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Development of Improved Guidelines For Frontage Road Driveway Access Location

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16. Abstract

Access on the frontage road in close proximity to exit ramp terminals can amplify the amount and severity of weaving and lead to operational and safety problems on the frontage road. This report summarizes research activities directed at evaluating the operation of frontage roads with unsignalized marginal access located at varying distances from exit ramp terminal points and developing guidelines for appropriate spacing under these conditions.

The basic research approach consisted of: 1) analyzing accident data; 2) making field observations to identify distances required to safely make weaving maneuvers; and 3) developing an analytical model to predict the density of the weaving section on the frontage road as a function of frontage road volume, exit ramp volume, total driveway volume, frontage road configuration, and exit ramp to access spacing. The model was developed from the results of a computer simulation (using CORSIM) that was calibrated using field data from several frontage road sites in Texas. Results of the accident and weaving (field observation) analyses were used to develop recommended "minimum" distances between exit ramp terminal points and the nearest frontage road access, while the analytical model was used to develop "desirable" distances.

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DEVELOPMENT OF IMPROVED GUIDELINES FOR FRONTAGE ROAD DRIVEWAY ACCESS LOCATION

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IMPLEMENTATION STATEMENT

The Texas Department of Transportation (TxDOT) sponsored this research in an effort to improve existing guidelines for spacing between the terminus of an exit ramp and the nearest downstream frontage road access point. The principal objective of this research effort was to collect, analyze, and interpret data to assess the feasibility of alternate methods for accomplishing this task.

Through the course of conducting this research project, several design guidelines were considered and presented to TxDOT staff in various formal and informal meetings. These meetings specifically consisted of a two-way exchange of information, with research staff presenting data and interpretation and TxDOT staff providing valuable input with regard to implementability. The net result of these two-way exchanges of information is a new set of guidelines which should be directly implementable to TxDOT's Operations and Procedures Manual. As such, it is recommended that TxDOT strongly consider immediate implementation of the new guidelines presented herein.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration or the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation, nor is it meant for construction, bidding, or permit purposes. This report was prepared by Marc Jacobson, Lewis Nowlin, and Russell H. Henk (Texas certification number 74460).

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TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

Project 2927 is a three-year study that began on September 1, 1996. The objective of this project is to develop recommended spacings between an exit ramp and a downstream driveway along a frontage road as well as between frontage road driveway access and a downstream entrance ramp. This report summarizes the research procedures and results from the study of exit ramp to downstream frontage road access spacing and presents the research recommendations to date.

Problem Statement

The Texas Department of Transportation Design Division *Operations and Procedures Manual* currently prohibits the location of frontage road access within 15 meters upstream and 75 meters downstream of a freeway exit ramp(1). While these guidelines may be adequate for low-volume conditions, the manual maintains that longer distances between exit ramps and downstream driveways are desirable when high volumes exist on the exit ramp and/or frontage road. Therefore, if the Department is going to successfully establish and maintain safe and efficient operations for freeway ramps and frontage roads in high-volume urban areas, the development of more specific guidelines for driveway access location is critical.

Following this brief introductory section is an overview of the general research approach and some specific procedures utilized in this study. The report presents the findings associated with each major phase of the analysis and concludes with recommendations for new guidelines regarding exit ramp to frontage road access spacing. Guidelines for frontage road access to downstream entrance ramp spacing will be included in the final (i.e., separate) report.

II. RESEARCH APPROACH

The research team's approach to this project can be divided into three major efforts: 1) performing accident analyses at existing frontage road sites; 2) determining required distance to weave (using field data/observations); and 3) simulating the frontage road weaving environment. Using this approach helped the researchers develop guidelines that ensure both safe and efficient traffic operations for the exit ramp/frontage road environment. The findings from each of these efforts are presented in the sections that follow.

Using the results from these studies, researchers developed recommended minimum ramp-to- driveway spacings. They used the results from the accident analyses to account for the safety of the exit ramp-frontage road junction. The results from the field studies ensured that the recommended spacings provided at least the minimum required distance to complete the weaving maneuver. Finally, the desirable ramp-to-driveway spacings were developed based on the results from the computer simulation study so that a desirable level of service in the weaving area could be maintained.

The study work plan involved the following specific seven tasks:

Task 1: Review Literature;
Task 2: Identify Study Site;
Task 3: Analyze Accident Data;
Task 4: Collect Field Data;
Task 5: Perform Computer Simulation;
Task 6: Develop Guidelines; and
Task 7: Prepare Final Report.

Following are discussions of the study results associated with each of these tasks.

III. RESULTS

Literature Review

A literature review revealed that few studies have specifically addressed exit-ramp-to-driveway spacing. From those studies that were reviewed, the following findings were noted:

- The majority of drivers use between 60 and 120 meters to weave from an exit ramp to the right-most lane on a frontage road; however, a few drivers use as much as 150 meters(2).
- The major factors affecting the distance required to complete a two-sided weaving maneuver on a frontage road are frontage road volume and number of frontage road lanes(2).
- A 1980 survey of state and local agencies around the U.S. revealed that existing distances between a ramp terminal and nearest access point ranged between 30 and 460 meters(3).
- A 1976 study reported that general design guidelines for the Interstate Highway System suggest that access control should extend along the crossroad beyond the terminal about 30 meters or more in an urban area and about 90 meters or more in a rural area(4).

Accident Analysis

The accident analysis performed in this current study examined frontage road accident rates in the vicinity of an exit ramp at several sites. The sites that were studied exhibited a variety of exit ramp-to-driveway spacings and driveway densities. Site selection criteria included frontage road volume, exit ramp volume, number of frontage road lanes, level of commercial development, posted speed limit, and ramp-to-driveway spacing. Analyses were performed in an attempt to relate accident rate to each of the above factors, specifically ramp-to-driveway spacing.

Figure 1 shows an example of the phenomenon seen between exit ramps and closely-spaced frontage road access. In this specific example (northbound SH 183 frontage road in Irving, Texas), the number of accidents is two to three times higher within the critical weaving sections following

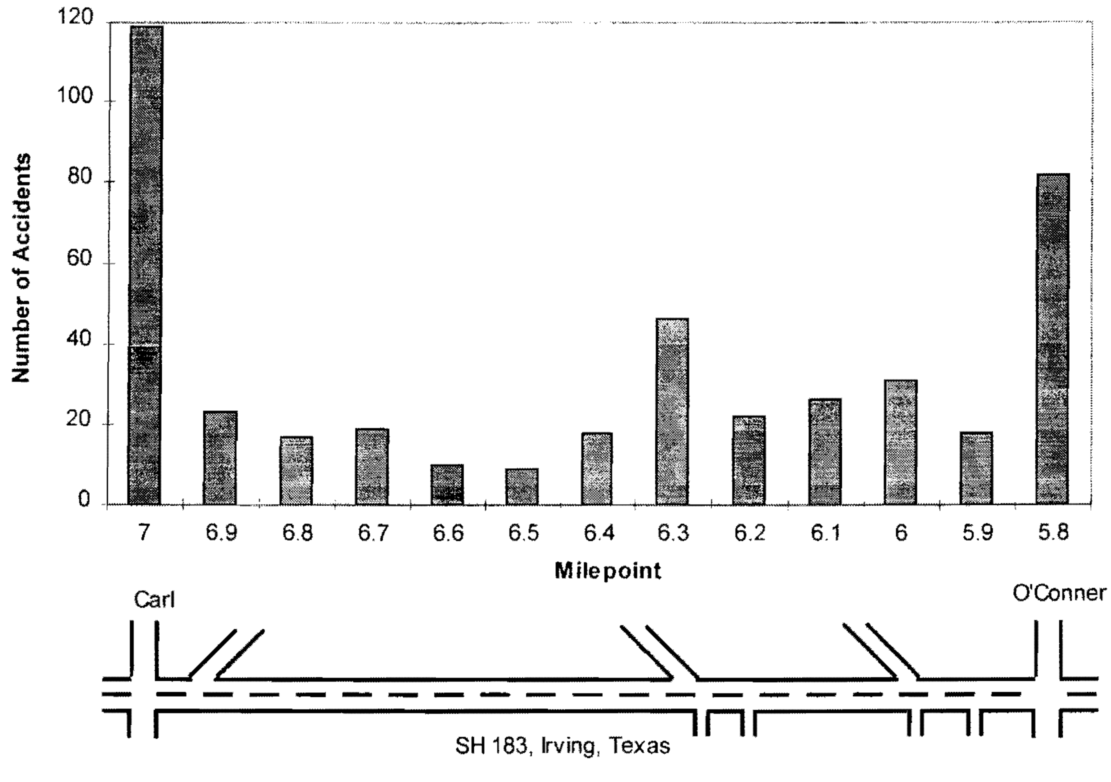

Figure 1. Accident Profile--Northbound SH 183 Frontage Road, Irving, Texas

the exit ramps in comparison to the remainder of the frontage road. Also noted in Figure 1 is a typical accident pattern (i.e., increased accident frequency) at signalized intersections— in this case the intersecting streets of O'Conner and Carl.

