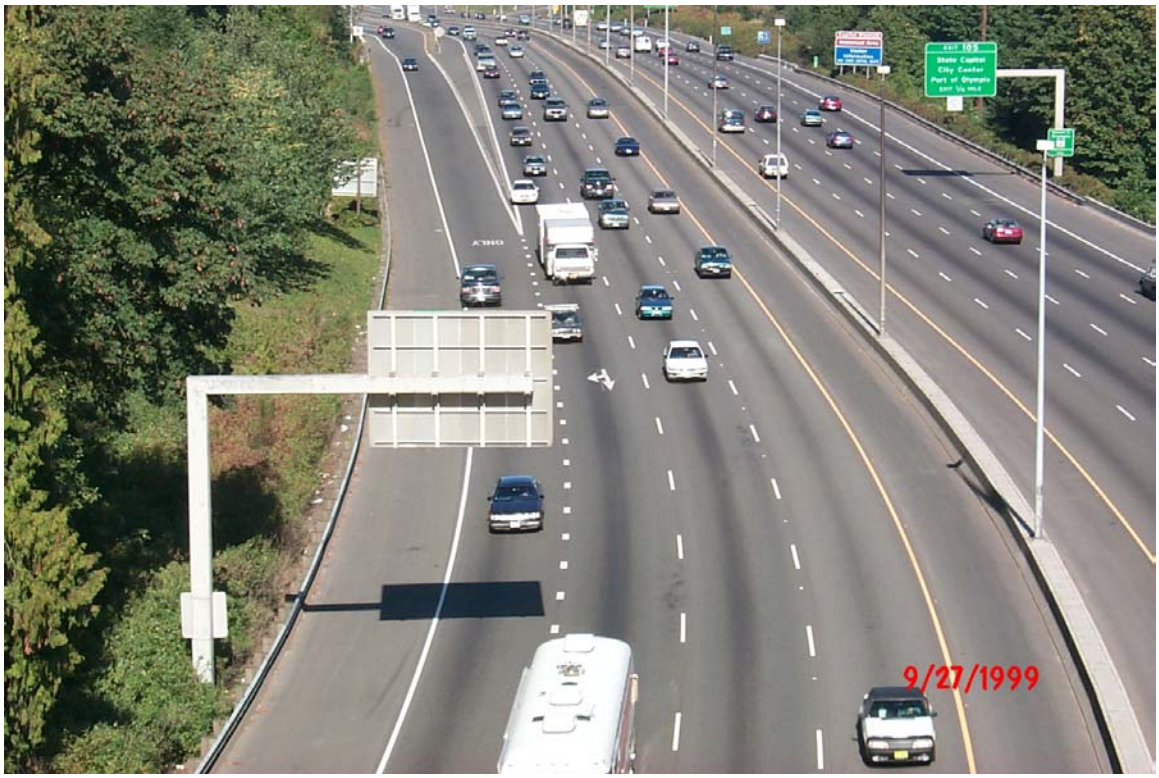
WEAVE ANALYSIS AND PERFORMANCE:

THE WASHINGTON STATE CASE STUDY



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ABSTRACT

This research study summarizes current practices for weaving section design and their development. Current methodologies and modeling techniques were assessed and then tested with operating characteristics of a major weave section in Washington State. The analysis compared estimated level of service for the existing configuration and alternative designs to evaluate operational improvement opportunities. A safety analysis for collision type and severity was developed from the history of accidents through the weaving section and used to estimate collision reduction opportunities from the alternative designs. The study recommended that weaving sections undergo critical review of traffic projections and roadway characteristics before implementation to avoid operational impacts that may extend beyond the weaving section. Further research on the safety impacts in weaving sections is also recommended.

INTRODUCTION

As vehicle demands continue to increase on the nation's highways, previously overlooked highway elements will become critical to highway optimization and operation. Much research exists analyzing highway operations during peak demand periods. This research shows that urban freeways can perform adequately until a disturbance, such as a traffic crash, occurs. Recurring localized operational problems such as overloaded weaving sections have also been analyzed, albeit, to a much lesser extent. While it is clear from this previous research that safety and mobility can be improved through the use of a well-designed weaving section, we do not know the impact that many of the design decisions have on the current and future performance of weaving sections.

