Application of Simulation To Evaluate the Operation of Major Freeway Weaving Sections

A. SKABARDONIS, M. CASSIDY, A. D. MAY, AND S. COHEN

This paper describes the findings from the application of the INTRAS microscopic simulation model to evaluate the traffic performance at major freeway weaving sections. The work performed is part of an ongoing research project to develop improved weaving analysis procedures that are particularly applicable to California conditions. The INTRAS model was modified to predict the speeds of weaving and nonweaving vehicles and applied on eight major freeway weaving sections for a range of traffic conditions at each site. Good agreement was obtained between the measured and predicted values. Comparisons with speeds estimated from existing analytical procedures indicated that INTRAS predictions are considerably closer to the field measurements. The potential of the model to predict the capacity and level of service at weaving areas was also investigated. The model produced consistent results on the data sets tested, indicating that it may be used in conjunction with field measurements to develop improved methodologies for the design and analysis of freeway weaving sections. Future steps in this direction are discussed.

Weaving is defined as the crossing of two or more traffic streams traveling in the same general direction, along a significant length of the roadway, without the aid of traffic control devices (*1*). Weaving sections are common design elements on freeway facilities, such as near ramps and freeway-to-freeway connectors. The operation of freeway weaving areas is characterized by intense lane changing maneuvers and influenced by several geometric and traffic characteristics. Because of the complexity of vehicle interactions, operational problems may occur at weaving areas even when traffic volumes are less than capacity.

As a result of continuous traffic growth, major efforts are currently under way to design new interchanges or improve existing ones. Therefore, accurate procedures are needed to assess the operation of existing facilities, the effectiveness of alternative designs, and other operational improvements. However, a recent evaluation of the existing weaving analysis techniques (*2*) found significant discrepancies between the performance measures estimated from the existing methods and the field measurements, indicating that additional research is needed. Further research on this topic was also recognized as the second highest priority from 29 research problem statements recently published by the TRB Committee on Highway Capacity and Quality of Service (*3*).

A. Skabardonis, M. Cassidy, and A. D. May, Institute of Transportation Studies, University of California, Berkeley, Calif. 94720. S. Cohen, Federal Highway Administration, 6300 Georgetown Pike, McLean, Va. 22101.

All of the existing weaving design and analysis procedures are based on empirical data collected at a number of weaving sections nationwide. Simulation is an alternative approach for evaluating the operation of weaving areas, and a simulation model is most suitable to test the effectiveness of alternative designs and traffic management schemes before their field implementation. Simulation results could also be used in the development of design and analysis procedures, provided the model employed is capable of replicating known field conditions.

The purpose of this paper is to present the findings from the application of the INTRAS microscopic simulation model on eight major freeway weaving sections and the comparison of the model's results with field measurements. The objectives of the simulation experiments were

- To assess if simulation can predict the operation of weaving areas with reasonable accuracy, and
- To investigate the potential of simulation to augment field data in developing improved methods for the design and analysis of weaving sections.

The paper first gives an overview of the ongoing research on freeway weaving sections in California. The INTRAS model is briefly described, along with the modifications and enhancements performed to the model for this study. The application of the model on the selected test sites, and the analysis of the results, are presented. Additional model applications and results are discussed. The final section summarizes the major findings from the study and discusses future research directions.

OVERVIEW OF CURRENT RESEARCH

The research reported in this paper is part of an ongoing project to develop improved weaving design/analysis methods that are particularly applicable to California conditions (*2*; see paper by Cassidy et al. in this Record). The work focuses on large, complex weaving sections near or at freeway-to-freeway interchanges. The objectives of the project are

- To evaluate the existing methods for design and analysis of weaving sections considering their methodology, accuracy, and ease of application using field data from major weaving sites, and

- To develop an improved weaving design and analysis procedure as needed.

Major tasks performed include (a) a detailed literature search on the topic, (b) collection of a large amount of data at several major freeway weaving areas throughout the state, (c) evaluation of existing weaving analysis procedures, and (d) statistical analysis of the field data to better understand the operation of weaving areas and to develop empirical prediction models. Currently, an improved weaving design/analysis procedure is being developed based on field data supplemented by simulation modeling.

A parallel study on weaving operations is also under way in California (*4*). This study is concerned with "simple" or "ramp" weaving sections (one-lane onramp and one-lane right-side offramp with a continuous auxiliary lane). Field data have been collected at several sites using video recording. Current findings indicate that both the 1985 *Highway Capacity Manual* (HCM-85) method (*1*) and the Leisch method (*5*) underestimate the speeds of the weaving vehicles, and the Level D method (*6*) reasonably predicts the distribution of traffic flows in the weaving area.

