EVALUATION OF METHODOLOGIES FOR THE DESIGN AND ANALYSIS OF FREEWAY WEAVING SECTIONS

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ABSTRACT

Weaving sections are common design elements on freeway facilities such as near ramps and freeway to-freeway connectors. Traffic operational problems often exist at weaving areas even when traffic demands are less than capacity because of the complexity of vehicle interactions, resulting in poor level of service (LOS) and potential safety problems. The objective of the work described in this paper is to evaluate the new weaving analysis methodology developed for the forthcoming edition of the Highway Capacity Manual (HCM2010). We applied the method to 30 real-world weaving sections throughout the US covering a wide range of design and traffic characteristics, for a total of 289 data points of volumes and speeds. The analysis of the results from the application of the method indicates that the method overpredicts the density of the weaving sections.

INTRODUCTION

Weaving sections are common design elements on freeway facilities such as near ramps and freeway-to-freeway connectors. When the traffic demands exceed the capacity at weaving areas congestion may occur, which affects the operation of the entire freeway section. Traffic operational problems also may exist at weaving areas even when traffic demands are less than capacity because of the complexity of vehicle interactions, resulting in poor level of service (LOS) and potential safety problems.

Efforts to develop procedures for the design and analysis of freeway weaving sections began in the 50's. However, the existing procedures have several shortcomings, and their practical application often produces inconsistent results. This is mostly due to the lack of empirical data on weaving operations. Most of the existing methods are based on limited data that are not representative of the entire range of the geometric configurations and traffic patterns in weaving areas. The systematic evaluation of existing weaving methods and the development of an improved analysis method have been recognized as high priority research needs. Recently, a new weaving analysis method [1] was developed as part of the new edition of the Highway Capacity Manual (HCM2010) [2].

The objective of this research described in the paper is to evaluate the proposed 2010 weaving analysis procedure based on field data. This is part of an ongoing research effort to evaluate existing weaving analysis procedures to determine under which design and operating conditions the "best available" tools are most effective [3].

BACKGROUND

The first formal procedure for analysis of weaving sections appeared in the 1965 edition of HCM [4], based on research conducted by O.K. Normann [5]. The basic model in the 1965 HCM is a relationship between weaving length, total weaving volume, and Quality of Service. The 1965 HCM method was widely used and brought some national consistency to the analysis and design of weaving areas. The methodology covered a wide range of situations and configurations in which weaving could exist. However, the method was based on very limited field data.

The Level D Method was developed in California by Moskowitz & Newman to analyze weaving sections under heavy traffic conditions (Level of Service (LOS) is D or E) [6]. The method applied to weaving sections with one lane on-ramp followed by an off-ramp with a continuous auxiliary lane. The method provides the percentages of on-ramp and off-ramp traffic remaining in the auxiliary lane and the right-most through lane at 500 ft intervals through the weaving section, as well as the proportion of the freeway through traffic remaining in outer through lane in the weaving section. The analyst estimates the traffic volumes in the right most through lane and the auxiliary lane at 500 ft intervals using the provided percentages. These values are compared against the lane capacities in the weaving section. The Level D method was later extended for other types of weaving sections with multiple on- and off-ramps [7].

The Leisch Method was developed by J. Leisch based on data from 48 weaving sections around the US [8]. The method uses concepts similar to the 1965 HCM and a nomograph approach. The primary relationship is between the length of the weaving section and the total weaving volume. Solution of the nomographs results in determination of either the LOS of a weaving section with known design characteristics, or the number of lanes needed to obtain a specified LOS. The method accounts for the difference in operational characteristics between lane-balanced and unbalanced weaving sections. Lane balanced sections have one more lane going away, such as an optional lane at exit; i.e., one weaving movement is not required to change lanes. The advantage of the Leisch method is that it is relatively easy to apply, and could be manipulated to produce design and/or operational analysis results. However the development and calibration of nomographs was mostly based on experience and judgment with very limited field data.

The HCM2000 Method [9] was originated from the weaving analysis method developed by the Polytechnic Institute of New York [10] and the research for the development of the 1985 Highway Capacity Manual [11,12]. This method is based on the same field data as the Leisch method, but it explicitly recognizes the geometric configuration of the weaving section. Freeway weaving sections are classified into three configurations, depending on the minimum number of lane changes required by weaving vehicles (Figure 1).

