulated as:

Find a parameter combination ($p_1, p_2, \ldots, p_n$) that satisfies the following conditions:

$$100 \frac{\left| x_i^{\mathrm{mod}} \left(p_1, p_2, \cdots p_n \right) - x_i^{obs} \right|}{x_i^{obs}} \le \varepsilon \qquad \forall i \tag{7}$$

$$subject\ to: \quad p_j^{Min} < p_j \le p_j^{Max} \qquad \forall j \tag{8}$$

where:

ε (%) = permitted error set to ±5 to 10 percent in our study and
p_j^{Min}, p_j^{Max} = the minimum and maximum value pairs that define feasible intervals where close to optimum values of each model parameter p_j may be searched.

Based on a few initial runs, speed and lane changes were found to be sensitive to eight model parameters: two car-following and six lane-changing parameters. Table 4-5 lists these parameters. These driver behavior parameters were adjusted in the model calibration process. Default values and feasible ranges (search intervals) for the parameters are also reported in this table.

Table 4-5. Driver Behavior Parameters Considered in Model Calibration.

Parameters	Default Value	Search Interval
Car-Following Parameters		
Minimum look ahead distance (ft)	0	(0 , 200)
Headway time (sec)	0.9	(0.7 , 1.5)
Lane Changing Parameters		
Maximum deceleration of lane changing vehicle (ft/s^2)	-13.12	(-16 , -9)
Maximum deceleration of trailing vehicle (ft/s^2)	-9.84	(-16 , -9)
Accepted deceleration of lane changing vehicle (ft/s^2)	-3.28	(-10 , -1)
Accepted deceleration of trailing vehicle (ft/s^2)	-1.64	(-10 , -1)
Safety distance reduction factor	0.6	(0.1, 0.6)
Maximum deceleration for cooperative braking (ft/s^2)	-9.84	(-29 , -9)

The calibration process involved an iterative search for the best possible parameter values within the search intervals specified in Table 4-5. In each iteration step, a simulation run was completed and the model predicted speed data were compared to the vehicle speeds observed at the same locations in the field. Model parameters were systematically changed within their search interval until the difference between model-predicted and observed data was reduced to a level below the permitted error threshold of ±5 to 10 percent.

It is important to note that weaving operations observed at the study sites could not be appropriately modeled using a single parameter set. A review of the video tapes recorded at the field study sites suggested that drivers do not behave uniformly along the entire length of freeway segment between entrance and exit ramps. It was observed that many drivers who were not able to find sufficient gap for lane changes became more aggressive as they approached the exit ramp. Both exiting and entering vehicles were willing to accept shorter gaps when they were running out of space for safe lane changing maneuvers. Based on these observations, it seemed logical to apply different driver behavior parameters in different segments of the weaving section. It was found that weaving operations at most study sites could be modeled fairly well using the four driver behavior categories and parameter sets specified in Table 4-6.

Table 4-6. Calibrated Driver Behavior Categories and Parameter Sets.

Parameter	Relaxed	Normal	Moderately Aggressive	Aggressive
Car-Following Parameters				
Minimum look ahead distance (ft)	0	0	100	100
Headway time (s)	1.3	0.9	0.9	0.9
Lane Changing Parameters				
Maximum deceleration of lane changing vehicle (ft/s^2)	-9.84	-13.12	-13.12	-13.12
Maximum deceleration of trailing vehicle (ft/s^2)	-9.84	-9.84	-9.84	-13.12
Accepted deceleration of lane changing vehicle (ft/s^2)	-1.64	-3.28	-3.28	-9.84
Accepted deceleration of trailing vehicle (ft/s^2)	-1.64	-1.64	-2.46	-9.84
Safety distance reduction factor	0.7	0.6	0.3	0.1
Maximum deceleration for cooperative braking (ft/s^2)	-9.84	-9.84	-16.4	-19.69

The best results were obtained when the four parameter sets were varied along the weaving sections, as shown in Table 4-7. Note that in segment A different parameter sets apply to vehicles arriving from the freeway and the entrance ramp. The same parameter sets were applied in a similar manner to the final simulation runs.

Table 4-7. Recommended Parameter Set Variation along Weaving Sections.

	Segment			
	A	**B**	**C**	**D**
Segment Length	L_A = 250 ft	$L_B = L-L_A-L_C-L_D$	L_C = 250 to 500 ft	L_D = 250 ft
Vehicles from Freeway	Relaxed	Normal	Moderately Aggressive	Aggressive
Vehicles from Entrance Ramp	Normal	Normal	Moderately Aggressive	Aggressive
L = Weaving length				

SIMULATION OF RAMP SPACING SCENARIOS

Once the model parameters had been calibrated, a range of ramp spacing and traffic condition scenarios was defined and arranged in a simulation scenario matrix. The scenario matrix was used as a guide in conducting the simulation runs for studying the relationship between ramp spacing and selected key variables, such as speed, volume, and weaving maneuver that may affect traffic operations between freeway ramps. Various traffic conditions were created by systematically changing design speed (85th percentile speed), freeway volume, and origin-destination percentages. Note that the entrance ramp traffic also varied, although not independently of the freeway volume. In each scenario, it was specified as 30 percent of the freeway volume.

Table 4-8 and Table 4-9 show the simulation scenario matrix. There are five different ramp spacing configurations, from 1000 to 5000 ft with 1000-ft increment. For each ramp spacing value, 72 combinations of different freeway volume, origin-destination pattern, and design speed scenarios were considered. The O-D information was specified by two variables:

- percentage of traffic from freeway to exit ramp and
- percentage of traffic from entrance ramp to freeway.

The total number of simulation scenarios (i.e., combinations of different ramp spacing and traffic conditions) was 360.

A simulation test bed was developed for each of the five ramp spacing scenarios. They had different geometric configurations, but used the same calibrated model parameters. Although the parameter sets were the same for each ramp spacing scenario, the length of freeway segments to which they were applied varied with the weaving length, as shown in Table 4-10.

Data collection points were defined at 500-ft intervals in each freeway lane within the weaving section. As for the initial runs, the purpose of setting up these data collection points was to determine vehicle speed, lane changes, and weaving maneuvers in multiple points along the freeway.

By varying vehicle input and O-D data, these test beds were used for the simulation of all 360 combinations specified in Table 4-8 and Table 4-9. Due to the stochastic nature of some of the input parameters (e.g., desired speed, gap acceptance, and other driver characteristics), the simulation of each scenario was repeated 10 times using different random seed numbers, increasing the total number of required simulations to 3600. Running multiple simulations with different random seeds and averaging the output from these simulations helped avoid possible skewed results due to random anomalies in the input data.

After completion of all simulation runs, relevant measures of effectiveness were extracted from the simulation output. Again, due to the large number of simulation files a program was developed to partially automate the extraction process. Extracted MOEs for each ramp spacing scenario were combined into a single comma-separated value file that could be imported to almost any statistical package for subsequent data analysis.

Table 4-8. Simulation Scenario Matrix (Part 1: 60 and 80 mph).

Ramp Spacing (ft)																			
1000				2000				3000				4000				5000			
v_{85}	V_F	F-R	R-F	v_{85}	V_F	F-R	R-F	v_{85}	V_F	F-R	R-F	v_{85}	V_F	F-R	R-F	v_{85}	V_F	F-R	R-F
60	1200	5	75 100	60	1200	5	75 100	60	1200	5	75 100	60	1200	5	75 100	60	1200	5	75 100
		15	75 100			15	75 100			15	75 100			15	75 100			15	75 100
		25	75 100			25	75 100			25	75 100			25	75 100			25	75 100
	1500	5	75 100		1500	5	75 100		1500	5	75 100		1500	5	75 100		1500	5	75 100
		15	75 100			15	75 100			15	75 100			15	75 100			15	75 100
		25	75 100			25	75 100			25	75 100			25	75 100			25	75 100
	1800	5	75 100		1800	5	75 100		1800	5	75 100		1800	5	75 100		1800	5	75 100
		15	75 100			15	75 100			15	75 100			15	75 100			15	75 100
		25	75 100			25	75 100			25	75 100			25	75 100			25	75 100
	2100	5	75 100		2100	5	75 100		2100	5	75 100		2100	5	75 100		2100	5	75 100
		15	75 100			15	75 100			15	75 100			15	75 100			15	75 100
		25	75 100			25	75 100			25	75 100			25	75 100			25	75 100
80	1200	5	75 100	80	1200	5	75 100	80	1200	5	75 100	80	1200	5	75 100	80	1200	5	75 100
		15	75 100			15	75 100			15	75 100			15	75 100			15	75 100
		25	75 100			25	75 100			25	75 100			25	75 100			25	75 100
	1500	5	75 100		1500	5	75 100		1500	5	75 100		1500	5	75 100		1500	5	75 100
		15	75 100			15	75 100			15	75 100			15	75 100			15	75 100
		25	75 100			25	75 100			25	75 100			25	75 100			25	75 100
	1800	5	75 100		1800	5	75 100		1800	5	75 100		1800	5	75 100		1800	5	75 100
		15	75 100			15	75 100			15	75 100			15	75 100			15	75 100
		25	75 100			25	75 100			25	75 100			25	75 100			25	75 100
	2100	5	75 100		2100	5	75 100		2100	5	75 100		2100	5	75 100		2100	5	75 100
		15	75 100			15	75 100			15	75 100			15	75 100			15	75 100
		25	75 100			25	75 100			25	75 100			25	75 100			25	75 100

Table 4-9. Simulation Scenario Matrix (Part 2: 100 mph).

Ramp Spacing (ft)																			
1000				2000				3000				4000				5000			
v_{85}	V_F	F-R	R-F	v_{85}	V_F	F-R	R-F	v_{85}	V_F	F-R	R-F	v_{85}	V_F	F-R	R-F	v_{85}	V_F	F-R	R-F
100	1200	5	75 100	100	1200	5	75 100	100	1200	5	75 100	100	1200	5	75 100	100	1200	5	75 100
		15	75 100			15	75 100			15	75 100			15	75 100			15	75 100
		25	75 100			25	75 100			25	75 100			25	75 100			25	75 100
	1500	5	75 100		1500	5	75 100		1500	5	75 100		1500	5	75 100		1500	5	75 100
		15	75 100			15	75 100			15	75 100			15	75 100			15	75 100
		25	75 100			25	75 100			25	75 100			25	75 100			25	75 100
	1800	5	75 100		1800	5	75 100		1800	5	75 100		1800	5	75 100		1800	5	75 100
		15	75 100			15	75 100			15	75 100			15	75 100			15	75 100
		25	75 100			25	75 100			25	75 100			25	75 100			25	75 100
	2100	5	75 100		2100	5	75 100		2100	5	75 100		2100	5	75 100		2100	5	75 100
		15	75 100			15	75 100			15	75 100			15	75 100			15	75 100
		25	75 100			25	75 100			25	75 100			25	75 100			25	75 100

v_{85} = 85th percentile speed (mph)
V_F = Freeway volume (vphpl)
F-R = Freeway to ramp percentage (%)
R-F = Ramp to freeway percentage (%)

Table 4-10. Segmentation of Parameter Sets for Different Ramp Spacing.

Parameter Sets for Vehicles….	…from Freeway	Relaxed	Normal	Moderately Aggressive	Aggressive
	…from Entrance Ramp	Normal	Normal	Moderately Aggressive	Aggressive
Ramp Spacing		**Segment A**	**Segment B**	**Segment C**	**Segment D**
1000 ft		0-250	250-500	500-750	750-1000
2000 ft		0-250	250-1250	1250-1750	1750-2000
3000 ft		0-250	250-2250	2250-2750	2750-3000
4000 ft		0-250	250-3250	3250-3750	3750-4000
5000 ft		0-250	250-4250	4250-4750	4750-5000

CHAPTER 5

ANALYZE RESULTS

EVALUATION OF THE EFFECTS OF WEAVING LENGTH

The field data (see Chapter 3) and simulation data (see Chapter 4) were used to develop prediction equations for free-flow mean speeds using variables such as traffic volume, weaving length, posted speed, number of through lanes, presence of an auxiliary lane, and others with the goal to assess the effect of weaving length on the free-flow mean speeds. There were various volume measures (e.g., right lane upstream volume, entering ramp volume, exiting ramp volume, merging volume, and so on) and many of them are highly correlated, which could lead to the multi-collinearity problem in regression if they are included simultaneously in the model. To prevent this potential multi-collinearity problem, correlations among independent variables were carefully examined and only the variables not having high correlations with the existing predictors were selected for inclusion.

WEAVING LENGTHS

As mentioned in Chapter 3 and illustrated in Figure 3-5 and Figure 3-6, the length of the weaving section can be influenced by the location of the following features: physical gore, marked gore, and solid white line markings. Figure 5-1 illustrates the locations of these features within the weaving area for the seven field sites. When the measurement is *short*, it includes the distance between end points of solid painted lines meant to discourage lane changing. The *base* weaving length is the distance between respective gore areas where the left edge of the ramp travel lanes and the right edge of the freeway travel lanes meet. The distance between physical barriers marking the ends of the merge and diverge gore areas is the *long* weaving length. Figure 5-1 includes lengths of the sections between physical and painted gores, solid line areas, from painted gores to the ends of the solid lines (or to the end of merging taper/beginning of diverging taper for the site on IH30 WB), and the short length, which is the length of the skip line section (or from the end of merging taper to the beginning of diverging taper for the site on IH30 WB, Site 7).

The preferred weaving length (short, base, long) to use in the evaluations is not clear from preliminary evaluations, from consideration of driver's behavior (e.g., drivers willingness to drive over the solid white line), or from a review of the definitions. Therefore all three weaving lengths were included in the evaluations.

The range of the speeds measured for each weaving length is shown in Figure 5-2 for short weaving lengths, Figure 5-3 for base weaving lengths, and Figure 5-4 for long weaving lengths.