SIMULATION OF WEAVING AREAS

Selection of the Simulation Model

A number of simulation models have been developed over the past 20 years to analyze traffic operations on freeways (*7*). These models generally fall into two major categories:

1. Macroscopic models, either static or dynamic, consider the average traffic stream characteristics (flow, speed, density), incorporate analytical procedures to evaluate existing conditions, and predict performance under different design and control scenarios. The FREQ and FREFLO models (*7*) are examples of such macroscopic models, which are commonly used for freeway corridors. These models handle the effects of weaving using analytical procedures, such as those in the 1965 *Highway Capacity Manual* (HCM-65) (*8*).
2. Microscopic models consider the characteristics of each individual vehicle, and its interactions with other vehicles in the traffic stream. Therefore, they can simulate traffic operations in much greater detail than the macroscopic models, but they usually require additional data, staff time, and computer resources for their application.

For this study, a microscopic simulation model was chosen because it can model the complexity of the vehicle interactions at weaving areas. Of the microscopic models identified, the INTRAS model (*9,10*) was selected because it is the most detailed and well-documented freeway simulation model publicly available.

Description of the INTRAS Model

INTRAS (Integrated Traffic Simulation) is a microscopic model that simulates the movement of each individual vehicle on the freeway and surface street network, based on car-following, lane-changing, and queue-discharge algorithms. The model was originally developed for the FHWA in the late 1970s to assess the effectiveness of freeway control and management strategies (e.g., ramp metering and incident detection). The model was successfully used recently to generate design alternatives for improving the operation of existing weaving sections (*11*).

The model is operational on mainframe computers. Computer run times for typical weaving sections range from 15 to 60 sec of CPU time on an IBM3091 mainframe for a 30-min duration of simulation, depending on the length of the weaving section, the number of vehicles being processed, and the output options.

INTRAS requires that the network first be coded into links and nodes. Links represent unidirectional traffic streams with homogeneous traffic and geometric characteristics, and nodes indicate the locations where these characteristics change. Figure 1 illustrates the INTRAS coding of a typical weaving section in this study. An important factor in the development of the link/node diagram is the correct designation of lanes between the different links (lane alignment); this ensures that the design configuration of the weaving section is correctly interpreted by the model. Numerous preliminary computer runs were performed on each site to verify that the data had been coded correctly.

Input to the model consists of data on design characteristics for each link (length, number of lanes, location, and length of the acceleration and deceleration lanes), free-flow speeds, vehicle composition, traffic volumes (total and lane distributions), and percent of trucks for the freeway and ramps. Origin-destination (O-D) data can be input or computed by the program.

The output from the standard version of the model provides the total travel (veh-mi), average and total travel time, volume, density, average speed, number of lane changes, and average and total delay. These of effectiveness (MOEs) are provided for each link and for the total network at user specified time intervals during the simulation.

Model Modifications and Enhancements

Because the model output did not provide the speeds of the weaving and nonweaving vehicles, which are the MOEs most used to determine the level of service (LOS) at weaving areas, the program was modified to estimate the average travel times and speeds of vehicles for each origin and destination. Here, the freeway origins are the upstream end of the freeway and the onramps (Nodes 1 and 2 in Figure 1), while the freeway destinations are the offramps and the downstream end of the freeway (Nodes 3 and 4). The average speeds of weaving and nonweaving vehicles could be then estimated using the O-D specific information and the speeds and travel times in the weaving section. The calculation of speeds consisted of the following steps:

1. The average travel time was calculated for each movement in the weaving section (Link 2,3 in Figure 1). For example, the average travel time of the freeway-to-freeway vehicles is equal to the O-D travel time between Nodes 1 and 2, minus

the average travel times on freeway Links 1,2 and 3,4. Similarly, the average travel time of the onramp-to-freeway vehicles is equal to the travel time between Nodes 2 and 4, minus the average travel time on freeway Link 3,4.

2. The average travel time for the weaving and nonweaving vehicles was calculated using the movement-specific predicted volumes and travel times. For example, the average travel time of weaving vehicles is equal to the volume-weighted average of the freeway-to-ramp and ramp-to-freeway travel times estimated in Step 1.

3. The speeds of the weaving and nonweaving vehicles were calculated from the weaving section length and the average travel times estimated in Step 2.

This process was automated using spreadsheet microcomputer packages (Lotus, Quattro). The output from the INTRAS model was transferred directly from the mainframe to the microcomputer. Procedures were written for the spreadsheet programs to process the output and calculate the performance measures.

Modifications were also made to the logic to improve the ability of the model to simulate the ramp merging situation. The process of lane changing in general, and ramp merging in particular, can be described as a gap acceptance phenomenon. Consider Vehicle *A*, which desires to merge into a gap between Vehicles *B* and *C* (*B* currently is the leader of *C*). Vehicle *A* will accept the gap if the time headway between it and Vehicle *B* is greater than some critical value $g(A,B)$ and the time headway between itself and Vehicle *C* is greater than some critical value $g(A,C)$. However, the critical time headway values are not constant but are dependent on the following considerations:

- The critical time headways depend on the speeds of the two vehicles. For instance, Vehicle *A* will accept a smaller value of the critical headway if it is going slower than Vehicle *B* than it will if it is going faster than Vehicle *B*.
- The lane change takes place over a finite period of time. During this time period, the lane changer can adjust position with respect to the new leader by braking.
- The new follower may cooperate with the lane changer by braking to increase the size of the gap.