- Type A: each weaving vehicle must make one lane-change (ramp weaves)
- Type B: major weaving configurations requiring one lane change for the one weaving movement and none for the other weaving movement (balanced sections)
- Type C: major weaving configurations requiring two or more lane changes for one weaving movement and none for the other weaving movement (unbalanced sections)

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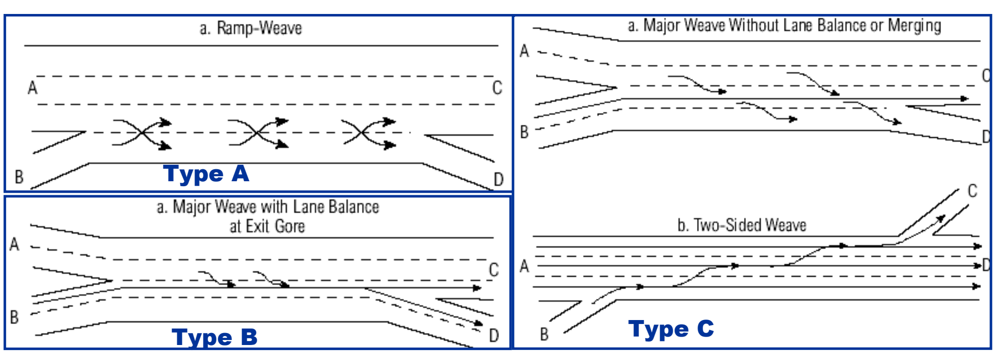

Figure 1. Configurations of Freeway Weaving Sections (1985/2000 HCM)

The HCM2000 method also introduced the concept of constrained vs. unconstrained operations. Constrained operations occur when the geometry of the section constrains weaving vehicles from using certain freeway lanes. Under constrained operations weaving vehicles occupy a smaller proportion of the roadway than they would without the constraint of geometry; non-weaving vehicles occupy more space, and the difference between non-weaving and weaving vehicle speeds increases.

The LOS is defined based on the speeds of weaving and non-weaving vehicles:

$$S_{w,nw} = 15 + \frac{FFS - 10}{1 + \left[\frac{a(1 + VR)^b \left(\frac{v}{N}\right)^c}{L^d}\right]}$$

where: S_w: average speed of weaving vehicles, mph
S_{nw}: average speed of non-weaving vehicles, mph
FFS: freeway free-flow speed
VR: volume ratio; ratio of weaving flow rate to total flow rate
v: total demand flow rate under equivalent ideal conditions (pc/h)
N: number of lanes in the weaving section
L: length of the weaving section (ft)
a-d: constants of calibration, depending on weaving section configuration

Several concerns have been expressed by transportation researchers and professionals regarding the HCM2000/HCM1985 method because a) it could not provide capacity estimates; b) it uses rather complex equations for estimating weaving and non-weaving vehicle speeds to determine LOS, and the logic of these formulae is not readily apparent, and c) it often inappropriately reflects impacts created by changes in geometric configuration of the weaving areas.

The HCM2010 Methodology

The newly developed CM2010 weaving analysis methodology brings important differences compared to the existing HCM2000 procedure; for example, a) it does not classify the weaving sections into A,B, or C types, b) it includes a direct method for estimating the capacity of weaving sections, and c) it includes a new definition of the weaving section length.

The HCM2010 methodology explicitly considers the number of lane changes in the weaving segment. The total lane-changing rate (LC_W) for weaving vehicles is the sum of the minimum lane changes (LC_{MIN}) plus the optional lane changes for weaving vehicles that could occur in the weaving segment:

$$LC_W = LC_{MIN} + 0.39[(L_S - 300)^{0.5} N^2 (1 + ID)^{0.8}]$$

where:

$$LC_{MIN} = (LC_{RF} \times v_{RF}) + (LC_{FR} \times v_{FR})$$

L_S: short length of the weaving segment, which is the distance between the end points of any barrier markings (solid lines) that prohibit or discourage lane-changing (ft)
ID: interchange density (int/mi)
$LC_{RF\ (FR)}$: minimum number of lane changes that one ramp-to-freeway (freeway-to-ramp) vehicle must make to complete the desired weaving maneuver
$v_{RF\ (FR)}$: ramp-to-freeway (freeway-to-ramp) demand flow rate in the weaving segment (pc/h)