The Washington State Department of Transportation (WSDOT) has limited experience in studying major weaving sections but has a number of weaving sections in operation on the highway system. Operational problems with freeway weaving sections are routinely being experienced on the Washington State highway system. These problems include congestion as well as delays caused by incidents in weaving sections.

Weaving sections currently are designed in accordance with the *Highway Capacity Manual*. WSDOT and the Federal Highway Administration (FHWA) recognized a need to analyze the effectiveness of this procedure and consider other tools in assessing the performance and forecasting of weaving sections. A direct benefit of this project would provide analysis and guidance for WSDOT staff in the use of the Traffic Software Integrated System (ITRAF) simulation modeling programs that were developed for the FHWA.

In addition to the analysis of these methods, WSDOT also anticipates direct benefits in evaluation of a case study of a weaving section on the Interstate 5 corridor in Olympia that is currently exhibiting operational problems.

The research described in this paper identifies: (1) a literature search of weave analysis research, (2) an assessment of current methodologies and modeling techniques for traffic predictions in weaving sections, and (3) a comparison of predicted outcomes to actual characteristics from the analysis programs for weaving sections.

LITERATURE REVIEW

Weaving sections

A methodology for weaving design and analysis was first presented in the 1950 *Highway Capacity Manual* (HCM). It was based on field data collected at six weaving sites in the Washington D.C. and Arlington, Virginia, areas in 1947. Since that time, a number of approaches to analyzing weaving sections have been developed. Much of this work has been based on data collected in the late 1960s and the 1970s. This literature section provides a chronological review of weaving research, modeling, and model development, and safety research.

The 1950 HCM stated that at no instant could the number of vehicles in the act of crossing the crown line exceed the number that can crowd into a single lane. Thus, the total number of vehicles passing through a weave section, if all vehicles must perform weaving maneuvers more or less simultaneously, cannot exceed the capacity of a single lane. The manual stated that the effective length of a weaving section is influenced, at least at the better levels of service, by the distance in advance of the weaving section that drivers on one approach road can see traffic on the other approach road. This distance is used by drivers to adjust their speeds and positions before reaching the weave section. The manual also stated that the speed in combination with the length of the section also plays an important role in the function of the weaving section. Since it was understood that unless a section had sufficient gaps in the traffic stream, drivers might need to stop before entering the traffic stream so a facility with ordinary oblique entry has a capacity of about 1,200 vehicles per hour. This amounts to a loss of capacity from the maximum 1,500 vehicles per hour operating at 40 miles per hour. The manual found that maximum

volumes for weaving sections occur at speeds between 20 and 30 miles per hour. Higher speeds are possible only when volumes and traffic density were lower. The manual stated that whenever traffic density exceeds the critical density, speeds fall below 20 miles per hour, the capacities are lowered, and complete congestion or stagnation can occur within a few seconds. Doubling the traffic volume triples the length of the section required and doubles the number of lanes required for the weaving vehicles. A chart was presented for determining the operating characteristics of weaving sections.

Additional research (Normann, 1957; Hess, 1963; Leisch, 1958; Leisch, 1964) significantly expanded the chapter devoted to weaving sections in the next revision of the HCM (1965). The 1950 HCM chart used for determining the operating characteristics of weaving sections, the traffic volumes, and operating speeds attained by them, was further developed in graphical form. The chart was used in conjunction with a related formula to analyze a weaving section. The relationship between quality of flow and maximum lane service volumes was presented in a table to determine the number of lanes that were required on the weaving section under heavy flow conditions. The 1965 HCM recognized that weaving performance is fundamentally dependent on the length and width of the weaving section, as well as the composition of traffic. The 1965 HCM suggested that, regardless of length or number of lanes, a weaving section will become badly congested when the number of weaving vehicles approach the possible capacity of two traffic lanes. The manual also stated that the section will never operate satisfactorily unless traffic on the approach roadway is well below the practical capacities of these approaches and the weaving section has one more lane than would normally be required

for the combined traffic from both approaches. The manual presented methods for multiple weaving sections.

Although the 1965 HCM was a major improvement to weaving section analysis, it was not without inconsistencies. Research performed by Roess, McShane, and Pignataro (1974) understood that methods from the 1965 HCM were inaccurate in the prediction of level of service (LOS) and that these inaccuracies could be traced to ambiguities in the specification of service standards and the k-factor equivalence expansion mechanism of the HCM weaving procedure. The authors further speculated that inaccuracies were attributed to the fact that lane configuration was not considered as a parameter in the design and analysis procedure. The HCM method only determined the number of lanes needed and not the utilization of each lane.