The data for the accident analysis were obtained from the Texas Department of Public Safety Accident Data Files. These data cover a six year period from 1990 to 1995 for 32 exit ramp locations located on five freeways. The freeways were spread throughout the Amarillo, Fort Worth, and Dallas districts of the Texas Department of Transportation (TxDOT). Accident data were obtained for a 0.48 kilometer section beginning at the frontage road/exit ramp junction and continuing downstream toward the signalized intersection. Field sketches were used to identify the number and location of driveways, the distance to the downstream signalized intersection, the land use of adjacent properties, and the geometry of the frontage road.

Two groups of accidents were analyzed at each study area. The "Total Accidents" groups represented all accidents on the frontage road and ramp in the desired direction of travel between the exit ramp and the signalized intersection. The second group of accidents was the subset of the total accidents that included only those vehicles that were completing a weaving maneuver at the time of the incident. Those accidents identified as a weaving accident contained one or more of the following characteristics:

- those accidents specifically listed as driveway-related;
- sideswipe accidents involving vehicles moving toward the right lane; and/or
- accidents in which one of the vehicles originated from the exit ramp.

One disadvantage of attempting to identify the weaving accidents in this manner is that the accident must be properly coded by the reporting officer. Those weaving accidents that are misreported would not have the characteristics listed above identified in the report. Thus, it is necessary to look at all of the accidents occurring between the exit ramp and the signalized intersection in order to eliminate bias due to misreporting of incidents.

For each group of accidents, researchers calculated an accident rate for the study section. They determined this rate by dividing the number of accidents by the average frontage road volume over the six year period. The average frontage road volume was assumed to be 15 percent of the annual average daily traffic (AADT) for the entire freeway in the vicinity of the exit ramp. This assumption was based upon sampling done from field data in Houston and San Antonio. The accident rate for each section was reported as the number of accidents per million vehicles. The rates that were found for each of the site based on the exit ramp to driveway distance are shown in Figures 2 and 3.

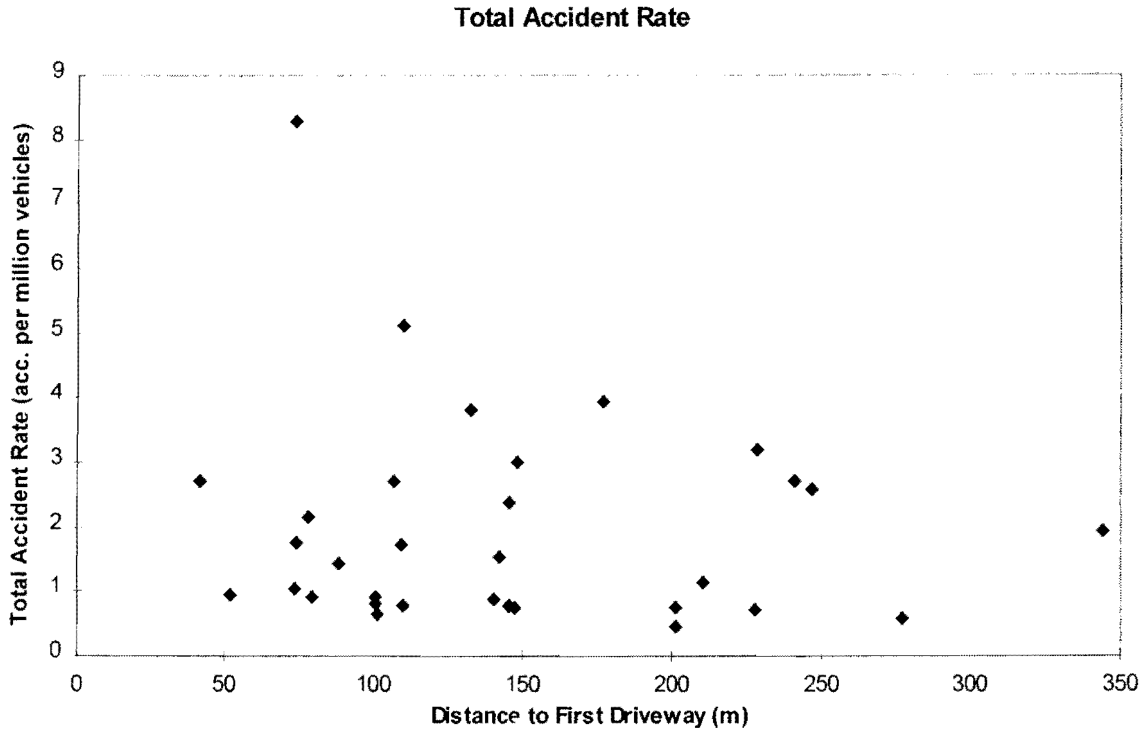

Figure 2. The Total Accident Rate at the Study Sites.

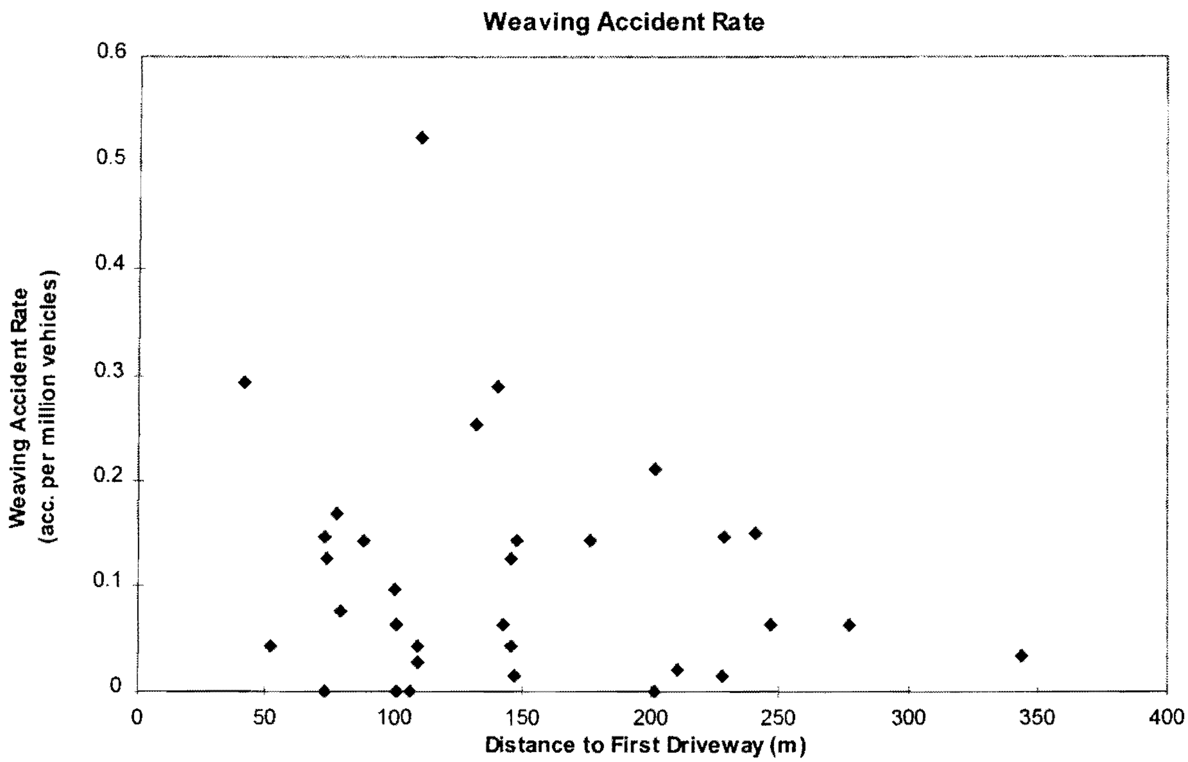

Figure 3. The Weaving Accident Rate at the Study Sites.

