Proposed Analytical Technique for Analyzing Type A Weaving Sections on Frontage Roads

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The analysis of nonfreeway or slow-speed weaving sections is documented. Previous research in this area has been limited almost exclusively to freeway weaving sections. Specifically, Type A weaving areas on frontage road facilities with ramps on the left side were evaluated. Special consideration should be given to both the length of the section and the number of lanes when designing the geometrics of a weaving section. Access points such as driveways can also have a significant effect on traffic operations within these sections. It was determined by previous weaving studies as well as this research that speed was not an adequate measure of effectiveness because of its insensitivity to volume. Two additional measures of effectiveness were studied: density and lane changing intensity (LCI). Density was also eliminated because of its relationship at constant speeds. Models were developed to predict LCI using three levels of service. These models require only the identification of geometric conditions and traffic volumes to predict lane change operations. The evaluation of performance measures for the LCI model found it to be an effective means of nonfreeway weaving analysis. This methodology is also consistent with the approach used in the 1985 *Highway Capacity Manual.*

A weaving section is formed when a merge area is followed closely by a diverge area. Weaving is defined by the 1985 *Highway Capacity Manual* (HCM) as "the crossing of two or more traffic streams traveling in the same direction along a significant length of highway, without the aid of traffic control devices" (*1*).

Weaving sections have unique operational characteristics and require special design consideration. In the past, weaving section research has concentrated almost exclusively on freeway weaving sections. Consequently, methodologies for analyzing weaving sections do not provide adequate means for analyzing nonfreeway or slow-speed weaving sections. A procedure is needed for analyzing frontage road and arterial weaving sections.

A typical Type A frontage road weaving section is shown in Figure 1. A Type A weaving section is defined in the 1985 HCM as requiring "that each weaving vehicle make one lane change in order to execute the desired movement" (*1*). Weaving occurs between the merge and diverge points of the section and can be affected by several factors. These factors include lane balance through the section, lane widths, lane configuration, section length, speed limits on the frontage road and ramps, and shoulder widths.

Research at the Institute of Transportation Studies at the University of California, Berkeley, has shown that current weaving section analysis methods are not reliable (*2,3*). This is primarily due to the use of speed as a performance measure. Speed has been found to be insensitive to other traffic factors and is therefore difficult to predict. Measures of effectiveness considered for this project were density and lane changing intensity (LCI).

One of the first methods for analyzing the operations and design of freeway weaving sections was published in the 1950 edition of the HCM (*4*). This procedure was based on an empirical analysis of data collected before 1948. The U.S. Bureau of Public Roads initiated an effort in 1953 that resulted in a new method for the analysis and design of freeway weaving sections and was published in the 1965 HCM (*5*).

The Polytechnic Institute of New York (PINY) developed a methodology that was published in *NCHRP Report 159* (*6*) in 1976. The PINY procedure was found to be difficult to apply because of its complexity and therefore was not widely accepted as a useful methodology. A modified PINY procedure was presented in TRB's *Circular 212* (*7*) in 1980 to simplify the structure of the procedure.

Circular 212 also contained a procedure previously published in the *ITE Journal* (*8*). This method, developed by Leisch, was similar in structure to the 1965 HCM procedure and used two nomographs: one for two-sided configurations, and one for one-sided configurations.

FHWA sponsored a project from 1983 through 1984 to compare the PINY and Leisch procedures and make recommendations for a procedure to be included in the 1985 HCM. This study, conducted by JHK & Associates (*9*), concluded that neither method was adequate for analyzing operations of freeway weaving areas. The study proposed a method consisting of two equations: one for the prediction of the average speed of weaving vehicles, and one for the prediction of the average speed of nonweaving vehicles.

NCHRP Project 3-28B in 1984 recalibrated equations similar to those in the JHK method for the prediction of weaving and nonweaving speeds in weaving sections for the three basic types of configurations and for constrained and unconstrained operations. The result was a procedure consisting of 12 calibrated equations that was subsequently approved by TRB's Committee on Highway Capacity and Quality of Service and included in the 1985 HCM (*1*).

Fazio and Raiphail (*10*) revised the JHK method by using an increased amount of calibration data and introducing a new "lane shift" variable into the speed equations. This variable represents the minimum number of lane shifts that must be executed by the driver of a weaving vehicle from his lane of origin to the closest destination lane.

Researchers at the Institute of Transportation Studies began a study in 1987 that examined six existing methods for the design and analysis of freeway weaving sections. The study found that the existing models did not accurately predict weaving and nonweaving speeds and that speed was insensitive to changes in geometric and traffic factors over the range of values in the data set used. The

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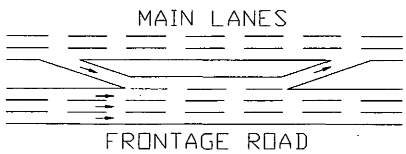

FIGURE 1 Typical frontage road weaving section.

study suggested that average travel speed is not an ideal measure of effectiveness (*2*).