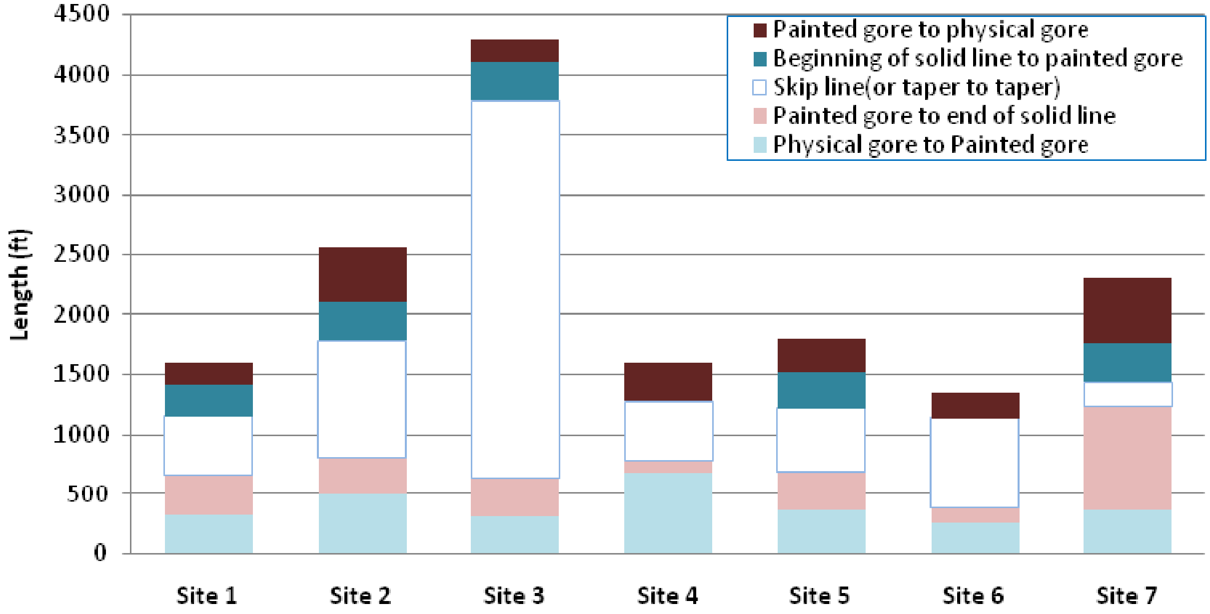
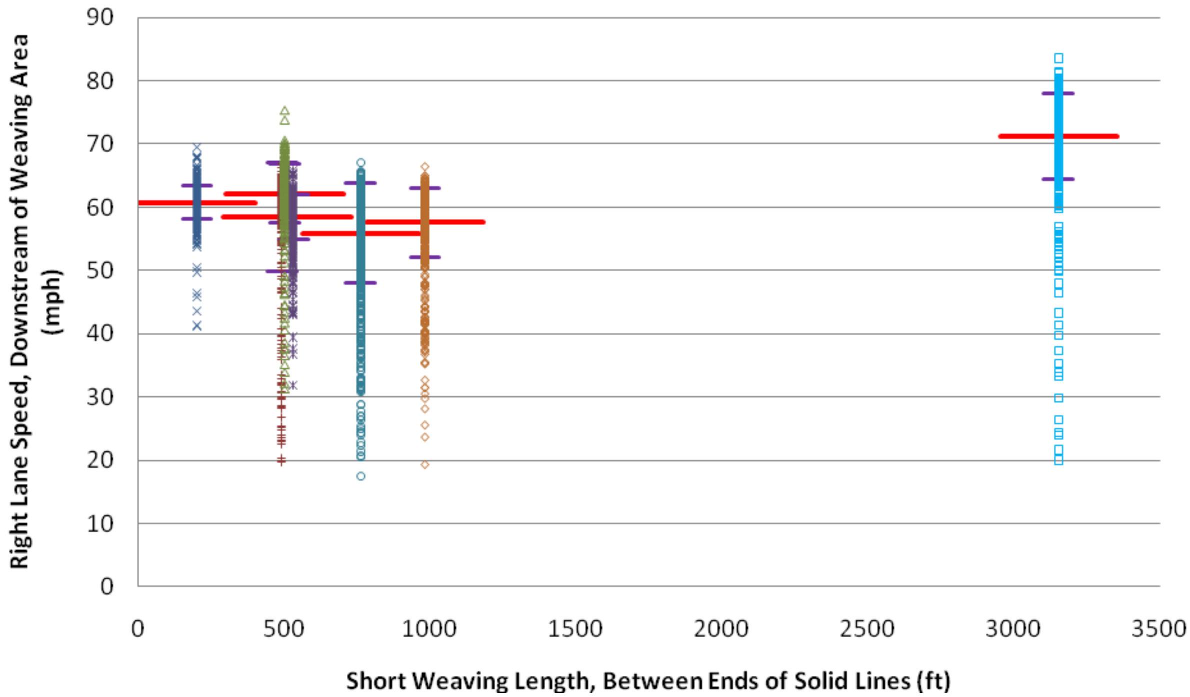
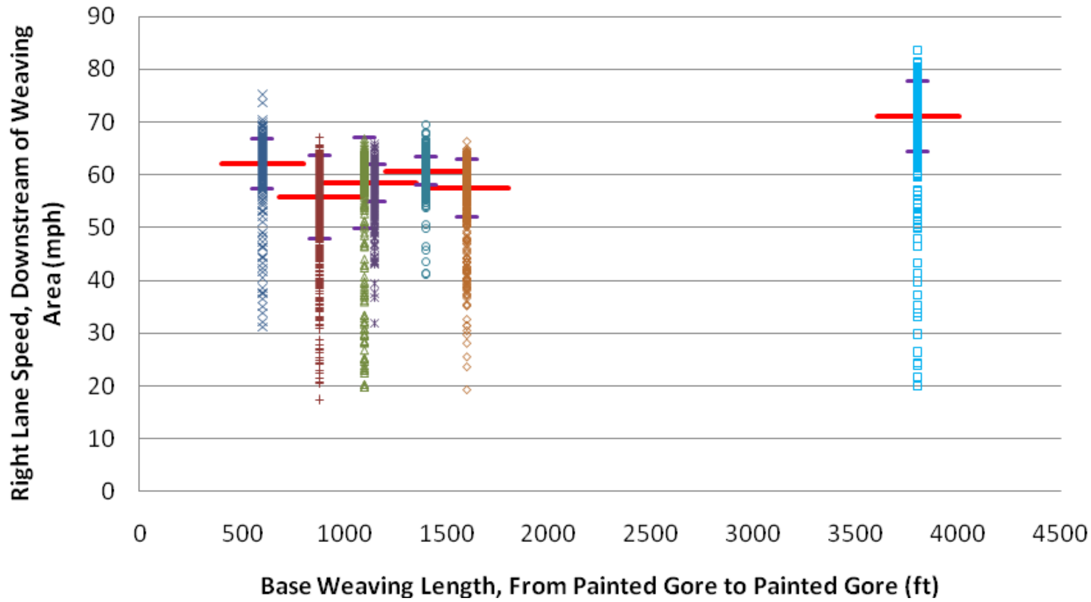


Figure 5-1. Weaving Lengths.



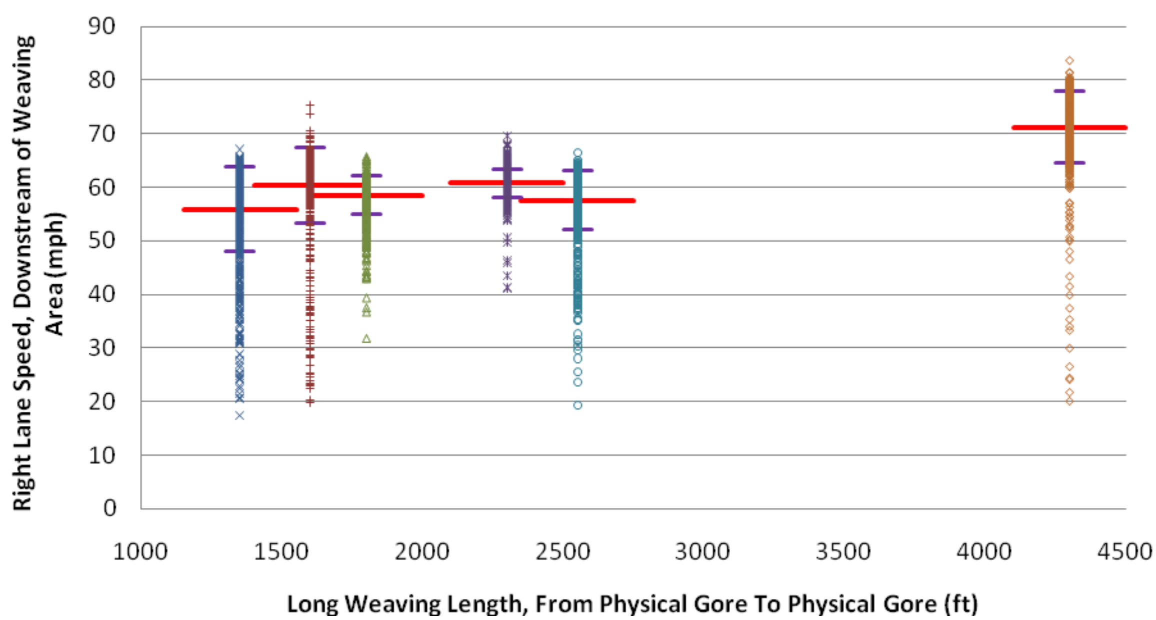
Length (ft)	200	490	500	530	760	980	3150
Data points	816	576	616	910	916	1104	864

Figure 5-2. Measured Speed by Short Weaving Length (Long Horizontal Line Represents Average and Shorter Horizontal Lines Represent One Standard Deviation).



Length (ft)	600	880	1100	1150	1400	1600	3800
Sample size	616	916	576	910	816	1104	864

Figure 5-3. Measured Speed by Base Weaving Length (Long Horizontal Line Represents Average and Shorter Horizontal Lines Represent One Standard Deviation).



Length (ft)	1350	1600	1800	2300	2550	4300
Sample size	916	1192	910	816	1104	864

Figure 5-4. Measured Speed by Long Weaving Length(Long Horizontal Line Represents Average and Shorter Horizontal Lines Represent One Standard Deviation).

SPEED BY VOLUME

Figure 5-5 shows the average speed within 5-minute bins by the 5-minute volume converted to a hourly flow rate for Sites 1 and 2. Figure 5-6 shows similar graphs for Sites 3, 4, and 5. Sites 6 and 7 are shown in Figure 5-7. The effects of congestion are revealed at the higher flow rates in these graphs. Several sites show the characteristic "button hook" pattern with the presence of both low and high speeds for similar flow rates. The lower speeds represent the period when the facility is recovering from reaching capacity. The presence of these lower speeds will have a significant impact on the statistical evaluations, including affecting the fundamental statistical approaches being used. Due to the focus of this study, the research team eliminated these recovery speeds from the data set. Speeds that were greater than 10 mph below the posted speed limit were removed from the evaluation.

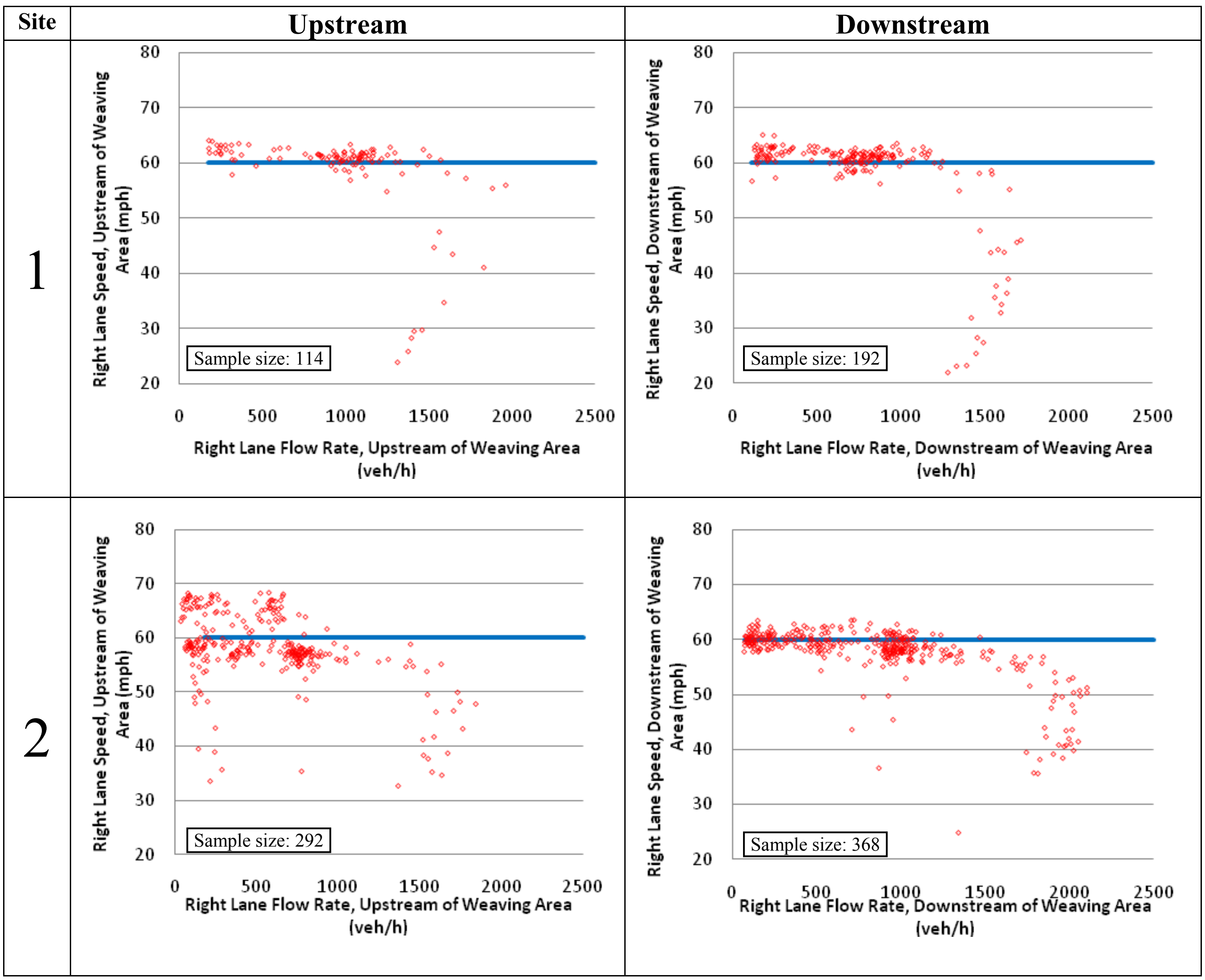


Figure 5-5. Average Speed by Flow Rate for Sites 1 and 2 (Horizontal Solid Line Represents Speed Limit).

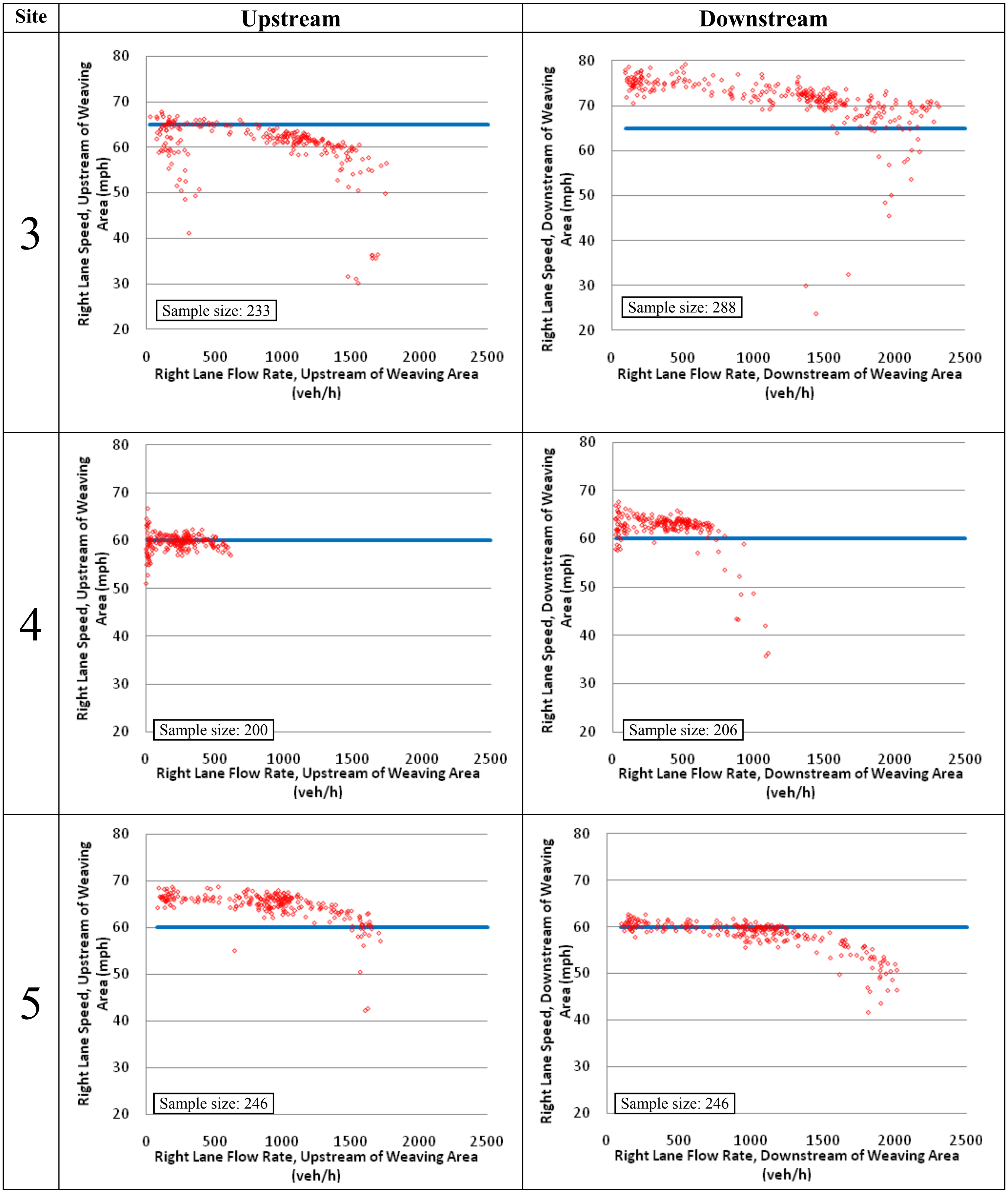
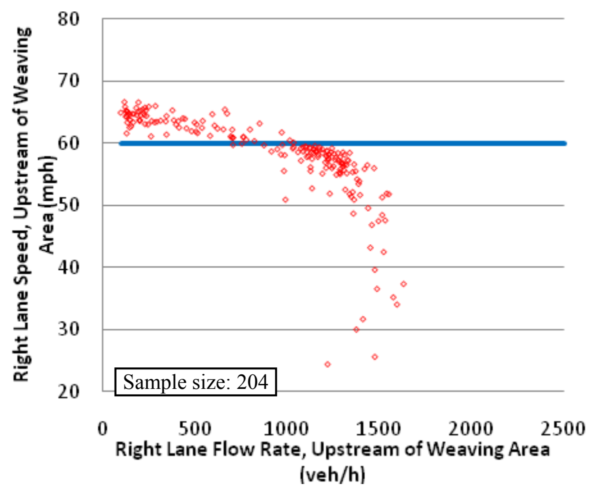
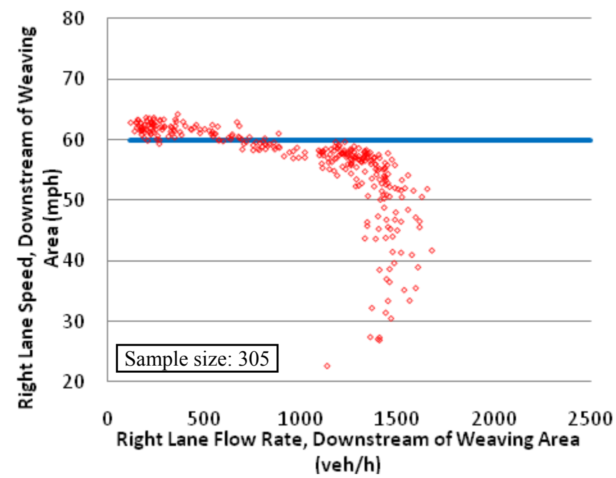


Figure 5-6. Average Speed by Flow Rate for Sites 3, 4, and 5 (Horizontal Solid Line Represents Speed Limit).