One goal of the accident analyses was to identify a critical ramp-to-driveway spacing for which spacings below the critical value would result in a significant increase in accident potential. The critical spacing value would then be used to identify a recommended absolute minimum ramp-to-driveway spacing. As the figures indicate, there appears to be a general trend of decreasing accident rate as the exit ramp to driveway spacing increases. The maximum accident rates were found to occur at approximately 100 meters and shorter. This would indicate the critical ramp-to-driveway spacing should be larger than the 75 meter minimum spacing that is currently allowed.

Field Studies

Data were collected in the field for the following two purposes: 1) to determine the distance that drivers used to weave between an exit ramp and a driveway along a frontage road; and 2) to calibrate/evaluate the computer simulation program. Later sections of this report discuss the efforts related to computer simulation.

Data Collection

The typical study site included a frontage road section with an exit ramp followed by a driveway. Sites from various large urban areas in Texas were included in the study. Sites were selected based upon the following criteria:

- Type and level of commercial development;
- Exit ramp-to-signalized intersection spacing;
- Traffic volumes;
- Traffic speed; and
- Number of frontage road lanes.

Table 1 lists the ten data sites. To collect field data, researchers used video cameras to count traffic volumes and to monitor traffic operations between and around the exit ramp and downstream driveway. Speeds were collected using traffic detectors (Numetric Hi-Star). A typical field setup is shown in Figure 4.

Table 1. Description of Field Sites

Site	City	Highway	Location	Distance to Driveway (m)	Frontage Road Configuration [1]
1	San Antonio	US 281 NB	Henderson Pass	134	2-Lane w/ Aux
2		IH 410 SB	Exchange Pkwy	88	2-Lane w/ Aux
3		IH 410 WB	Summit Pkwy	232	2-Lane w/ Aux
4		IH 35 NB	Walzem Road	75	2-Lane w/ Aux
5	Austin	IH 35 NB	St. Johns Blvd	156	2-Lane w/ Aux
6		IH 35 SB	26th St. / Manor Rd	50	2-Lane w/ Aux
7		US 183 SB	Balcones / Duvall	38	2-Lane w/ Aux
8	Irving	SH 183 WB	Story Rd.	105	2-Lane
9	Houston	US 59 SB	Beechnut St.	163	2-Lane
10		IH 10 EB	Garth Road	150	3-Lane

[1] Sites with an auxiliary lane (Aux) provide an exclusive lane for exiting vehicles that begins at the frontage road gore. Sites without an auxiliary lane force exiting drivers to immediately merge with the frontage road traffic.

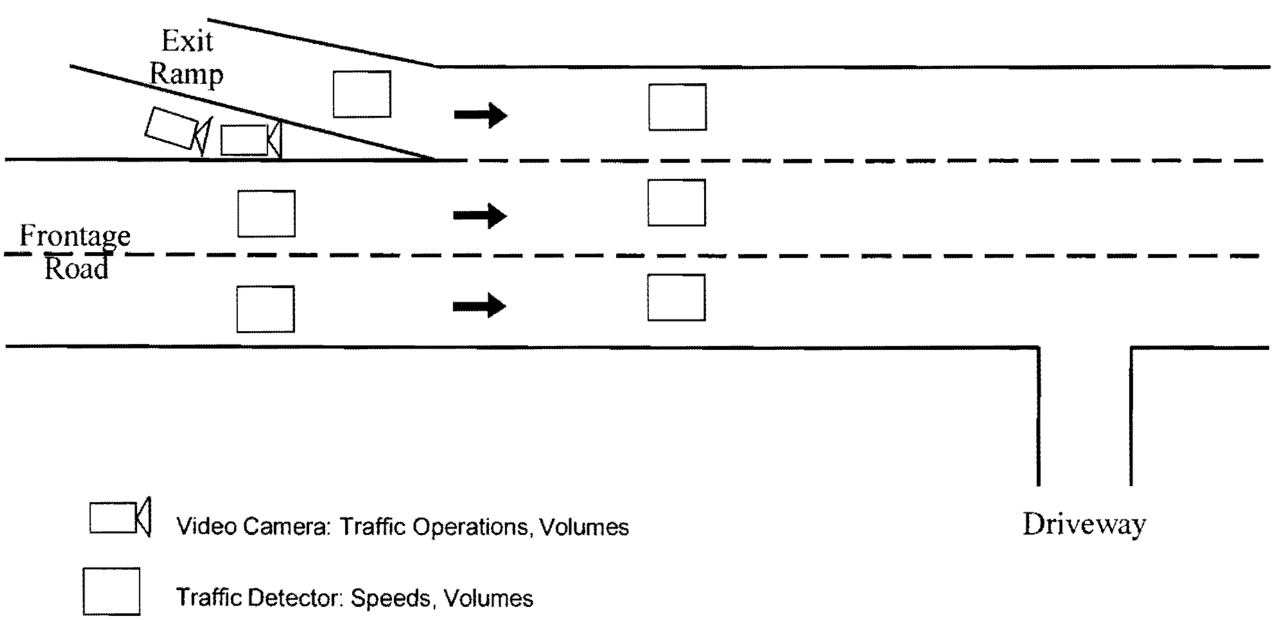

Figure 4. Typical Field Data Collection Setup

Data Reduction

To determine the distance that drivers use to weave from an exit ramp to a downstream driveway, data from three field sites were reduced (Sites 1, 8, and 10 in Table 1). The total distance to weave included the distance required to make each lane change and the distance required to decelerate before turning (see Figure 5).

While reducing the data, technicians tracked each vehicle (including both turning and non-turning) that made a weaving maneuver from the exit ramp to the right-most lane. Three hours of data were reduced from each of the three field sites. While tracking each vehicle, the following information was recorded:

- Time that vehicle reached the physical exit ramp gore;
- Time and distance to complete the first lane change (LC1);
- Time and distance to complete each additional lane change (LC2);
- Time that vehicle turned into the nearest driveway (for those vehicles turning); and
- Traffic conditions on frontage road (i.e., constrained or unconstrained).

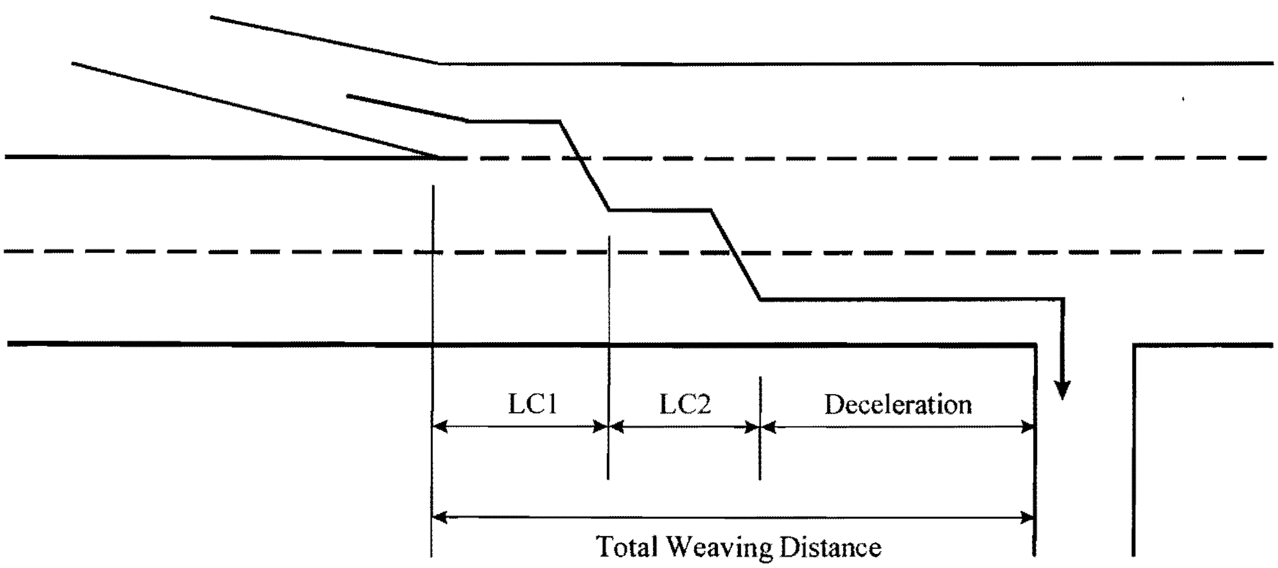

Figure 5. Distance to Weave

Data Analysis

As shown in Figure 5, the total distance to weave consists of distances required for each lane change (LC1 and LC2) and the distance required to decelerate before making the turning maneuver. The analyses described in the following sections were conducted to determine these distances.