Cassidy and May developed a new analytical procedure for the capacity and level of service (LOS) for freeway weaving sections that uses prevailing traffic flow and geometric conditions to predict vehicle flow rates in critical regions within the weaving section. Predicted flows are then used to assess the capacity sufficiency or LOS of a weaving area (*3*).

The Center for Transportation Studies and Research at the New Jersey Institute of Technology published a report in 1991 in which a model for analyzing weaving areas under nonfreeway conditions was proposed. The proposed model consisted of equations for predicting weaving and nonweaving speeds similar to those used in the 1985 HCM (*11*).

STUDY DESIGN AND METHODOLOGY

The objective of this project was to develop a method of analyzing Type A weaving areas on collector-distributor and frontage road facilities that is both reasonably accurate and simple to use. This procedure should define a measure of effectiveness and take into consideration weaving and nonweaving volumes, weaving section length and width, and any intermediate disturbances within the weaving section. To accomplish this, it was necessary to establish a data base to provide operational and physical information needed to formulate a method for analyzing the weaving sections. Another objective was to provide some general guidelines for the design of weaving sections on collector-distributor and frontage road facilities.

Data Collection and Analysis

Data for this study were collected in two phases. Phase 1 consisted of the data used to formulate the proposed models, and Phase 2 consisted of the data used to test the proposed models.

Data Requirements

Data collection activities for this study included traffic volume, vehicle classification, lane changing activity, speed, density, and weaving section geometry. All operational data were collected by personnel at the Texas Transportation Institute using video recording equipment. The weaving section geometry was obtained from roadway plans and field measurements.

Study Site Selection

Data were collected at eight sites in Texas (Table 1). The sites were chosen using the following criteria:

- Weaving sections should be less than 457 m (1,500 ft) in length from gore point to gore point, preferably less than 305 m (1,000 ft), and
- Intermediate disturbances such as intersections and driveways should be minimal.

Originally, only study sites in the Houston area were to be considered for this project. However, not enough sites were found in Houston, and it was necessary to use sites in other Texas cities. Several sites were chosen in Austin and the Dallas–Fort Worth area. The two Houston sites were not used for the Phase 1 analysis of the study because of reconstruction activities in the area. Data from these two sites were collected after the completion of the reconstruction activities and used in the Phase 2 analysis for model testing purposes.

RESULTS

Once the required traffic data were collected, the appropriate operational data were extracted directly from the videotape documen=

TABLE 1 Nonfreeway Weaving Study Sites

LOCATION	PHASE	CITY	LANES	WIDTH m (ft)	LENGTH. m (ft)
IH35 SB-FR @ Felix	I	Ft. Worth	3	11 (36)	136 (447)
SH360 SB-FR @ Green Oaks	I	Arlington	4	13 (44)	142 (467)
IH820 WB-FR @ Wichita	I	Ft. Worth	4	15 (48)	184 (604)
US75 SB-FR @ Midpark	I	Dallas	4	13 (44)	230 (755)
US75 NB-FR @ Spring Valley	I	Dallas	4	13 (44)	256 (841)
IH35 NB-FR @ Riverside	I	Austin	4	15 (48)	335 (1100)
US59 SB-FR @ Beechnut	II	Houston	3	11 (36)	293 (960)
US59 NB-FR @ Fondren	II	Houston	3	11 (36)	342 (1120)

tary. These data were summarized in 5-min intervals. This time interval was used to increase the sample size. All large vehicles traveling on the weaving sections were converted to passenger car equivalents according to procedures for freeways given in the 1985 HCM (*1*). Data sets with average flow rates of fewer than 200 vehicles per hour were excluded, as the focus of this project was on operations at higher volumes. From the eight sites, 335 data points were obtained.

Volumes of traffic entering the weaving sections and volumes of weaving vehicles were measured from the videotaped data. Densities were also obtained directly from the videotapes by counting the number of vehicles in a weaving section at a given time, as opposed to calculating densities on the basis of speeds and volumes. This was done by pausing the videotape every 10 sec, recording the densities for each lane, and averaging the readings to obtain a density value for each 5-min period. Average speeds were calculated by two methods, the first by using the stopwatch feature on the video camera to determine the time it takes a vehicle to travel a known distance, and the second by dividing the average volumes by the average densities.

It was not possible at most locations to obtain speeds via the first method described. The direct measurement method was instead used to verify the average speed calculations for the volume/density method. Lane changes were counted directly from the videotaped data. All lane changes within the entire weaving section were counted and summed for each 5-min period; these values were then converted to lane changes per hour per mile per lane. Weaving section lengths were measured between the painted gore points.