<table>
<tr><th>Site</th><th>Upstream</th><th>Downstream</th></tr>
<tr><td>6</td><td>
</td><td>
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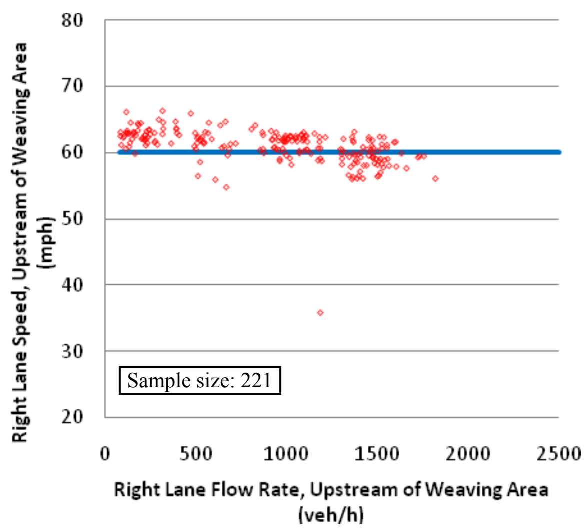
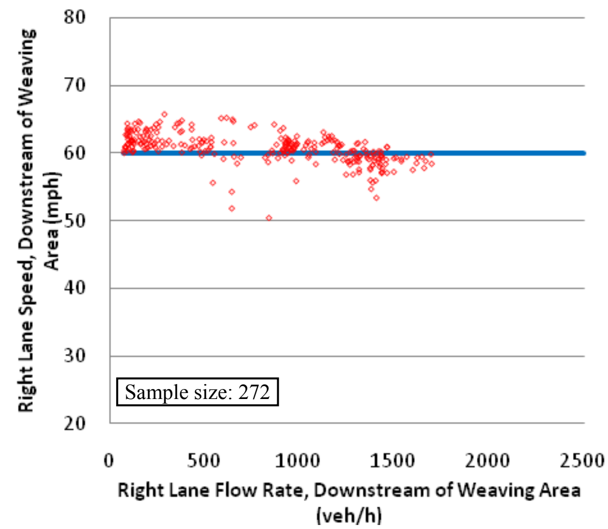
<tr><td>7</td><td>
</td><td>
</td></tr>
</table>

Figure 5-7. Average Speed by Flow Rate for Sites 6 and 7 (Horizontal Solid Line Represents Speed Limit).

SPEED LOCATION

Speeds were measured in the following four locations at each study site (see Figure 3-3 and Figure 3-4 for typical layouts of a site):

- in the rightmost lane, just upstream of the weaving area (location A2 or F2);
- on the entrance ramp, at the end of the solid white line separating the entrance ramp from the freeway main lanes (location B1 or G1);

- on the exit ramp, at the beginning of the solid white line separating the exit ramp from the freeway main lanes (location C1 or I1); and
- in the rightmost lane, just downstream of the weaving area (location E2 or J2).

Initial evaluations examined the relationship of weaving length to speed at each of the above locations. The best results in terms of strongest relationship and in usability for this study were identified for location E2/J2 (i.e., just downstream of weaving area) and will be the focus of the discussion in this chapter.

FIELD DATA EVALUATIONS

5-Minute Bin Counter Data with Weaving Length as a Continuous Variable

Several models were considered in the evaluations using 5-minute bins of speed and flow. In some cases coefficient estimates that were either not significant and/or had counterintuitive signs on the coefficients resulted. Based on experience, the expectation is that as volume or percent trucks increase the speed on the facility will decrease. As more cars, or as more larger vehicles (i.e., larger percent trucks), are in the same area speeds will decrease. The expectation is also that as the weaving length increases, speeds will increase because greater space is available for the weaving maneuvers.

Note that expected relationships, such as speeds increasing due to increase in weaving length, may not always be present in a regression evaluation based on observational data. The inclusion of other variables can change the dynamics of the relationship. For example, the inclusion of number of lanes or shoulder width may explain some of the effects of available space on speeds. Also, the weaving length characteristics may be confounded with or interact with other site characteristics such as speed limit. Because the relationship between an independent variable and the dependent variable may not be as initially envisioned, the research team did not automatically remove a variable from the analysis just because of a counterintuitive sign. The presence of a counterintuitive sign, however, would result in additional reviews and evaluations to assist in understanding and explaining the relationships.

Several variables were considered in the evaluations using the 5-minute bins, including the following:

- measure of weaving length (short, base, or long);
- posted speed (60 or 65 mph);
- light level (dawn, day, dusk, night);
- measure of volume (e.g., volume at E2/J2, A2/F2, etc.);
- measure of percent trucks (e.g., at E2/J2, etc.);
- number of lanes; and
- presence of auxiliary lane.

All of the evaluations using the 5-minute bin counter data and weaving length as a continuous variable resulted in the base weaving length and the long weaving length being not significant (e.g., these values had p-values greater than 0.8). Most of the models had short weaving length as not significant (p-value about 0.15). One combination of variables did result in the short weaving length being significant (although negative) with a p-value of 0.0228. These results are shown in Table 5-1. In addition to short weaving length, posted speed, light level, volume, and percent trucks were significant.

Table 5-1. Output for Speeds Using 5-Minute Bin Counter Data and Short Weaving Lengths as a Continuous Variable.

Response AL-MnSp-E2/J2

Summary of Fit

RSquare	0.819906
RSquare Adj	0.819677
Root Mean Square Error	2.331505
Mean of Response	61.68995
Observations (or Sum Wgts)	5512

Parameter Estimates

Term	Estimate	Std Error	DFDen	t Ratio	Prob>|t|
Intercept	77.138214	1.770956	3.969	43.56	<.0001*
Po_Sp[60]	-11.2374	1.238979	3.93	-9.07	0.0009*
Light[Dawn]	0.5832166	0.130055	5504	4.48	<.0001*
Light[Day]	0.0660633	0.068862	5502	0.96	0.3374
Light[Dusk]	0.0339011	0.121083	5500	0.28	0.7795
AL_Vol_E2/J2_Tu	-0.053659	0.001185	5059	-45.26	0.0000*
%Tru_E2/J2	-5.697315	0.602127	5375	-9.46	<.0001*
L_s	-0.003392	0.000934	3.932	-3.63	0.0228*

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Po_Sp	1	1	3.93	82.2629	0.0009*
Light	3	3	5467	23.4191	<.0001*
AL_Vol_E2/J2_Tu	1	1	5059	2048.910	0.0000*
%Tru_E2/J2	1	1	5375	89.5290	<.0001*
L_s	1	1	3.932	13.1761	0.0228*

5-Minute Bin Counter Data with Weaving Length as a Discrete Variable

Because of the challenges with identifying a clear relationship between weaving length and speed, additional evaluations were conducted by assembling the weaving lengths into groups. Table 5-2 lists the groups developed for when weaving length is measured as short, base, or long. The results of the evaluations are shown in Table 5-3 for short, Table 5-4 for base, and Table 5-5 for long weaving lengths.

As can be seen in the LS Means plots shown in Tables 5-3 to 5-5, Groups 1, 2, and 3 have similar speeds while Group 4's speed is noticeably greater—on the order of more than 10 mph. As shown in Table 5-2, Group 4's length, whether short, base, or long, is also noticeably greater than the lengths at the other sites.

Table 5-2. Weaving Length (L) Groups.

Group	L-short	L-base	L-long
1	Site 7 (200)	Site 4 (600) Site 6 (880)	Site 6 (1350)
2	Site 1 (490) Site 4 (500) Site 5 (530)	Site 1 (1100) Site 5 (1150)	Site 1 (1600) Site 4 (1600) Site 5 (1800)
3	Site 2 (980) Site 6 (760)	Site 2 (1600) Site 7 (1400)	Site 2 (2550) Site 7 (2300)
4	Site 3 (3150)	Site 3 (3800)	Site 3 (4300)

Table 5-3. Output for Speeds Using 5-Minute Bin Counter Data and Groups of Short Weaving Lengths.

Response AL-MnSp-E2/J2

Summary of Fit

RSquare	0.819908
RSquare Adj	0.819646
Root Mean Square Error	2.331505
Mean of Response	61.68995
Observations (or Sum Wgts)	5512

Parameter Estimates

Term	Estimate	Std Error	DFDen	t Ratio	Prob>|t|
Intercept	67.501186	0.284276	4.396	237.45	<.0001*
AL_Vol_E2/J2_Tu	-0.053609	0.001186	5326	-45.18	0.0000*
%Tru_E2/J2	-5.704686	0.602397	5459	-9.47	<.0001*
Light[Dawn]	0.5814238	0.130063	5503	4.47	<.0001*
Light[Day]	0.0652144	0.068868	5503	0.95	0.3437
Light[Dusk]	0.0337518	0.121084	5500	0.28	0.7804
Ls_group_char[Ls1]	-2.28242	0.503847	2.978	-4.53	0.0204*
Ls_group_char[Ls2]	-3.269562	0.360173	3.016	-9.08	0.0028*
Ls_group_char[Ls3]	-4.633517	0.399761	2.966	-11.59	0.0015*

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
AL_Vol_E2/J2_Tu	1	1	5326	2041.623	0.0000*
%Tru_E2/J2	1	1	5459	89.6804	<.0001*
Light	3	3	5493	23.1946	<.0001*
Ls_group_char	3	3	2.987	147.4487	0.0010*

Ls_group_char

Least Squares Means Table

Level	Least Sq Mean	Std Error
Ls1	61.221430	0.61435538
Ls2	60.234287	0.35752408
Ls3	58.870333	0.43530320
Ls4	73.689349	0.61535347

LS Means Plot

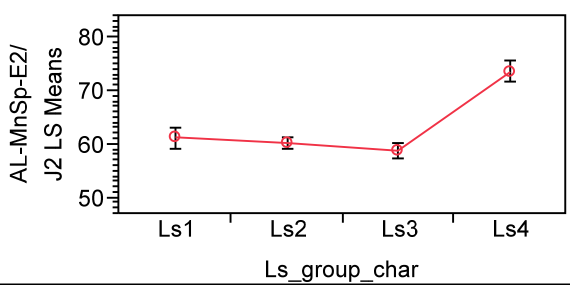


Table 5-4. Output for Speeds Using 5-Minute Bin Counter Data and Groups of Base Weaving Lengths.

Response AL-MnSp-E2/J2

Summary of Fit

RSquare	0.819909
RSquare Adj	0.819647
Root Mean Square Error	2.331504
Mean of Response	61.68995
Observations (or Sum Wgts)	5512

Parameter Estimates

Term	Estimate	Std Error	DFDen	t Ratio	Prob>|t|
Intercept	67.371444	0.536724	3.302	125.52	<.0001*
AL_Vol_E2/J2_Tu	-0.053529	0.001186	5498	-45.14	0.0000*
%Tru_E2/J2	-5.699826	0.602167	5502	-9.47	<.0001*
Light[Dawn]	0.579185	0.130058	5501	4.45	<.0001*
Light[Day]	0.0636713	0.068864	5501	0.92	0.3552
Light[Dusk]	0.0335244	0.121083	5500	0.28	0.7819
Lb_group_char[Lb1]	-3.56633	0.845306	3.006	-4.22	0.0242*
Lb_group_char[Lb2]	-3.405909	0.845001	3.001	-4.03	0.0274*
Lb_group_char[Lb3]	-3.334197	0.84481	2.999	-3.95	0.0290*

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
AL_Vol_E2/J2_Tu	1	1	5498	2037.840	0.0000*
%Tru_E2/J2	1	1	5502	89.5962	<.0001*
Light	3	3	5502	22.9153	<.0001*
Lb_group_char	3	3	3.002	30.7076	0.0094*

Lb_group_char

Least Squares Means Table

Level	Least Sq Mean	Std Error
Lb1	59.813581	0.9388923
Lb2	59.974002	0.9387740
Lb3	60.045714	0.9383142
Lb4	73.686348	1.3268523

LS Means Plot

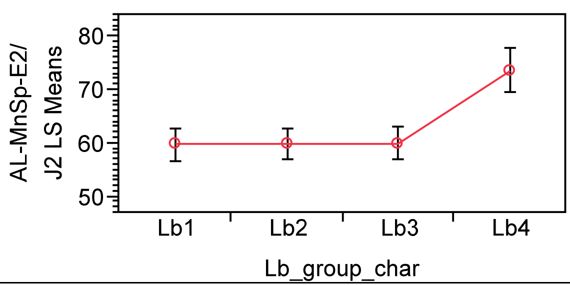


Table 5-5. Output for Speeds Using 5-Minute Bin Counter Data and Groups of Long Weaving Lengths.

Response AL-MnSp-E2/J2
Summary of Fit

RSquare	0.819909
RSquare Adj	0.819647
Root Mean Square Error	2.331504
Mean of Response	61.68995
Observations (or Sum Wgts)	5512

Parameter Estimates

Term	Estimate	Std Error	DFDen	t Ratio	Prob>|t|
Intercept	67.198491	0.49391	3.388	136.05	<.0001*
AL_Vol_E2/J2_Tu	-0.053511	0.001186	5496	-45.13	0.0000*
%Tru_E2/J2	-5.697861	0.602202	5503	-9.46	<.0001*
Light[Dawn]	0.578557	0.130057	5501	4.45	<.0001*
Light[Day]	0.0632512	0.068865	5502	0.92	0.3584
Light[Dusk]	0.0335727	0.121083	5500	0.28	0.7816
Li_group_char[Li1]	-4.342719	0.936949	3.002	-4.63	0.0189*
Li_group_char[Li2]	-2.971673	0.66828	3.014	-4.45	0.0209*
Li_group_char[Li3]	-3.163016	0.744186	3.003	-4.25	0.0238*

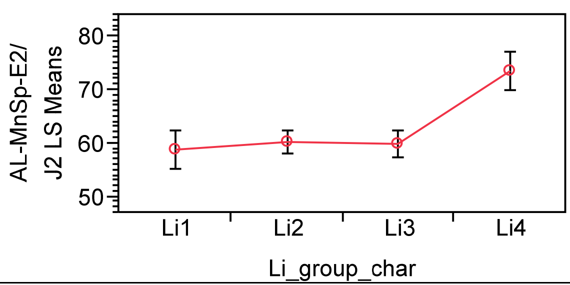
Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
AL_Vol_E2/J2_Tu	1	1	5496	2036.401	0.0000*
%Tru_E2/J2	1	1	5503	89.5241	<.0001*
Light	3	3	5502	22.8408	<.0001*
Li_group_char	3	3	3.006	41.9525	0.0059*

Li_group_char
Least Squares Means Table

Level	Least Sq Mean	Std Error
Li1	58.865572	1.1399959
Li2	60.236618	0.6596412
Li3	60.045274	0.8065047
Li4	73.685699	1.1404251

LS Means Plot



5-Minute Bin Video Data with Weaving Length as a Continuous Variable

The lane changes occurring between lanes were counted for several hours of data. The availability of lane-changing data provides opportunity to include variables that better reflect the conditions present during the 5-minute period. A disadvantage is that less data are available. Because several of the variables were correlated, for example, total upstream volume and total downstream volume, several combinations of variables were considered. Variables were not retained in the model if they were correlated with other variables.