The INTRAS model combines the three considerations listed above into a measure called "risk." The lane change phenomenon can then be described as the acceptance or rejection of a critical value of risk, with respect to both the leader and follower in the new lane. The existing INTRAS model uses a constant value for the value of critical risk. Although the model works well in that vehicles complete their merge from an acceleration lane, it leads to a rather asymmetric distribution of successful merges versus the distance from the end of the acceleration lane. Thus, the model was modified by adopting logic developed for the FRESIM model, currently under development, which will be the successor to INTRAS. The modification consists of replacing the constant value of critical risk with a function that starts with a low value at the beginning of the acceleration lane and increases to a maximum value at the end of the acceleration lane. The rate of increase is the square root of the ratio between the distance of the vehicle from the end of the acceleration lane and the length of the acceleration lane. Preliminary results indicate that this process provides a good description of the merge process.

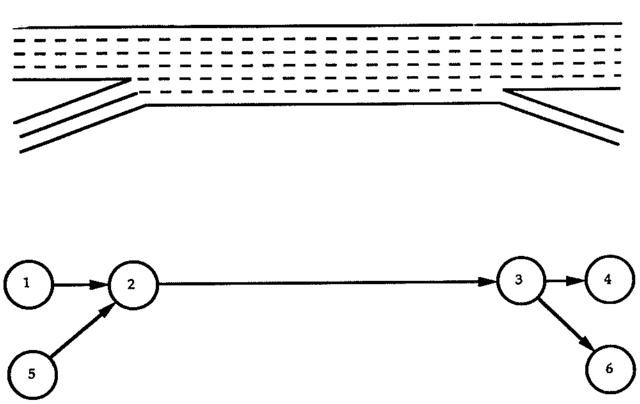

FIGURE 1 Sample coding for the INTRAS model.

MODEL APPLICATION

INTRAS was initially applied to several sample data sets to gain experience with the model and to test the sensitivity of input data and model parameters. The results from this initial application indicated that the model can simulate weaving operations with reasonable accuracy and can be used to predict traffic performance at existing freeway weaving sites.

The Data Base

Eight major freeway weaving sections were chosen for the application of the model. The selected sites represented a wide range of section configurations and design characteristics, such as length, number of lanes (*N*) in the weaving section, number of approaching freeway lanes, and number of lanes for the onramp and offramp) (see Figure 2). The configuration of each test site (A, B, or C) is given according to the definitions in the HCM. This classification is based on the minimum number of lane changes that must be made by weaving vehicles as they travel through the section. Type A weaving areas require that each weaving vehicle make one lane change to execute the weaving movement. Type B sections require vehicles in one weaving movement (onramp to freeway or freeway to offramp) to make one lane change while vehicles in the other weaving movement may accomplish their maneuver without changing lanes. Type C sections require vehicles in one weaving movement to make two or more lane changes while vehicles in the other weaving movement may accomplish their maneuver without changing lanes.

Information on traffic characteristics was collected using video recordings (see paper by Cassidy et al. in this Record). Six hours of operations were filmed on each site to obtain a range in traffic conditions. The data extracted from the tapes consisted of traffic volumes for each movement in the weaving area; the proportion of trucks, buses, and recreational vehicles; and the speeds of weaving and nonweaving vehicles. The data were extensively checked and verified for accuracy; data from 12 hr of operation were discarded due to congestion, incidents, and inclement weather during the videotaping. The