Distance for Lane Changes

From the three field sites studied, a total of 1,066 weaving vehicles were tracked. After data reduction, the first step was to separate weaving distance data by traffic conditions (constrained and unconstrained) and by whether the weaving vehicle turned into the driveway or not. This effort resulted in the four data sets shown in Table 2.

Table 2. Data Sets for Weaving Distance Data

Data Set	Turning Maneuver	Traffic Conditions	Number of Data Points
1	Turn	Constrained	45
2	Turn	Unconstrained	291
3	No Turn	Constrained	148
4	No Turn	Unconstrained	582

The data were further broken down by lane change (i.e., time and distance to complete the first lane change (LC1); time and distance to complete each additional lane change (LC2)). The minimum, maximum, and average weaving distances for each of the scenarios are shown in Table 3.

Table 3. Results from Field Observations

Lane Change	Turning Maneuver	Traffic Conditions	Weaving Distance (m)		
			Min.	Max.	Avg.
LC1	Turn	Constrained	24	137	55
		Unconstrained	14	122	***52***
	No Turn	Constrained	27	178	91
		Unconstrained	18	110	74
LC2	Turn	Constrained	14	192	44
		Unconstrained	9	110	***38***
	No Turn	Constrained	20	274	73
		Unconstrained	9	261	62

Observing the average values in Table 3, it is seen that the constrained turning maneuvers required longer distances than the unconstrained maneuvers. In addition, vehicles not turning took longer distances than those turning.

Because the goal of the field study was to determine the minimum distances that drivers from the exit ramp needed to weave to the right-most lane of the frontage road, the distances required for unconstrained turn maneuvers were used (shown in italics and bold in Table 3). After discussions with the study panel, the decision was made to use the 50^{th} percentile lane changing distances to represent field conditions. The resulting distances represent the minimum distance required by half the drivers to complete a lane change. Therefore, rounding to the nearest value of ten, the following values were selected as the minimum distances required to make a lane change maneuver:

LC1 = 60 meters

LC2 = 30 meters

Distance for Deceleration

The distance required to decelerate from operating speed to make a turning maneuver was determined using the American Association of State Highway and Transportation Officials (AASHTO) equation for stopping distance(5). This equation is described as follows:

$$D = \frac{V_0^2 - V_f^2}{254\,f} \qquad \text{Equation 1}$$

where: D = deceleration distance, m;

V_0 = initial speed, km/h;

V_f = final speed, km/h;

f = coefficient of friction.

Figure 6 illustrates the distance required to decelerate. Calculations assumed a final speed (V_f), or turning speed of 25 km/h. The initial speed (V_0) was then estimated using the assumed final speed, distance from the driveway at the last lane change, d (obtained from field data), and travel time from last lane change to driveway, t (obtained from field data). Researchers estimated the initial speed of each turning vehicle using the kinematic equations. Once the initial speeds of all turning vehicles were known, the average speed was calculated to be approximately 48 km/h. Once again, calculations used the 50^{th} percentile initial speeds of 65 km/h.

Assuming a coefficient of friction (f) of 0.3, the initial speed (65 km/h) and the assumed final speed (25 km/h) were entered into Equation 1 to calculate a deceleration distance of 22 m. This value was rounded to the nearest value of 10 for a recommended deceleration distance of 20 m. When combined with the lane changing distances presented earlier, the minimum weaving distances based on the field data are those presented in Table 4.

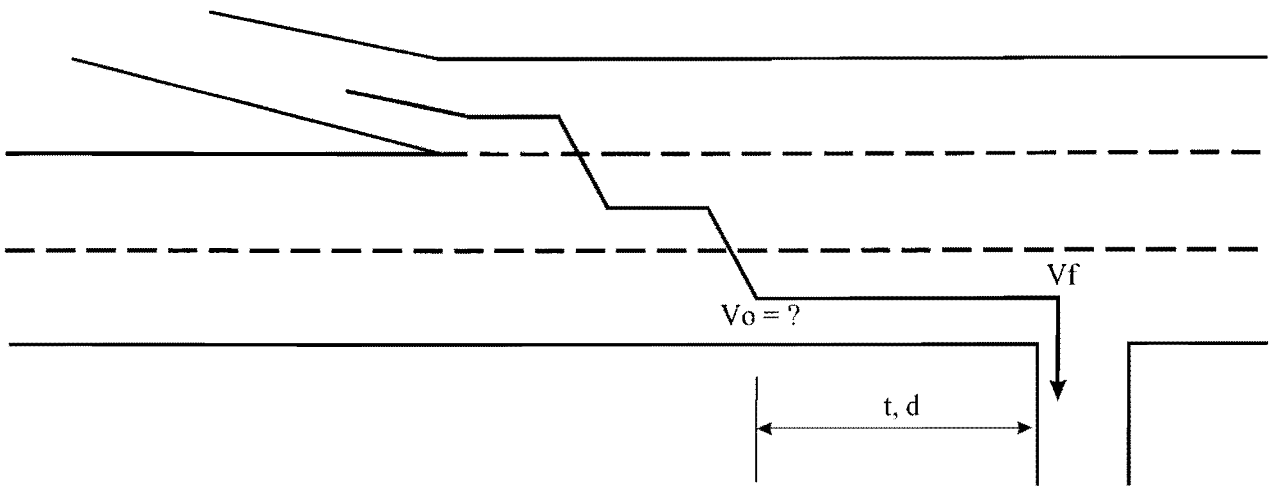

Figure 6. Deceleration Distance

Table 4. Minimum Required Distances to Weave from Exit Ramp to First Driveway

Number of Lanes in Weaving Section (No. of Lane Changes)	Minimum Weaving Distance (m) [1]
2[1]	80
3[1]	110
4[1]	140

[1] Based on 50^{th} percentile weaving and decelerating distances from field observation.

Additional detailed data regarding exit ramp to frontage road access weaving operations were gathered at the northbound frontage road of IH 35 in San Antonio downstream of the Walzem Road exit ramp as well as the southbound frontage road of IH 410 in San Antonio downstream of the Ingram Road exit ramp (Figures 7 and 8). As can be noted in Figure 7, approximately 173 vehicles exited northbound I-35 to Walzem Road and utilized the first frontage road access point available. This maneuver (if performed legally) took place over a distance of approximately 75 meters — which coincides with existing TxDOT spacing guidelines. It should, however, be further noted that approximately 35 percent of the exiting traffic performing this maneuver (62 out of 173) was observed crossing the painted gore area of the ramp in order to have greater distance within which to make the maneuver; thus, suggesting that the existing 75 meters is inadequate.

