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16. Abstract

The current procedures for analyzing freeway weaving sections with four or more directional freeway lanes contain approximations and estimates based on observed freeways with fewer lanes. The use of larger cross-section freeways to cope with congestion reinforce the need for updated ramp merge/diverge and weaving area analysis procedures. This study documents the inappropriate results provided by the 1985 Highway Capacity Manual method of analysis. The new FRESIM microscopic freeway simulation model under development by FHWA provides reasonable estimates of merge/diverge and weaving area operations. This study substantiates the validity of the FRESIM model to predict the general performance of four and five lane freeways in Texas. Finally, recommendations for use of auxiliary lanes in Texas, based on FRESIM simulations, are presented in a tabular "operational matrix."

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AN ALTERNATIVE METHOD FOR ANALYZING MERGE/DIVERGE AND WEAVING AREAS ON FREEWAYS WITH FOUR OR MORE DIRECTIONAL LANES

by

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Research Report 1232-19
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IMPLEMENTATION STATEMENT

In order to meet the increasing demands on highways, the Texas Department of Transportation needs reliable tools and analysis procedures to aid in the evaluation and development of improvement alternatives. This report provides a summary of the existing method of evaluating merge/diverge and weaving areas for freeways with four or more directional lanes and the inadequacies that result from their use. This report also presents an "operational matrix" of various volumes and ramp separations and the simulated level-of-services that result. The simulated matrix provides a better representation of the expected freeway operations than does the existing 1985 Highway Capacity Manual method.

DISCLAIMER

The contents of this report reflect the views of the author who is responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

Due to increasing congestion, freeway planners and designers in Texas urban areas are being forced into cross-sections that are larger than ever expected. In an attempt to analyze these larger freeways, transportation officials have encountered some inadequacies in the analysis procedures. Specifically, this report concentrates on finding an analysis procedure that can be used to determine when an auxiliary lane is needed on freeway segments with four or more directional lanes.

In order to design for the increased demand, analysis procedures must adequately project not only the future operations, but as a minimum, adequately reflect the existing operations. The current analysis procedure (1985 HCM) and its computer software application (HCS) were used on ramp merge/diverge and weaving area field data and demonstrated to produce simulated operations much lower than observed.

FRESIM, a microscopic freeway simulation model undergoing development by the Federal Highway Administration (FHWA), was used and demonstrated that it could predict ramp merge/diverge and weaving area operations reasonably well in aggregate (across all lanes). Numerous FRESIM simulations were conducted to develop an "operational matrix" that shows the simulated speeds (i.e. level-of-service) for a ramp merge/diverge for various mainlane and ramp flowrates and ramp separations for four and five lane freeways. When the simulated speed dropped below 45 mph (72 km/hr) for the merge/diverge section, the operations are considered unacceptable (LOS E) and an auxiliary lane should be installed. The results of this study indicate that in general, merge/diverge ramp spacings should be a minimum of 2000 ft (610 m).

INTRODUCTION

In order to address the operational aspects of congestion, traffic engineers have begun to re-analyze potential bottleneck locations for improvements. New design and construction practices allow for much greater volumes than currently exist by providing much larger roadway cross-sections. The 1985 Highway Capacity Manual (HCM) (1) analysis procedures that are currently in use do not provide a consistent and reliable analysis procedure for roadways with more than 3 directional lanes. The HCM methods for analysis of freeways has, more often than not, been found by analysts to produce questionable results. Furthermore, the equations are tedious and difficult to use and contain approximations for the operational estimation of sections with more than four lanes. Therefore, it is necessary to evaluate the design procedure and operations of auxiliary lanes in weaving areas with four or more basic directional lanes. The results of this study will be procedures for determining when an auxiliary lane is needed.

Research Scope

The guidelines proposed within this report are for use on freeways with simple weaving areas. Simple weaves are formed by on-ramp/off-ramp sequences joined by continuous auxiliary lanes, these are called one-sided or ramp weaves. On-ramps followed by off-ramps that are not joined by a continuous auxiliary lane are not considered weaving areas.

This report serves two purposes. First, it documents the range of results produced by the current HCM method of analysis for ramp-junctions and weaving areas. Secondly, it presents a new microscopic method of analysis. Recently, FRESIM, a microscopic freeway simulation model, was developed that provides a detailed analysis for sections with intense vehicle-vehicle interactions. Actual freeway data from a ramp-junction and a weaving area was collected to document the inappropriateness of the HCM procedures and validate the FRESIM analysis. The objective of this project is to develop a set of guidelines (based on reliable and consistent analysis procedures) that can aid the planner or engineer in determining when an auxiliary lane should be considered between a right-handed entrance followed by an exit.

Problem Statement

Freeways in urban areas are used for local access to urban centers as well as interstate trips. Because of the importance of freeways, accurate and reliable procedures are needed to estimate the operational effects of various geometric configurations. The cross-section of Texas freeways has expanded and driver behavior has changed since research last evaluated the design and operation of weaving sections in Texas. The next generation of freeways will require larger cross-sections than those upon which the current analysis procedures are based. Also, the use of auxiliary lanes has become more common in weaving sections between entrance and exit ramps. It is necessary to evaluate the current design and operation of auxiliary lanes as they relate to weaving areas with four or more basic directional lanes.

There are several important reasons to study the analysis and operational procedures used in evaluating ramp junctions and weaving sections on freeways. Ramp junctions and weaving areas are common bottleneck locations along urban freeways. Due to the nature of these areas (accelerating and decelerating vehicles, lane changes, and limited space), higher than average driver workloads exist, which can result in poorer operational performance and an increase in accident rates.

Research Objectives

The objectives of this research were to:

1. Review the current methodology for evaluating simple single-side/ramp weaves.
2. Study traffic behavior within existing weaving sections with four or more directional lanes.
3. Develop guidelines for determining when an auxiliary lane is needed.

Phase 3. Simulation Techniques

Phase 3 of this study involved the use of mathematical models to "simulate" traffic conditions. Freeway operational data that had been collected was used as input first into the Highway Capacity Software (HCS), the computer software version of the 1985 HCM to demonstrate its inadequacies. The new microscopic FRESIM model, under development by FHWA, was then used to simulate the same freeway sections. After validation of the FRESIM model, the weaving length, number of lanes, mainlane volumes and ramp volumes were then varied to determine the effect each had on the operating speed of the freeway.

Phase 4. Prepare Recommendations

The measure-of-effectiveness used to determine how well a weaving section operates is speed. The HCS results give speed (for weaving and non-weaving vehicles) which can be translated to a level-of-service (LOS). The ramp junction of HCS produces checkpoint volumes and a LOS output. FRESIM can be configured to output speed by lane, and due to its microscopic nature and use of lane-changing and car-following equations, produced more reliable overall information on operations. Recommendations for the installation of an auxiliary lane were based on the various configurations' simulated ability to maintain a LOS D or better.

BACKGROUND AND CURRENT PRACTICE

Ramp Freeway Junction

The 1985 Highway Capacity Manual is the accepted method of evaluating freeways and weaving sections today. If a segment of freeway does not have an auxiliary lane between an entrance and an exit ramp, then the freeway operations are determined using the freeway ramp junctions section of Chapter 5. One of the ramp configurations specifically covered in Chapter 5 is that of an on-ramp followed by an off-ramp. The Manual provides a rather complicated methodology for evaluating the operations of a freeway segment with up to four directional lanes (excluding acceleration or deceleration lanes). The critical elements of a ramp junction that were identified include:

- Merge Volume - The total volume in the traffic stream which will join.
- Diverge Volume - The total volume in the traffic stream which will separate.
- Freeway Volumes - The freeway volume at the point where it is at the maximum level, upstream of an off-ramp or downstream of an on-ramp.
- Ramp Separation - The distance between consecutive ramps.

The procedure uses a nomograph or table to calculate the lane 1 volumes upstream of the merge area. Volumes are then converted to passenger car equivalents. Critical checkpoint volumes are computed and these values are compared to Table 5-1 of the HCM to determine the level of service. This procedure has several limits for application which are shown in Figure 1.

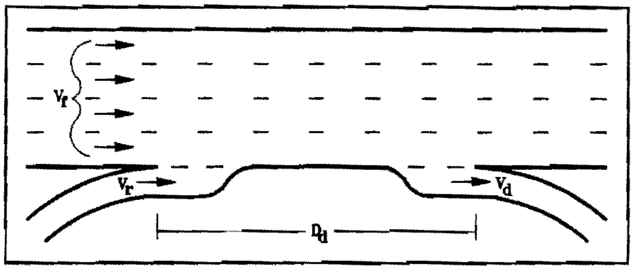


Figure 1. Limitations of HCM Ramp Junction Analysis.

Normal limits of use: V_f = 3000 to 7100 vph

V_r = 300 to 1100 vph

V_d = 100 to 800 vph

D_d = 1500 to 3000 ft (457 to 914 m)

If the study section does not conform to the limits indicated, then the user has the option of extending the lines on the nomograph or using tables for approximations of lane 1 volumes and ramp service flow rates.

Ramp merges are considered to have an influence zone of:

- 500 ft (152 m) upstream or 2500 ft (762 m) downstream of an on-ramp
- 2500 ft (762 m) upstream or 500 ft (152 m) downstream of an off-ramp

The HCM states "Freeway segments with five lanes in a single direction are not common but do occur in some major urban areas," and therefore, it does not provide an exclusive nomograph for the calculation of the lane 1 volume for five-lane sections. The table that is provided estimates the volume in the fifth lane, and subtracts it from the total freeway volume allowing the freeway to be treated as a four lane segment. Freeways with six-lanes in a single direction are not addressed in the 1985 HCM.

One of the major interests of this study was to determine under what conditions it is operationally desirable to add an auxiliary lane. In order to evaluate the operations of the freeway section shown in Figure 2 using the HCM method, one would use the tables and equations listed in Chapter 5 of the HCM (Ramp and ramp junctions section of HCS). If an alternative with an auxiliary lane were to be analyzed, different equations from Chapter 4 or the HCS weaving section could be utilized.

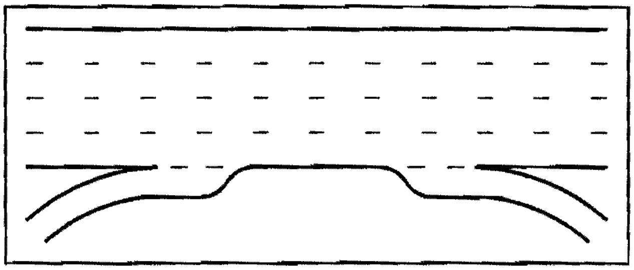


Figure 2. Example Freeway Ramp Junction.

In order to show the HCM approximations of the relative limits of flow rates for a freeway segment shown above, part of Table 5-1 from the HCM is presented in Table 1 below.
The ramp/ramp junction section of the HCS has level-of-service as its output; no speed calculations are listed. AASHTO (2) recommends that the designer design urban or suburban freeways for a LOS C. The HCM method calculates the merge flow, diverge flow, and freeway flow and compares each of these values to the flow rates listed in HCM Table 5-1. It should be noted that from Table 1, a LOS D corresponds to a 70 mph (113 km/hr) design speed freeway flow rate of 1850 pcphpl at ramp-freeway terminals. This flow rate appears to be excessively low for a design value. A recently published TTI report (3) on freeway capacity used several urban data collection sites across the state. The study concluded that a maximum sustainable flow rate of 2200 pcphpl is the recommended value for freeway capacity in Texas. The Transportation Research Board (TRB) Committee on Highway Capacity is recommending that a value of 2300 pcphpl be adopted as the maximum freeway capacity value.