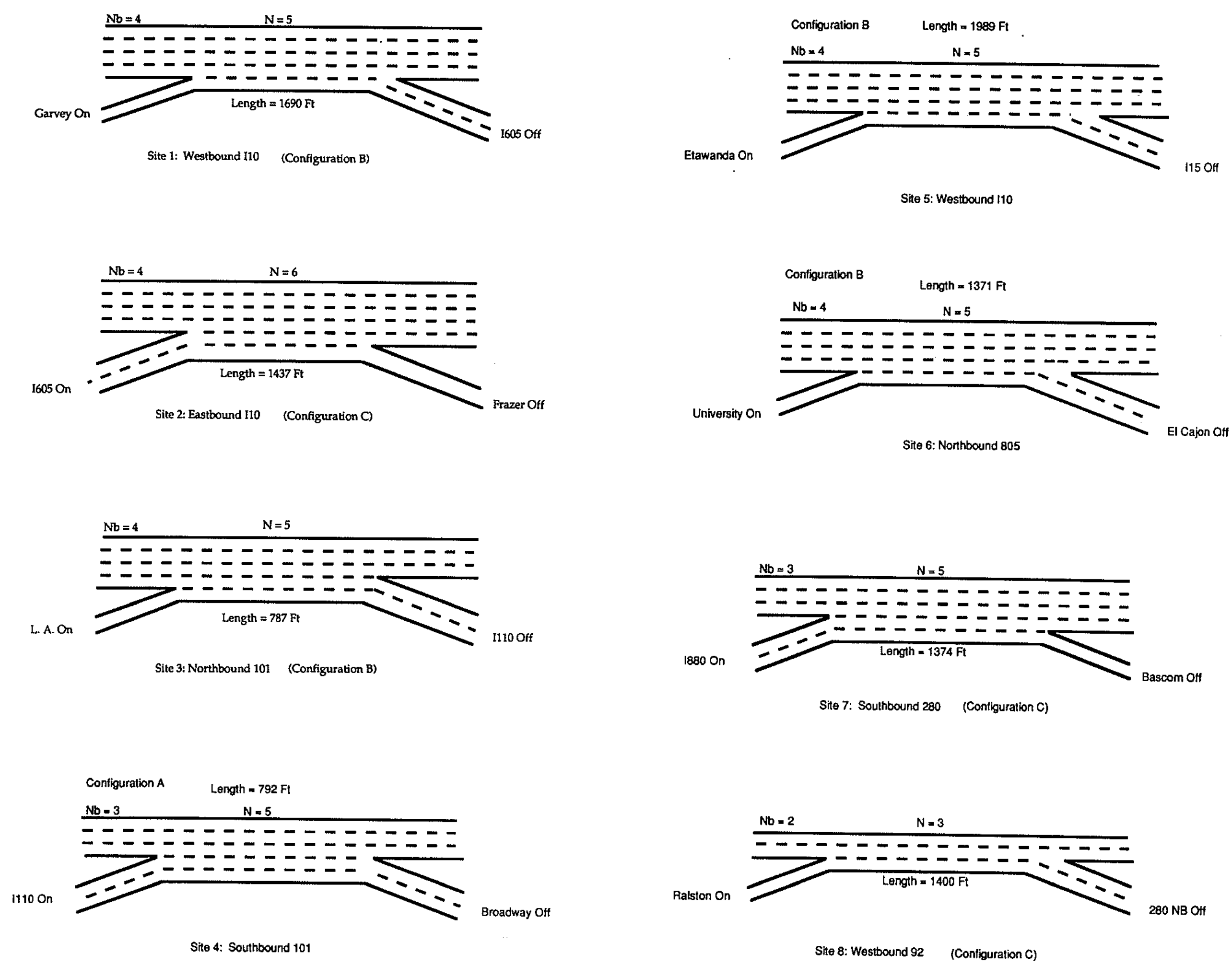

FIGURE 2 Selected test sites.

final data base consisted of 36 data points considering hourly volumes (in pce/hr), and represented a range of operating conditions at each test site.

Application to the Test Sites

The INTRAS model was applied to all the data sets using the field-collected data as input parameters. Regarding the application of INTRAS in this study:

- No adjustment of the internal model parameters was performed to get the best possible match of field measurements with the model predictions on each individual site. Therefore, the results represent the straightforward application of INTRAS and not the findings from calibrating the model on particular sites.
- INTRAS is a stochastic model, i.e., through random numbers, driver/vehicle characteristics are assigned. Therefore, the results from a simulation run may vary with the input random number seed for otherwise identical input data. Ideally, repeated simulations with different input random seeds should be made to gauge the effect of different random numbers. The results from tests performed on a number of data sets indicated that this variation in the predicted speeds of vehicles was between 1 and 2 percent.
- The results from the INTRAS model may also vary with the length of simulation time, especially for congested conditions. In this study, 30-min simulation runs were performed on all data sets. Intermediate cumulative outputs (every 10 min) were also printed, and the results were examined to test the stability of the simulation results. On most of the data sets, this variation was minimal (less than 1 percent), indicating that the model results are stable.

Analysis of the Results

Comparison with Field Measurements

Figure 3 shows a comparison of the measured and INTRAS-predicted speeds of all vehicles in the weaving area under different flow levels in different weaving sections. Each data point represents the average speeds of all vehicles for a 1-hr time period. The differences between the measured and INTRAS-predicted speeds were within 10 percent (approximately 5 to 6 mph) for the entire range of simulated operating conditions. Also, the mean percent difference was only about

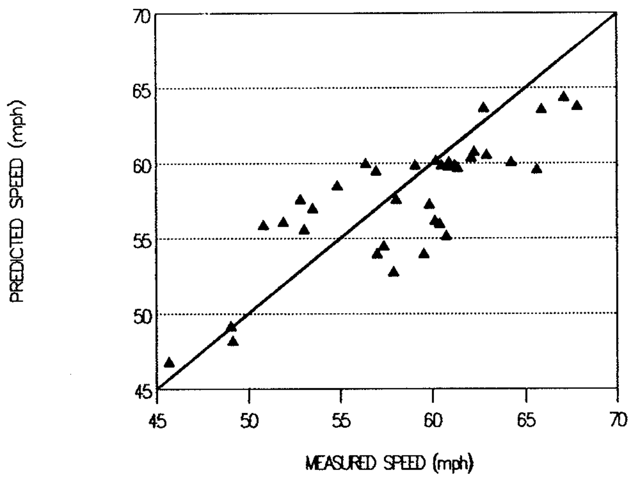

FIGURE 3 Average speeds, all vehicles—measured versus predicted.