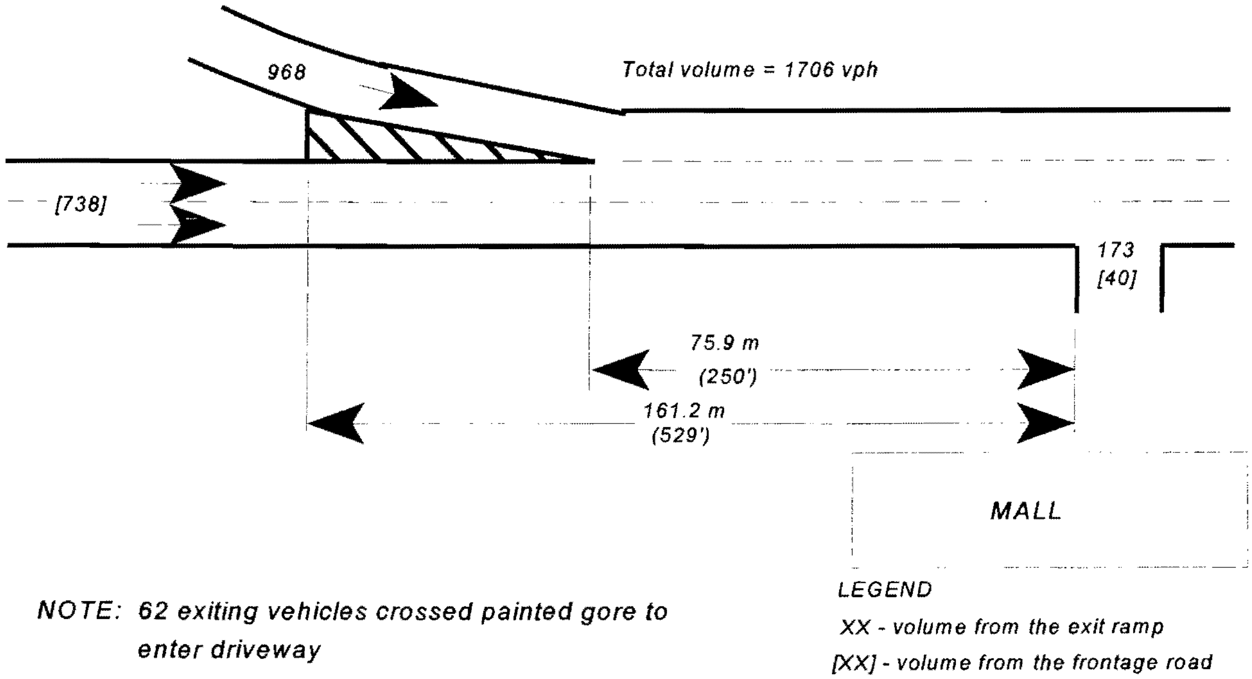

Figure 7. Ramp-to-Access Weaving Operations--Walzem Road, San Antonio, Texas

A different scenario depicting a similar conclusion is illustrated in Figure 8. At this location, a driveway is available approximately 77 meters downstream of the exit ramp, and a second driveway is available approximately 180 meters downstream of the ramp. It should further be noted that both driveways can be used to access all of the land use adjacent to the frontage depicted in Figure 8. Given these conditions, 85 percent of the exiting traffic trying to access this location (168 out of 197) used the second access point. In short, given a greater distance to weave, the vast majority (85 percent) choose the safer option. The data illustrated in Figures 7 and 8 further support the need for increased spacing.

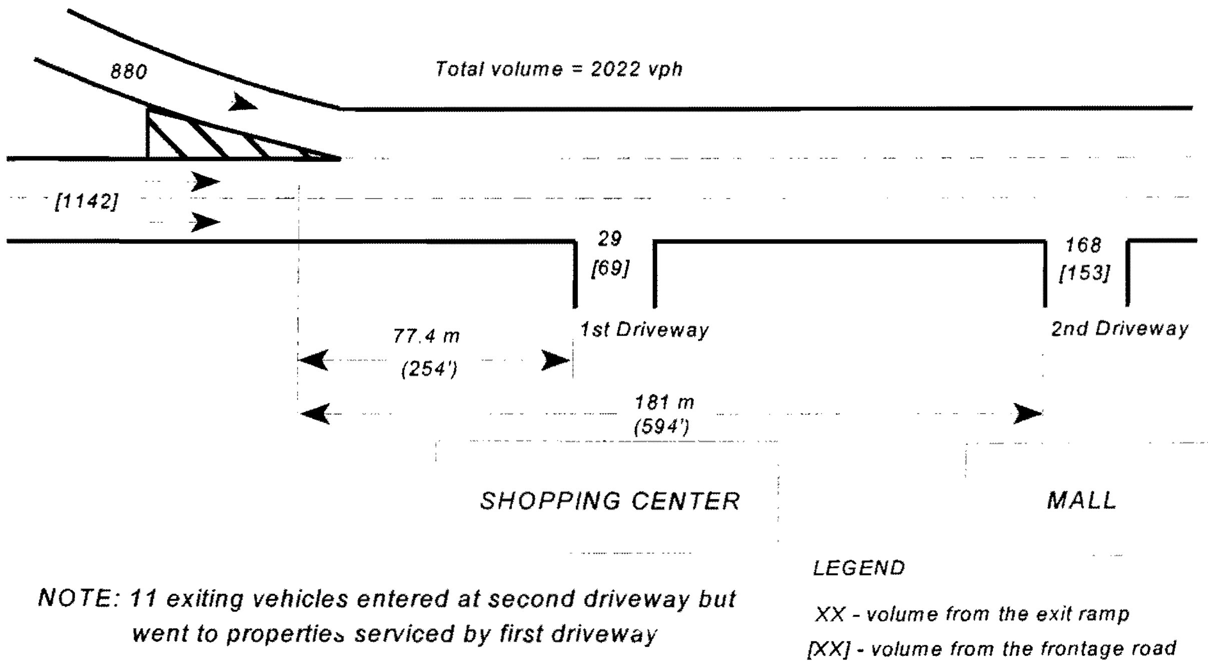

Figure 8. Ramp-to-Access Weaving Operations--Ingram Road, San Antonio, Texas

Computer Simulation

For the final phase of the analysis, traffic operations at existing frontage road sites were analyzed and supplemented with computer simulation. Existing field sites were video taped to monitor traffic operations and driver behavior under various conditions as discussed in the previous section. In addition to determining the weaving distance required by drivers, the field data were used to calibrate/evaluate the computer simulation model under various traffic and roadway conditions.

Since it is difficult and costly to collect a wide range of study variables (e.g., ramp-to-driveway spacings, traffic volumes, etc.) in the field, computer simulation was utilized. A computer simulation model was used to study frontage road operations between an exit ramp and driveway under various conditions. The goal of the computer simulation study was to develop recommended desirable ramp-to-driveway spacings to maintain a desirable level of service within the frontage road weaving area.

One of the most flexible microscopic traffic simulation tools available is the CORSIM package developed for the Federal Highway Administration. This microscopic model combines the previous NETSIM traffic network simulator with the new FREESIM freeway simulator. For this study, only the NETSIM portion of the simulation was used, since the environment being modeled was better represented as an arterial network rather than a freeway system.

Data collected in the field at several sites were coded into the computer for the purpose of calibrating the computer simulation. Calibration of the computer simulation was needed to ensure that results from the simulation closely matched what was occurring in the field. The calibration was accomplished by comparing the results produced by the simulation to equivalent measures that were obtained in the field. The measure that was chosen to calibrate the model for this study was the speed of the vehicles in the weaving section on the frontage. This speed was measured by the traffic detectors during data collection and could easily be compared to simulation outputs(6).

Once the model was successfully calibrated and the simulation results were as close as possible to the equivalent field measures, the simulation was then used to analyze frontage road sites with different characteristics than the field sites. The idea behind model calibration is that if the simulation can accurately reproduce the conditions measured in the field, it is more likely to accurately represent other similar scenarios that can not easily be obtained from the field.

Following calibration, those variables that were believed to have an effect on frontage road operations and could be measured in the field were selected for simulation. The selected variables and their ranges are illustrated in Figure 9. These ranges encompass the values measured in the field and used to calibrate the simulation. In some cases, these ranges were extended beyond the field data to examine additional frontage road configurations that may be encountered.

Each variable combination was examined for five geometric configurations. These frontage road configurations included one-lane with auxiliary lane, two-lane with and without an auxiliary lane, and three-lane with and without an auxiliary lane. Using the Highway Capacity Manual definitions, all but the one-lane with auxiliary one and two-lane without auxiliary lane case can be classified as a Type C weaving section since two lane changes are required for exiting vehicles to reach the driveway or street. The remaining configuration's auxiliary lane would be classified as a Type B weaving section as only one lane change is required(7). All of the possible variable and geometric combinations resulted in a total of 1,500 simulation runs.

Based on the computer simulation results, linear regression models were developed for each of five configurations that were considered in this study. Density of the weaving link was used as the measure of effectiveness for frontage road operations after examination revealed that weaving speed, which is currently used for freeway weaving, was not a good measure for the frontage road environment. The model parameters included total volume in the weaving section (frontage road volume + exit ramp volume), total volume entering driveway, and the distance between the exit ramp and the first access (see Figure 9). By solving the regression equations for the exit-ramp to driveway spacing, the minimum spacing required to maintain a particular level of density at a given volume level can be calculated(6).