Data Verification

The accuracy of the data used to develop and calibrate the weaving models was a vital aspect of this project. Approximately 10 percent of the data were extracted from the videotape a second time to serve as an accuracy check. Any data sets with discrepancies of more than 5 percent were extracted a third time. Only one data set was found to have any discrepancies in the density values and was therefore extracted a third time. In many instances, total movements (i.e., ramp to frontage road, frontage road to frontage road, frontage road to ramp, and ramp to ramp flows) could be compared with lane changing activity data.

Fundamental Relationships

Before a model was developed for analyzing weaving section performance, the relationships between speed, flow, density, and LCI were examined to gain a better understanding of the operational characteristics of weaving sections. Frontage road flow rates in the weaving sections are generally limited by the intersection capacities upstream of the weaving sections. Each of the weaving sections in this study was preceded by an upstream traffic signal: consequently, the flow rates are lower than those on a freeway weaving section. Vehicle platooning significantly affects the operational characteristics of frontage road weaving sections. However, this study did not attempt to quantify this effect.

Speed-Flow Relationships

Relationships between speed and volume were studied initially. Average flow rates per lane were used to normalize the weaving section volumes, and speeds were obtained from the videotaped data by calculating speeds from the volume and density data. A scatter plot of average speed versus average flow is illustrated in Figure 2 (pcphpl = passenger cars per hour per lane). Aggregated 5-min observation data from the six Phase 1 study sites were used to construct the scatter plot.

Figure 2 reveals a high degree of scatter among the data. Speed appears to be insensitive to flow for the flow rates measured (e.g., fewer than 600 vehicles per hour per lane). There is less scatter at higher volumes, however, indicating that speed may be somewhat sensitive to flow as it nears capacity. From the data collected, no

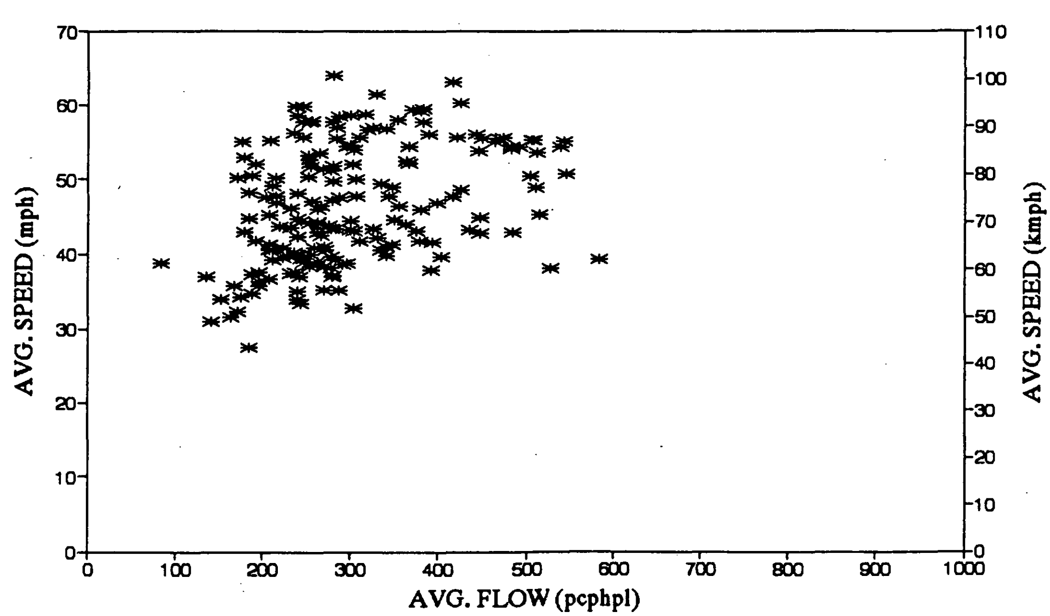

FIGURE 2 Speed versus flow.

obvious relationship between speed and flow was found, supporting the conclusions of other weaving studies that speed is not an adequate performance measure.

Density-Flow Relationships

Relationships between density and volume were also examined. Densities were measured directly from the videotaped data over the length of each weaving section. Figure 3 illustrates the density-flow relationship using average densities and average flows for 5-min periods (vpmpl = vehicles per mile per lane, vpkmpl = vehicles per kilometer per lane). There is much less scatter among the density-flow data than the speed-flow data. This is due partly to volume being contained in both axes of the plot. Density appears to be sensitive to flows, although the scatter increases at higher flows.

There is a conceptual flaw in the relationship between density and flow, however. For a given weaving section, the average speeds are nearly constant until traffic flows approach the capacity level. In this study, traffic flows for the weaving sections studied did not approach capacity. This resulted in density values consisting of volumes divided by an essentially constant speed. In this case (generally uniform speeds), the plot of density versus flow is the same as flow versus flow, which would obviously be a strong linear relationship. It was determined that a model for predicting densities on the basis of flow would not be the most effective procedure for predicting traffic operations in weaving areas on frontage roads.