The best models included the following variables:

- VolDown – total volume leaving the system and is the sum of all main lanes at the section just downstream of the weaving area along with exit ramp volume.
- Ramp Ratio – a measure of the proportion of the total volume in the weaving area attributed to the ramps.
- L – length of weaving section.

Table 5-6, Table 5-7, and Table 5-8 show the outputs for the short, base, and long weaving lengths, respectively, when the relationship between weaving length and speed is assumed to be linear. In all cases, weaving length was significant at the 0.05 level.

Models using a transformation of weaving length was also explored. Of the transformations considered, only the square root of weaving lengths resulted in weaving length being nearly significant (generally 0.06 or 0.07 when 0.05 is the desired value). Table 5-9, Table 5-10, and Table 5-11 show the outputs for the short, base, and long weaving lengths, respectively.

Table 5-6. Output for Speeds Using 5-Minute Bin Video Data, Short Weaving Length as a Continuous Variable, and Linear Relationship between Speed and Weaving Length.

Response AL-MnSp-E2/J2
Summary of Fit

RSquare	0.596744
RSquare Adj	0.591661
Root Mean Square Error	2.557861
Mean of Response	59.39643
Observations (or Sum Wgts)	242

Parameter Estimates

Term	Estimate	Std Error	DFDen	t Ratio	Prob>|t|
Intercept	69.524953	1.679721	16.42	41.39	<.0001*
VolDown	-0.023916	0.001953	238	-12.25	<.0001*
RampRatio	-22.11119	4.860614	189.8	-4.55	<.0001*
L_s	0.0026176	0.000902	4.931	2.90	0.0342*

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
VolDown	1	1	238	149.9865	<.0001*
RampRatio	1	1	189.8	20.6939	<.0001*
L_s	1	1	4.931	8.4305	0.0342*

Table 5-7. Output for Speeds Using 5-Minute Bin Video Data, Base Weaving Length as a Continuous Variable, and Linear Relationship between Speed and Weaving Length.

Response AL-MnSp-E2/J2
Summary of Fit

RSquare	0.59684
RSquare Adj	0.591758
Root Mean Square Error	2.557598
Mean of Response	59.39643
Observations (or Sum Wgts)	242

Parameter Estimates

Term	Estimate	Std Error	DFDen	t Ratio	Prob>|t|
Intercept	68.255373	1.914089	11.09	35.66	<.0001*
VolDown	-0.023875	0.001952	237.9	-12.23	<.0001*
RampRatio	-22.19639	4.85826	191.6	-4.57	<.0001*
L_b	0.0024776	0.000855	5.091	2.90	0.0331*

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
VolDown	1	1	237.9	149.6280	<.0001*
RampRatio	1	1	191.6	20.8739	<.0001*
L_b	1	1	5.091	8.4040	0.0331*

Table 5-8. Output for Speeds Using 5-Minute Bin Video Data, Long Weaving Length as a Continuous Variable, and Linear Relationship between Speed and Weaving Length.

Response AL-MnSp-E2/J2
Summary of Fit

RSquare	0.596966
RSquare Adj	0.591885
Root Mean Square Error	2.557461
Mean of Response	59.39643
Observations (or Sum Wgts)	242

Parameter Estimates

Term	Estimate	Std Error	DFDen	t Ratio	Prob>|t|
Intercept	66.4042	2.597427	7.574	25.57	<.0001*
VolDown	-0.023707	0.001951	237.8	-12.15	<.0001*
RampRatio	-22.00734	4.868963	202.8	-4.52	<.0001*
L_l	0.0024748	0.000968	5.114	2.56	0.0499*

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
VolDown	1	1	237.8	147.5906	<.0001*
RampRatio	1	1	202.8	20.4297	<.0001*
L_l	1	1	5.114	6.5316	0.0499*

Table 5-9. Output for Speeds Using 5-Minute Bin Video Data, Short Weaving Length as a Continuous Variable, and Square Root Relationship between Speed and Weaving Length.

Response AL-MnSp-E2/J2

Summary of Fit

RSquare	0.596886
RSquare Adj	0.591805
Root Mean Square Error	2.557873
Mean of Response	59.39643
Observations (or Sum Wgts)	242

Parameter Estimates

Term	Estimate	Std Error	DFDen	t Ratio	Prob>|t|
Intercept	67.035612	2.593984	6.979	25.84	<.0001*
VolDown	-0.023845	0.001954	237.8	-12.20	<.0001*
RampRatio	-22.23463	4.881958	210.4	-4.55	<.0001*
Sqrt(L_s)	0.1766742	0.076809	4.952	2.30	0.0703

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
VolDown	1	1	237.8	148.8630	<.0001*
RampRatio	1	1	210.4	20.7430	<.0001*
Sqrt(L_s)	1	1	4.952	5.2908	0.0703

Table 5-10. Output for Speeds Using 5-Minute Bin Video Data, Base Weaving Length as a Continuous Variable, and Square Root Relationship between Speed and Weaving Length.

Response AL-MnSp-E2/J2

Summary of Fit

RSquare	0.596941
RSquare Adj	0.59186
Root Mean Square Error	2.557669
Mean of Response	59.39643
Observations (or Sum Wgts)	242

Parameter Estimates

Term	Estimate	Std Error	DFDen	t Ratio	Prob>|t|
Intercept	64.356864	3.440675	5.943	18.70	<.0001*
VolDown	-0.02382	0.001953	238	-12.20	<.0001*
RampRatio	-22.31775	4.877016	208.4	-4.58	<.0001*
Sqrt(L_b)	0.2052303	0.085067	5.112	2.41	0.0596

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
VolDown	1	1	238	148.7299	<.0001*
RampRatio	1	1	208.4	20.9408	<.0001*
Sqrt(L_b)	1	1	5.112	5.8205	0.0596

Table 5-11. Output for Speeds Using 5-Minute Bin Video Data, Long Weaving Length as a Continuous Variable, and Square Root Relationship between Speed and Weaving Length.

Response AL-MnSp-E2/J2

Summary of Fit

RSquare	0.597007
RSquare Adj	0.591928
Root Mean Square Error	2.557504
Mean of Response	59.39643
Observations (or Sum Wgts)	242

Parameter Estimates

Term	Estimate	Std Error	DFDen	t Ratio	Prob>|t|
Intercept	60.60386	5.068713	5.536	11.96	<.0001*
VolDown	-0.023666	0.001952	237.9	-12.12	<.0001*
RampRatio	-22.05749	4.877322	210	-4.52	<.0001*
Sqrt(L_l)	0.244222	0.10538	5.117	2.32	0.0671

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
VolDown	1	1	237.9	146.9926	<.0001*
RampRatio	1	1	210	20.4526	<.0001*
Sqrt(L_l)	1	1	5.117	5.3709	0.0671

The coefficients from the regression can be used to develop a prediction equation for speed for just downstream of the weaving section. For example, using the results for the base weaving length shown in Table 5-7 and Table 5-10, the equations would be:

<u>Linear weaving length</u>

$$Sp = 68.255373 - 0.023875\ Vol_{down} - 22.19639*RR + 0.0024776*\ B\text{-}Len_{weave} \tag{9}$$

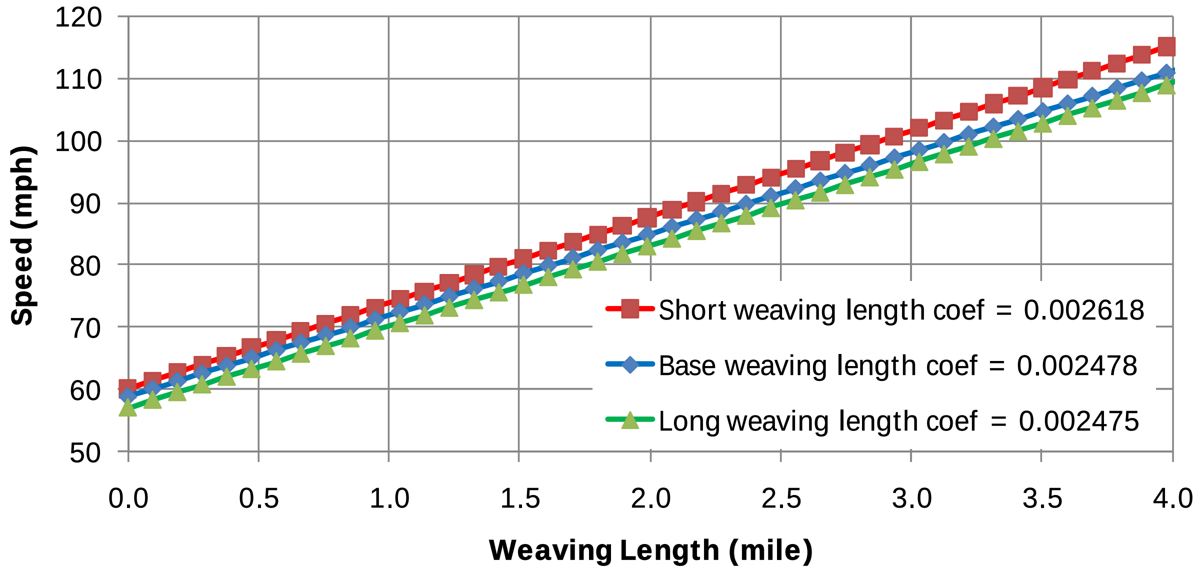
<u>Square root weaving length</u>

$$Sp = 64.356864 - 0.02382\ Vol_{down} - 22.31775*RR + 0.2052303*(B\text{-}Len_{weave})^{0.5} \tag{10}$$

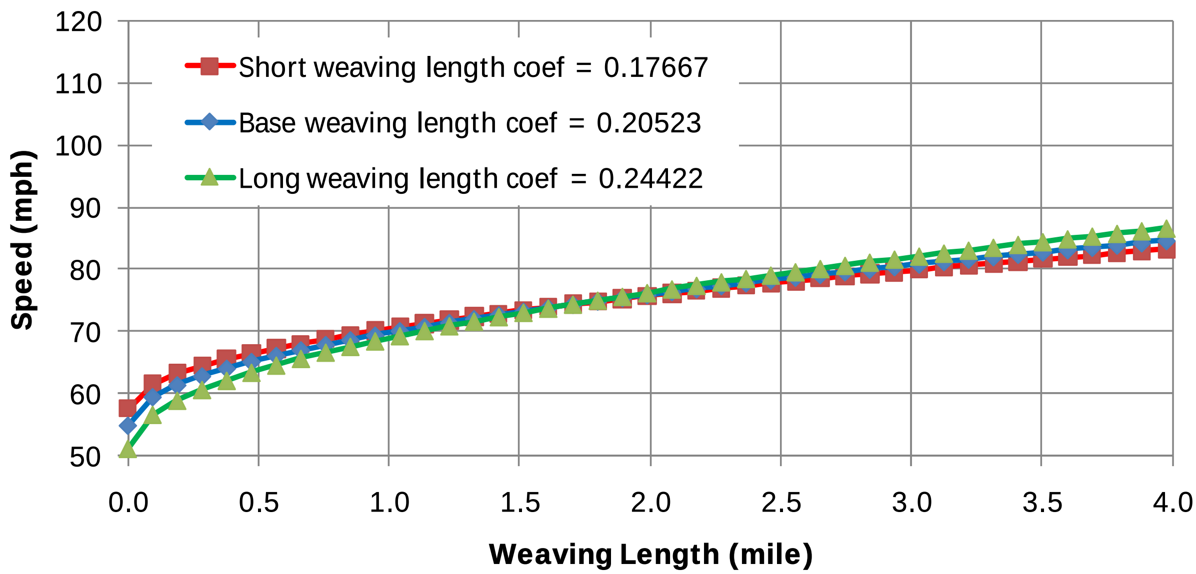
where:

- Sp = Predicted mean speed downstream of weaving section (mph),
- Vol_{down} = Freeway volume measured downstream of the weaving area and the exit ramp volume (veh/5 minutes),
- RR = Ramp Ratio = Proportion of ramp volume (both entrance and exit) to total volume entering system, and
- $B\text{-}Len_{weave}$ = Base weaving length measured as the distance between respective gore areas where the left edge of the ramp travel lanes and right edge of the freeway travel lanes meet (ft).

The equations can be used to develop plots of the predicted speeds. Figure 5-8 shows the plots of the predicted speeds when varying weaving length and holding the other variables constant.



(a) Linear



(b) Square Root

Figure 5-8. Predicted Speed for Range of Weaving Lengths.

To obtain a measure of "low volume," cumulative distributions of the field data were determined and the values that represent approximately 25 percent were selected (i.e., 75 percent of the data had these values or higher). The downstream volume was assumed to be 293 veh/5 min and weaving ratio was assumed to be 0.11 in Figure 5-8. The plots show predicted speeds up to 4 miles; however, note that the longest weaving length available in the field data was only 0.8 mile (4300 ft). The longer lengths are shown in the plots to provide an appreciation of the length needed to have predicted speeds near 100 mph. Curves for all three weaving lengths are shown. For the linear graph, Figure 5-8(a), the same relationship is shown regardless of the weaving length measurement used. For the square root graph, Figure 5-8(b), the relationship changes at about weaving length of 2 miles with the long length measurement predicting higher speeds than a similar dimension short weaving length (which is counterintuitive). This condition is an example of the caution one needs to take with extrapolating beyond the limits of the data used to generate a regression equation.

Figure 5-9 shows the predictions for base weaving length using both model forms. A range of freeway/ramp volume (293 and 600 veh/5 min or 3516 and 7200 veh/hr) and weaving ratio (0.1 and 0.15) is also included to provide an appreciation of the effects on the curves. These values were selected to represent low and high volume levels. Near the limit of the field data (about 0.8 mile), both equations predict similar speeds. Depending upon which model form selected along with the freeway/ramp volume and weaving ratio values will give estimates of the speed at longer weaving lengths. Care needs to be exercised in using these equations past the limit of the data available in their development. Whether the relationship between weaving length and speed is similar at higher weaving lengths, say at 1 or 2 miles, is debatable. The linear model predicts 80 mph speed for a 1.6 mile weaving length (assuming low volume and weaving ratio), while the square root equation does not predict 80 mph until about 3.0 miles.

The evaluations using the field data collected as part of this project identified a weaving length of about 2500 ft to reach 65 mph when assuming low freeway/ramp volume and weaving ratio (293 veh/5 min and 0.11, respectively). The weaving length for other predicted speeds using the assumed low freeway/ramp volume and weaving ratio are:

- 70 mph: 4500 ft or 0.9 mi,
- 80 mph: 8500 ft or 1.6 mi,
- 90 mph: 12,500 ft or 2.4 mi, and
- 100 mph: 16,500 ft or 3.1 mi.

The coefficients for a parameter can provide an appreciation of the impact the parameter has on the dependent variable; for example, the impact weaving length has on speeds. If all other parameters were held constant an increase in weaving length of 1 ft is associated with an increase in speed of approximately 0.0025 mph for the linear model. Figure 5-10(a) illustrates the relationship. Figure 5-10 also shows the relationship with speed for each of the other parameters included in the linear regression models. As can be seen by the overlapping lines in Figure 5-10, the relationship between speed and the given parameter is similar for the different approaches used to measure weaving length.