Table 1. Level-of-Service Criteria for Checkpoint Flow Rates at Ramp-Freeway Terminals

LEVEL OF SERVICE	MERGE FLOW RATE (PCPH)[a] v_m	DIVERGE FLOW RATE (PCPH)[b] v_d	FREEWAY FLOW RATES (PCPH)[c] V_f 70-MPH (113 KM/HR) DESIGN SPEED		
			4-LANE	6-LANE	8-LANE
A	≤ 600	≤ 650	≤ 1,400	≤ 2,100	≤ 2,800
B	≤ 1,000	≤ 1,050	≤ 2,200	≤ 3,300	≤ 4,400
C	≤ 1,450	≤ 1,500	≤ 3,100	≤ 4,650	≤ 6,200
D	≤ 1,750	≤ 1,800	≤ 3,700	≤ 5,550	≤ 7,400
E	≤ 2,000	≤ 2,000	≤ 4,000	≤ 6,000	≤ 8,000
F	WIDELY VARIABLE				

[a] Lane-1 flow rate plus ramp flow for one-lane, right-side on-ramps.

[b] Lane-1 flow rate immediately upstream of off-ramp for one-lane, right-side ramps.

[c] Total freeway flow rate in one direction upstream of off-ramp and/or downstream of on-ramp.

Weaving Areas

Weaving areas are highway segments where the paths of entering and leaving traffic cross each other. Weaving areas are created when a merge is followed closely by a diverge, and the two ramps are connected by a continuous auxiliary lane (Figure 3). Weaving sections may occur at interchanges, between on-ramps and off-ramps, or between overlapping roadways. Weaving areas are generally considered to be 2500 feet (762 m) or less in length. Weaving areas may be longer in length, but tend to operate as individual merge/diverge areas at the larger ramp separations.

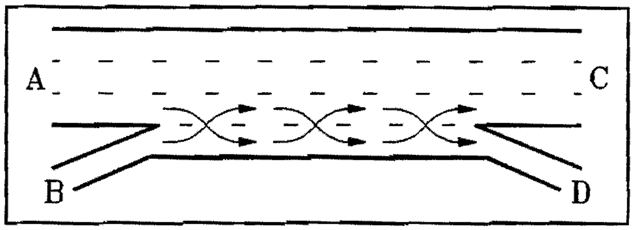


Figure 3. Example Freeway Weaving Area.

Weaving areas are characterized by intense lane-changing confined to a relatively short distance. The vehicles involved are also characterized by different acceleration attributes, with entering vehicles attempting to accelerate and exiting vehicle decelerating. The aspect of limited space and lane-changing emphasizes the importance of geometrics when designing or evaluating weaving areas. The three key geometric characteristics that define a weaving are the length of a weave, the configuration, and the number of lanes.

Length of Weave

The length of the weaving area, also referred to as ramp separation, is defined as a point where the right edge of the freeway shoulder lane and the left edge of the merging lane are 2 ft (1 m) apart to a point at the diverge gore area where the two edges are 12 ft (4 m) apart (Figure 4). In general, as the length of the weaving area decreases, lane-changing becomes more intense and, thus, operations (level-of-service) decline.

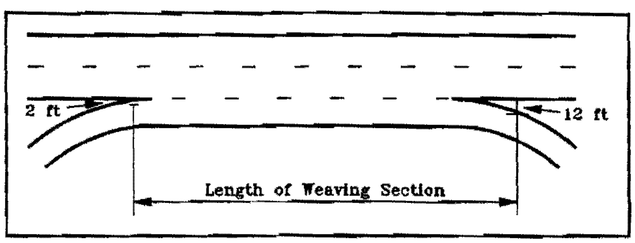


Figure 4. Definition of Weaving Length.

Configuration

Configuration refers to the design of the weaving section, where entry and exit points are located with respect to one another, and the number of lanes in each. Three configuration types are defined in the 1985 HCM. The research presented in this report concentrated on Type A weaving areas, most common along Texas freeways due to the predominant usage of "diamond interchanges." Specifically, using the HCM terminology, ramp weave/ one-sided weaves with four and five directional lanes were studied. Type A weaves are characterized by all on-ramp vehicles having to make a lane-change out of the auxiliary lane into the outer freeway lane and all off-ramp vehicles must make a lane-change from the outer lane of the freeway to the auxiliary lane.

Number of Lanes

This parameter is one of the major areas of concern within this study. The concern is whether or not the number of through lanes to the left of the auxiliary lane has an effect on the operations of the segment as a whole. In general, it is assumed that vehicles within a weaving area will make the appropriate lane changes to distribute themselves into the available lanes in such a way that all of the vehicles in the weaving area achieve approximately the same average speed. However, speeds of weaving vehicles will be somewhat slower than the speeds of non-weaving vehicles. Speed by lane will be one the variables discussed in a later section.

HCM Procedures

If a freeway section has an auxiliary lane connecting an on-ramp and an off-ramp, it would be considered a weaving section and equations from Chapter 4 of the HCM would be used for analysis and design purposes. Equations for the speed of both weaving and non-weaving vehicles and the number of weaving lanes could be used. The order of application of the HCM weaving equations is:

- Determine type of weaving section (configuration).
- Convert all traffic volumes to peak 15-minute flow rates.
- Compute unconstrained weaving speeds.
- Check for constrained operation. The calculated weaving speeds for weaving and non-weaving vehicles are used to calculate the number of lanes required for unconstrained operation. If this calculated number is greater than the maximum value listed in HCM Table 4-4 then the weaving section is constrained and the weaving and non-weaving speeds must be recalculated.
- Determine the level-of-service by comparing the weaving and non-weaving speeds to HCM Table 4-6.

Whereas the operations of a ramp junction are described by checkpoint flow rates and a level-of-service, the operations of a weaving section are based on the average running speeds of weaving and non-weaving vehicles. The speed classification for each level of service is defined in Table 4-6 of the HCM, and reproduced in Table 2.

Table 2. Level-of-Service Criteria for Weaving Sections

LEVEL OF SERVICE	MIN. AVG WEAVING SPEED, S_W(MPH)	MIN. AVG. NON-WEAVING SPEED, S_{nw} (MPH)
A	55	60
B	50	54
C	45	48
D	40	42
E	35/30[a]	35/30[a]
F	< 35/30[a]	< 35/30[a]

1 mile = 1.61 kilometers

[a] The 35 mph (57 km/hr) boundary for LOS E/F is used when comparing computed speeds using the equations of HCM Table 4-3. The 30 mph (49 km/hr) boundary is used for comparison to field-measured speeds.

AASHTO (2) cites the HCM as the analytical base for design calculations and decisions, but it also states, "It is generally accepted that a reduction in operating speed of about 5 mph below that for the highway as a whole can be considered a tolerable degree of congestion for weaving sections." A freeway designed for LOS D would (using HCM procedures) exhibit weaving area speeds in the 40 to 45 mph (64 to 72 km/hr) range for weaving vehicles and 42 to 48 mph (68 to 77 km/hr) for non-weaving vehicles, these speeds are 20 mph (32 km/hr) lower than the 60 mph (97 km/hr) free-flow speed.

In order to determine if an auxiliary lane is necessary at a site, a consistent methodology for analysis is necessary. The analysis procedure must be applicable for the examination of the existing and proposed configurations (without and with an auxiliary lane). HCS does address weaving sections (sections with auxiliary lanes) for roadways up to five lanes. However, the ramp/freeway junction section (no auxiliary lanes) does not adequately address freeways with four or more lanes.

FIELD DATA

Ramp Junction Study Site

The previous section was presented to demonstrate the design and analysis values that are currently accepted. This field comparison section was included to observe flow rates and speeds for a merge/diverge ramp junction site.

One of the sites used in the TTI capacity study (3) was a ramp merge/diverge location, U.S. 290 in Houston, Texas. The site was instrumented with inductive loop detectors as shown in Figure 5. Although the site has only three directional lanes, it can be used for comparison. The data that was collected at the site included the speed, length and headway of each vehicle upstream of the merge, on the on-ramp, and downstream of the merge. This section of freeway is level with three 11 ft. (3 m) lanes, a 10 ft. (3 m) outside shoulder, and a 1 ft. (<1 m) inside shoulder.

The on-ramp volume at the U.S. 290 site was approximately 750 from 4:00 to 5:00 p.m. and increased to approximately 1100 vph from 5:00 to 6:00 p.m. The off-ramp volume was approximately 700 vph from 4:00 to 5:00 p.m. and decreased to approximately 500 vph from 5:00 to 6:00 p.m. Data was collected for 15 days at the U.S. 290 study site. The collection period included 2 to 3 hours for each day during the p.m. peak. The peak 15-minute flow rates at the loops between the on-ramp and off-ramp are given in Table 3. The lane number scheme for the site has lane 1 nearest the median and lane 3 is the right-most lane. The average 15-minute flow rates by lane ranged from 2201 vphpl to 2333 vphpl. Table 3 also shows the average traffic volumes by lane, with lane 1 carrying slightly more vehicles than lanes 2 or 3.

The report also states that the maximum flow rates presented are unstable and are not sustainable, resulting in breakdown. Queue discharge rates are considered the maximum sustainable flow. These tables, however, do not address the issue of speed or level of service.

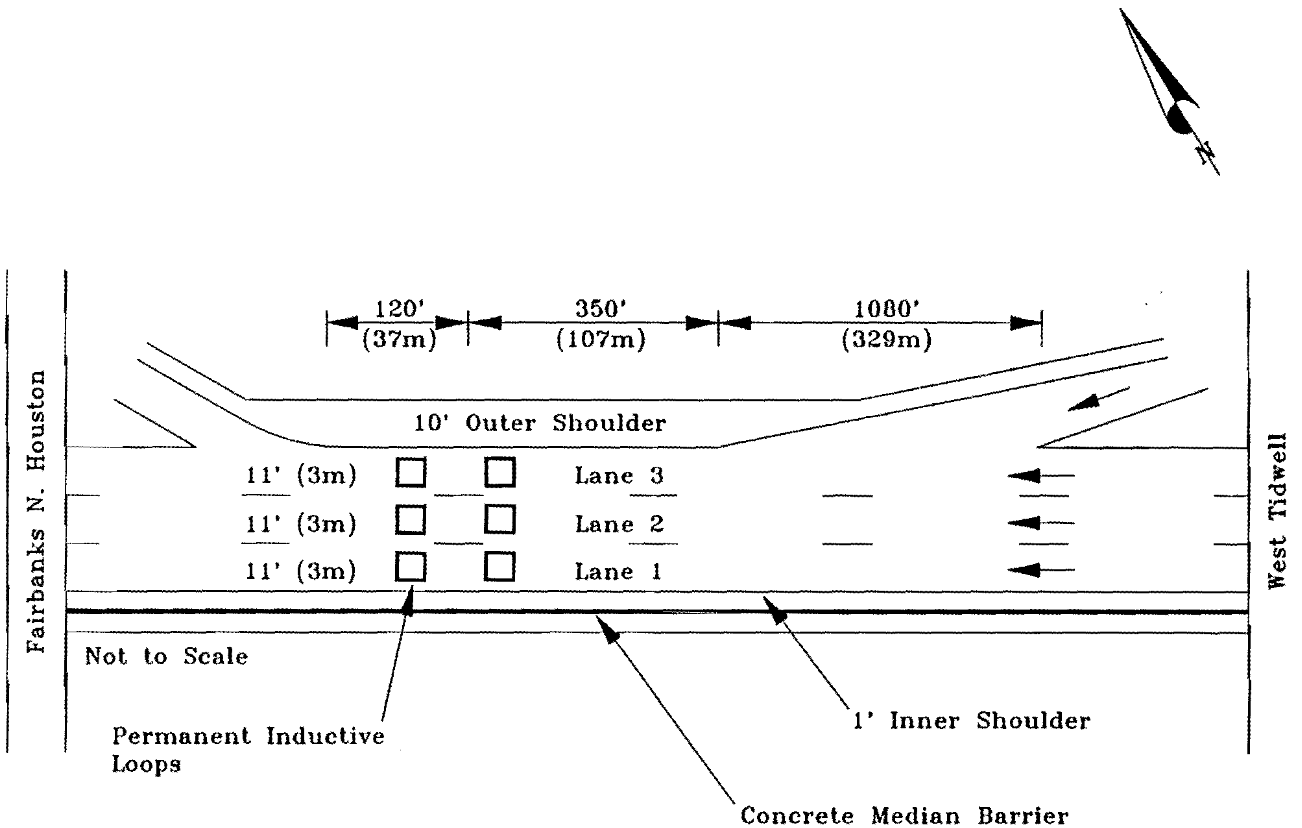
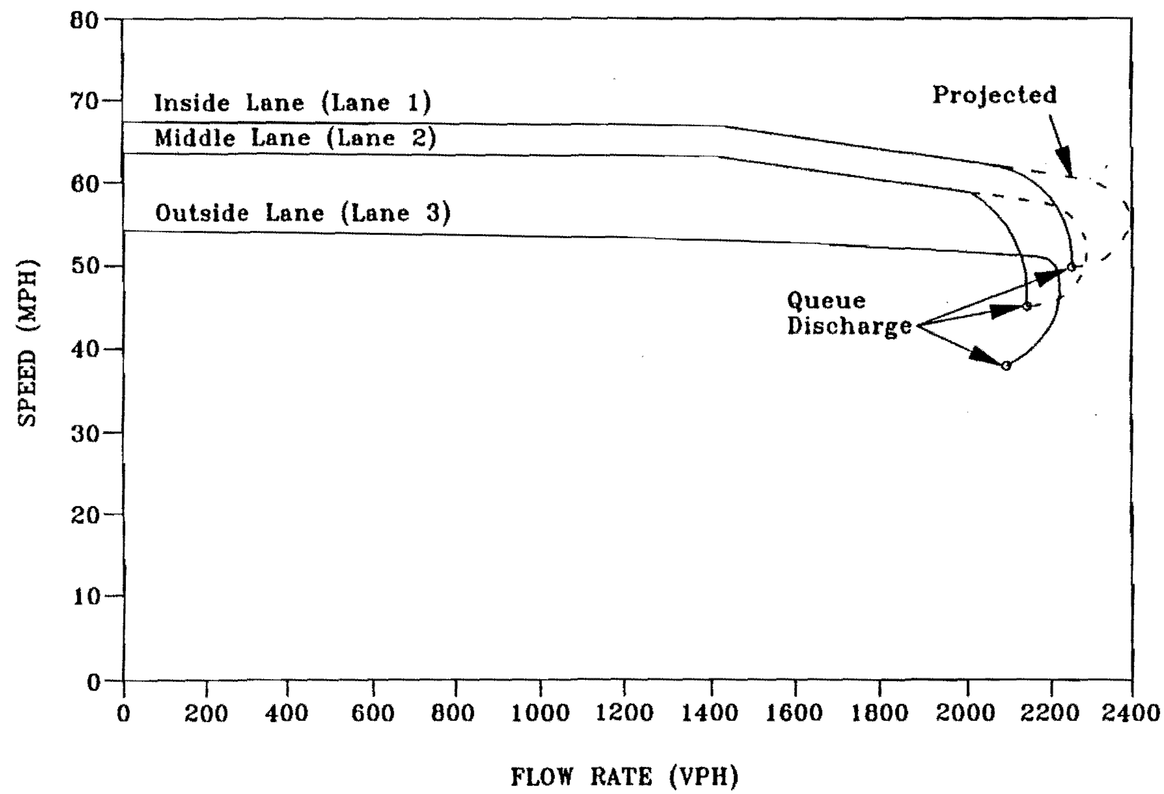