The average speed of the weaving vehicles (S_W) is:

$$S_W = 15 + \frac{(FFS - 15)}{(1 + W)}$$

Where W is the weaving intensity factor, which represents the density of the lane changes and depends on the total lane-changing rate within the weaving segment. It is computed as follows:

$$W = 0.226 \left(\frac{LC_{ALL}}{L_S}\right)^{0.789}$$

where LC_{ALL} is the total lane-changing rate of all vehicles in a weaving segment.

The speed of non-weaving vehicles (S_{NW}) is computed using the following equation:

$$S_{NW} = FFS - (0.0072LC_{MIN}) - (0.0048\frac{v}{N})$$

As expected, the speed of non-weaving vehicles decreases with an increase in the weaving turbulence, caused by either increases in the LC_{MIN} or the total demand flow rate per lane.

Finally, the HCM 2010 calculates the space mean speed of all vehicles in the weaving segment by using the following equation:

$$S = \frac{v_W + v_{NW}}{\left(\frac{v_W}{S_W}\right) + \left(\frac{v_{NW}}{S_{NW}}\right)}$$

where v_W and v_{NW} are the weaving and non-weaving demand flow rate in the weaving segment respectively.

Next, the density for the weaving section is computed from the average speed and flow rate. The LOS is determined from the computed density value based on the following table (Table 1):

Table 1. LOS Criteria for Freeway Weaving Sections

LOS	Density (pc/mi/ln)
A	0-10
B	>10-20
C	>20-28
D	>28-35
E	>35
F	Demand Exceeds Capacity

The HCM 2010 computes two capacities for each weaving segment – one based upon a density of 43 pc/mi/ln, which according to the HCM is the value that freeway breakdowns occur, and the other based upon the maximum weaving flow rates. The minimum of the two values is the capacity of the weaving section.

The capacity of a weaving segment determined by the freeway breakdown density is estimated as follows:

$$c_{IWL} = c_{IFL} - [438.2(1 + VR)^{1.6}] + [0.0765L_S] + [119.8N_{WL}]$$

where:
c_{IWL}: capacity of the weaving segment under equivalent ideal conditions, per lane (pc/h/ln)
c_{IFL}: capacity of a basic freeway segment with the same free-flow speed as the weaving segment under equivalent ideal conditions, per lane (pc/h/ln)

The respective total capacity under prevailing conditions is calculated as follows:

$$c_W = c_{IWL} N f_{HV} f_P$$

where f_{HV} and f_P are adjustment factors for heavy-vehicle presence and driver population respectively. The capacity of a weaving segment determined by the weaving demands is estimated as follows:

$$c_{IW} = \frac{2{,}400}{VR} \text{ for } N_{WL} = 2 \text{ lanes}$$

$$c_{IW} = \frac{3{,}500}{VR} \text{ for } N_{WL} = 3 \text{ lanes}$$

where c_{IW} is the capacity of all lanes in the weaving segment under ideal conditions in pc/h and N_{WL} is the number of lanes from which weaving maneuvers may be made with either one lane change or no lane changes. As before the respective total capacity under prevailing conditions is calculated as follows:

$$c_W = c_{IW} f_{HV} f_P$$

The final capacity of the weaving segment is defined as the smaller of the two estimates above.

THE STUDY DATABASE

We have assembled a database of 30 real-world weaving sections throughout the US covering a wide range of design and traffic characteristics. The final database consists of a total of 289 data points of volumes and speeds. Table 2 shows the available datasets per geometric characteristics (number of lanes and configuration). The sources and characteristics of data are further described below:

California Studies —Major Weaving Sections: Data on eight major weaving sections in the data were collected using video and processed to obtain volumes per traffic movement, speeds of weaving and non-weaving vehicles and lane distribution of component flows. All the sites are major weaving sections with more than one on or off-ramps, typical of urban freeway weaving sites. The data were reviewed for accuracy and coded into the study database for further analysis. There are a total of eight test sites and 31 data points of volume/speed conditions.