The plots can be used to identify the predicted change in speed with a change in the weaving length or the plots can be used in the other direction and give the change in weaving length that is associated with a change in speed. Each weaving length increment of 4000 ft is associated with a 10-mph speed change. The 10-mph speed difference was selected because it matches the recommendation for when to consider a passing or climbing lane (*3*).

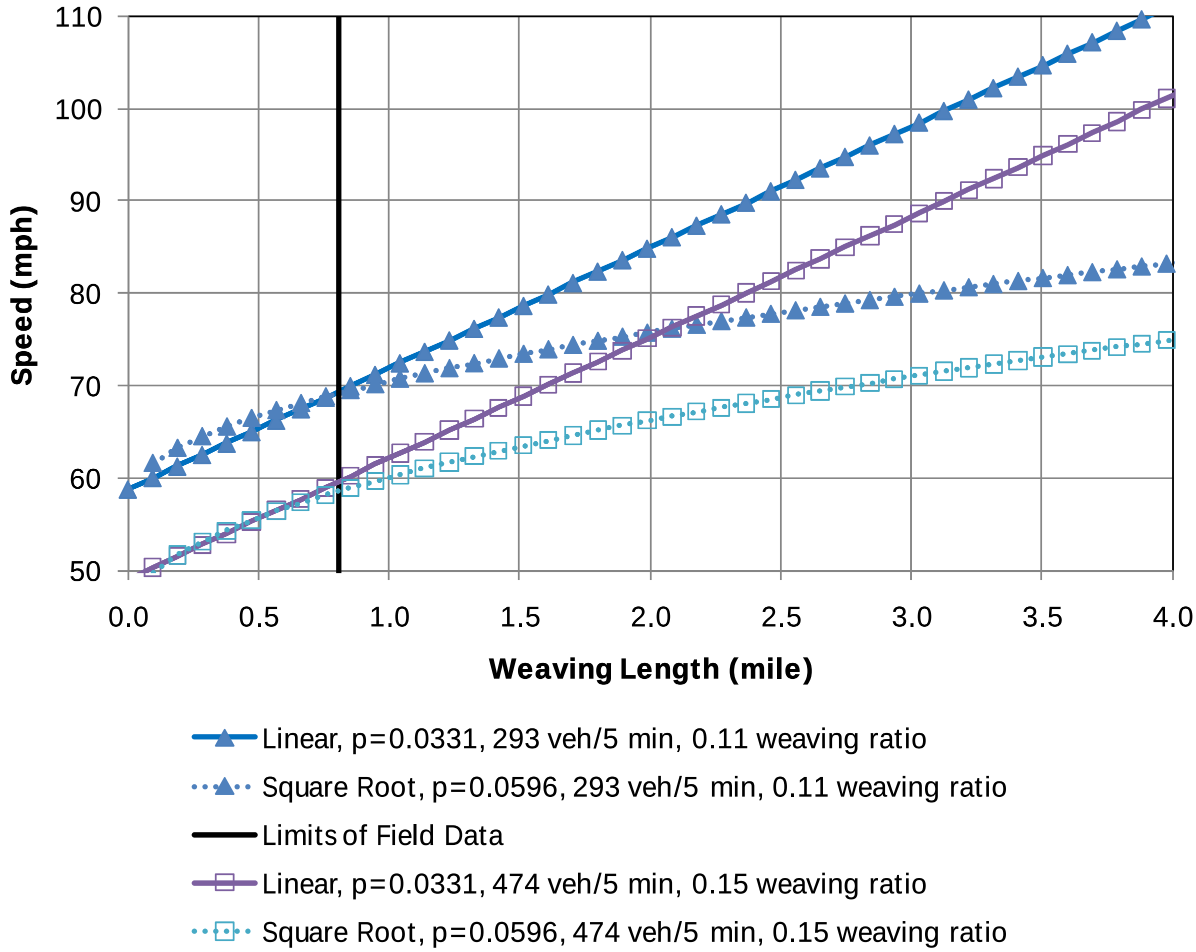
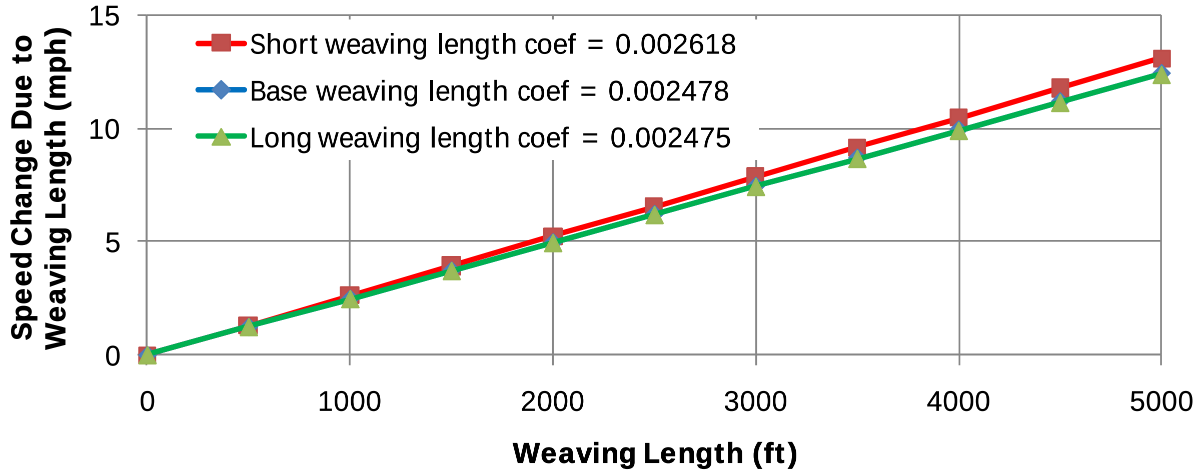
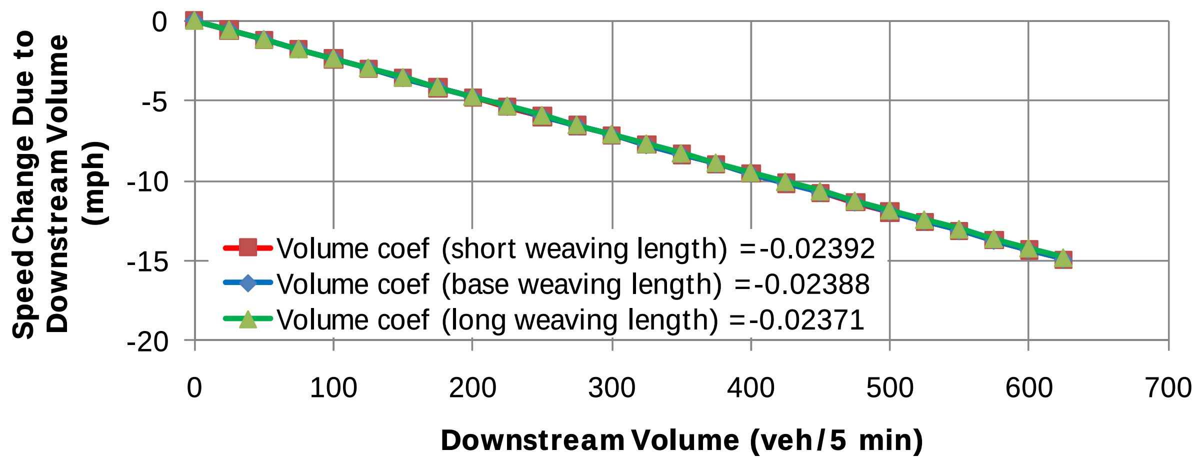


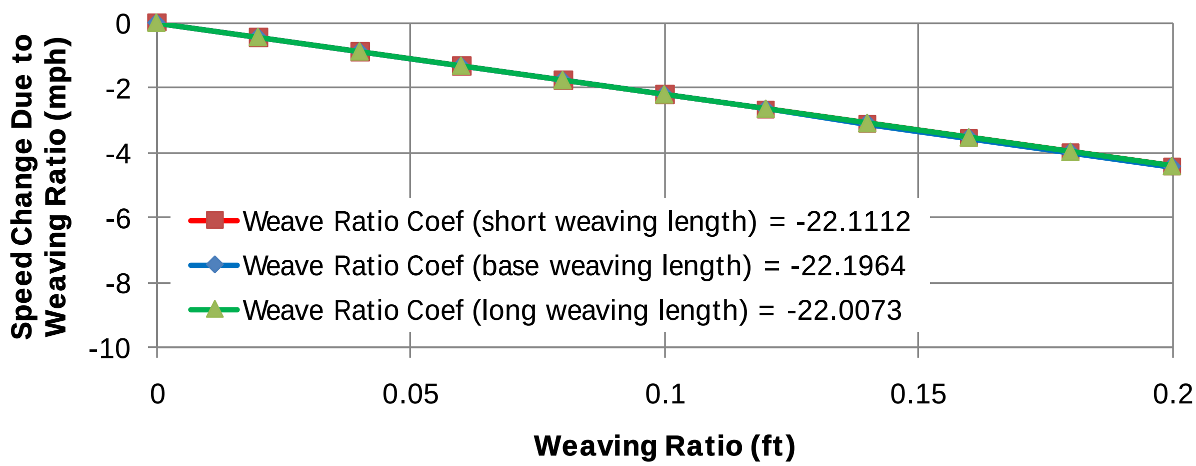
Figure 5-9. Predicted Speed for Range of Weaving Lengths, Freeway/Ramp Volume, and Weaving Ratio.



(a) Weaving Length



(b) Downstream Volume



(c) Weaving Ratio

Figure 5-10. Parameter and Speed Relationship Based on Regression Equation.

5-Minute Bin Video Data with Weaving Length as a Discrete Variable

The weaving length groups were also used with the 5-minute bin video data. The results were mixed. The base weaving length variable was not significant, and the evaluation that included the short weaving length variable did not converge. Table 5-12 shows the output for the model that includes the long weaving length variable.

Table 5-12. Output for Speeds Using 5-Minute Bin Video Data and Long Weaving Length Groups.

Response AL-MnSp-E2/J2
Summary of Fit

RSquare	0.59658
RSquare Adj	0.588033
Root Mean Square Error	2.554121
Mean of Response	59.39643
Observations (or Sum Wgts)	242

Parameter Estimates

Term	Estimate	Std Error	DFDen	t Ratio	Prob>|t|
Intercept	72.531321	1.294844	67.45	56.02	<.0001*
VolDown	-0.023825	0.001933	167.4	-12.33	<.0001*
RampRatio	-23.07173	4.384628	36.73	-5.26	<.0001*
Li_group[1]	-3.729108	0.829482	6.698	-4.50	0.0031*
Li_group[2]	-0.115601	0.549955	4.612	-0.21	0.8425
Li_group[3]	-2.456624	0.581933	3.975	-4.22	0.0136*

Fixed Effect Tests

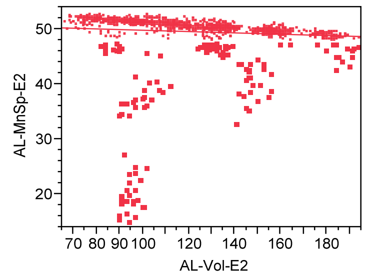
Source	Nparm	DF	DFDen	F Ratio	Prob > F
VolDown	1	1	167.4	151.9655	<.0001*
RampRatio	1	1	36.73	27.6882	<.0001*
Li_group	3	3	4.416	26.2957	0.0029*

SIMULATION DATA EVALUATION

The total number of observations in the original simulated data was n = 4320. For each of the three posted speed limits (60, 80, and 100 mph), 1440 observations were obtained. Again, speeds at several locations were evaluated. The results at E2 are presented in this chapter. Table 5-13 contains the scatter plots of speed and volume at E2 for each posted speed limit (PSL) and the result of the bivariate fit. As can be seen from the plots, the original data contain many non-free flow speeds, which calls for data screening before the main analysis. To select the free-flow speeds, the speed observations at E2 that are less than 0.8*Posted Speed Limit were removed from the data. Those removed observations are highlighted in bold in each plot of Table 5-13. The remaining number of observations (after removing non-free flow speeds based on speeds at E2) was n =1318 for PSL = 60 mph data, n =1321 for PSL = 80 mph data, and n =1262 for PSL = 100 mph data.

Table 5-13. Bivariate Fit of Speeds by Volume at E2.

Linear Fit, AL-MnSp-E2 = 50.873364 - 0.011151* AL-Vol-E2



Summary of Fit

RSquare	0.00554
RSquare Adj	0.004849
Root Mean Square Error	4.507228
Mean of Response	49.5121
Observations (or Sum Wgts)	1440

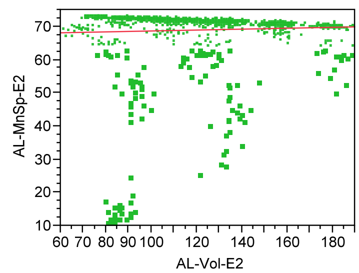
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	162.754	162.754	8.0115
Error	1438	29213.121	20.315	**Prob > F**
C. Total	1439	29375.875		0.0047*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	50.873364	0.495383	102.69	0.0000*
AL-Vol-E2	-0.011151	0.00394	-2.83	0.0047*

Linear Fit, AL-MnSp-E2 = 67.394474 + 0.0130458* AL-Vol-E2



Summary of Fit

RSquare	0.002074
RSquare Adj	0.00138
Root Mean Square Error	8.713303
Mean of Response	68.97133
Observations (or Sum Wgts)	1440

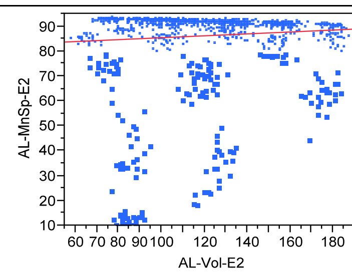
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	226.92	226.921	2.9889
Error	1438	109175.33	75.922	**Prob > F**
C. Total	1439	109402.25		0.0841

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	67.394474	0.940547	71.65	0.0000*
AL-Vol-E2	0.0130458	0.007546	1.73	0.0841

Linear Fit, AL-MnSp-E2 = 81.651364 + 0.0368124* AL-Vol-E2



Summary of Fit

RSquare	0.005948
RSquare Adj	0.005257
Root Mean Square Error	14.53679
Mean of Response	86.06574
Observations (or Sum Wgts)	1440

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	1818.21	1818.21	8.6042
Error	1438	303875.62	211.32	**Prob > F**
C. Total	1439	305693.83		0.0034*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	81.651364	1.552917	52.58	0.0000*
AL-Vol-E2	0.0368124	0.01255	2.93	0.0034*

Analysis of Speed Data at E2

Table 5-14 contains the scatter plots and the result of the bivariate fit of speed and volume at E2 after removing non-free flow speeds for each PSL.

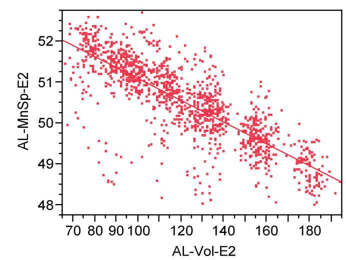
Numerous models, each having a different set of predictors, were investigated. As pointed out earlier, significant correlation among independent variables was one of the big obstacles in model building. Even after removal of strongly correlated independent variables, it was observed that inclusion of one variable often affected the significance or sign of the coefficient of other variable(s), probably because of the remaining weak to moderate correlation between independent variables. Researchers tried to keep all important variables while ensuring that signs on the coefficients were intuitive in the fitted model. An attempt was made to fit a single model to the data from all three PSLs together with inclusion of the PSL variable. However, there seems to be an interaction effect between the main factor of interest, weaving distance, and the PSL; i.e., the effect of weaving distance is different for different PSLs. Therefore, a separate model was fitted to the data obtained under each PSL.

Table 5-15 contains the result of one such model fit for each PSL with treating weave distance (Wea_dist) as a continuous variable. It can be observed from Table 5-15 that the effect of weaving length is not significant when PSL = 60, but is significant when PSL = 80 or 100 mph. Also, the effect of weaving length seems to be larger when PSL = 100 compared to when PSL = 80. The volume at E2 has a negative effect on speeds. The effect of lane changing (RMerDiv/Total) on speeds is negative and gets stronger as PSL increases. RMerDiv/Total is the proportion of ramp weaving to all weaving activity on the freeway and ramp.