Figure 5. U.S. 290 Study Site

In order to show the operational aspect of speed, speed/flow curves were constructed for each day of data. The average speed/flow relationships for the U.S. 290 by lane are shown in Figure 6. The speeds for flow rates past 2000 vph are well within the LOS A to LOS B range (using speed designations for weaving sections from the HCM). Therefore, all measurements of the flow rates exceed the values given in the 1985 HCM.

Table 3. U.S. 290 Peak 15-Minute Flow Rates (occurring between 3:30-5:30 p.m.)

Sample	Peak 15-Minute Flow Rate (vphpl)			
	Lane 1	Lane 2	Lane 3	Average
1	2336	2256	2348	2313
2	2320	2200	2140	2220
3	2300	2244	2456	2333
4	2380	2240	2060	2227
5	2288	2172	2180	2213
6	2368	2204	2312	2295
7	2260	2224	2120	2201
8	2228	2196	2228	2217
9	2220	2268	2132	2207
10	2384	2256	2188	2276
11	2496	2244	2172	2304
12	2252	2220	2348	2273
13	2408	2344	2156	2303
14	2248	2356	2028	2211
15	2312	2240	2068	2207
Average	2320	2244	2196	2253



1 mile = 1.61 km

Figure 6. Observed Speed-Flow Curves by Lane for U.S. 290 Study Site.

Weaving Area Study Site

As stated before, Texas has begun to design freeways with four or more basic directional freeway lanes; however, few are currently constructed that meet all of the following site requirements:

1. Four or more directional basic freeway lanes
2. 1-lane, right-hand entrance
3. 1-lane, right-hand exit
4. Entrance and exit connected by a continuous auxiliary lane
5. Weaving length of 2500 ft (762 m) or less
6. No or minimal effects from adjacent ramps

One site was located that met all site requirements and individual vehicle information was collected for the auxiliary lane and the freeway lane adjacent to the auxiliary lane. A schematic of the site (U.S. 59) is shown in Figure 7. The site has a slight upgrade and then a slight downgrade, contains five 12 ft (4 m) lanes, a 10 ft (3 m) inner and 12 ft (4 m) outer shoulder. The on-ramp is connected to the exit ramp by a full-length 12 ft (4 m) auxiliary lane. The distance from the physical nose of the entrance gore (edge of curb) to the nose of the exit gore (edge of curb) is approximately 1920 ft (585 m). A pair of contact axle sensors were placed in lane 1 upstream of the on-ramp, on the on-ramp, and in lane 1 and in the auxiliary lane approximately 850 ft. (259 m) from the nose of the on-ramp gore. Video taping was also conducted for the entire study segment from an adjacent high-rise building.

The locations of the axle sensors were constrained by the limited number of traffic counters available with enough memory to collect individual vehicle data for extended periods of time. The type of data collected included speed, length, headway, and number of axles for each vehicle. The on-ramp volume at the U.S. 59 site was approximately 1380 vph with a mainlane total volume of 8700 vph during the p.m. peak hour. The exit ramp volume for the p.m. peak hour was 700 vph.

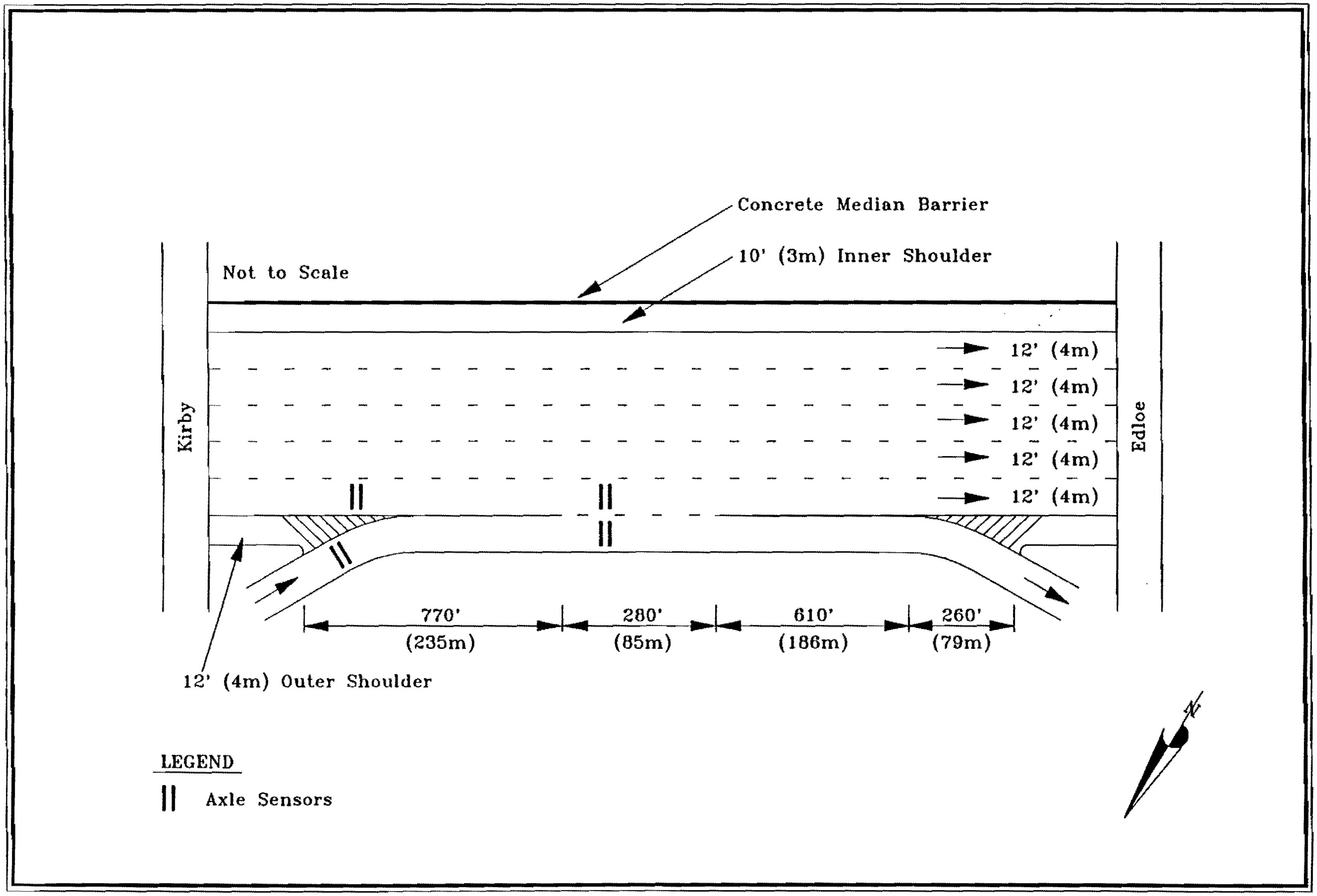


Figure 7. U.S. 59 Study Site

This segment of freeway has just recently undergone major reconstruction to add lanes, relocate ramps, and add a center HOV lane. The additional capacity has yet to be fully utilized and extremely congested conditions do not currently occur at this location. The observed flows per lane are well below those observed at the U.S. 290 site.

Highway Capacity Software (HCS)

The Highway Capacity Software is basically a menu driven, PC based software package that automates the calculations of the equations found in the 1985 HCM. The operations of basic freeway segments in the HCM are defined by density and speed. The operations of weaving sections are defined by the speeds of weaving and non-weaving vehicles. The operation of ramp-freeway merges, however, are defined using only volumes. In order to have a basis for comparison, the following assumption was made:

- The minimum acceptable design level-of-service would be LOS D.
  AASHTO states that a LOS D may be appropriate for freeways in heavily developed metropolitan areas. LOS D is characterized by merging vehicles having to adjust their speed to avoid conflicts in the merge area. On-ramp queues may begin to form, and turbulence will affect several freeway lanes. The speed corresponding to a LOS D is >46 mph (74 km/hr) for a basic freeway segment, >40 mph (64 km/hr) for weaving vehicles in a weaving area and >42 mph (68 km/hr) for non-weaving vehicles in a weaving area.

The U.S 290 study site geometrics with varying ramp and mainlane volumes were used as input into the HCS Ramp-Merge Analysis section. The output from this section includes the level-of-service for the freeway and merge and diverge. The lesser of the three LOS is generally used to define the operations for that segment of freeway. The output from the calculations is summarized in Table 4; the shaded area corresponds to those volumes that produce acceptable design levels of service (LOS D or better). For this comparison, the on-ramp and off-ramp volumes used were equal.