LCI-Volume Relationships

In previous weaving studies (*2*), LCI was suggested as a possible measure of effectiveness, but none of these studies developed this concept. LCI is a more direct measure of the turbulence experienced within a weaving section than speed; it can be expressed as the number of lane changes per hour per mile per lane, as shown in the following equation:

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

LCI was found to be sensitive to flow. The data were stratified for different lengths of weaving sections to improve the relationship as illustrated by the degree of scatter in the data and represented by the coefficient of correlation, r^2. The data were separated by weaving section length into three groups; the first, 122.0 to 182.6 m (400 to 599 ft); the second, 182.9 to 274.1 m (600 to 899 ft); and the third, 274.4 to 365.9 m (900 to 1,200 ft). Scatter plots for each weaving section group are illustrated in Figures 4, 5, and 6 (lcphpmpl = lane changes per hour per mile per lane, lcphpkmpl = lane changes per hour per kilometer per lane).

Proposed Models for LCI Prediction

A linear model was constructed for each of the three weaving section length groups using a regression program. These models estimate the LCI in a frontage road weaving section on the basis of the average volume per lane. The three LCI models, developed from 5-min observation data, are listed here:

$$\text{122.0–182.6 m (400–599 ft): LCI} = 10.46\,(V/n) + 372 \quad (2)$$

$$\text{182.9–274.1 m (600–899 ft): LCI} = 8.52\,(V/n) + 79 \quad (3)$$

$$\text{274.4–365.9 m (900–1200 ft): LCI} = 391\,(V/n) + 590 \quad (4)$$

where

LCI = lane changes per hour per lane per mile (to convert to kilometers, divide by 0.621),
V = hourly volume entering weaving section, and
n = number of lanes in weaving section.

The coefficient of correlation (r^2) is a measure of how much of the variability of the dependent variable, LCI in this case, is

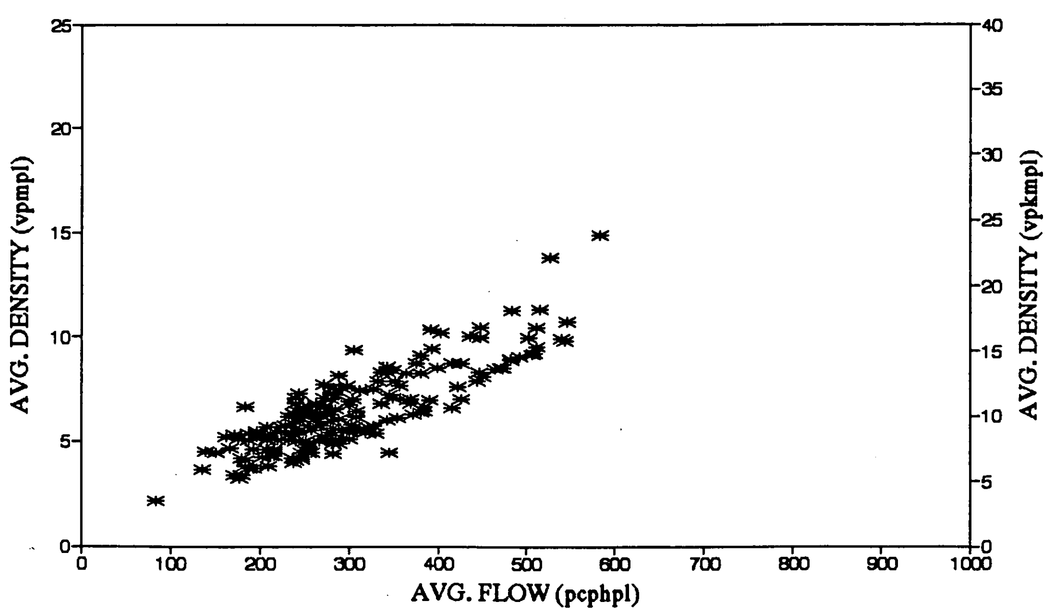

FIGURE 3 Density versus flow.