Note that for the models in Table 5-15, the effect of weaving length was assumed to be linear. In case the assumption of linear effect of weaving length on speeds is violated, the ANACOVA (Analysis of Covariance) model with treating Wea_dist as a discrete ordinal variable was also implemented. Table 5-16 contains the result of the ANACOVA model fit for posted speed limit of 60 mph. Table 5-17 has the output for posted speed limit of 80 mph, while Table 5-18 shows posted speed limit of 100 mph. It can be observed from Tables 5-16 to 5-18 that the effect of weaving length is statistically significant for all three PSLs, although the effect is different for different PSL (see LS Means Plot of Wea_Dist and LSMeans Differences for each PSL). Effects of volume at E2 and RMerDiv/Total on speeds are both negative and get stronger as PSL increases. A review of the residual plots shows that there are many outliers in the data. To ensure that those outliers do not affect the results significantly, the models were re-fit without those outliers. The results of the model fit without outliers are presented in Tables 5-19, 5-20, and 5-21 for posted speed limits 60, 80, and 100 mph, respectively.

Table 5-14. Bivariate Fit of Free-Flow Speeds by Volume at E2.

Linear Fit, AL-MnSp-E2 = 53.773987 - 0.0267876* AL-Vol-E2



Summary of Fit

RSquare	0.646244
RSquare Adj	0.645975
Root Mean Square Error	0.594895
Mean of Response	50.50949
Observations (or Sum Wgts)	1318

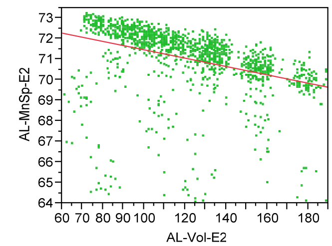
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	850.8043	850.804	2404.080
Error	1316	465.7325	0.354	**Prob > F**
C. Total	1317	1316.5368		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	53.773987	0.068566	784.26	0.0000*
AL-Vol-E2	-0.026788	0.000546	-49.03	<.0001*

Linear Fit, AL-MnSp-E2 = 73.539232 - 0.0205886* AL-Vol-E2



Summary of Fit

RSquare	0.147899
RSquare Adj	0.147253
Root Mean Square Error	1.497642
Mean of Response	71.04339
Observations (or Sum Wgts)	1321

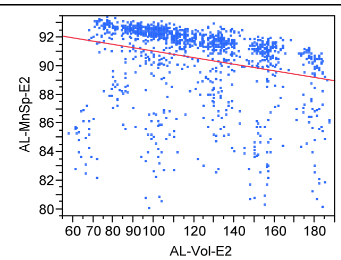
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	513.4922	513.492	228.9379
Error	1319	2958.4274	2.243	**Prob > F**
C. Total	1320	3471.9196		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	73.539232	0.170021	432.53	0.0000*
AL-Vol-E2	-0.020589	0.001361	-15.13	<.0001*

Linear Fit, AL-MnSp-E2 = 93.370234 - 0.023262* AL-Vol-E2



Summary of Fit

RSquare	0.069879
RSquare Adj	0.06914
Root Mean Square Error	2.557133
Mean of Response	90.56407
Observations (or Sum Wgts)	1262

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	618.9879	618.988	94.6619
Error	1260	8239.0533	6.539	**Prob > F**
C. Total	1261	8858.0412		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	93.370234	0.297267	314.10	0.0000*
AL-Vol-E2	-0.023262	0.002391	-9.73	<.0001*

Table 5-15. Results of Multiple Regression Model Fit Treating Weave Distance as a Continuous Variable.

Response AL-MnSp-E2 Sp85=60

Summary of Fit

RSquare	0.649528
RSquare Adj	0.648728
Root Mean Square Error	0.592578
Mean of Response	50.50949
Observations (or Sum Wgts)	1318

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	855.1271	285.042	811.7421
Error	1314	461.4097	0.351	**Prob > F**
C. Total	1317	1316.5368		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	54.098232	0.115989	466.41	0.0000*
Wea_Dist	-3.171e-6	1.23e-5	-0.26	0.7966
AL-Vol-E2	-0.027853	0.000631	-44.16	<.0001*
RMerDiv/Total	-0.932147	0.271765	-3.43	0.0006*

Response AL-MnSp-E2 Sp85=80

Summary of Fit

RSquare	0.319893
RSquare Adj	0.318344
Root Mean Square Error	1.339
Mean of Response	71.04339
Observations (or Sum Wgts)	1321

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	1110.6425	370.214	206.4866
Error	1317	2361.2772	1.793	**Prob > F**
C. Total	1320	3471.9196		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	72.692025	0.261897	277.56	0.0000*
Wea_Dist	0.0005074	2.782e-5	18.24	<.0001*
AL-Vol-E2	-0.024411	0.001433	-17.03	<.0001*
RMerDiv/Total	-1.462447	0.607067	-2.41	0.0161*

Response AL-MnSp-E2 Sp85=100

Summary of Fit

RSquare	0.459996
RSquare Adj	0.458708
Root Mean Square Error	1.949966
Mean of Response	90.56407
Observations (or Sum Wgts)	1262

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	4074.6628	1358.22	357.2040
Error	1258	4783.3784	3.80	**Prob > F**
C. Total	1261	8858.0412		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	93.042657	0.385995	241.05	0.0000*
Wea_Dist	0.001301	4.327e-5	30.06	<.0001*
AL-Vol-E2	-0.041711	0.002185	-19.09	<.0001*
RMerDiv/Total	-8.236173	0.907974	-9.07	<.0001*

Table 5-16. Results of ANACOVA Model Fit Treating Weave Distance as a Discrete Variable and Posted Speed Limit of 60 mph.

Response AL-MnSp-E2 Sp85=60

Summary of Fit

RSquare	0.662515
RSquare Adj	0.660971
Root Mean Square Error	0.58216
Mean of Response	50.50949
Observations (or Sum Wgts)	1318

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	6	872.2258	145.371	428.9368
Error	1311	444.3110	0.339	**Prob > F**
C. Total	1317	1316.5368		<.0001*

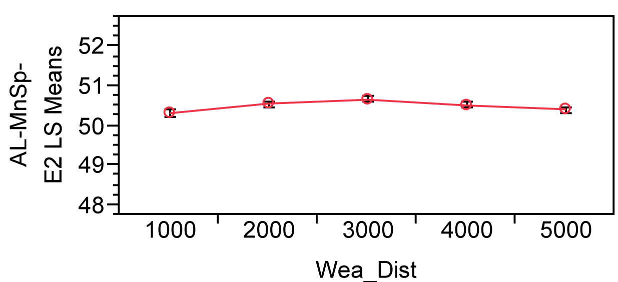
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	54.01553	0.113261	476.91	0.0000*
Wea_Dist[2000-1000]	0.2255893	0.057026	3.96	<.0001*
Wea_Dist[3000-2000]	0.1192919	0.048872	2.44	0.0148*
Wea_Dist[4000-3000]	-0.134277	0.048514	-2.77	0.0057*
Wea_Dist[5000-4000]	-0.135669	0.048514	-2.80	0.0052*
AL-Vol-E2	-0.028391	0.000626	-45.39	<.0001*
RMerDiv/Total	-1.172098	0.269688	-4.35	<.0001*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Wea_Dist	4	4	17.12205	12.6302	<.0001*
AL-Vol-E2	1	1	698.19741	2060.126	<.0001*
RMerDiv/Total	1	1	6.40161	18.8888	<.0001*

LS Means Plot



LS Means Differences

Level				Least Sq Mean
3000	A			50.668694
2000	A	B		50.549402
4000		B		50.534416
5000			C	50.398748
1000			C	50.323812

Levels not connected by same letter are significantly different.

Table 5-17. Results of ANACOVA Model Fit Treating Weave Distance as a Discrete Variable and Posted Speed Limit of 80 mph.

Response AL-MnSp-E2 Sp85=80
Summary of Fit

RSquare	0.599149
RSquare Adj	0.597318
Root Mean Square Error	1.02915
Mean of Response	71.04339
Observations (or Sum Wgts)	1321

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	6	2080.1960	346.699	327.3372
Error	1314	1391.7236	1.059	**Prob > F**
C. Total	1320	3471.9196		<.0001*

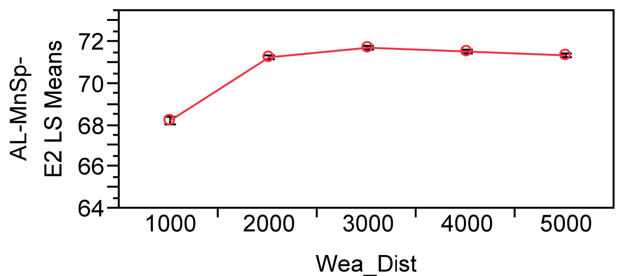
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	72.646506	0.200229	362.82	0.0000*
Wea_Dist[2000-1000]	3.0484882	0.10042	30.36	<.0001*
Wea_Dist[3000-2000]	0.4523802	0.086743	5.22	<.0001*
Wea_Dist[4000-3000]	-0.199155	0.085763	-2.32	0.0204*
Wea_Dist[5000-4000]	-0.182395	0.085763	-2.13	0.0336*
AL-Vol-E2	-0.030144	0.001118	-26.97	<.0001*
RMerDiv/Total	-3.668132	0.472254	-7.77	<.0001*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Wea_Dist	4	4	1566.0381	369.6449	<.0001*
AL-Vol-E2	1	1	770.4412	727.4144	<.0001*
RMerDiv/Total	1	1	63.8994	60.3308	<.0001*

LS Means Plot



LS Means Differences

Level					Least Sq Mean
3000	A				71.744194
4000	A	B			71.545039
5000		B	C		71.362644
2000			C		71.291814
1000				D	68.243326

Levels not connected by same letter are significantly different.

Table 5-18. Results of ANACOVA Model Fit Treating Weave Distance as a Discrete Variable and Posted Speed Limit of 100 mph.

Response AL-MnSp-E2 Sp85=100

Summary of Fit

RSquare	0.587191
RSquare Adj	0.585218
Root Mean Square Error	1.706952
Mean of Response	90.56407
Observations (or Sum Wgts)	1262

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	6	5201.3660	866.894	297.5250
Error	1255	3656.6752	2.914	**Prob > F**
C. Total	1261	8858.0412		<.0001*

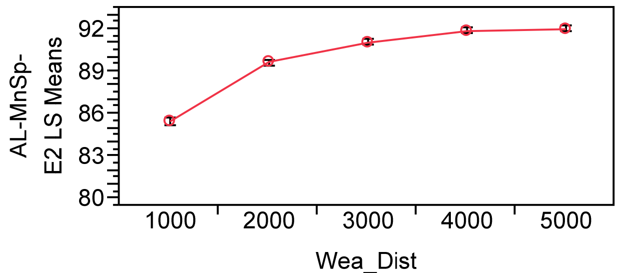
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	93.810123	0.339144	276.61	0.0000*
Wea_Dist[2000-1000]	4.116311	0.182934	22.50	<.0001*
Wea_Dist[3000-2000]	1.4433212	0.147641	9.78	<.0001*
Wea_Dist[4000-3000]	0.847821	0.142251	5.96	<.0001*
Wea_Dist[5000-4000]	0.1394266	0.142246	0.98	0.3272
AL-Vol-E2	-0.049764	0.001957	-25.43	<.0001*
RMerDiv/Total	-11.23677	0.809563	-13.88	<.0001*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Wea_Dist	4	4	4563.6529	391.5705	<.0001*
AL-Vol-E2	1	1	1884.3737	646.7320	<.0001*
RMerDiv/Total	1	1	561.3374	192.6554	<.0001*

LS Means Plot



Level		Least Sq Mean
5000	A	92.060673
4000	A	91.921247
3000	B	91.073426
2000	C	89.630104
1000	D	85.513793

Table 5-19. Results of ANACOVA Model Fit Treating Weave Distance as a Discrete Variable and Posted Speed Limit of 60 mph without Outliers.

Response AL-MnSp-E2 (PSL = 60)

Summary of Fit

RSquare	0.709115
RSquare Adj	0.707771
Root Mean Square Error	0.53342
Mean of Response	50.52708
Observations (or Sum Wgts)	1306

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	6	901.0387	150.173	527.7803
Error	1299	369.6138	0.285	**Prob > F**
C. Total	1305	1270.6525		0.0000*

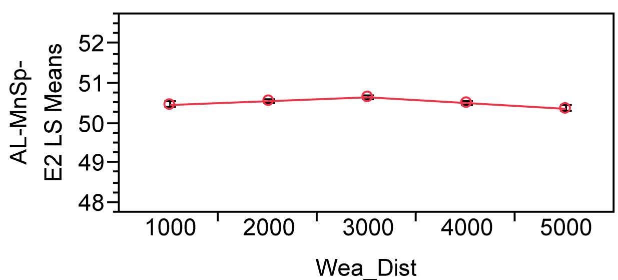
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	54.08927	0.104168	519.25	0.0000*
Wea_Dist[2000-1000]	0.0789039	0.05334	1.48	0.1393
Wea_Dist[3000-2000]	0.1023918	0.044867	2.28	0.0226*
Wea_Dist[4000-3000]	-0.134529	0.044452	-3.03	0.0025*
Wea_Dist[5000-4000]	-0.13576	0.044452	-3.05	0.0023*
AL-Vol-E2	-0.028393	0.000574	-49.48	<.0001*
RMerDiv/Total	-0.725101	0.248833	-2.91	0.0036*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Wea_Dist	4	4	11.14423	9.7915	<.0001*
AL-Vol-E2	1	1	696.72135	2448.613	<.0001*
RMerDiv/Total	1	1	2.41613	8.4915	0.0036*

LS Means Plot



LS Means Differences

Level				Least Sq Mean
3000	A			50.660914
2000	A	B		50.558522
4000		B		50.526385
1000		B	C	50.479618
5000			C	50.390625

Levels not connected by same letter are significantly different.

Table 5-20. Results of ANACOVA Model Fit Treating Weave Distance as a Discrete Variable and Posted Speed Limit of 80 mph without Outliers.

Response AL-MnSp-E2 (PSL = 80)

Summary of Fit

RSquare	0.785601
RSquare Adj	0.784567
Root Mean Square Error	0.640608
Mean of Response	71.17468
Observations (or Sum Wgts)	1251

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	6	1870.6191	311.770	759.7131
Error	1244	510.5107	0.410	**Prob > F**
C. Total	1250	2381.1299		0.0000*

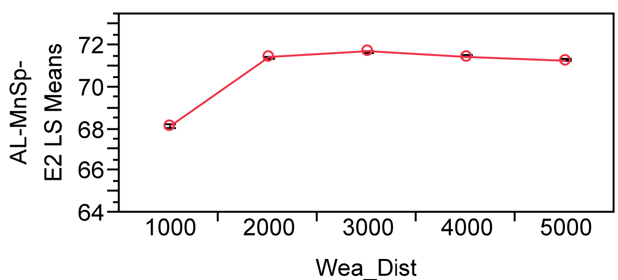
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	71.623711	0.134247	533.52	0.0000*
Wea_Dist[2000-1000]	3.297096	0.071135	46.35	<.0001*
Wea_Dist[3000-2000]	0.2717744	0.054436	4.99	<.0001*
Wea_Dist[4000-3000]	-0.200339	0.053384	-3.75	0.0002*
Wea_Dist[5000-4000]	-0.182282	0.053385	-3.41	0.0007*
AL-Vol-E2	-0.02761	0.000705	-39.17	<.0001*
RMerDiv/Total	-0.585616	0.303178	-1.93	0.0536

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Wea_Dist	4	4	1198.5395	730.1429	0.0000*
AL-Vol-E2	1	1	629.7880	1534.652	<.0001*
RMerDiv/Total	1	1	1.5311	3.7310	0.0536

LS Means Plot



LS Means Differences

Level					Least Sq Mean
3000	A				71.706593
4000		B			71.506255
2000		B	C		71.434819
5000			C		71.323973
1000				D	68.137723

Levels not connected by same letter are significantly different.