1 percent, considering the absolute percent differences on each data set.

The largest differences between measured and INTRAS-predicted speeds occurred on test sites that had considerable variation in the measured average speeds for similar traffic volumes and patterns (see Figure 4). The field data exhibits a much larger scatter than the INTRAS-predicted values. This scatter would not likely be replicated in a simulation model, which uses car-following algorithms equivalent to fundamental speed-flow relationships and apparently does not include sufficient random variations.

The measured and INTRAS-predicted average speeds were compared separately for the weaving and nonweaving vehicles (see Figure 5). The estimated mean percent differences between measured and predicted speeds were very small (1 percent for the nonweaving vehicles and about 3 percent for the weaving vehicles). Again, the mean differences were calculated based on the absolute percent differences on each data set. These differences are insignificant, considering the stochastic nature of the INTRAS model.

The differences between measured and predicted values were within 10 percent in most of the data sets. Larger discrepancies were observed for a few data points, especially for the weaving vehicles. This occurred again at test sites for which the measured speeds were higher for higher volumes, contrary to what is normally expected. Such variabilities in the field data, also noted in the speed/volume scatter plots shown in Figure 4, could be due to the differences in driver behavior for different times of day (peak versus off-peak conditions). Comparisons were made between the predicted and measured speeds, considering only the peak period data (24 data points) (see Figure 6). Closer agreement was obtained between measured and predicted values (most of the differences were between 5 and 7 percent) for most of the data points, and the average differences were insignificant.

Comparison with Existing Analytical Procedures

The existing procedures for the design and analysis of freeway weaving sections generally fall into two major categories: those based on traffic volumes (*5,8*), and those based on the speeds of vehicles in the weaving section (*1,12–14*). The volume-based approaches are generally design oriented, whereas the speed-based procedures are more suitable for operational analysis. All methods, except the HCM-65 technique, estimate the average speeds of weaving and nonweaving vehicles and determine the LOS of the weaving section based on those predicted speeds. All methods use the same basic geometric and traffic data (number of lanes and length of the weaving section, and volume for each movement) to estimate the average speed of vehicles. The basic difference in the existing methods is the way the weaving section configuration is considered to account for the number of lane changes (*2*).

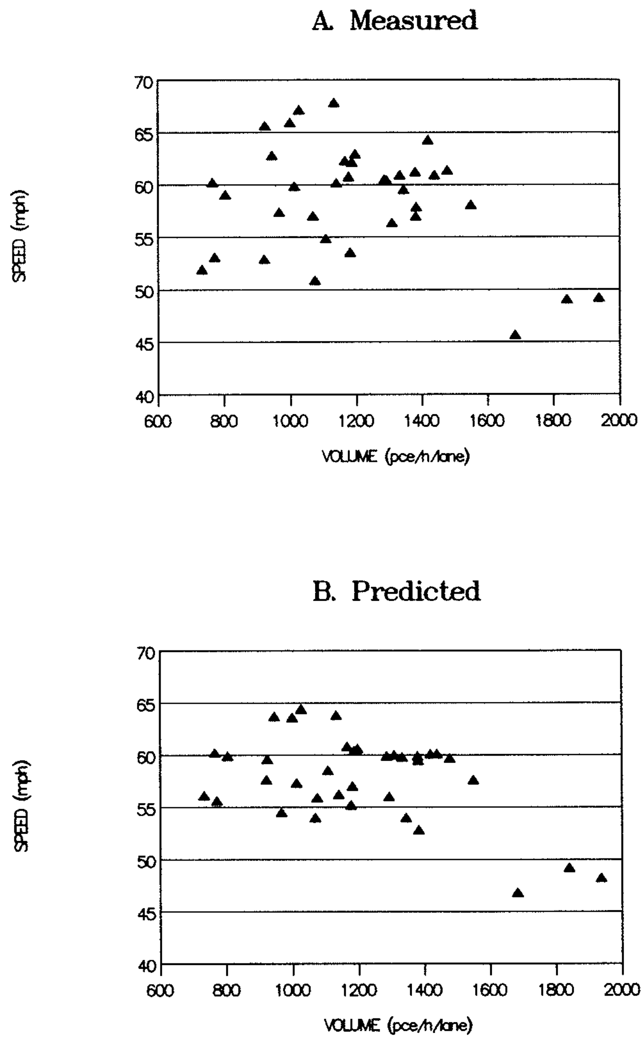

FIGURE 4 Speed/volume relationships.