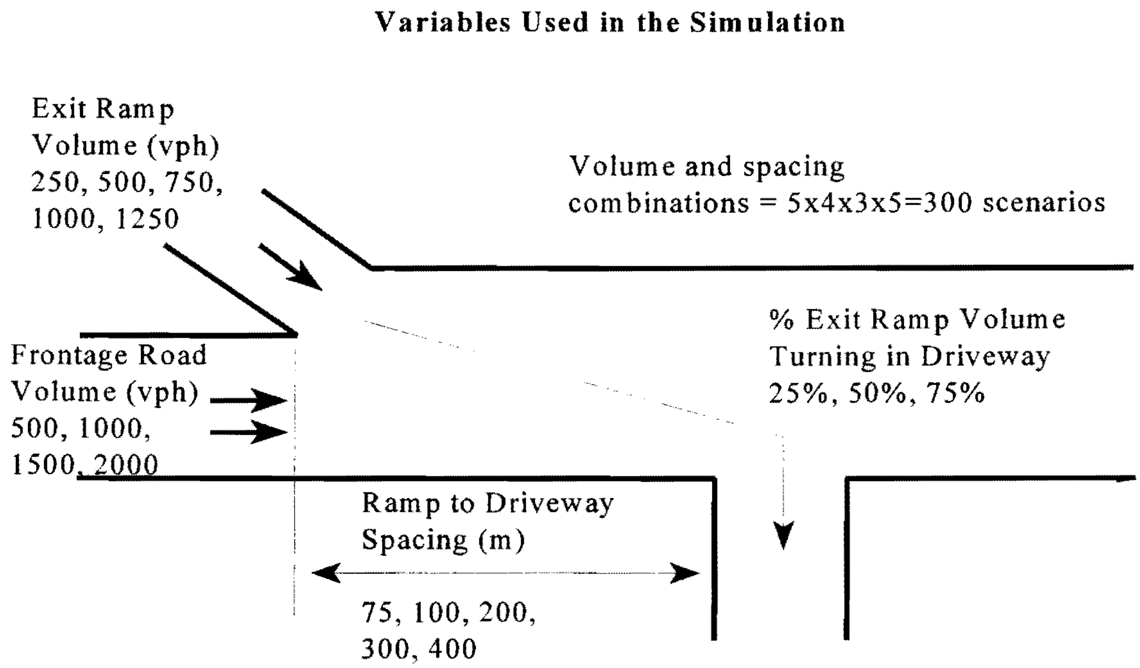

Figure 9. The Variables That Were Simulated in CORSIM.

The results associated with the CORSIM modelling were also used to identify volume thresholds which would help define conditions for which more stringent spacing guidelines (between exit ramps and frontage road access) should be implemented. The plot shown in Figure 10 illustrates the typical trends associated with the CORSIM modelling process. Once total volume in the weaving section (i.e., exit ramp volume plus upstream frontage road volume) reached a level of approximately 2,000 vehicles, operations would typically deteriorate. As is noted later in the text, this threshold is utilized to distinguish when recommended desirable spacings should be implemented.

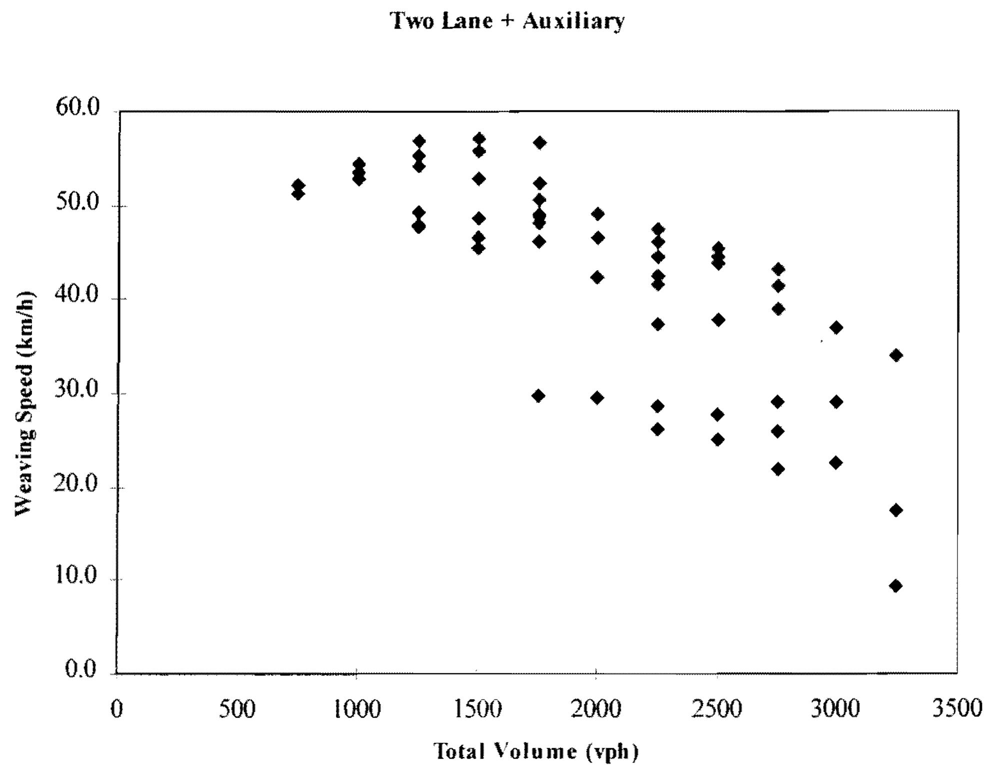

Figure 10. Results of CORSIM Modelling Applications

The SAS statistical analysis package was used to analyze the significance of each variable in predicting density and to develop linear regression equations to act as the mathematical model. Linear regression suits this application because all of the relationships appear to be linearly related with density over the range of simulated conditions. Due to poor correlations that resulted when one equation was used for all geometric configuration, separate linear models were developed for each geometric configuration. Thus, a total of five models were developed: one-lane with auxiliary lane, two-lane, two-lane with auxiliary lane, three-lane, and three-lane with auxiliary lane.

The regression coefficients for each configuration vary slightly. The resulting equations and the R^2 values are listed in Table 5. By solving the regression equations for the exit-ramp to driveway spacing, the minimum spacing required to maintain a particular level of density at a given volume level can be calculated.

Table 5. Regression Equations to Predict Frontage Road Density

GENERAL FORM: Density = a + b (V_{TOT}) + c (V_{TD}) - d (L)				
	Constants			
Configuration	a	b	c	d
One Lane with Auxiliary Lane (R^2 = 0.58)	-6.174	0.0286	0.0066	0.0217
Two Lanes (R^2 = 0.86)	-1.603	0.0239	0.0078	0.0269
Two Lanes with Auxiliary Lane (R^2 = 0.80)	0.1013	0.0148	0.0041	0.0178
Three Lanes (R^2 = 0.89)	-0.2119	0.0128	0.0033	0.0108
Three Lanes with Auxiliary Lane (R^2 = 0.81)	0.0593	0.0094	0.0035	0.0099

Density = predicted density of the weaving link (veh/km/ln),
V_{TOT} = total weaving section volume (exit ramp + frontage road) (vph),
V_{TD} = total driveway volume (vph),
L = exit ramp to driveway or street spacing (m), and
a, b, c, d = regression coefficients

Development of Level-of-Service Criteria

By observing vehicle behavior in the field and examining breakpoints in the computer simulation data, three levels of service were established for frontage road operation: LOS A-B, LOS C-D, and LOS E-F. The criteria for accessing the frontage road level of service are not intended to represent exact divisions in operations. Rather, the level of service criteria developed in this research can be used to compare frontage road operations after improvements are made at a site, or between two sites.

The LOS A-B designation represents the desired situation in which vehicles on the frontage road are not affected by vehicles weaving to the unsignalized access point. Vehicles can travel or accelerate at their desired rate and have the option to pass a slower moving vehicle by utilizing another lane in the weaving section. Observations indicated that this type of operation occurs when the density on the frontage road is below 25 veh/km/ln.