Table 5-21. Results of ANACOVA Model Fit Treating Weave Distance as a Discrete Variable and Posted Speed Limit of 100 mph without Outliers.

Response AL-MnSp-E2 (PSL=100)
Summary of Fit

RSquare	0.848821
RSquare Adj	0.847957
Root Mean Square Error	0.604128
Mean of Response	91.41891
Observations (or Sum Wgts)	1057

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	6	2151.6472	358.608	982.5674
Error	1050	383.2188	0.365	**Prob > F**
C. Total	1056	2534.8660		0.0000*

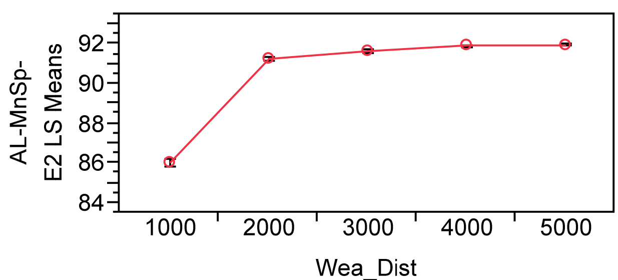
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	89.758405	0.146893	611.05	0.0000*
Wea_Dist[2000-1000]	5.2339411	0.090382	57.91	0.0000*
Wea_Dist[3000-2000]	0.3729689	0.059939	6.22	<.0001*
Wea_Dist[4000-3000]	0.2741572	0.052617	5.21	<.0001*
Wea_Dist[5000-4000]	0.0664816	0.050659	1.31	0.1897
AL-Vol-E2	-0.027073	0.000777	-34.83	<.0001*
RMerDiv/Total	-2.421044	0.311518	-7.77	<.0001*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Wea_Dist	4	4	1824.3218	1249.637	0.0000*
AL-Vol-E2	1	1	442.7294	1213.056	<.0001*
RMerDiv/Total	1	1	22.0444	60.4005	<.0001*

LS Means Plot



LS Means Differences

Level					Least Sq Mean
5000	A				91.974993
4000	A				91.908511
3000		B			91.634354
2000			C		91.261385
1000				D	86.027444

Levels not connected by same letter are significantly different.

Observations from Simulation

For the simulation data, when using multiple regression with continuous weave distance and speed at E2, the coefficient for weave distance is not significant. When using ANACOVA and weave distance in discrete groups, weave distance groups are significant. Other variables included in the model are volume at E2 and weaving activity.

While there are statistically significant differences between the weaving lengths, the practical differences give other results. At 60 mph posted speed limits the predicted speeds are all essentially 50 mph (see LS Means Differences in Table 5-19). For posted speed limits of 80 and 100 mph, there is a practical difference between the predicted speed at 1000 ft and the predicted speed at all other weaving lengths. This finding supports having at least a 2000-ft weaving length.

CHAPTER 6

DEVELOP RECOMMENDATIONS

Several methods were explored as part of this project to assist in developing guidance on ramp spacing. The development of geometric criteria in some cases is rather straightforward and laws of physics (e.g., stopping sight distance) or policy (e.g., vertical clearance) control. In other cases the influences of driver behavior may be critical. Developing the distance between ramps is an example of a situation when driver behavior needs to be considered.

Following is a summary of the methods explored in this project along with the suggested ramp spacing distance that the method would support.

ENGLAND

Ramp spacing guidance contained in the *Design Manual for Roads and Bridges* published by the Highways Agency in England is based on effective signing and signaling and the specific characteristics of different roadway types (*32*). Recommended spacing is dependent only on design speed for ramp sequence combinations of exit followed by exit, exit followed by entrance, and entrance followed by entrance. It is determined by the following formula (converted to U.S. standard units):

$$\text{Spacing} = 19.8 * V \tag{11}$$

where:

Spacing = recommended spacing and weaving length (ft) and
V = design speed (mph).

An exception to the use of the above formula is when an entrance is followed by exit (i.e., weaving). Recommended weaving lengths are:

- 3300 ft for rural all-purpose roads,
- 6600 ft for rural motorways, and
- speed and volume dependent for urban roadways. The graphs available to determine absolute minimum weaving length for urban roadways (see Figure 2-13 of this report) is limited to 60 mph (which is associated with about 1000 ft on the graph). The minimum weaving length is dependent on flow and ranges up to approximately 3000 ft.

The *Design Manual for Roads and Bridges* (*32*) indicates that the maximum possible weaving length, interpreted as meaning the boundary between weaving sections and sections out of the realm of weaving, is 9800 ft on rural motorways and 6600 ft on all-purpose rural roads.

MINIMUM DECELERATION AND ACCELERATION LENGTHS

The intent of an auxiliary weaving area is to provide room for drivers to weave onto or off of the freeway. In theory, the length required to accelerate (for an entrance) or decelerate (for an exit) occurs on the ramp and not in the auxiliary weaving area, thus leaving the auxiliary area for gap acceptance and weaving. A method of determining the desired length of the auxiliary weaving area, however, could be the length needed for a driver to come to a complete stop at the start of the auxiliary area followed by the length needed for a driver to accelerate from a complete stop to the freeway speed. When using design speed for the freeway speed and deceleration and acceleration values identified from research (see discussion in Chapter 2), the resulting rounded suggested weaving lengths are listed in Table 6-1.

Table 6-1. Potential Minimum Deceleration and Acceleration Lengths.

Conditions	**Rounded Suggested Weaving Length (ft) Based on Minimum Acceleration and Deceleration**				
	60 mph	**70 mph**	**80 mph**	**90 mph**	**100 mph**
Extrapolating *Green Book* values	1750	2250	2600	3100	4300
Updating freeway speed assumptions	2600	3650	4700	5900	7200
Updating freeway speed and deceleration/acceleration rate assumptions	1500	2000	2600	3300	4100

DECISION SIGHT DISTANCE

Decision sight distance, as defined by the AASHTO *Green Book* (*3*), is "the distance required for a driver to detect an unexpected or otherwise difficult-to-perceive information source or hazard in a roadway environment that may be visually cluttered, recognize the hazard or its threat potential, select an appropriate speed and path, and initiate and complete the required maneuver safely and efficiently." Decision sight distance could serve as the minimum for ramp spacing. Table 6-2 summarizes decision times suggested in the literature along with the decision sight distances calculated from those times.

Table 6-2. Potential Decision Sight Distance Values.

Design Speed (mph)	**2004 *Green Book* for Suggested Time, Distances Rounded from Calculated Value**		**Times from Study by Lerner et al. (*44*)**			
			Time for 65 to 69 Year Old Group		**Time for 70 and Older Group**	
	Total Time (sec)	**Rounded Distance (ft)**	**Time (sec)**	**Rounded Distance (ft)**	**Time (sec)**	**Rounded Distance (ft)**
60	11.2 to 14.5	1000 to 1300	17.6	1600	18.8	1700
70	11.2 to 14.5	1200 to 1500	17.6	1800	18.8	1900
80	11.2 to 14.5	1300 to 1700	17.6	2100	18.8	2200
90	11.2 to 14.5	1500 to 1900	17.6	2300	18.8	2500
100	11.2 to 14.5	1600 to 2100	17.6	2600	18.8	2800

NCHRP PROJECT 3-75

A recent NCHRP project (*30, 31*) analyzed performance in freeway weaving sections with the intent to develop a new chapter for the next edition of the *Highway Capacity Manual*. The model proposed has a notable difference from the earlier edition of the *Highway Capacity Manual*; it includes a lane changing algorithm that is intended to capture the impact of weaving configuration and type of operations on resulting speed and densities.

As in previous editions, the results of the NCHRP study did not provide recommended lengths for designing a weaving section. It does discuss the concept of "maximum length" of a weaving section. Maximum length of the weaving section occurs when the methodology results in a capacity of the weaving section that is similar to the capacity of a basic freeway section with the same number of lanes. The formula they provide to determine the maximum weaving length does not include a design speed component. The weaving length is a function of the volume ratio that is the weaving demand flow rate divided by the total demand flow rate. When the volume ratio is low (say 0.10) the weaving length is 3540 ft. When the volume ratio is high (say 0.50) the weaving length is 7826 ft.

PROJECT 0-5860 FIELD STUDIES AND SIMULATION

Field and simulation data were gathered as part of this project to assist in identifying relationships between weaving length and operations. The data were used to develop prediction equations for free-flow mean speeds using parameters such as traffic volume, weaving length, posted speed, number of through lanes, presence of an auxiliary lane, and others, with the goal to assess the effect of weaving length on the free-flow mean speeds.

The field data evaluations did find weaving length to be significant under selected conditions. Posted speed was also significant under selected conditions; however, a similar relationship was found for each of the posted speeds considered. Using the coefficient for weaving length available from the statistical evaluations can provide an appreciation of the impact weaving length has on operating speeds. If other parameters were held constant, to achieve a 10-mph increase in operating speed within a weaving area, the weaving length would need to be 4000 ft longer. The regression equations were used to predict speeds when varying weaving length and holding other variables constant. A weaving length of about 2500 ft is needed to reach 65 mph when assuming low freeway/ramp volume and weaving ratio. The weaving lengths for other predicted speeds are 4500 ft (70 mph), 8500 ft (80 mph), 12,500 ft (90 mph), and 16,500 ft (100 mph).

The limitations of the field data (e.g., shorter weaving lengths, lower speeds) was to be overcome through the use of simulation. Simulation provides the opportunity to have systematic variations in ramp spacing and other key variables affecting traffic operations within a weaving section that are not possible under field conditions. The evaluation of the simulation data found weaving length to not be significant when weaving length was included as a continuous variable. When weaving length was assembled into groups, the weaving length groups containing 1000 ft was significantly different from the groups containing 2000 to 5000 ft weaving lengths for the simulations using posted speeds of 80 and 100 mph. Therefore, the simulation findings support using weaving lengths of at least 2000 ft.

SAFETY

A review of the literature regarding the safety relationships between weaving length and crashes revealed only a few studies. Results show that, for a given weaving area length, crash rates decrease as volume decreases. A review of the trends in Figure 2-16 illustrates that crash frequency decreases as interchange spacing increases. Reviewing the curve for low volume shows that the curve flattens at approximately 1 mile. Stated in another manner, the number of crashes is about the same for interchange spacing greater than 1 mile for low volume conditions. Note that only a few studies are available that identify the relationship between interchange spacing and crashes. These results should be considered preliminary, as more investigation is needed.

RECOMMENDATION FOR MINIMUM LENGTH

Case 1: Entrance Ramp Followed by Exit Ramp

Historically, the minimum weaving length with an auxiliary lane has been 1500 ft and 2000 ft without an auxiliary lane (see Figure 1-1). Findings from the literature do not support a dimension less than these values. The literature on safety has trends that indicate longer spacing is associated with fewer crashes. The investigation into the relationship between minimum weaving length and crashes, however, is still preliminary and significant additional work is needed before a clear relationship can be identified. While the trends do not support a specific number, it does support accepting a value that is larger than the values currently used for higher design speeds.

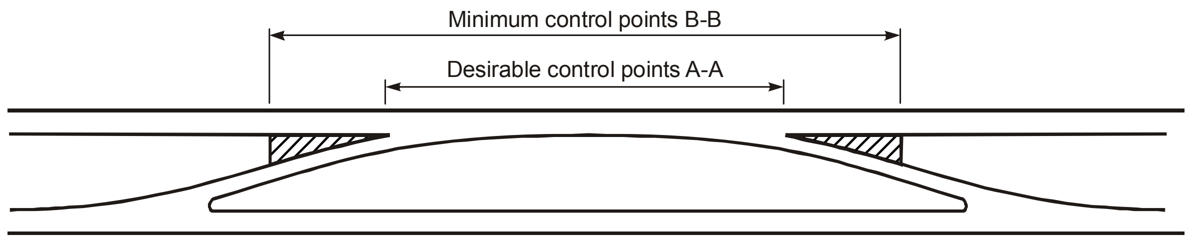
Figure 6-1 lists the dimensions suggested by this research. The Alternative 1 weaving lengths are the values calculated using minimum acceleration and deceleration values. These values can be used to provide a range of lengths for the range of design speeds. The Alternative 2 weaving lengths are the values determined based on consideration of the preliminary findings from safety investigations along with the value being used in England for rural motorways.

The evaluations using the field data collected as part of this project identified a weaving length of about 2500 ft to reach 65 mph when assuming low freeway/ramp volume and weaving ratio (293 veh/5 min and 0.11, respectively). The weaving length for other predicted speeds using the assumed low freeway/ramp volume and weaving ratio are:

- 70 mph: 4500 ft or 0.9 mi,
- 80 mph: 8500 ft or 1.6 mi,
- 90 mph: 12,500 ft or 2.4 mi, and
- 100 mph: 16,500 ft or 3.1 mi.

These values were selected as Alternative 3 weaving lengths.

While the suggested Alternative 2 and 3 dimensions are much greater than values currently recommended for Texas, they can provide the opportunity for flexibility in managing future operations. They also reflect the mobility emphasis for the proposed higher speed (e.g., 100 mph) corridors.



Design Speed (mph)	Suggested Weaving Length (ft)		
	Alternative 1	Alternative 2	Alternative 3
Below 70	1500	6600	2500
70	2000	6600	4500
80	2600	6600	8500
90	3300	6600	12,500
100	4100	6600	16,500

Alternative 1 reflects the situation when a vehicle is at the design speed at the end of the entrance ramp and must come to a complete stop and then accelerate back to freeway speed.

Alternative 2 is based on England's recommendation for weaving lengths for rural motorways and consideration of preliminary safety findings.

Alternative 3 are the values calculated using regression equations developed from this project's field studies and low freeway/ramp volume and weaving ratio.

Figure 6-1. Suggested Design Values for Case 1: Entrance Ramp Followed by Exit Ramp.

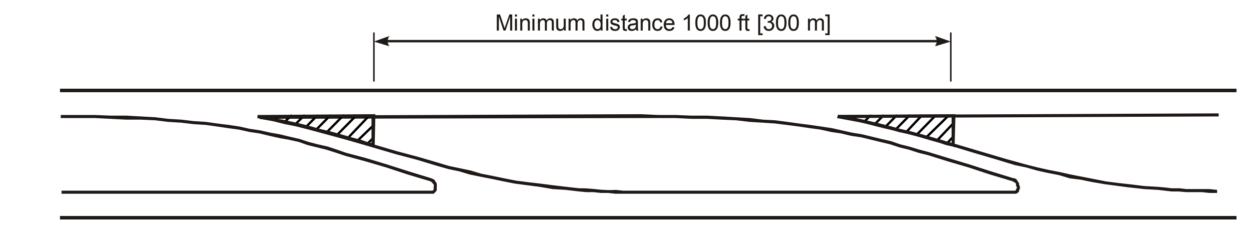
Case 2: Exit Ramp Followed by Exit Ramp

Hawkins et al. (*51*) examined guide sign characteristics for a 90 mph freeway. The researchers recommended that additional guide sign installations be considered due to limitations in the amount of information one sign can contain at that speed. Given that additional guide signs may be needed for these higher speed facilities, longer ramp spacing seems appropriate. The spacing required could be a function of the specific signing needs for the ramps; therefore, the determination of ramp spacing may need to be calculated for each unique design. Similar to the note referring the designer to the AASHTO *Green Book* and the *Highway Capacity Manual* for more specific information regarding operational aspects requiring longer distances, the *RDM* note should refer the reader to appropriate documents regarding sign design. These documents could include:

- *Texas Manual on Uniform Traffic Control Devices* (*49*),
- TxDOT *Freeway Signing Handbook* (*50*), or
- Institute of Transportation Engineers (ITE) *Traffic Control Devices Handbook* (*54*).

The recommendations to be considered for the *RDM* figure should be generous enough to accommodate typical existing needs and anticipate reasonable future needs. Figure 6-2 lists suggested lengths. These lengths were selected based upon the following:

- Alternative 1 is based on England's recommendation for ramp spacing, rounded. Canada also has dimensions that are a function of the design speed (see Figure 2-12) with values slightly less than the values from England. England provided an equation that was used to generate the values for the higher speeds.
- Alternative 2 is based on decision sight distance using reaction time found for a 70 year old and over group.
- Alternative 3 is 1 mile selected because the *TMUTCD* section 2E.30 guidance for interchange guide signing is to place an advance guide sign at 1 mile (2 miles if spacing permits). An exit-to-exit spacing of 1 mile would minimize the inclusion of signing for an exit that is located beyond the upcoming exit, thus providing additional space for using more redundancy of signs and/or using fewer units of information per sign.