All the existing analytical methods were applied to the same eight test sites used in the simulation experiments. The predicted and measured performance measures were then compared with field measurements and the INTRAS predictions.

Figure 7 shows the mean and standard deviation of the differences between the measured and predicted speeds for all the data sets. The results from the HCM-65 method are not shown since this method does not provide the speeds of weaving and nonweaving vehicles. The results shown in Figure 7 indicate that fairly large discrepancies exist between the

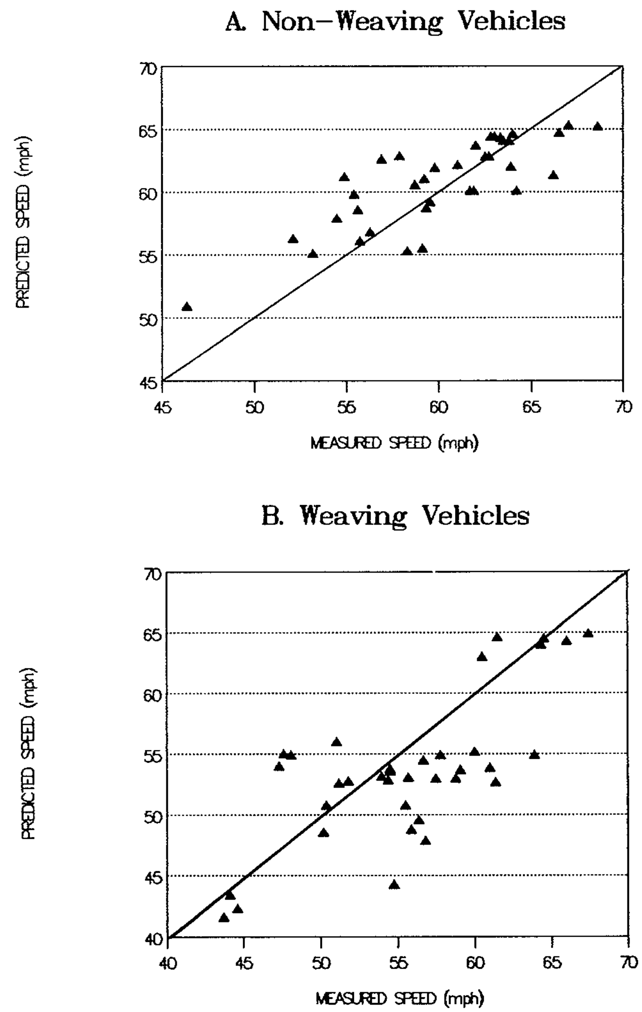

FIGURE 5 Measured versus predicted speeds.

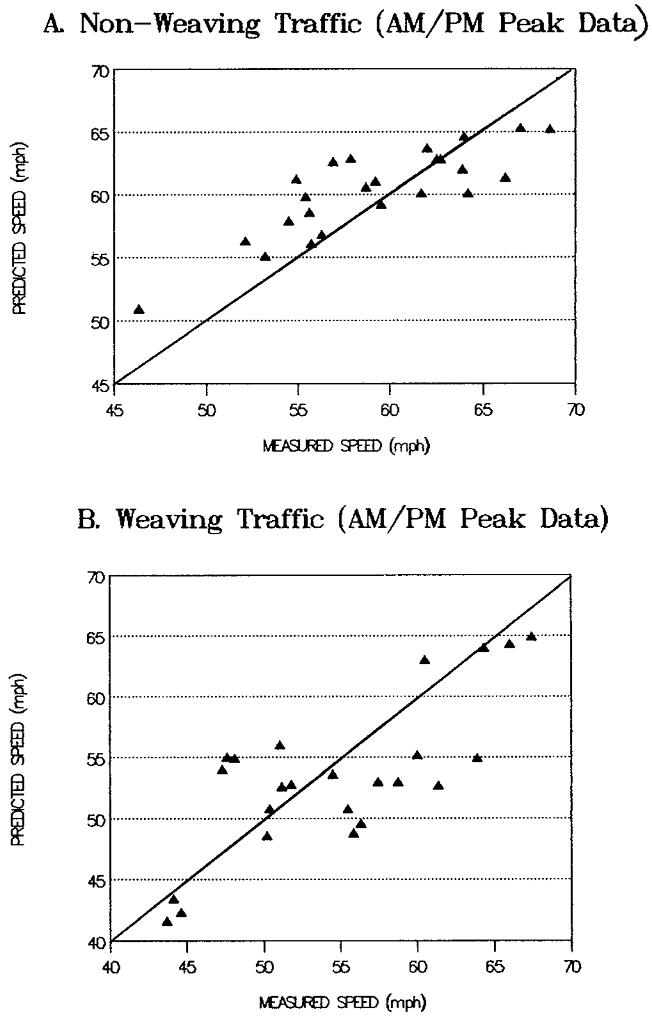

FIGURE 6 Measured versus predicted speeds (a.m./p.m. peak data).

measured and predicted values from the existing analytical procedures. INTRAS estimates, in contrast, are fairly close to the field data. The following comments could also be made from the application of existing methods:

- All methods underestimate the speeds in the weaving section. No consistent patterns were found in the differences between predicted and observed speeds. Large differences were noted between sites.
- Several of the existing methods have limits for certain geometric and traffic parameters (including section length, total or proportion of weaving traffic) that preclude their application on a number of sites with commonly occurring conditions.