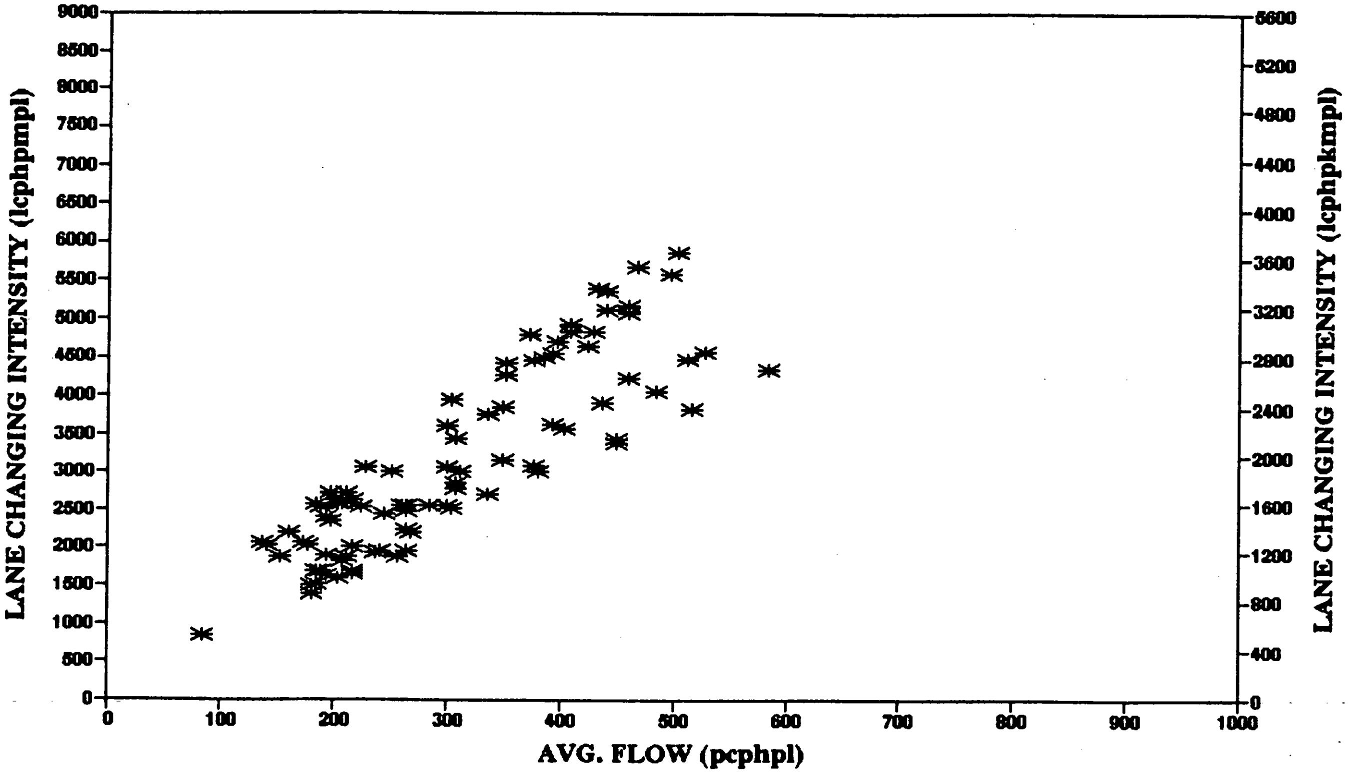

FIGURE 4 LCI versus average flow, 122.0 to 182.6 m (400 to 599 ft).