As the density in the weaving section increases, constrained operations result. This level of service is designated LOS C-D and indicated by more severe impacts from those vehicles attempting to weave to the driveway or street. The presence of a weaving vehicle forces some frontage road vehicles to slow or stop as the weaving vehicle completes the maneuver to the driveway. Examination of the operating characteristics in the field indicated that the impacts under LOS C-D are usually limited to one lane of the frontage road and exist up to a density of 40 veh/km/ln. (i.e., 25-40 veh/km/ln)

The final level of service is defined as LOS E-F. Once the density increases beyond 40 veh/km/ln, multiple lanes of the frontage road are impacted by the presence of vehicles weaving to the first unsignalized access point. The frontage road vehicles are forced to slow or stop and are unable to change lanes to avoid the slower weaving vehicle. Drivers are often forced to apply their brakes to avoid a collision(6)

IV. RECOMMENDATIONS

Using the results of this three-tiered approach, recommended guidelines for access spacing on non-freeway weaving sections were developed. The guidelines have been broken down into two components: minimum weaving distance and desirable weaving distance. Each component is discussed in the following sections.

Minimum Weaving Distance

The minimum weaving distance guidelines are based on the results of the safety and weaving distance studies. To provide an easy-to-use guideline with a wide range of applicability, a four lane weaving configuration was assumed in the development of the recommended minimum weaving distances. The four lane configuration represents the largest configuration usually encountered on a frontage road. The four lanes would require a driver to make an initial lane change (LC1) followed by two subsequent lane changes (LC2). Also, the driver must be able to safely decelerate to turn into the driveway. These components result in a minimum distance to weave of 140 meters. Since this distance is greater than the safety threshold of 100 meters that was identified in the accident analysis, it was selected as the recommended minimum ramp-to-access spacing. The recommended guideline is shown graphically in Figure 11.

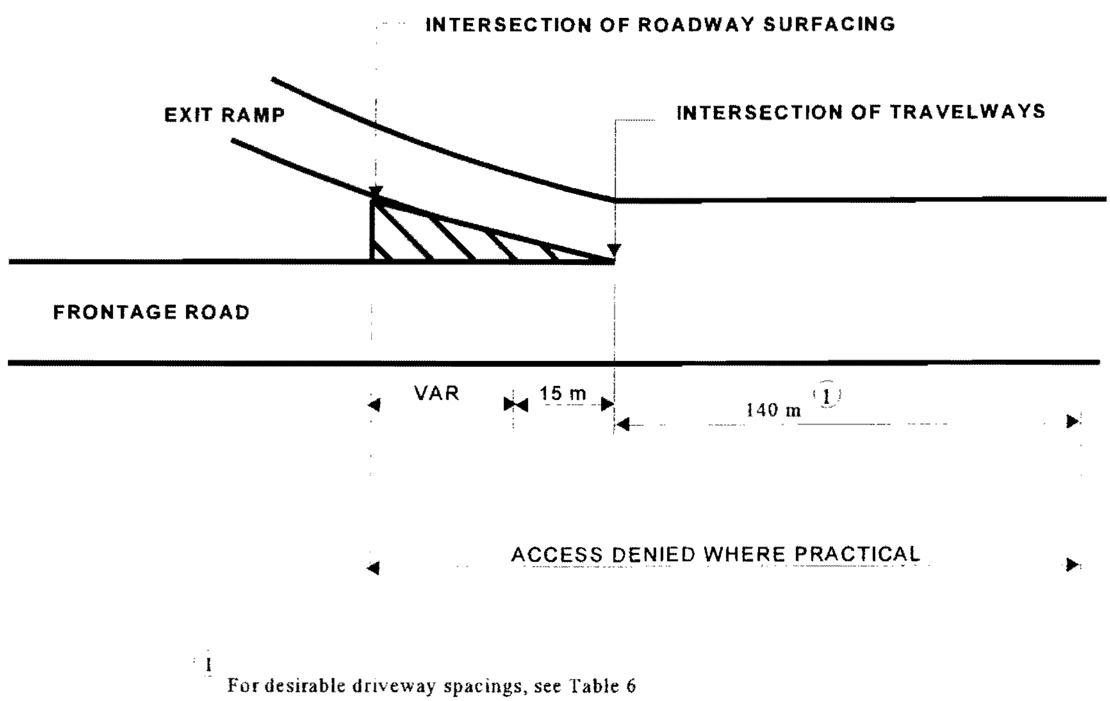

Figure 11. The Recommended Minimum Spacing Guidelines.

Desirable Weaving Distance

While the minimum spacing guidelines satisfy the driver's minimum needs and safety concerns, they do not consider the level of operation of the frontage road. In order to consider the frontage road level-of-service, the total frontage road volume as well as the driveway volume must be measured or forecasted. With this information, the desirable weaving distance can be identified from Table 6. These values are based on a combination of the distance to weave requirements and the density equations formulated from the computer simulation. A practical maximum of 300 meters was placed on all configurations (see Table 6).

The unadjusted results of applying the regression equations (i.e., no maximum of 300 meters applied) are summarized in Appendix A. These results are accompanied by a more thorough explanation of equation development and research methodologies.

Table 6. Recommended Desirable Spacing Guidelines

Total Volume (vph)	Driveway Volume (vph)	Spacing (m) Number of Weaving Lanes		
		2	3	4
< 2000	All	75 [1]	75 [1]	75 [1]
> 2000	< 250	140	140	170
	>250	160	140	170
	> 500	180	140	170
	> 750	240	140	170
	> 1000	300	140	170
> 2500	< 250	280	140	170
	> 250	290	140	170
	> 500	300	140	170
	> 750	300	180	210
	> 1000	300	240	270
> 3000	< 250	300	230	260
	>250	300	250	280
	> 500	300	300	300
	> 750	300	300	300
	> 1000	300	300	300

[1] Absolute minimum under all conditions.

To compute the values for the two lane weaving sections, a maximum density of 25 veh/km/ln was used to determine the required spacing. The three and four lane weaving section values were based on the model results for a maximum density of 35 veh/km/ln plus an additional 30 meters for each weaving lane greater than 2. This formula accounts for the fact that higher densities can be tolerated in sections with more than two lanes; however, additional lanes also require a longer distance to complete the lane change maneuver. In all cases, if the value produced by the above methodology was less than the 140 meters minimum spacing, the desirable spacing was set at the minimum. Thus, three and four lane sections can handle higher volumes before additional spacing beyond the minimum is required.

Field data, as well as results of the CORSIM modelling, indicate that the recommended desirable spacings become critical when the total weaving section volume (i.e., exit ramp plus upstream frontage road) reaches 2,000 vehicles. Since this total volume (of 2,000 vehicles) is commonplace in many urban areas, it is recommended that the desirable spacings be implemented in urbanized areas whenever possible to account for future traffic growth and sustain safe and efficient operations.

REFERENCES

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4. Copas, T.L., and H.A. Pennock. Design and Control of Freeway Off Ramp Terminals. Transportation Research Board. NCHRP Synthesis of Highway Practice 35. 1976.
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7. Highway Capacity Manual. Special Report No. 209, Transportation Research Board, National Research Council, Washington, D.C. 1994.

APPENDIX A

Unadjusted Recommended Driveway Spacings

The material included in this appendix serves to summarize the results associated with the direct application of the regression equations developed in this research. As cited within the body of the report, the recommended distances for exit ramp terminus to driveway spacing on frontage roads was capped at a maximum of 300 meters (approximately 1,000 feet). This measure was taken to place a realistic limit on recommended spacing in light of anticipated cooperation from land developers (i.e., getting a landowner/developer to agree to more than 1,000 feet would be unlikely).

For the purpose of conveying (in further detail) the complete output from this research, this appendix has been included to provide the "unadjusted" recommended spacings and associated explanation. The research approach consisted of developing 50th percentile and 85th percentile recommended spacing scenarios. The results of these approaches are summarized in Tables A-1 through A-6. The 50th percentile, scenario (results outlined in Tables A-1 through A-3) consisted of applying the predictive regression equations developed via the 1,500 CORSIM simulation runs and/or utilizing the weaving distance required to allow 50 percent of the vehicles to make additional lane changes beyond two (2) lanes (whichever was greater).

For example, referring to Table A-1 under a condition of 2,600 total vehicles, 510 vehicles accessing the driveway, a desired maximum density of 25 vehicles per kilometer per lane (veh/km/lane), and a two-lane (no auxiliary) frontage road cross-section, the recommended spacing would be 350 meters (1,155 feet). If the frontage road cross-section were three lanes (no-auxiliary) under these same travel demands, the recommended spacing would be 140 meters. This significantly lower recommended spacing is due to the 2,600 total vehicles being spread out over three lanes (as opposed to two-lanes) and the associated provisions of longer (and more frequent) gaps to facilitate weaving.