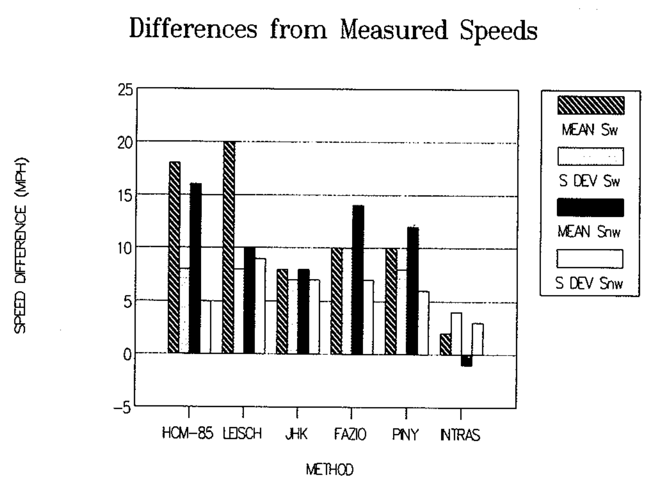

FIGURE 7 Comparison of methods.

PREDICTING WEAVING AREA OPERATIONS

The comparison of the INTRAS-predicted and field-measured performance measures indicates that simulation can reasonably replicate field conditions at weaving areas. Therefore, it can potentially be used to assist in the development of design and analysis procedures by predicting traffic performance under different geometric and traffic conditions.

The next step in this study was to investigate the potential of INTRAS to predict the "capacity" of a weaving section (i.e., at which level of traffic volumes the traffic performance becomes unacceptable, considering the speeds of vehicles and other MOEs. It is extremely difficult to estimate the capacity of weaving sections due to the range of the configurations of major weaving sections, the proportion of weaving vehicles in the traffic stream, and several other factors. Therefore, such application of the model should be considered as exploring the model's potential rather than developing capacity estimates.

Two test sites were selected for the simulation experiments: westbound I-10 in Los Angeles (WB10; Site 1) and northbound 805 in San Diego (NB805; Site 6). As shown in Figure 2, both sites have five lanes in the weaving section and have the same configuration (Type B sections according to the definition in HCM-85). The basic difference between those sites is the weaving ratio (*WR*), which is the ratio of the smaller weaving volume to the total weaving volume. On the NB805 test site, the weaving movements are balanced throughout all time periods ($WR = 0.45$), but they are unbalanced on the WB10 weaving section ($WR = 0.07$). In addition, the WB10 site has a longer length (1,690 ft) than the NB805 section (1,371 ft).

The simulation experiments were performed as follows:

- Input data on geometrics, free-flow speeds, the ratio of weaving and nonweaving traffic, the *WR*, and the proportion of ramp traffic in the total volume were held constant for all simulation runs. The data on traffic characteristics were taken to equal the average values from the different traffic conditions at each test site.
- The total volume was allowed to vary on each run to yield different volume/capacity (v/c) ratios at the weaving section. A typical capacity of 2,000 pce/hr/lane was assumed to determine the input total volume for each run.

A total of 11 simulation runs were performed on each test site for different volumes corresponding to v/c values between 0.2 and 1.25. The model outputs were then analyzed to obtain the average speeds of vehicles, traffic volumes, density, and the number of lane changes at the weaving section.

The results for each test site are shown in Figure 8. The speeds plotted are the average speeds of all vehicles in the weaving section for a 1-hr time period. The INTRAS-predicted speed against v/c curves are very similar for both sites, despite the large differences in lane-changing activity between the two sites, and show that the capacity is higher than 2,000 pce/hr/lane. The model predictions indicate that a value of 2,200 to 2,300 pce/hr/lane might be used for capacity that corresponds to a v/c ratio between 1.1 and 1.15. Figure 8 also shows that the average speeds remain about the same, approximately 35 mph, for even higher v/c ratios. However, examination of the model outputs indicated the results were unstable, and the volumes predicted to pass through the weav-