Design Speed (mph)	Suggested Length (ft)		
	Alternative 1	Alternative 2	Alternative 3
50	1000	1500	5280
60	1200	1700	5280
70	1400	1900	5280
80	1600	2200	5280
90	1800	2500	5280
100	2000	2800	5280

Alternative 1 is based on England's recommendation for ramp spacing, rounded.
Alternative 2 is based on decision sight distance using reaction time found for 70 year old and over group.
Alternative 3 is 1 mile selected because the *TMUTCD* section 2E.30 guidance for interchange guide signing is to place an advance guide sign at 1 mile (2 miles if spacing permits).

Figure 6-2. Suggested Design Values for Case 2: Exit Ramp Followed by Exit Ramp.

Case 3: Entrance Ramp Followed by Entrance Ramp and Case 4: Exit Ramp Followed by Entrance Ramp

The current guidance for ramp spacing for the atypical conditions of entrance ramp followed by entrance ramp or exit ramp followed by entrance ramp is listed in Table 6-3. Changes are not suggested by the research team to the guidance currently in the *Roadway Design Manual* for these cases.

General Note

The TxDOT *Roadway Design Manual* figure on successive ramps includes the following note:

> "The distances shown above are generally used but reference should be made to the AASHTO publication 'A Policy on Geometric Design of Highways and Streets' and the Highway Capacity Manual for more specific information since operational aspects are influenced by traffic volumes and may require longer distances."

A comment regarding the need to check for adequate sign spacing for exits should be included in the note. For example, the following could be added to the end of the note:

> "In addition, the spacing needed to accommodate the required signs for an exit ramp should also be considered. See TxDOT Freeway Signing Handbook for additional information on sign design."

Table 6-3. Suggested Design Values for Case 3: Entrance Ramp Followed by Entrance Ramp or Case 4: Exit Ramp Followed by Entrance Ramp.

Case	**Case 3: Entrance Ramp Followed by Entrance Ramp**	**Case 4: Exit Ramp Followed by Entrance Ramp**
Existing	This situation will be encountered only on infrequent occasions and special design treatment will be required. It will usually require an added freeway lane.	The distance between an exit ramp followed by an entrance ramp will be governed by the geometrics of the connections to the adjacent roadway or connecting roadway.
Recommendation	No change	No change

FUTURE NEEDED STUDIES

Providing wider or longer dimensions in geometric design has historically been assumed to result in a safer environment; however, there are currently questions regarding whether this is always true (e.g., larger radius horizontal curves are associated with higher speeds). Therefore, the relationship between weaving length and crashes needs to be investigated, especially as these longer dimensions are used in design or as higher speed facilities are constructed. Freeways are designed for high speed driving with the result that the speed in many sections of the freeway being controlled by the speed limit or by driver expectations rather than the geometry or traffic control devices (e.g., signal). Thus providing generous weaving lengths should not have the unintended consequence of increasing crashes.

Another research question could be as follows: "What is the length of a weaving area when a driver assumes that the lane is added to the freeway rather than only serving as an area to facilitate weaves onto or off of the freeway?" Investigation of how signing and pavement markings for that area influences a driver's decision would also need to be considered. A focus of the pavement markings could explore how the use of lane drop markings rather than typical skip patterns for the lane line between the freeway lanes and the weaving lane affect a driver's expectation.

Previous research examined signing needs for higher speed facilities. The findings indicated that additional guide signs are desired because of limitations in the amount of information that can be included on a sign for the higher speeds. Research is needed to gain a better understanding of driver's reading time and signing requirements for higher speeds.

CHAPTER 7

SUMMARY AND CONCLUSIONS

SUMMARY OF RESEARCH

Existing geometric design guidance related to interchange ramp spacing in the Texas *Roadway Design Manual* (*1*) and the AASHTO *Green Book* (*3*) is not speed-dependent even though intuition indicates spacing and speed are related. Geometric design guidance documents published in Canada and England, two countries with freeway, interchange, and ramp design considerations and principles similar to the United States, include speed-dependent ramp spacing criteria. Understanding the relationship between interchange ramp spacing, speed, and freeway operations is important, especially in developing potential design values for higher speeds (i.e., 85 to 100 mph).

The objectives of this project were to: (a) investigate relationships between weaving length, speed, and overall vehicle operations on Texas freeways and (b) propose updates to current Texas Department of Transportation guidance on recommended distances between ramps.

Current ramp spacing guidelines, illustrated in Figure 1-1 and Figure 2-1, are intended for use in planning and conceptual design. Detailed operational analyses are recommended during final design. Both the *Green Book* and *RDM* reference the *Highway Capacity Manual* in this regard. The *HCM* includes analysis techniques for weaving sections and freeway-ramp junctions with results that are generally consistent with intuition and data complied over 50-plus years even though large, comprehensive data sets for model calibration do not exist.

Weaving

Successful and unsuccessful attempts to model weaving sections and freeway-ramp junctions with microscopic simulation models were considered as part of the literature review. The literature review also provided an appreciation of the emerging relationships being identified between weaving length and crashes. Material in the literature provided resources to develop minimum weaving lengths using the time for decision sight distance or the distance needed for deceleration to and acceleration from a stop position.

Traffic management center cameras in combination with pneumatic tubes were used to collect speed and weaving data at seven locations as part of this TxDOT study. Pairs of tubes were used to collect speed and volume on the rightmost lane of the freeway just upstream and just downstream of the weaving area. Data were collected for at least three consecutive days at each location. The following general data reduction steps were followed:

1. Video and tube data were scanned to identify day and time periods when the TMC camera was set at the desired view and the pneumatic tubes were functioning.
2. Lane changes were counted and aggregated for 5-minute intervals during selected time periods.

3. Volumes in the outer lanes (i.e., where there were no tubes) were manually counted using the video for the same time periods that lane changes were counted and aggregated for 5-minute intervals.
4. Volumes collected with the pneumatic tubes were aggregated for 5-minute intervals for all hours of data collection.
5. Speed data were aggregated into 5-minute speed bins and mean speed was computed for all hours of data collection.
6. Volume, speed, and lane change data were merged into one file using the date and time as linking variables.

The result of these six steps was two comprehensive data sets spanning several days at each site. One data set, called the Counter Data, included tube volumes and speeds. The other data set, called the Video Data, included lane changes and counted volumes where available. Selected time intervals where the tube and count data overlapped were used for calibration of the microscopic simulation models.

Systematic variations in ramp spacing and other key variables affecting traffic operations within a weaving section can be done using properly calibrated traffic simulation models. In this study traffic simulations were used for studying a range of ramp spacing scenarios under various traffic conditions. A calibration of the traffic simulation model is needed to ensure that it replicates field conditions as faithfully as possible. Model input (e.g., freeway and ramp volumes, speed distributions, and O-D patterns) for each calibration test bed was determined from the field data observed at the corresponding study site. Based on initial runs, speed and lane changes were found to be sensitive to eight model parameters; two car-following and six lane-changing parameters (minimum look-ahead distance, headway time, maximum deceleration of lane-changing vehicle, maximum deceleration of trailing vehicle, accepted deceleration of lane-changing vehicle, accepted deceleration of trailing vehicle, safety distance reduction factor, and maximum deceleration for cooperative braking). These driver behavior parameters were adjusted in the model calibration process.

It is important to note that weaving operations observed at the study sites could not be appropriately modeled using a single parameter set. A review of the video recorded at the field study sites suggested that drivers do not behave uniformly along the entire length of freeway segment between entrance and exit ramps. It was observed that many drivers who were not able to find sufficient gap for lane changes became more aggressive as they approached the exit ramp. Both exiting and entering vehicles were willing to accept shorter gaps when they were running out of space for safe lane-changing maneuvers. Based on these observations, it seemed logical to apply different driver behavior parameters in different segments of the weaving section. It was found that weaving operations at most study sites could be modeled fairly well using different behavior categories that increased in aggressiveness toward the end of the weaving section.

The field and simulation data were used to develop prediction equations for free-flow mean speeds using variables such as traffic volume, weaving length, posted speed, number of through lanes, presence of an auxiliary lane, and others with the goal to assess the effect of weaving length on the free-flow mean speeds. The evaluations of the 5-minute video data with weaving length as a continuous variable provided the most usable results. The coefficients from the regression produced the following equation:

$$Sp = 68.255373 - 0.023875\ Vol_{down} - 22.19639*RR + 0.0024776*\ B\text{-}Len_{weave} \qquad (12)$$

where:

Sp = Mean speed downstream of weaving section (mph),

Vol_{down} = Freeway volume measured downstream of the weaving area and the exit ramp volume (veh/5 minutes),

RR = Ramp Ratio = Proportion of ramp volume (both entrance and exit) to total volume entering system, and

$B\text{-}Len_{weave}$ = Base weaving length measured as the distance between respective gore areas where the left edge of the ramp travel lanes and right edge of the freeway travel lanes meet (ft).

This equation results in a weaving length of about 2500 ft for a 65 mph speed when assuming low freeway/ramp volume and weaving ratio (293 veh/5 min and 0.11, respectively). The weaving length for other predicted speeds using the assumed low freeway/ramp volume and weaving ratio are:

- 70 mph: 4500 ft or 0.9 mi,
- 80 mph: 8500 ft or 1.6 mi,
- 90 mph: 12,500 ft or 2.4 mi, and
- 100 mph: 16,500 ft or 3.1 mi.

For the simulation data, when using multiple regression with continuous weave distance, the coefficient for weave distance is not significant. When weave distance is in discrete groups, the weave distance group of 1000 ft is statistically different from the 2000 to 5000 ft weave groups. Other variables included in the model are volume and weaving activity.

Several methods were explored as part of this project to assist in developing guidance on weaving length. The development of geometric criteria in some cases is rather straightforward and laws of physics (e.g., stopping sight distance) or policy (e.g., vertical clearance) control. In other cases the influence of driver behavior needs to be considered. Developing the distance between an entrance ramp and an exit ramp is an example of a situation when driver behavior needs to be considered. The methods or resources used to generate potential weaving lengths included:

- guidance provided in *Design Manual for Roads and Bridges* published by the Highways Agency in England,
- minimum deceleration and acceleration length for freeway conditions,
- decision sight distance,
- NCHRP Project 3-75 findings,
- findings from field studies at seven sites,
- findings based on simulation conducted as part of this research, and
- safety relationships identified in the literature.

Sign Design

The amount of information on a guide sign is a key limiting factor for maintaining the legibility of signs on higher speed roadways. The authors of a study examining sign design for high speed roadways (*51*) recommended using more redundancy of signs. The redundancy will allow the use of fewer units of information per sign. The tradeoff is that a greater distance will be needed in advance of the ramp to adequately sign for the exit.

CONCLUSIONS

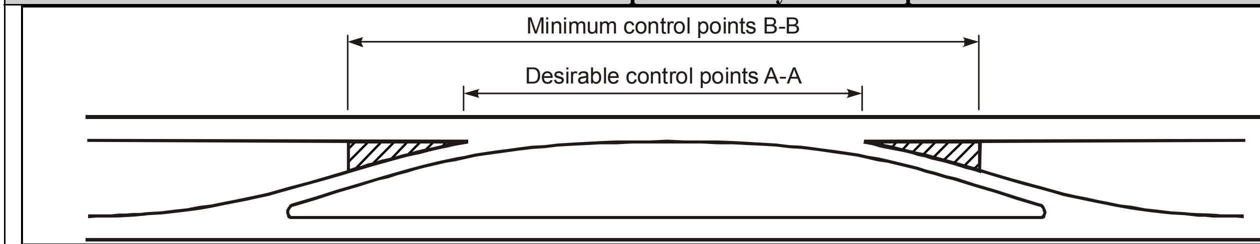
Historically, the minimum weaving length with an auxiliary lane has been 1500 ft. Findings from the literature do not support a value less than 1500 ft. The literature on safety has trends that indicate longer spacing is associated with fewer crashes. The investigation into the relationship between minimum weaving length and crashes, however, is still preliminary and significant additional work is needed before a clear relationship can be identified. While the trends do not support a specific number they do support accepting a value that is larger than the value currently used. Figure 6-1 lists the suggested dimensions developed during this research project for an entrance ramp followed by an exit ramp.

Figure 6-2 lists the suggested dimensions for the spacing between consecutive exit ramps. Previous research indicated that additional guide signs may be needed for these higher speed facilities; therefore, ramp spacing longer than the current 1000 ft is appropriate. Alternative values were identified based on values in England's manual. Values calculated using decision sight distance, and a 1 mile spacing based on the *TMUTCD* guidance that advance sign for an exit being at 1 mile before the exit (2 miles if spacing permits).

The current advice in the TxDOT *RDM* (*1*) for Case 3 and Case 4 of successive ramps is appropriate, and an additional comment regarding sign design is suggested for the note.

The suggestions for spacing between successive ramps is summarized in Figure 7-1. While the suggested dimensions are much greater than values currently recommended for Texas, they can provide the opportunity for flexibility in managing future operations. They also reflect the mobility emphasis for the proposed higher speed (e.g., 100 mph) corridors.

Case 1: Entrance Ramp Followed by Exit Ramp



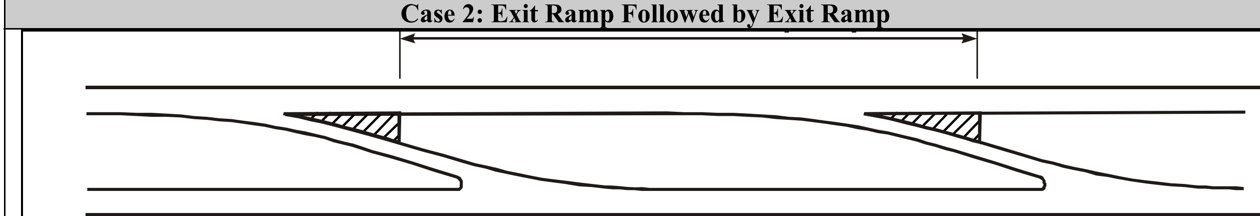
Design Speed (mph)	Suggested Weaving Length (ft)		
	Alternative 1	Alternative 2	Alternative 3
Below 70	1500	6600	2500
70	2000	6600	4500
80	2600	6600	8500
90	3300	6600	12500
100	4100	6600	16500

Alternative 1 reflects the situation when a vehicle is at the design speed at the end of the entrance ramp and must come to a complete stop and then accelerate back to freeway speed.

Alternative 2 is based on England's recommendation for weaving lengths for rural motorways and consideration of preliminary safety findings.

Alternative 3 are the values calculated using regression equations developed from this project's field studies and low freeway/ramp volume and weaving ratio.

Case 2: Exit Ramp Followed by Exit Ramp



Design Speed (mph)	Suggested Length (ft)		
	Alternative 1	Alternative 2	Alternative 3
50	1000	1500	5280
60	1200	1700	5280
70	1400	1900	5280
80	1600	2200	5280
90	1800	2500	5280
100	2000	2800	5280

Alternative 1 is based on England's recommendation for ramp spacing, rounded.

Alternative 2 is based on decision sight distance using reaction time found for 70 year old and over group.

Alternative 3 is 1 mile selected because guide signing for interchanges is to begin at 1 mile.

Case 3: Entrance Ramp Followed by Entrance Ramp

This situation will be encountered only on infrequent occasions and special design treatment will be required. It will usually require an added freeway lane.

Case 4: Exit Ramp Followed by Entrance Ramp

The distance between an exit ramp followed by an entrance ramp will be governed by the geometrics of the connections to the adjacent roadway or connecting roadway.

Note

The distances shown above are generally used but reference should be made to the AASHTO publication *A Policy on Geometric Design of Highways and Streets* and the *Highway Capacity Manual* for more specific information since operational aspects are influenced by traffic volumes and may require longer distances. In addition, the spacing needed to accommodate the required signs for an exit ramp should also be considered. See TxDOT *Freeway Signing Handbook* for additional information on sign design.

Figure 7-1. Suggested Successive Ramp Dimensions from Research Project 0-5860.

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