California Studies —Ramp Weaves: Caltrans staff collected data on weaving sections in the early 90's using video recordings, as part of a study to evaluate the accuracy of the Level D method. All the data were collected on urban freeways with a one lane on- and off-ramp connected with an auxiliary lane. Most of the data in each study site consisted of 5 minute volumes per movement. Speeds of weaving and non-weaving vehicles were extracted for seven sites. Note that all weaving sections are five lanes wide typical of urban freeways in Southern California. Also, at the time of the data collection there was a 55 mph posted speed limit on all locations. The final ramp weaves database consists of ten sites and 145 data points of volumes and speeds.

Table 2. The Study Database

CONFIGURATION	Number of Lanes in the Weaving Section		
	N=3	N=4	N=5 (or more)
RAMP WEAVE **One lane on- and off-ramps**	MD-100EB-1		US-101SB SR-91EB I-580EB I-210EB SR-134EB I-10EB US-101NB* SR-91WB I-110SB I-10WB SR-60EB I-5SB
MAJOR WEAVE **BALANCED** **More than one lane on- or off- ramps**	MD-100EB-2 SR-92WB SR-217SB	I-405EB SR-101WB I-5SB-1 SR-202EB	I-80EB I-95SB I-5SB-2 I-805NB I-10WB_SB I-10WB_LA
MAJOR WEAVE **UNBALANCED** **More than one lane on- or off-ramps**			US-101NB SR-101EB I-280SB I-10EB_LA*

*six lanes

The NGSIM Data Sets: Detailed data on freeway operations have been collected as part of the of Next Generation Simulation (NGSIM) program sponsored by FHWA [14]. The NGSIM database consists of vehicle trajectories and aggregate loop detector data from two weaving sections in California: I-80EB in San Francisco Bay area and US-101NB in Los Angeles. The I-80 site is Type B weaving section per HCM2000 with a length of 1,650 ft; there are six freeway lanes entering the weaving section and five freeway lanes leaving it. Lane 1 is an HOV lane. The US-101NB has six through lanes with a continuous auxiliary lane (ramp weave section). There are a total of nine data points of volumes and speeds in congestion and transition.

The NCHRP 3-75 Database: The data base for NCHRP Project 3-75 consisted of 10 sites for 104 data points in four different regions of the country. The data on traffic volumes and speeds were collected using video recordings. Most of the weaving sections are balanced sections with five lanes.

EVALUATION OF THE HCM2010 METHODOLOGY

The existing weaving analysis tools were applied to the all the datasets shown in Table 2. The HCM2010 method predictions were compared to the field measurements within a site and across all sites to determine the strengths and limitations of the methodology. The following sections describe sample results from the extensive analyses performed.

Figure 2 shows the observed and HCM2010 predicted densities at all ramp weave sections shown in Table 2. It can be seen that HCM2010 overestimates the densities in most data sets. On average, the HCM2010 predicted density is 24% higher than the observed values. The root mean square error (RMS) is 8.3 pce/mi/ln.

The observed and predicted density values for balanced weaving segments are shown in Figure 3. It can be seen that the HCM2010 predictions are fairly close to the field data; the average difference is less than 10% (RMS = 3.9 pce/mi/lh). The large differences (outliers) at a few data points are likely due to measurement errors for speeds of non-weaving vehicles at the I-95SB test site.

Figure 4 shows the observed and HCM2010 predicted densities at the unbalanced major weaving areas. Again, HCM 2010 over-predicts the densities by about 20% on average, and the RMS is 4.2 pce/mi/ln.