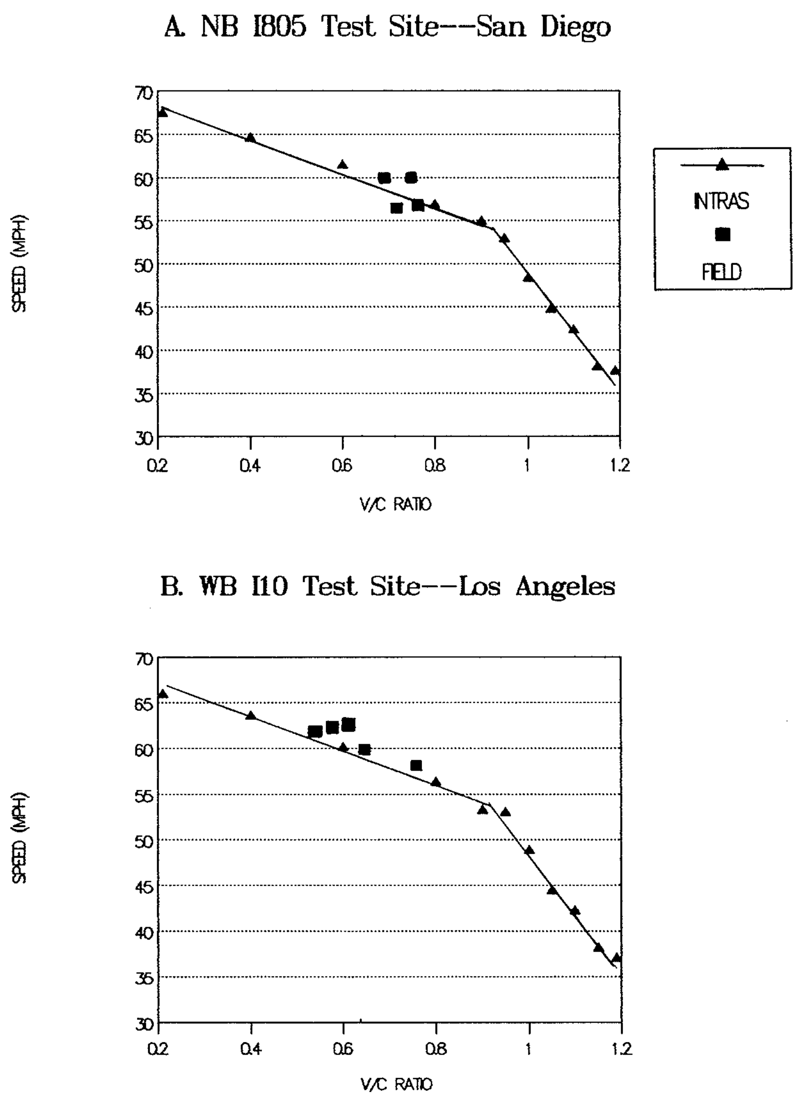

FIGURE 8 Relationship between speed and v/c ratio.

ing section were lower than the input values, indicating upstream congestion.

CONCLUSIONS

Summary of the Study Findings

The following significant findings were obtained from the application of the INTRAS microscopic simulation model, as modified for this study, on eight major freeway weaving sections:

- The INTRAS model reasonably replicated traffic operations on all eight weaving sites. In most of the data sets, the INTRAS-predicted average speeds of both weaving and nonweaving vehicles were within 10 percent of the field-measured values. Larger discrepancies (approximately 15 percent differences between measured and predicted values) were mostly due to the inherent variability in the field-collected data.
- The patterns of the simulation results were consistent for the entire range of traffic conditions on all sites. Good agreement between measured and predicted values was obtained for all combinations of design characteristics and demand patterns.
- The INTRAS-predicted performance measures are considerably closer to the field data than the estimated values from all existing analytical methods for the design/analysis of freeway weaving sections. In addition, the existing analytical procedures produced inconsistent results for several data sets, indicating that they may not be applicable for the entire range of commonly occurring field conditions.
- The results from the model application to predict the operation of the weaving areas for a range of traffic levels were very promising. The results were consistent for both sites, and the predicted capacities reflect recent measured values. Thus, the model can be used to predict performance for weaving sections when data are not available or are difficult to obtain.

Future Research

The findings reported in this paper, as well as other results from the ongoing research on major freeway weaving sections, clearly indicate that a better understanding of the operation of weaving areas and development of improved design and analysis procedures are high priority research needs. The simulation approach holds considerable potential for assisting in the development of such improved procedures.

The following steps are proposed for future research:

1. Operation of weaving sections near or at capacity conditions. Application of the INTRAS model and comparison of the results with field data from sections operating near or at capacity conditions will provide supplementary evidence on the ability of the model to predict performance accurately for a wide range of conditions.
2. Capacity versus weaving section configuration. The relationships between the length and configuration of the weaving section, lane changing, and upstream volume distribution are not well understood, and their implications for design and capacity analysis are not clear. Simulation will be used, in conjunction with field data, to explore these relationships and their effects in the operation of weaving areas.
3. Performance measures. The results from the INTRAS simulation runs, for the existing and additional test sites, will be further analyzed and compared with field data to determine if other performance measures (e.g., number of lane changes, density, and percent time delay) are more appropriate for design and operational analysis of weaving sections.

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