Table 4. HCS Level-of-Service (Freeway-Merge-Diverge) for U.S. 290 Geometrics

On/Off Ramp Flowrates (vph)	*Average Mainlane Flowrates (vph)			
	1400	1600	1800	2000
200	C-C-C	D-C-C	E-D-D	F-D-D
400	C-D-C	D-D-D	E-E-D	F-E-E
600	D-D-D	D-E-D	E-F-E	F-F-E
800	D-F-D	E-F-E	F-F-F	F-F-F
1000	D-F-E	E-F-F	F-F-F	F-F-F

*Total upstream freeway volume/number of lanes

In order to maintain a LOS D with the ramp geometrics at this site, a maximum freeway hourly flowrate of 1600 vphpl with a ramp flowrate of 400 vph or 1400 vphpl freeway and a ramp flowrate of 600 vph would be necessary. The actual speed flow diagram for U.S. 290, shown previously in Figure 6, shows that flowrates up to 2000 vphpl could be achieved while maintaining a speed of at least 55 mph (89 km/hr).

In order to determine the sensitivity of the HCS equations to the number of freeway mainlanes, ramp spacings, mainlane and ramp volumes, operations for a ramp merge/diverge similar to the U.S 290 site were evaluated for four and five directional lanes. Table 5 displays the HCS levels-of-service for a ramp merge/diverge site with four directional mainlanes with varying volumes and ramp spacings. Table 6 shows the levels-of-service for a ramp merge/diverge site with five directional mainlanes. The tables were shaded to show the volume ranges which would produce LOS D or better (freeway speeds approximately 40-45 mph, 64-72 km/hr). Results from HCS indicate that for ramp junctions, as the number of mainlanes increase, so does the range of volumes that produce acceptable operations.

Table 5. HCS Level-of-Service (Freeway-Merge Area-Diverge Area) for Ramp Merge/Diverge Freeway Section with Four Directional Mainlanes.

On/Off Ramp Flowrate (vph)	Ramp Spacing (Ft.)	*Average Mainlane Flowrates (vph)			
		1400	1600	1800	2000
400	1000	C-C-C	D-D-C	E-D-C	F-E-C
	2000	C-C-B	D-D-C	E-D-C	F-E-C
	3000	C-C-B	D-D-B	E-D-C	F-E-C
	4000	C-C-B	D-D-B	E-D-C	F-E-C
600	1000	C-D-C	D-E-D	E-E-D	F-F-D
	2000	C-D-C	D-E-C	E-E-C	F-F-C
	3000	C-D-C	D-E-C	E-E-C	F-F-C
	4000	C-D-C	D-E-C	E-E-C	F-F-C
800	1000	D-E-D	D-F-E	E-F-E	F-F-E
	2000	D-E-C	D-F-D	E-F-D	F-F-D
	3000	D-E-C	D-F-C	E-F-D	F-F-D
	4000	D-E-C	D-F-C	E-F-D	F-F-D
1000	1000	D-F-F	D-F-F	F-F-F	F-F-F
	2000	D-F-D	D-F-D	F-F-E	F-F-E
	3000	D-F-D	D-F-D	F-F-D	F-F-E
	4000	D-F-D	D-F-D	F-F-D	F-F-D

1 foot = .3048 meters

*Total upstream freeway volume/number of lanes

Table 6. HCS Level-of-Service (Freeway-Merge Area-Diverge Area) for Ramp Merge/Diverge Freeway Section with Five Directional Mainlanes.

On/Off Ramp Flowrate (vph)	Ramp Spacing (Ft.)	*Average Mainlane Flowrates (vph)			
		1400	1600	1800	2000
400	1000	C-C-C	C-D-C	C-D-C	D-E-C
	2000	C-C-B	C-D-C	C-D-C	D-E-C
	3000	C-C-B	C-D-B	C-D-C	D-E-C
	4000	C-C-B	C-D-B	C-D-C	D-E-C
600	1000	C-D-C	C-D-D	C-E-D	D-F-D
	2000	C-D-C	C-D-D	C-E-C	D-F-C
	3000	C-D-C	C-D-C	C-E-C	D-F-C
	4000	C-D-C	C-D-C	C-E-C	D-F-C
800	1000	C-E-D	C-F-E	D-F-E	D-F-E
	2000	C-E-C	C-F-D	D-F-D	D-F-D
	3000	C-E-C	C-F-C	D-F-D	D-F-D
	4000	C-E-C	C-F-C	D-F-D	D-F-D
1000	1000	C-F-F	C-F-F	D-F-F	D-F-F
	2000	C-F-D	C-F-D	D-F-E	D-F-E
	3000	C-F-D	C-F-D	D-F-D	D-F-E
	4000	C-F-D	C-F-D	D-F-D	D-F-D

1 foot = .3048 meters

*Total upstream freeway volume/number of lanes

The effects of the addition of an auxiliary lane was demonstrated by conducting an HCS analysis for the original three lane section of U.S. 290 with an auxiliary lane connecting the on and off-ramp. Table 7 shows the resulting operational calculations; the LOS is given first for weaving vehicles and then for non-weaving vehicles for each volume cell in the volume matrix. There is a substantial improvement in the calculated operations of the segment with the addition of an auxiliary lane. Mainlane flowrates of 2000 vphpl with ramp flows of 800 vphpl produce LOS D.

Table 7. HCS Level-of-Service (Weaving-Non-Weaving) for U.S. 290 Geometrics (3 Lanes) with the Addition of an Auxiliary Lane.

On/Off Ramp Flowrates (vph)	*Average Mainlane Flowrates (vph)			
	1400	1600	1800	2000
200	B-B	B-B	C-B	C-B
400	C-B	C-B	C-B	C-C
600	C-C	C-C	D-C	D-C
800	D-C	D-C	D-C	D-C
1000	E-C	E-C	E-C	E-C

*Total upstream freeway volume/number of lanes

HCS was next used to evaluate the operations of the weaving section at U.S. 59 (site 2) for varying volume levels. Since the segment already consisted of five directional mainlanes, the number of lanes could not be increased. As before, the ramp spacing was held constant, only the volumes were varied. The results of the HCS analysis are shown in Table 8. It is interesting to notice that as with the ramp junction section, the weaving section has improved operations for higher volumes for a segment with a greater number of lanes. LOS D (from HCS) or better operations could be achieved on U.S. 59 with mainlane volumes of 1400 vphpl and ramp volumes of 1400 vphpl and up to 2000 vphpl mainlane and 1000 vphpl on the ramps.

Table 8. HCS Level-of-Service (Weaving-Non-Weaving) for U.S. 59 Geometrics

On/Off Ramp Flowrates (vph)	*Average Mainlane Flowrates (vph)			
	1400	1600	1800	2000
200	B-B	B-B	C-B	C-B
400	C-B	C-B	C-B	C-B
600	C-B	D-B	D-B	C-C
800	D-B	D-B	D-B	D-C
1000	D-C	D-C	D-C	D-C
1200	D-C	D-C	D-C	E-C
1400	D-C	E-C	E-C	E-C
1600	E-C	E-C	E-C	E-C

*Total upstream freeway volume/number of lanes

Using the existing U.S. 59 ramp and mainlane volumes and ramp configuration as input into HCS, the resulting weaving vehicles would operate at LOS D and non-weaving vehicles would have LOS C operations.

ALTERNATIVE ANALYSIS

In order to analyze a ramp merge/diverge, and a weaving area and include the parameters listed previously (length of weave, configuration and number of lanes), the evaluation procedure must be fairly flexible. As pointed out, the HCS is the currently accepted procedure for analysis of freeway segments, weaves, and ramp junctions. Models also available for use include: CORFLO and FREQ, both macroscopic freeway simulation models; FREWEAV another macroscopic of freeway weaving areas; and FRESIM and INTRAS, both microscopic models.

CORFLO and FREQ, due to their macroscopic nature of treating the traffic stream with aggregate measures of speed flow and density, were considered too "coarse" in their treatment of vehicle to vehicle interactions to adequately model weaving or ramp junction areas. FREWEAV was obtained and tested, but was not used because it only models Type B and C major weaving sections. INTRAS is a mainframe microscopic freeway simulation model, developed specifically to analyze freeway weaving sections. FRESIM, however, is an enhanced PC based upgrade of INTRAS and was the model chosen for analysis in this study. Another major advantage of a model such as FRESIM is its ability to evaluate the operations of a corridor or "freeway system." The HCS will only provide operations for a point or single segment of freeway.

FRESIM Simulation Model

In order to find an appropriate analysis tool to evaluate freeway merging and weaving, several models were considered including CORFLO, FREQ, FREWEAV, INTRAS and FRESIM. The FRESIM model was chosen for use in this study primarily because it is a microscopic freeway simulation model. A microscopic simulation model is one in which each vehicle is modelled as a separate entity. The behavior of this entity is represented in the model through interaction with its environment (freeway geometry and other vehicles). As such, microscopic models are capable of representing traffic behavior in extreme detail.

The FRESIM model is a significantly enhanced and reprogrammed version of its predecessor the INTRAS model. Enhancements include improvements to the geometric representation, as well as the operational capabilities of the INTRAS model. Thus, FRESIM can simulate more complex freeway geometries and provides a more realistic representation of traffic behavior than INTRAS. The FRESIM model is also developed for use on desktop PCs, which makes it more accessible than the mainframe INTRAS model. FRESIM does, however, contain two limitations that constrained this study. First, FRESIM will only accommodate freeway segments up to five basic directional lanes. Secondly, FRESIM like HCS, will only allow the user to input four characters for an input flowrate. This meant that input flows were limited to 9999 vph, corresponding to a five lane freeway with nearly 2000 vphpl.

FRESIM simulations were conducted on the ramp-junction and the weaving area sites to show that the output adequately represented the overall actual operating conditions. Simulations were then performed for a variety of ramp spacings, volumes and lane numbers to produce a matrix of recommended parameters for design applications.

<u>Ramp Junction</u>

The FRESIM model was used to simulate the operations of the U.S. 290 site for the existing configuration. A typical day's data was selected from the 15 samples collected. Consecutive 15-minute volumes were used as input for a 2-hour simulation. All default values of FRESIM were used except the values for the car-following sensitivity factors. These values were adjusted slightly to more closely reflect the more aggressive driver population. FRESIM has the option of placing vehicle detectors (loops) in each lane and recording speeds and flowrates by lane for a user-specified time period.

The first check of the output of any simulation model is to determine that the model did indeed process all of the vehicles that were input. The actual total freeway flowrate and simulated total freeway flowrate are shown in Figure 8.

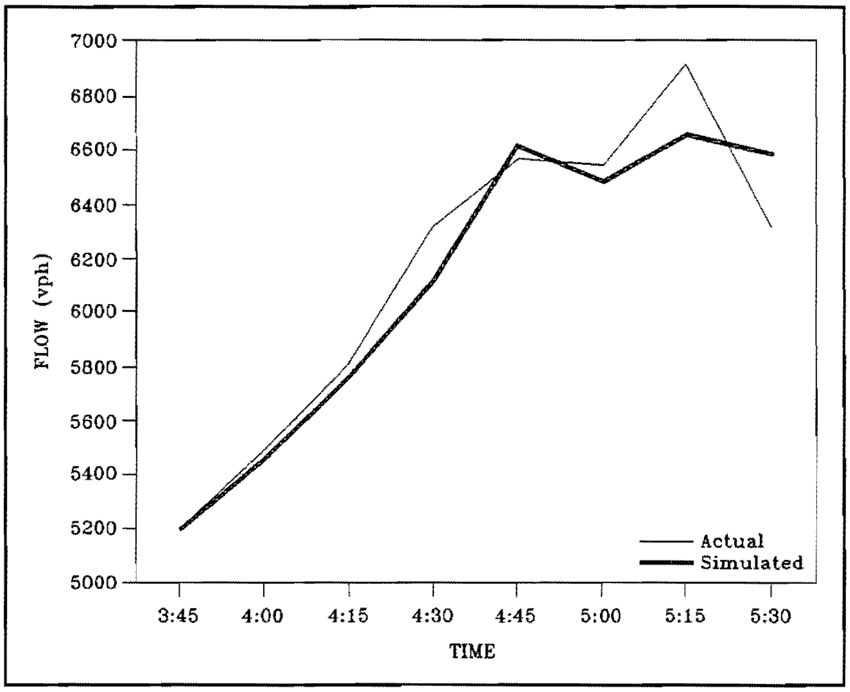


Figure 8. Total Freeway Flowrates Across All Lanes (U.S. 290).