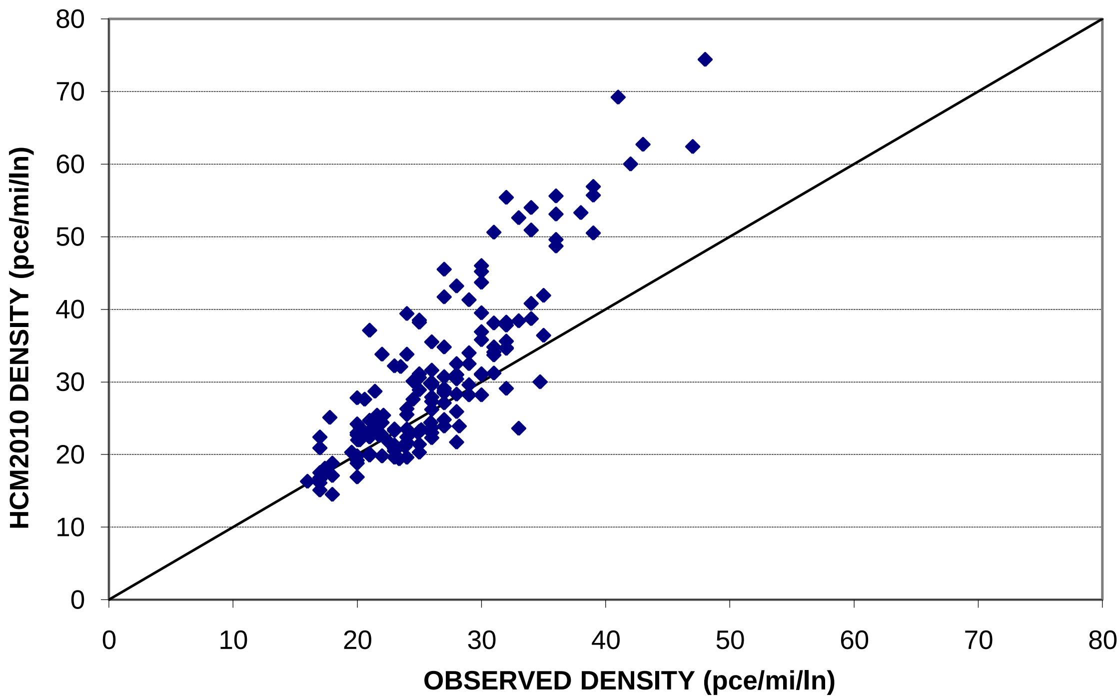

Figure 2. Freeway Weaving Sections Density: HCM2010 vs. Field Data–Ramp Weaves

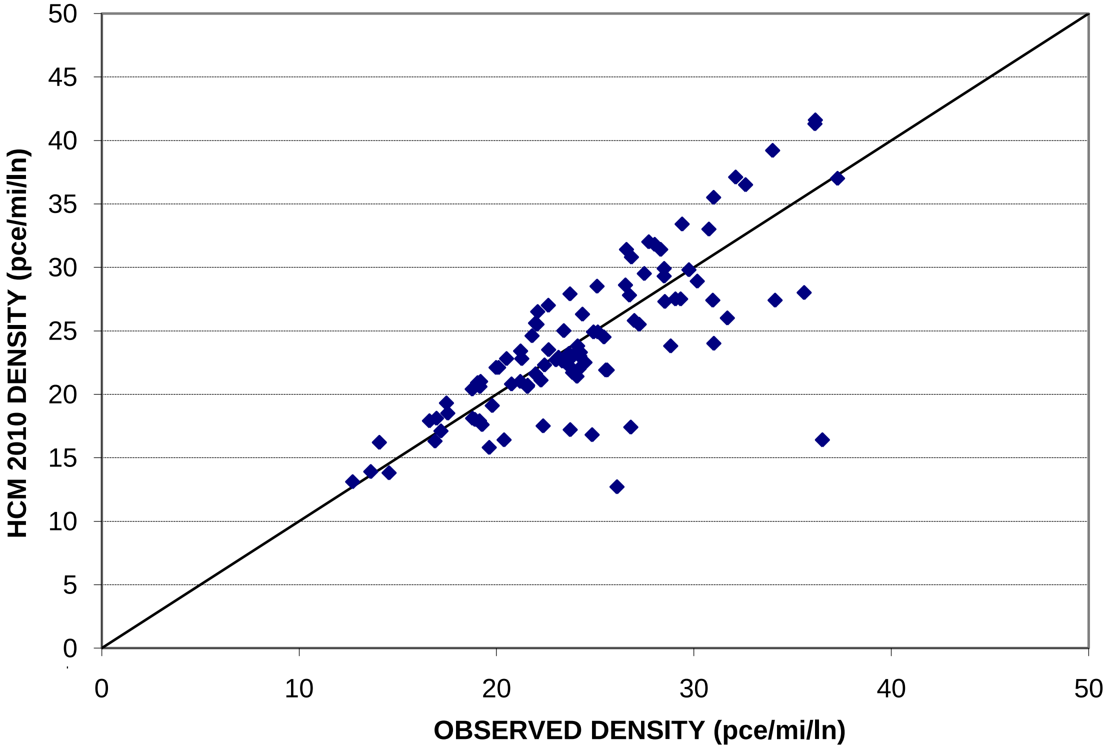

Figure 3. Freeway Weaving Sections Density: HCM2010 vs. Field Data – Major Weave Balanced

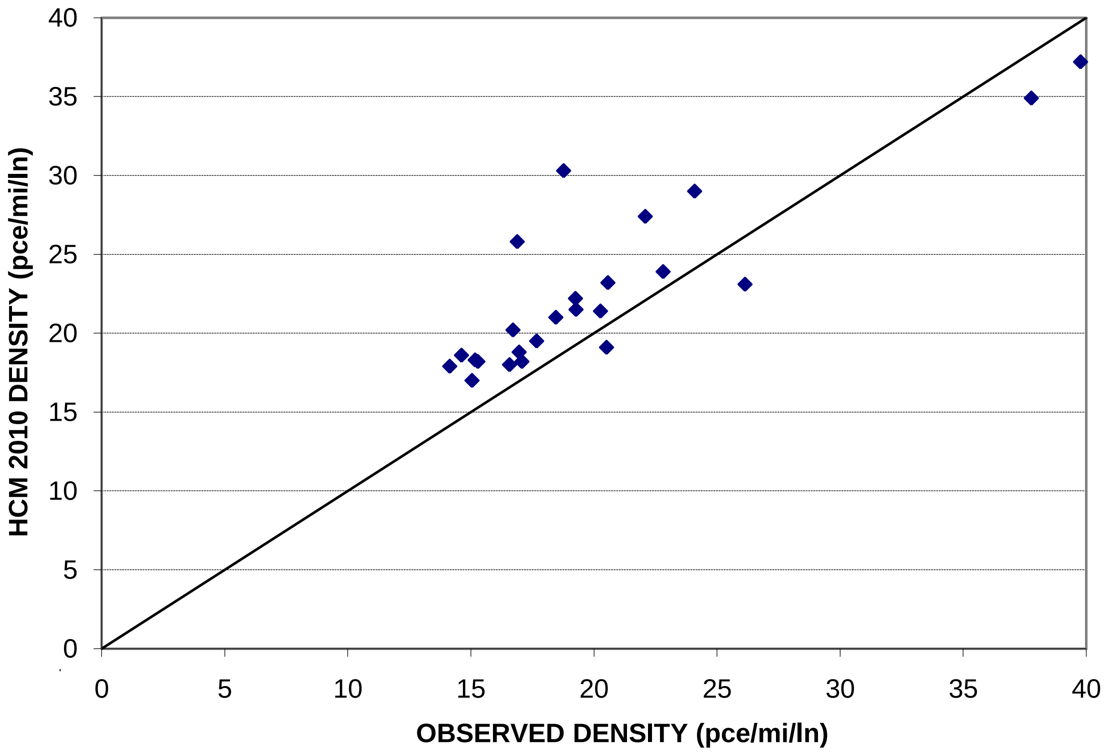

Figure 4. Freeway Weaving Sections Density: HCM2010 vs. Field Data – Major Weave Unbalanced

DISCUSSION

The paper describes ongoing work in evaluating analysis methodologies for the design and analysis of freeway weaving sections with field data covering a range of design and traffic characteristics. The finding of the study indicate that the new HCM2010 method provides reliable estimates for balanced major weaving sections, but significantly under-predicts the traffic performance at ramp weaving sections.

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