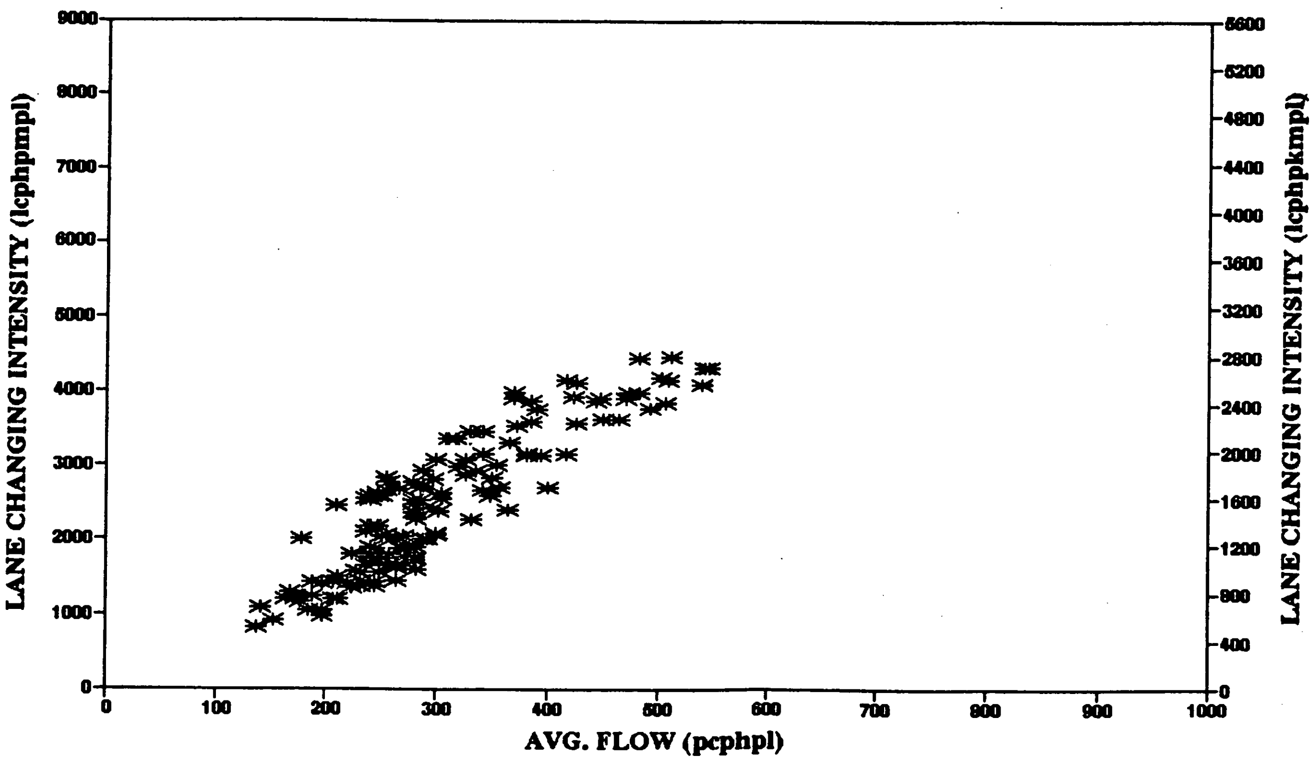

FIGURE 5 LCI versus average flow, 182.9 to 274.1 m (600 to 899 ft).

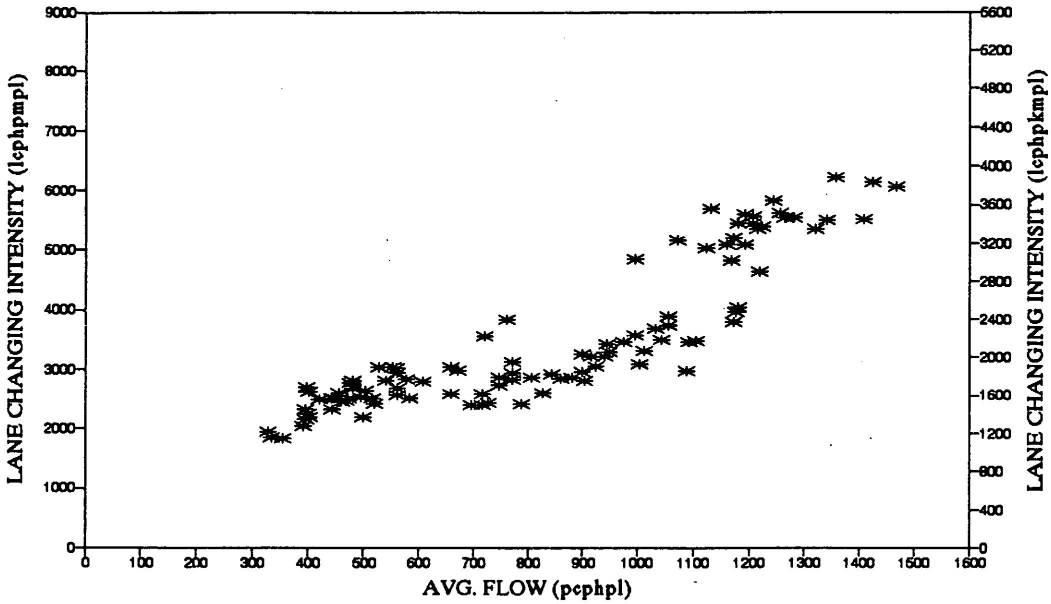

FIGURE 6 **LCI versus average flow, 274.4 to 365.9 m (900 to 1,200 ft).**

explained by the variability of the independent variable, average volume in this case. A value of +1.00 or −1.00 is perfect, and a value of 0.00 is the lowest possible. The adjusted r^2 value for Equation 2 is 0.94, the adjusted r^2 value for Equation 3 is 0.78, and the adjusted r^2 value for Equation 4 is 0.82. The three LCI equations are shown graphically in Figure 7.

The LCI models were developed using the Jandel Scientific Curve Table Software Package, and the analysis of variance was performed using the Statistical Analysis Software Package (SAS). A linear equation was chosen for each model for simplicity and because there were no obvious patterns in the data that suggested that the relationships might be nonlinear. It is possible, however, that as traffic operations near capacity, the relationships will become nonlinear. The equations each have a constant associated with them because the relationship between volume and LCI is not known as volume approaches 0. Although it is intuitively obvious that each model should begin at the origin, it is possible that the relationship is nonlinear at very low volumes. The models presented in this paper should be used only for the volume ranges shown in Figure 7.