The actual and simulated flowrates for each lane by 15-minute periods are shown in Figures 9 - 11. A queue forms at the merge point of the entrance ramp and the mainlanes daily, and occurred during this data at approximately 4:45 (resulting in queue discharge flows until the end of the study period). From the figures, it can be seen that FRESIM modelled the overall freeway flowrate extremely well. The mean difference between the actual and FRESIM simulated total flow was 32 vph for the two-hour simulation period. A paired T-Test indicated that the actual and FRESIM simulated total freeway flows are not statistically different with a T-statistic of 0.57. However, FRESIM over-estimated the flowrates during certain times on lanes 1 and 2 and under-estimated the flowrates for a majority of the time in lane 3 (where merging and diverging occur).

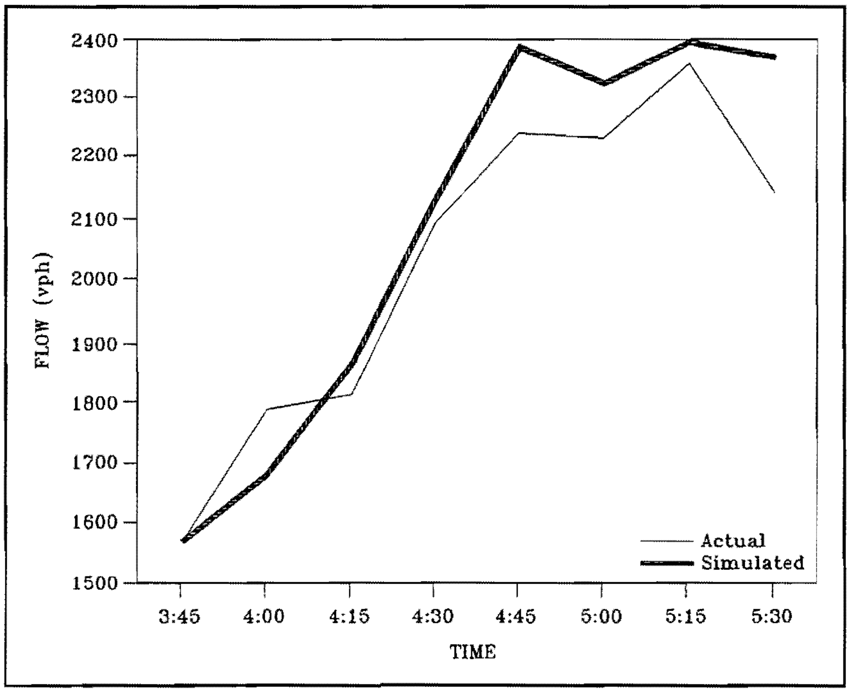


Figure 9. Freeway Flowrates in Lane 1 (Median Lane U.S. 290).

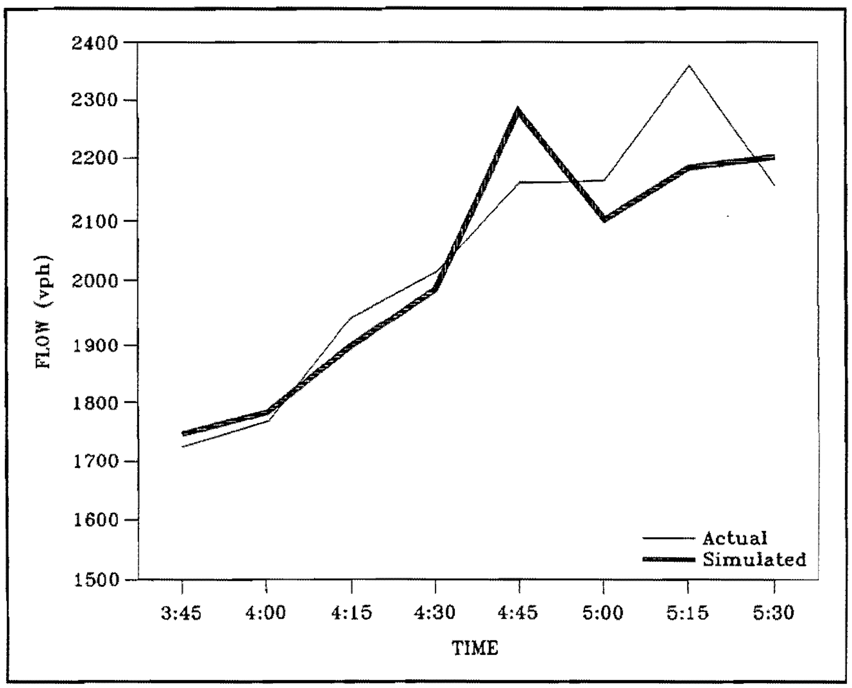


Figure 10. Freeway Flowrates in Lane 2 (U.S. 290).

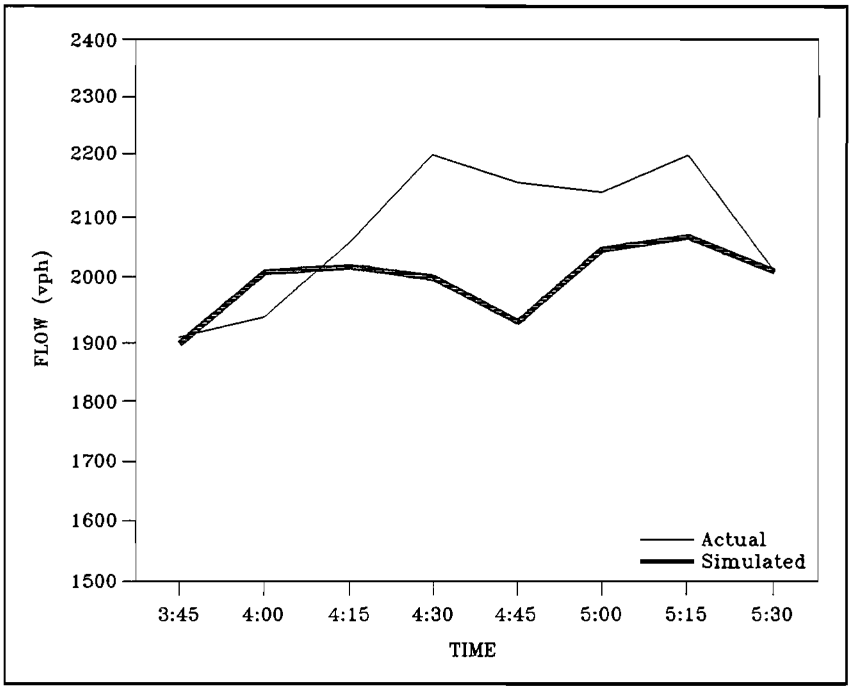


Figure 11. Freeway Flowrates in Lane 3 (U.S. 290).

The actual and simulated average freeway speeds (for all lanes) are shown in Figure 12. The actual and simulated speeds for each freeway lane between the merge/diverge area are shown in Figures 13 - 15. Again, FRESIM modelled the average freeway speeds very well, but under-estimated the speeds for lanes 1 and 2 for some time periods and over-estimated the speeds in lane 3. The mean difference between the actual and FRESIM simulated average speed was 3.6 mph (6 km/hr) for the two-hour simulation. The speed deviations can be explained in part by the inability of the model to distribute volumes across the lanes as observed. Lane 3, where the merging and diverging occurred, was limited in capacity by the model to less than the capacity of the other freeway through lanes. The under-estimation of the flow rate in lane 3 resulted in an over-estimation of vehicle speed. The capability for the user to input the volume distribution by lane was contained in the INTRAS model, but was not included in the FRESIM model. Since the user cannot adjust the lane volume distribution, the model cannot be expected to produce accurate lane specific output. However, FRESIM does produce a good overall representation of actual operations and would be acceptable for design purposes.

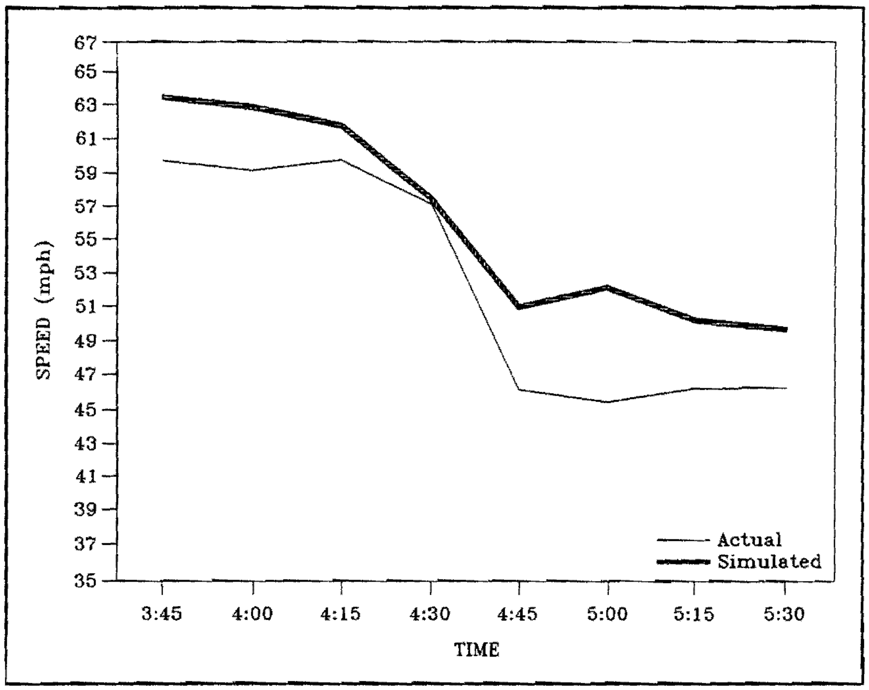


Figure 12. Average Freeway Speeds Across All Lanes (U.S.290).
1 mile = 1.61 km

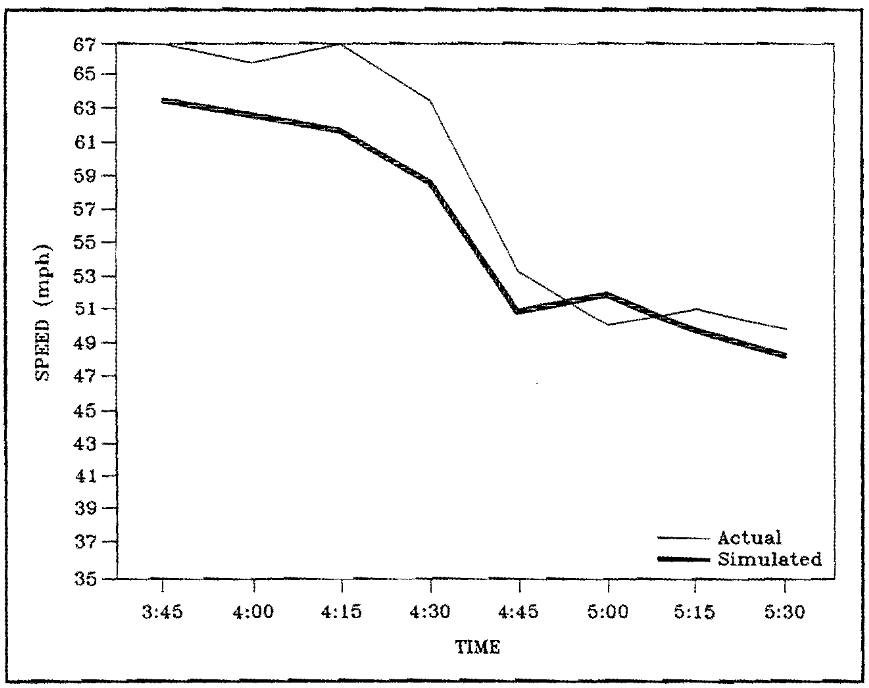


Figure 13. Freeway Speeds for Lane 1 (U.S. 290).