Within each "percentile" scenario, three different levels of vehicle density were examined. Field observations made during the data collection phase of the study revealed three fairly distinct break-points which could be characterized as general levels-of-service (LOS). Free-flow operations began to cease in the area of 25 veh/km/lane. This level was, therefore, considered to be compatible with

LOS C. At 30 veh/km/lane, operations were notably worse and were likened to LOS D. At 35 veh/km/lane and above, LOS E-F type conditions were observed.

These varying levels of density (and approximate levels-of-service) serve as potential LOS targets for prospective users of these guidelines. For instance, if a user wanted to ensure LOS C or better operations and design for the 85^{th} percentile level, Table A-4 would be the appropriate application. If, however, LOS D operations and design for the 50^{th} percentile were acceptable, Table A-2 would be used.

Another difference which is worth noting is the difference in recommended spacing one will find when comparing the tables in this appendix to Table 6 (page 27). The tables in this appendix reflect the direct output from the regression equations developed for each cross-section condition (i.e., two lanes with no auxiliary, two lanes with one auxiliary lane, etc.). The values shown in Table 6 (while capped at a maximum of 300 meters) reflect an additional adjustment in that the values entail the application of the regression equation for the "2-lane without auxiliary" scenario plus the additional distance required to safely weave across any additional lanes (greater than two). The values shown in this appendix do not include the additional required weaving distance.

As mentioned previously, the data included in this appendix is provided to expand upon details and issues addressed in this research effort. Based upon several meetings involving key TxDOT District, Design Division and FHWA staff, the recommended spacings outlined in Table 6 (page 27) are suggested for practical, everyday applications.

Table A-1. Recommended Spacing (50th %-ile — 25 veh/km/ln)
Minimum Spacing: 50th %-ile Weave Dist
Desirable Spacing: Opt Den = 25 veh/km/ln

Total Volume (vph)	Driveway Volume (vph)	Spacing (m)			
		2 Through Lanes		3 Through Lanes	
		No Auxiliary	Auxiliary	No Auxiliary	Auxiliary
< 2000	All	110	140	140	170
> 2000	< 250	110	140	140	170
	>250	120	140	140	170
	> 500	180	140	140	170
	> 750	240	140	140	170
	> 1000	300	140	140	170
> 2500	< 250	280	140	140	170
	> 250	290	140	140	170
	> 500	350	140	140	170
	> 750	400	140	140	170
	> 1000	460	140	140	170
> 3000	< 250	380	140	140	170
	>250	440	140	140	170
	> 500	500	150	140	170
	> 750	560	190	140	170
	> 1000	600	230	140	170
>3500	< 250	450	275	140	170
	>250	500	290	140	170
	> 500	550	320	180	170
	> 750	600	370	220	170
	> 1000	650	400	270	170

Table A-2. Recommended Spacing (50th %-ile — 30 veh/km/ln)
Minimum Spacing: 50th %-ile Weave Dist
Desirable Spacing: Opt Den = 30 veh/km/ln

Total Volume (vph)	Driveway Volume (vph)	Spacing (m)			
		2 Through Lanes		3 Through Lanes	
		No Auxiliary	Auxiliary	No Auxiliary	Auxiliary
< 2000	All	110	140	140	170
> 2000	< 250	110	140	140	170
	>250	110	140	140	170
	> 500	110	140	140	170
	> 750	110	140	140	170
	> 1000	170	140	140	170
> 2500	< 250	150	140	140	170
	> 250	160	140	140	170
	> 500	220	140	140	170
	> 750	280	140	140	170
	> 1000	330	140	140	170
> 3000	< 250	190	140	140	170
	>250	220	140	140	170
	> 500	270	140	140	170
	> 750	320	140	140	170
	> 1000	380	140	140	170
>3500	< 250	230	140	140	170
	>250	260	140	140	170
	> 500	310	140	140	170
	> 750	370	150	140	170
	> 1000	440	200	140	170

Table A-3. Recommended Spacing (50^{th} %-ile — 35 veh/km/ln)
Minimum Spacing: 50^{th} %-ile Weave Dist
Desirable Spacing: Opt Den = 35 veh/km/ln

Total Volume (vph)	Driveway Volume (vph)	Spacing (m)			
		2 Through Lanes		3 Through Lanes	
		No Auxiliary	Auxiliary	No Auxiliary	Auxiliary
< 2000	All	110	140	140	170
> 2000	< 250	110	140	140	170
	>250	110	140	140	170
	> 500	110	140	140	170
	> 750	110	140	140	170
	> 1000	110	140	140	170
> 2500	< 250	110	140	140	170
	> 250	110	140	140	170
	> 500	110	140	140	170
	> 750	150	140	140	170
	> 1000	200	140	140	170
> 3000	< 250	120	140	140	170
	>250	130	140	140	170
	> 500	170	140	140	170
	> 750	200	140	140	170
	> 1000	240	140	140	170
>3500	< 250	140	140	140	170
	>250	150	140	140	170
	> 500	200	140	140	170
	> 750	240	140	140	170
	> 1000	300	140	140	170

Table A-4. Recommended Spacing (85th %-ile — 25 veh/km/ln)
Minimum Spacing: 85th %-ile Weave Dist
Desirable Spacing: Opt Den = 25 veh/km/ln

Total Volume (vph)	Driveway Volume (vph)	Spacing (m)			
		2 Through Lanes		3 Through Lanes	
		No Auxiliary	Auxiliary	No Auxiliary	Auxiliary
< 2000	All	120	170	170	215
> 2000	< 250	120	170	170	215
	>250	120	170	170	215
	> 500	180	170	170	215
	> 750	240	170	170	215
	> 1000	300	170	170	215
> 2500	< 250	280	170	170	215
	> 250	290	170	170	215
	> 500	350	170	170	215
	> 750	400	170	170	215
	> 1000	460	170	170	215
> 3000	< 250	380	170	170	215
	>250	450	170	170	215
	> 500	510	170	170	215
	> 750	580	190	170	215
	> 1000	620	230	170	215
>3500	< 250	450	275	170	215
	>250	500	290	170	215
	> 500	560	320	180	215
	> 750	620	370	220	215
	> 1000	670	400	270	215

Table A-5. Recommended Spacing (85^{th} %-ile — 30 veh/km/ln)
Minimum Spacing: 85^{th} %-ile Weave Dist
Desirable Spacing: Opt Den = 30 veh/km/ln

Total Volume (vph)	Driveway Volume (vph)	Spacing (m)			
		2 Through Lanes		3 Through Lanes	
		No Auxiliary	Auxiliary	No Auxiliary	Auxiliary
< 2000	All	120	170	170	215
> 2000	< 250	120	170	170	215
	>250	120	170	170	215
	> 500	120	170	170	215
	> 750	120	170	170	215
	> 1000	170	170	170	215
> 2500	< 250	150	170	170	215
	> 250	160	170	170	215
	> 500	220	170	170	215
	> 750	280	170	170	215
	> 1000	330	170	170	215
> 3000	< 250	190	170	170	215
	>250	220	170	170	215
	> 500	280	170	170	215
	> 750	330	170	170	215
	> 1000	400	170	170	215
>3500	< 250	230	170	170	215
	>250	270	170	170	215
	> 500	320	170	170	215
	> 750	400	170	170	215
	> 1000	460	200	170	215

Table A-6. Recommended Spacing (85th %-ile — 35 veh/km/ln)
Minimum Spacing: 85th %-ile Weave Dist
Desirable Spacing: Opt Den = 35 veh/km/ln

Total Volume (vph)	Driveway Volume (vph)	Spacing (m)			
		2 Through Lanes		3 Through Lanes	
		No Auxiliary	Auxiliary	No Auxiliary	Auxiliary
< 2000	All	120	170	170	215
> 2000	< 250	120	170	170	215
	>250	120	170	170	215
	> 500	120	170	170	215
	> 750	120	170	170	215
	> 1000	120	170	170	215
> 2500	< 250	120	170	170	215
	> 250	120	170	170	215
	> 500	120	170	170	215
	> 750	150	170	170	215
	> 1000	200	170	170	215
> 3000	< 250	120	170	170	215
	>250	140	170	170	215
	> 500	180	170	170	215
	> 750	220	170	170	215
	> 1000	260	170	170	215
>3500	< 250	140	170	170	215
	>250	160	170	170	215
	> 500	220	170	170	215
	> 750	260	170	170	215
	> 1000	320	170	170	215