Model Testing

Data were collected for Phase 2 at two sites in Houston for the purpose of testing the LCI models. The two weaving sections were in the range of 274.4 to 365.9 m (900 to 1,200 ft) and thus were applic-

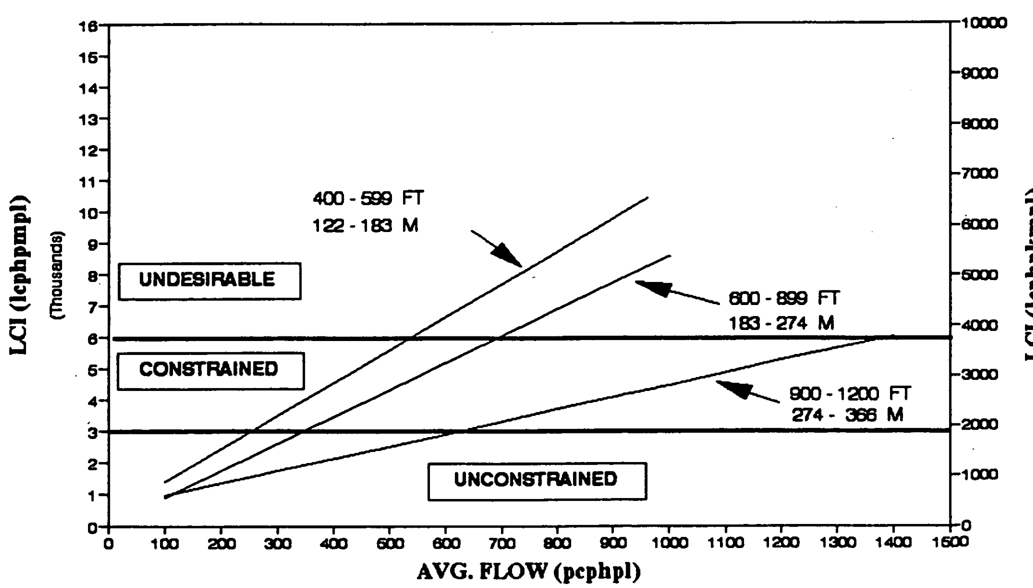

FIGURE 7 **Proposed LCI models.**

able to only one of the three models. Attempts to locate Phase 2 weaving sections in the Houston area to test the models for shorter weaving sections were unsuccessful.

The testing procedure consisted of a statistical analysis of the data collected at the two Phase 2 test sites by comparing the values observed for LCI with those predicted by the model. The two test sites experienced higher volumes than any of the original study sites, thereby enabling the boundaries of the model to be tested at these higher volumes. The data collected at the two test sites compared favorably with the predicted LCI values from the model and the other study sites. The adjusted r^2 value for this test was .75, indicating that the model is reasonably accurate. This result indicates a more reliable method than the previously mentioned current methods used to predict performance in weaving sections.

LOS Estimation

The criteria for determining LOS were developed to be consistent with those in the 1985 HCM, but with some differences. The 1985 HCM describes six levels (A through F). The criteria proposed in this paper have only three levels—unconstrained, constrained, and undesirable—because of the difficulty in differentiating between six levels over the range of data. It can also be argued that six separate levels do not exist. The criteria proposed in this paper can be compared to 1985 HCM criteria as follows:

- Unconstrained: A and B,
- Constrained: C and D, and
- Undesirable: E and F.

The unconstrained LOS represents free to stable flow conditions in which individual behavior is relatively unaffected by other traffic, and comfort and convenience levels are high. The constrained LOS represents a stable flow condition in which individual behavior is significantly affected by others and may become restricted. Comfort and convenience levels are noticeably lower. The undesirable LOS represents flow conditions approaching capacity in which comfort and convenience levels are poor and breakdowns in flow may occur with small changes in volume. The average speeds under these conditions would also be noticeably lower. The proposed LOS criteria are presented in Table 2 and shown graphically in Figure 7.

The values given in Table 2 were selected subjectively by viewing the videotaped data and identifying the periods in which each LOS was represented. The LCIs were determined at each LOS for all the weaving sections, and an average value was selected to represent each LOS boundary. This method of selection is subjective, and these values do not represent exact divisions in LOS. These values are intended to provide a general idea of what can be expected at a given weaving section. For example, in Figure 7, weaving sections greater than 274.4 m (900 ft) long reach the undesirable LOS at relatively high volumes. This suggests that at lengths greater than 274.4 m (900 ft), weaving is not a major concern on frontage roads. This topic is discussed later in this paper.

Design Procedures

Design procedures were established to properly analyze and develop Type A weaving sections on frontage roads. The necessary criteria are given in the following.

TABLE 2 LOS Criteria for LCI

LOS	Lane Changing Intensity (LCI)	
	Metric (lcphpmpl)	lcphpmpl
Unconstrained	0 - 1863	0 - 3000
Constrained	1863 - 376	3000 - 6000
Undesirable	> 3726	> 6000

Step 1: Establish Roadway Conditions

Existing or proposed roadway conditions must be specified before proceeding with the analysis. Roadway conditions include the length and number of lanes for the weaving section being studied (Figure 8).