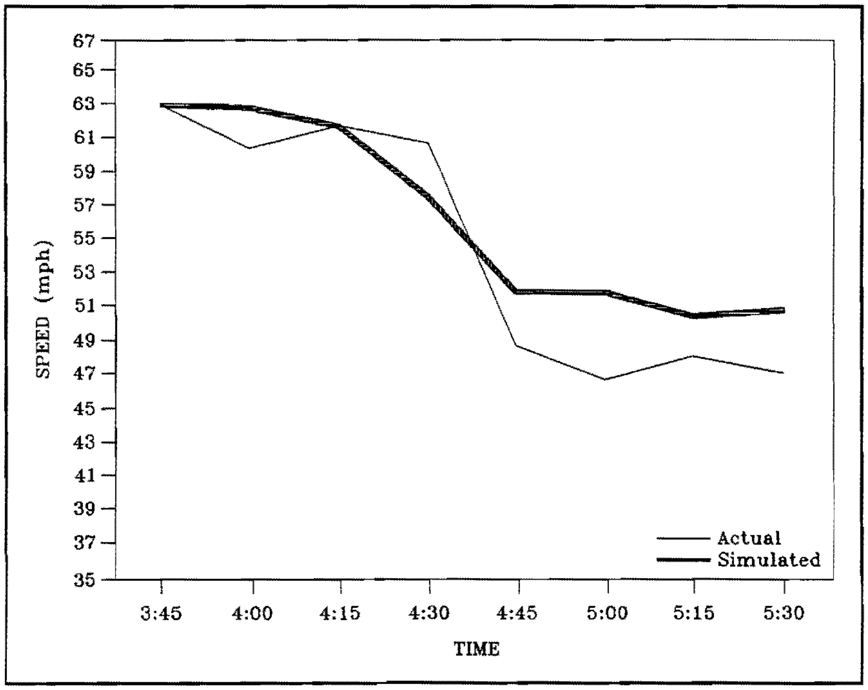


Figure 14. Freeway Speeds for Lane 2 (U.S. 290).

1 mile = 1.61 km

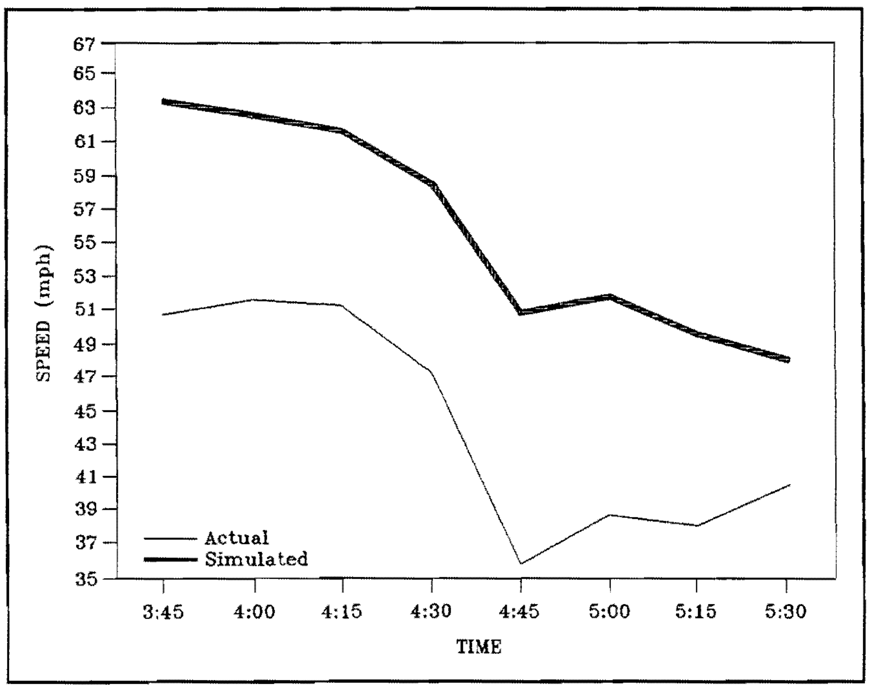


Figure 15. Freeway Speeds for Lane 3 (U.S. 290).

Weaving Area

The FRESIM model was used to simulate the operating conditions at the U.S. 59 site. As before, all of the default values of FRESIM were used except for the adjustment of driver sensitivity to reflect the observed driver population. Review of the data provided from the traffic counters in lane 5 and the auxiliary lanes showed that the frequency of lane changes between the two lanes produced considerable amounts of partial or questionable data. Therefore, flowrates by lane were calculated from volume counts conducted from the video tapes. Figures 16 - 21 show the simulated and actual flow rates for each of the freeway lanes and the auxiliary lane at the point where the axle sensors were located (850 ft, 259 m from the entrance ramp gore). As with the previous site, FRESIM underestimates the volumes in the right-most lane (the auxiliary lane). The flows in lanes 3, 4 and 5 (lane 5 is adjacent to the auxiliary lane) are overestimated by varying degrees and the flow in lanes 1 and 2 are underestimated. Figure 22 shows the total freeway flow in the weaving section, actual and FRESIM simulated. Again, FRESIM simulates the total freeway flow extremely well.

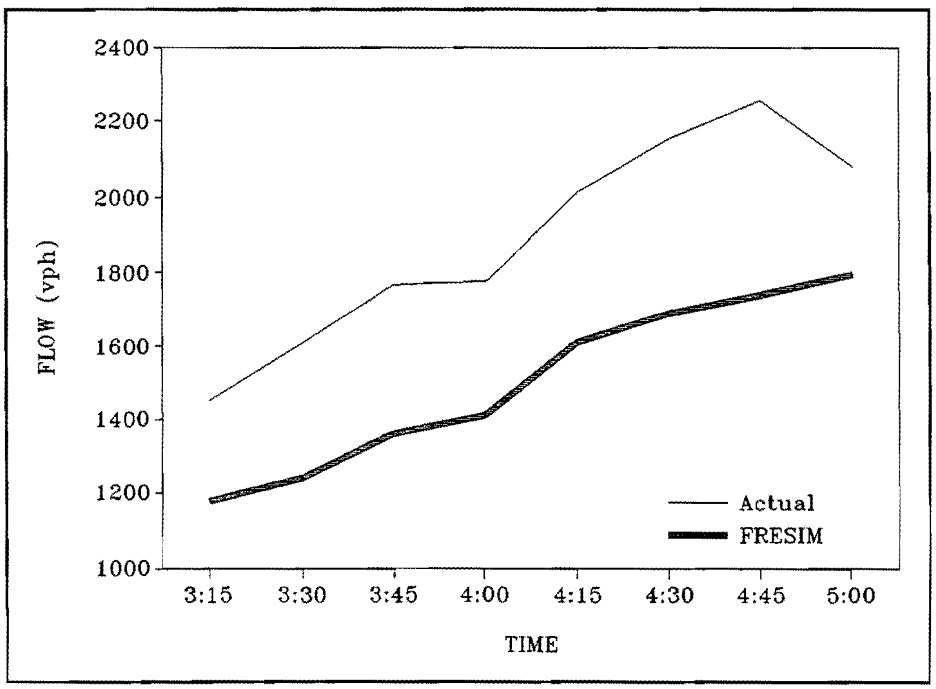


Figure 16. Freeway Flowrates in Lane 1 (Median Lane U.S. 59).

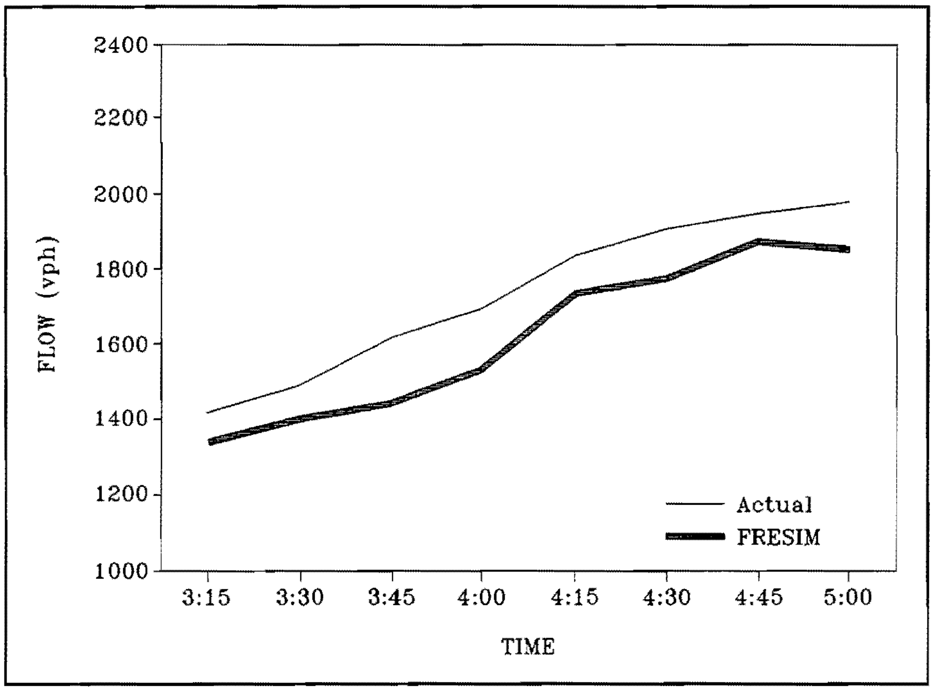


Figure 17. Freeway Flowrates in Lane 2 (U.S. 59).

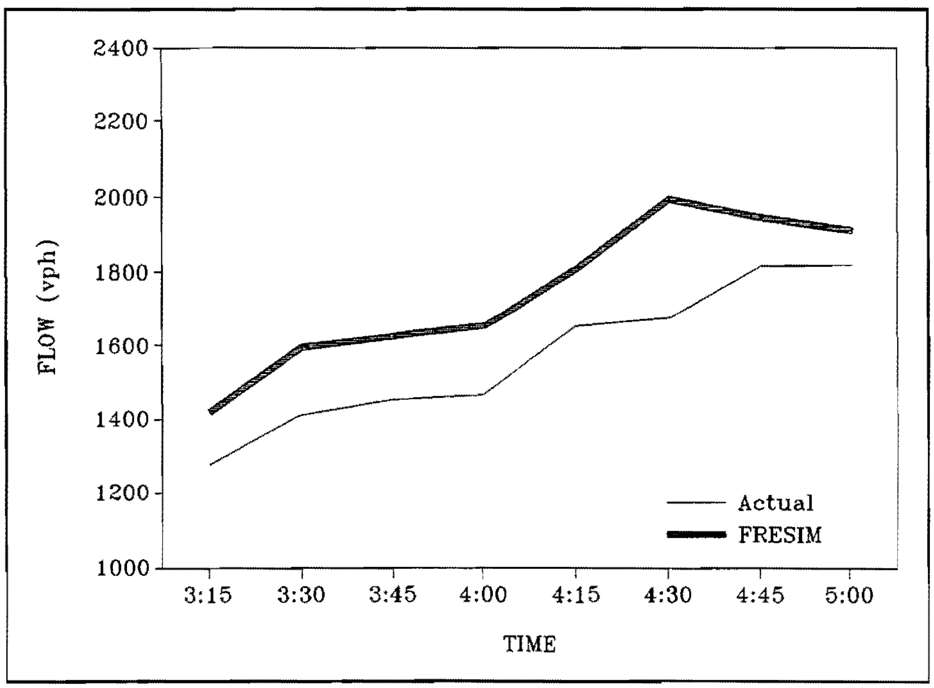


Figure 18. Freeway Flowrates in Lane 3 (U.S. 59).

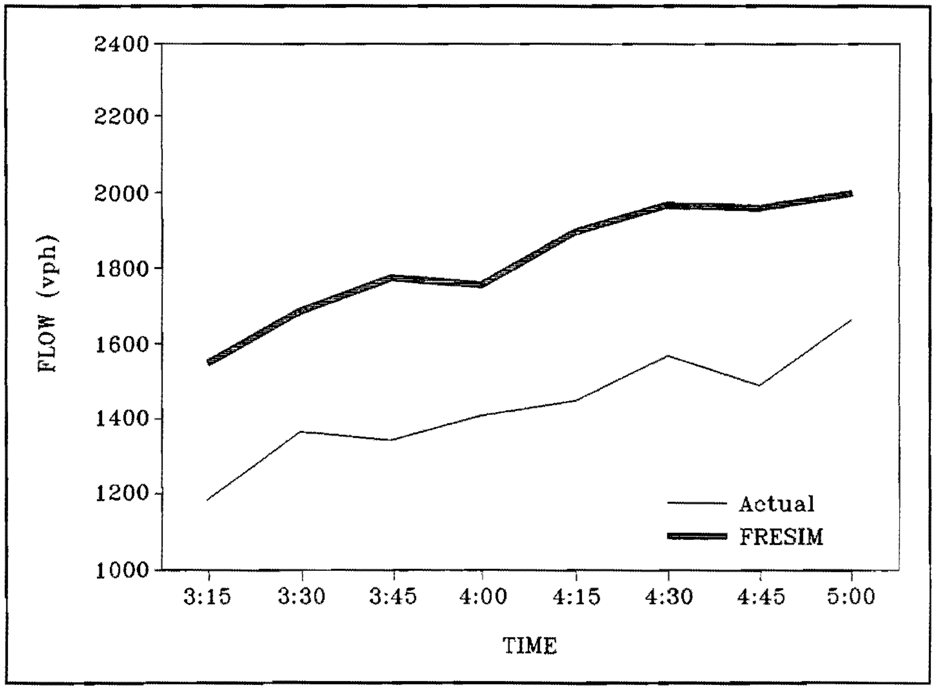


Figure 19. Freeway Flowrates in Lane 4 (U.S. 59).

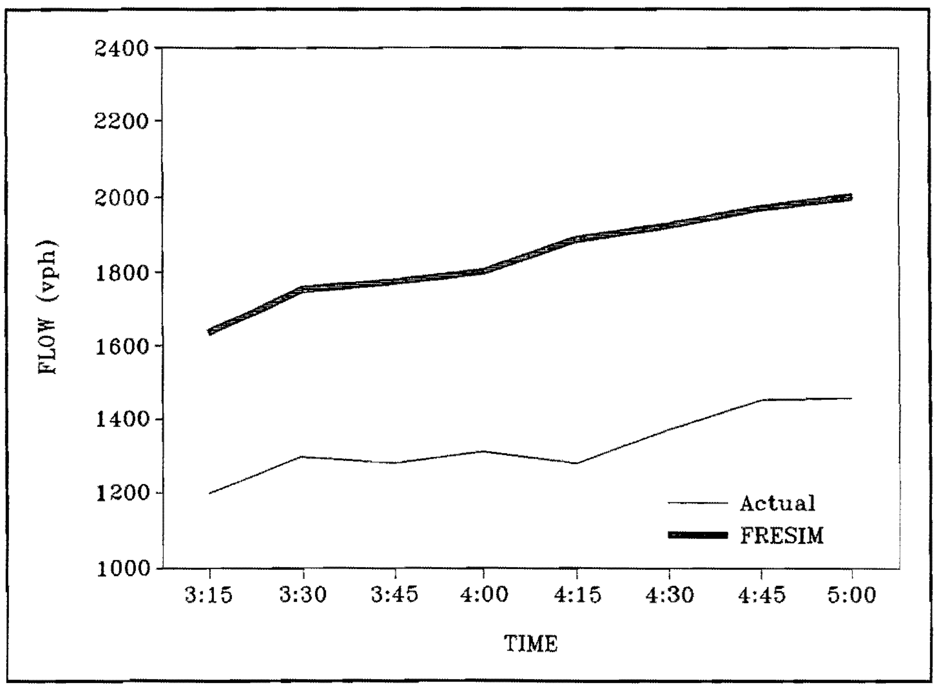


Figure 20. Freeway Flowrates in Lane 5 (U.S. 59)

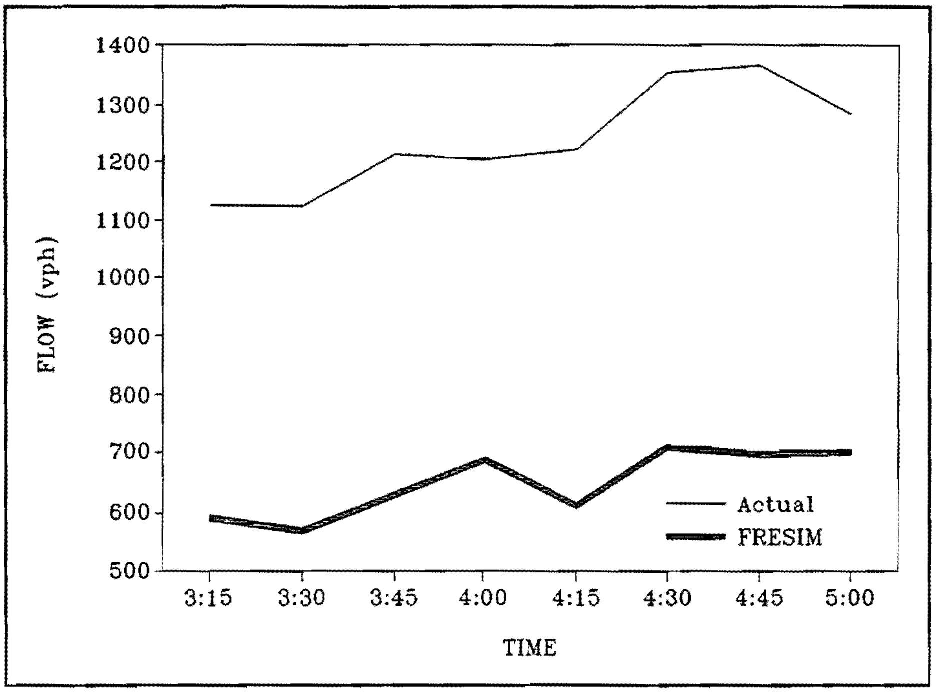


Figure 21. Freeway Flowrates in the Auxiliary Lane (U.S. 59).

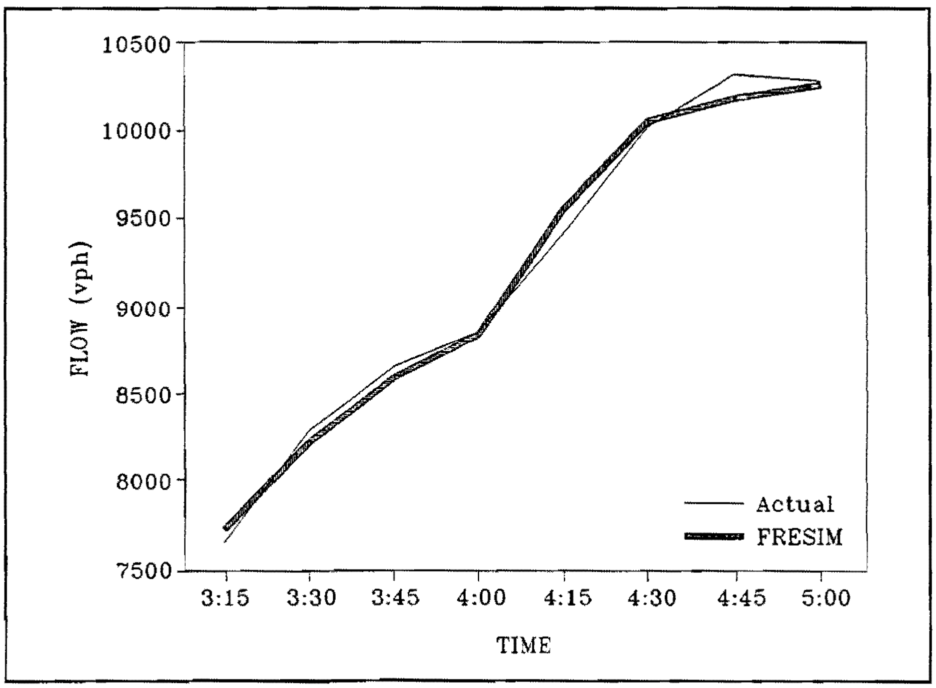


Figure 22. Total Freeway Flowrates Across All Lanes (U.S. 59).

Speed data was only collected in the weaving section for lane 5 and the auxiliary lane; the graphs of the actual and simulated speeds for these lanes are shown in Figures 23 and 24. As stated before, a considerable amount of the traffic counter data recorded had to be discarded since the lane changing that occurred often resulted in vehicles not crossing both axle sensors in the lane. FRESIM overestimates the speeds for both lanes during the study period. An explanation of the speed discrepancies is presented in the following section.

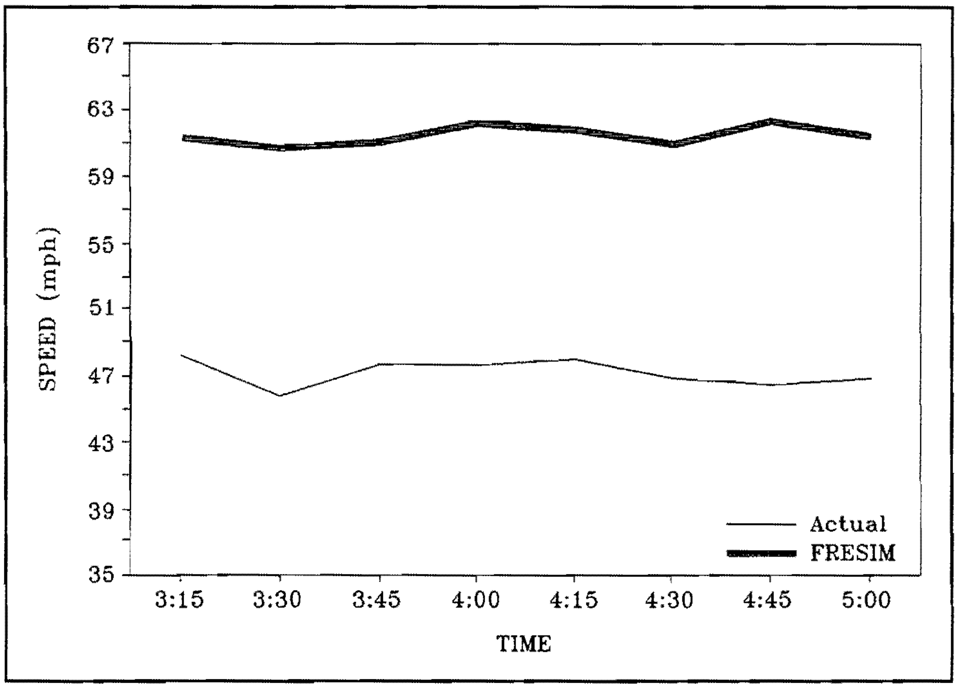


Figure 23. Freeway Speeds for Lane 5 (U.S. 59)

1 mile = 1.61 km

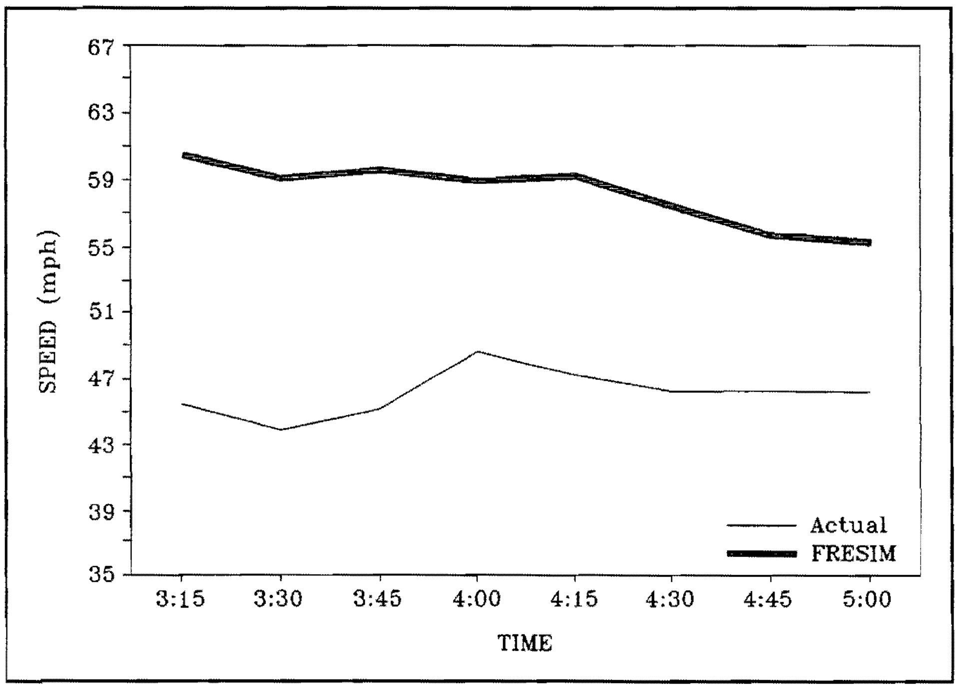


Figure 24. Freeway Speeds for Auxiliary Lane (U.S. 59).