Step 2: Determine Traffic Volumes

Traffic volumes should be expressed as hourly flow rates, which are obtained by identifying the peak 15-min interval within the hour of interest and multiplying this value by four. These values should be converted to passenger car equivalents. As shown in Figure 8, volumes are needed for ramp traffic and frontage road traffic entering the weaving section.

Step 3: Convert Traffic Volumes to Average Volume per Lane

Traffic volumes developed in Step 2 are converted to an average lane volume by adding the freeway exit ramp and frontage road volumes to obtain a total volume entering the weaving section and dividing this value by the number of lanes in the weaving section.

Step 4: Calculate LCI

LCI can be calculated using Equations 3 through 5 or can be obtained graphically from Figure 7.

Step 5: Determine LOS

LOS can be determined from the LCI by using the ranges of values given in Table 2 or by using Figure 7, which graphically illustrates the LOS boundaries.

FINDINGS AND RECOMMENDATIONS

Obviously, it is desirable not to have any weaving sections in a roadway design, but there are times when the alternatives are even less desirable. When a weaving section is to be part of a design,

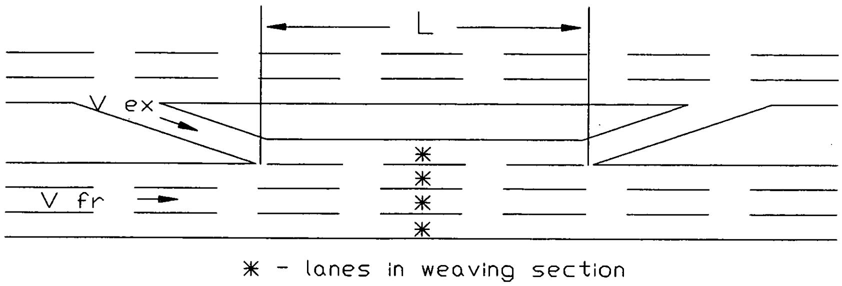

FIGURE 8 Weaving section analysis requirements.

special consideration should be given to both the length of the section and the number of lanes in the section. The projected LOS for a weaving section can be improved by adjusting the roadway conditions.

Lane Length

It is desirable to have a weaving section length in the range of 274.4 to 365.9 m (900 to 1,200 ft) as shown in Figure 8. A length in this range would help to ensure that weaving problems were minimized. It is desirable not to have a weaving section shorter than 182.9 m (600 ft). Weaving sections shorter than 182.9 m (600 ft) and significant traffic volumes will most likely experience operational problems.

Number of Lanes

A minimum of three lanes is recommended for weaving sections; this includes two through lanes and one auxiliary lane connecting the two ramps. Four lanes are recommended for weaving sections with significant volumes. The addition of a lane can help alleviate existing or projected operational problems, assuming the added lane is actually used. A lane could be added and not improve conditions if most of the traffic is weaving traffic and the additional lane is not used because there is little demand for through lanes in the weaving section.

Intermediate Disturbances

The design of weaving sections should not include intersections or driveways. The presence of driveways can have a significant effect on the operations of any facility, and this is especially true of weaving sections. The combination of the turbulence caused by weaving traffic and the effect of traffic turning into and out of cross streets or driveways could cause not only operational problems but safety problems as well.

Summary of Findings

The objective of this project was to develop a procedure for analyzing weaving section operations on nonfreeway facilities that was both reasonably accurate and simple to use. It has been determined by previous weaving studies and by this research that speed is not an adequate measure of effectiveness because of its insensitivity to traffic volumes typically experienced on frontage roads. Two possible measures of effectiveness were studied: density and LCI.

Density was eliminated as a possible measure of effectiveness because at uniform speeds, density is simply volume divided by a constant, and any model depicting this relationship would not be useful in predicting weaving operations.

Models were developed to predict LCI for three ranges of weaving section lengths. The resulting models had reasonable r^2 values and are easily used. LOS criteria were established for the LCI model, providing LCI ranges for three levels. Only three levels were defined because of the difficulty in determining the boundary values for each level.

LCI appears to be an effective performance measure for weaving sections. The relationship between LCI and average volume provided r^2 values that were higher than r^2 values for relationships currently being used (typically 0.50 to 0.60) for weaving section analysis (*11*). Application of the methodology outlined in this report is relatively simple and requires few data. Only geometric conditions and traffic volumes are required, both of which are easily attained. The methodology is also consistent in its approach to analyzing weaving sections with the 1985 HCM, other than using a different measure of effectiveness.

Future Research

Future research is required to calibrate the LCI model for different weaving configurations and to test sections of various lengths. The data used to develop the LCI model were obtained exclusively from Type A frontage road weaving sections with ramps on the left side. The LCI model is also intended to be used to analyze weaving sections on collector-distributor roads with ramps on the right side. It is possible that the LCI model will need to be recalibrated for these weaving sections.

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