Lane Changes

The overestimated speeds in the auxiliary lane may result from a combination of underestimated flows and atypical weaving properties by the model. Figure 25 shows the percentages of the observed entrance ramp traffic at the locations where they changed lanes from the auxiliary lane to lane 5.

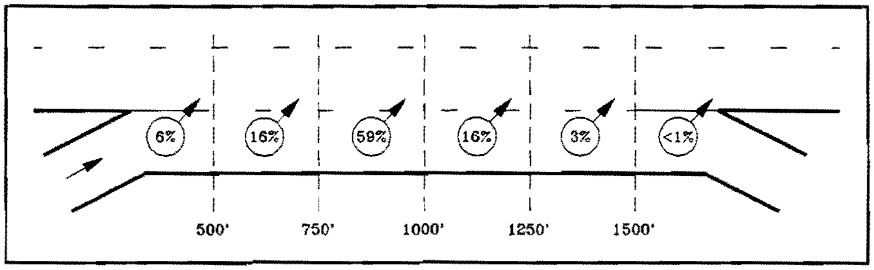


Figure 25. Entrance Ramp Lane Changes by Location (U.S. 59).

1 foot = .3048 meters

Figure 26 shows the percentages of the observed exit ramp traffic in relation to the location at which vehicles in lane 5 change lanes to the auxiliary lane. The majority of the entering vehicles change lanes in the 750 - 1000 ft (229-305 m) section, with a fairly normal distribution of lane changes on either side. A major portion of the exiting vehicles also changed lanes in the 750 - 1000 ft (229 - 305 m) section. However, the exiting distribution is skewed closer to the exit ramp. This shows that the major area of weaving occurs in the area where the axle sensors were placed (850 ft, 259 m).

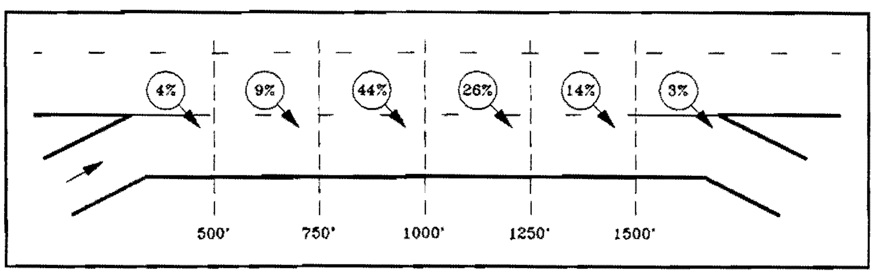


Figure 26. Exit Ramp Lane Changes by Location (U.S. 59).

Actual speeds in this area are expected to be lower than normal and lend credibility to the speeds collected by the traffic counters. Vehicles cannot be "tracked" in FRESIM, but flow rates by lane can be output for any location. Numerous simulations with FRESIM, varying the location of the point processing inductive loops, revealed that the model executes lane changes at the first possible opportunity that a vehicle encounters. The auxiliary lane flows for locations from the 50 ft (15 m) station to the 850 ft (259 m) station showed that the majority of the weaving was completed within the first several hundred feet (the flows did not significantly change). The flows output by FRESIM at the 850 ft (259 m) station reflect the exit ramp flows (Figure 27), where in actuality, almost half of the entrance ramp volume is still in the auxiliary lane. This "first chance" logic explains the underestimated volume in the auxiliary lane and the overestimated volume in the adjacent lane (lane 5) at the axle sensor location. Several inputs to FRESIM could be adjusted to aid in modifying the lane changing logic within the model, but only the default values were used to determine if the fundamental basis of the program produced logical results. Without the ability to specify input volume by lane, FRESIM cannot produce accurate lane specific output. The FRESIM model produced operations appropriate for the input.

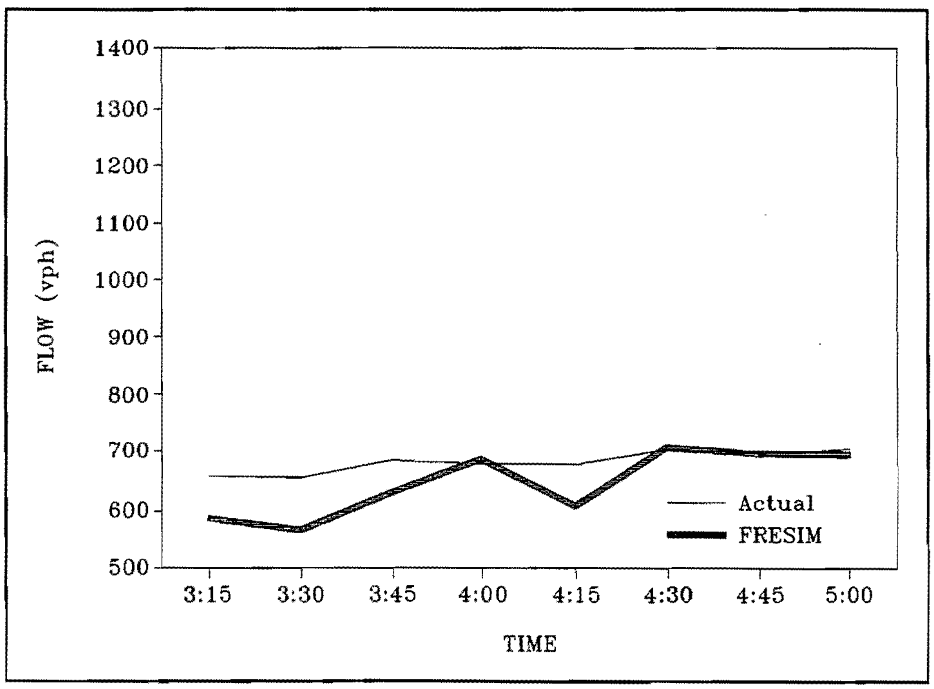


Figure 27. FRESIM Auxiliary Lane and Actual Exit Ramp Flows.

Operational Matrix

The purpose of this report is to develop guidelines for the use of auxiliary lanes for freeway segments with four or more directional lanes. The previous sections were presented to demonstrate the capabilities of the FRESIM freeway simulation model. Overall, when the freeway segment is viewed as a whole, the operational estimates produced by FRESIM are reliable.

The final application of the FRESIM model in this study was used to simulate a hypothetical freeway segment similar to the U.S. 290 site. Simulations were conducted for a freeway varying the number of lanes, the length between the entrance and exit ramp junctions, and mainlane and entrance/exit volumes. Simulations were performed for freeways with four and five directional mainlanes. Mainlane volumes were varied from 1600 vphpl to 2000 vphpl. Entrance and exit volumes were equal and ranged from 600 to 1000 vph (one lane ramps). The length between the entrance and exit ramps was varied from 1000 ft to 4000 ft (305 to 1219 m). Again, all default values were used, except for the adjustment of the driver sensitivity factors for a slightly more aggressive driver distribution. The measure of effectiveness used for comparison was the output average speed for the segment between the ramps. This average segment speed is computed using the segment vehicle-miles divided by the segment vehicle-minutes of travel. The results of these simulations are shown in Tables 9 and 10 for four and five lane freeways, respectively. The tables are shaded to show the volume and ramp spacings that corresponds to a freeway speed in excess of 45 mph, 72 km/hr (approximately LOS D). The FRESIM output table is considerably different than the HCS table presented previously (Tables 5 and 6). FRESIM shows that acceptable operations (LOS D) can be achieved with mainlane flowrates of 2000 vphpl for ramp flows of 600 vph for any of the ramp spacings used for four or five directional lanes. Acceptable operations were also attained for freeway flows of 2000 vphpl for ramp volumes of 800 and 1000 vph for most of the ramp spacings used. Additional simulations, varying the volumes of the entrance in relation to the exit, revealed that as the entrance volume decreased the freeway speeds increased (operations improved).

Table 9. FRESIM Simulated Average Freeway Speed for Ramp Merge/Diverge Section with Four Directional Mainlanes.

On/Off Ramp Flowrate (vph)	Ramp Spacing (Ft.)	*Average Mainlane Flowrates (vph)		
		1600	1800	2000
600	1000	54	51	47
	2000	54	53	50
	3000	56	54	51
	4000	56	55	53
800	1000	47	43	41
	2000	54	52	46
	3000	52	50	49
	4000	55	54	49
1000	1000	40	40	39
	2000	47	46	43
	3000	49	48	48
	4000	54	50	48

1 foot = .3048 meters

*Total upstream freeway volume/number of lanes

Table 10. FRESIM Simulated Average Freeway Speed for Ramp Merge/Diverge Section with Five Directional Mainlanes.

On/Off Ramp Flowrate (vph)	Ramp Spacing (Ft.)	*Average Mainlane Flowrates (vph)		
		1600	1800	2000
600	1000	55	54	45
	2000	56	54	50
	3000	56	53	51
	4000	56	54	53
800	1000	51	44	43
	2000	50	49	48
	3000	53	50	49
	4000	54	54	50
1000	1000	42	42	39
	2000	48	47	45
	3000	50	49	48
	4000	55	50	49

1 foot = .3048 meters

*Total upstream freeway volume/number of lanes

CONCLUSIONS

The objective of this study was to find a reliable procedure for determining when an auxiliary lane is needed on freeway segments with four or more directional lanes. The analysis procedure needed to be able to predict the operations that occurred first on a ramp merge/diverge freeway section (no auxiliary), and then on a weaving section (auxiliary lane). The conventional 1985 Highway Capacity Manual method of analyzing ramp merge/diverge and weaving areas was summarized. Field data, from a ramp merge/diverge and a weaving section, were used in the HCS (HCM software) to demonstrate the weakness of the current procedure. FRESIM, a microscopic model under development by FHWA, was chosen as the analysis procedure in this study because of its vehicle specific, car-following and lane-changing algorithms. The field data for the ramp merge/diverge and weaving sections were simulated using the FRESIM model. The results from the simulations indicate that on a lane by lane examination, speeds and volumes were not identical to the observed values. However, FRESIM did model the operations of the segments reasonably well when averaged across all lanes.

Numerous simulations for the ramp merge/diverge section were then conducted to construct an "operational matrix" of volumes, and ramp separations that would produce acceptable (LOS D) operations for segments with four and five directional lanes. Tables 9 and 10 are the primary results of this study and show that 1000 ft. (305 m) ramp spacings for ramp flows of 600 vph produce acceptable results, but when the ramp flows are increased only slightly to 800 vph, operations become unacceptable. Review of Tables 9 and 10 result in the conclusion that merge/diverge ramp spacings should in general be a minimum 2000 ft (610 m).

FRESIM did not produce results that exactly resembled the lane by lane operations that were observed. However, it does give reasonable overall predictions and is the best tool available for simulating the operations of freeway merge/diverge and weaving area sections.

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