The authors reviewed two potential lane configurations. They defined a ramp weaving section as a weaving section formed by consecutive on and off ramps joined by an auxiliary lane. A major weave section was defined to be one in which three or more entry and exit legs have two or more lanes forming a major fork, a major merge point, or both. The authors analyzed the effects of varying design and found that lane configuration sometimes resulted in weaving vehicles using only small portions of the roadway. The authors found that providing the correct total number of lanes was not sufficient to guarantee the predicted operating characteristics that were suggested by the 1965 HCM.

The authors also concluded that weaving movements in a ramp-weave take place in shoulder and auxiliary lanes. In major weaves, weaving flows tend to dominate the

movements through the weaving section. Where multilane entry and exit legs exist, weaving vehicles often occupy the majority of the roadway. The higher speed of nonweaving vehicles in the ramp-weave case indicated that weaving flow would expand to the outer lanes if the lane configuration and length permitted it. Where there was a balanced use of roadway space, an underutilization was apparent in the outer lanes and congestion occurred in the weaving lanes. In cases of wide speed differentials, lane configuration dictates that weaving vehicles become restricted to a limited portion of the roadway. The authors found that in major weaving sections there is a tendency to have higher weaving volumes and therefore it could be expected that weaving vehicles would take up a larger portion of the roadway section. The authors found that additional space is often available to traffic in ramp-weaves but exterior constraints prevent its use. Speed differentials of weaving and nonweaving vehicles in major weaving sections are less frequent and tend to be smaller and lane use in the exterior lanes is slightly higher than in ramp-weaves.

In 1975, National Cooperative Highway Research Program (NCHRP) Report 159 was published with a new procedure that takes into account additional variables, including geometrics, traffic composition, volumes of main line vehicles, and volumes of weaving vehicles for weaving section analysis. The study was conducted from field data collected at 14 northeastern sites. The intent of NCHRP Report 159 was to analyze the structure of the existing HCM procedures, evaluate the accuracy of each procedure, and analyze the consistency of the procedures in predicting performance. The study found that LOS and quality of flow are not functionally dependent upon each other, which was a fundamental belief of the 1965 HCM. A more accurate representation of LOS standards for weaving

and nonweaving vehicles seemed to produce a more accurate description of weaving section service characteristics. More importantly, the research found that geometric configuration is a vital design factor. The level of service accuracy in the 1965 procedure was generally found to be poor with LOS predictions that were often found to be higher than actual field conditions. To account for this the authors proposed the following changes to weave analysis: (1) Space mean speeds (average speeds for weaving and non-weaving traffic) rather than operating speeds should be used to develop LOS. (2) Service volume concepts of the HCM could be adapted and used for developing LOS of nonweaving traffic. (3) Volumes should be considered in passenger car equivalents adjusted in accordance with the HCM and that LOS should be defined separately for weaving and nonweaving flows. (5) Separate equations for major weaving sections and ramp weaving sections should be used. (6) Balanced design is sought but it should be recognized that configuration might prevent it from being realized.

Pignataro, McShane, Roess, Crowley, and Lee (1975) followed up on the NCHRP research and found that the best relationships describing weaving traffic were developed from the assumption that the ratio of weaving lanes to total lanes is proportional to the ratio of weaving volume to total volume. They found that the width required by weaving vehicles is directly related to the percentage of total traffic that the vehicles constitute. One of the prime results of the research leading to the new procedure was the determination of the maximum width that can be used by weaving traffic, which was dependent on configuration. The procedure allowed for analytic or nomographic solutions and was recommended for use in lieu of the 1965 HCM.

In 1979, Leisch presented the Highway Capacity and Quality of Service Committee with a procedure using nomographs for all solutions that he had developed using data available from previous work by the Bureau of Public Roads in 1963 and from the NCHRP report.

Users found the procedures presented in the NCHRP report difficult to apply, even though the procedures had demonstrated accuracy and sensitivity to lane configuration. Thus a modified procedure was developed and the results were published in an interim weaving procedure (TRB Circular 212, 1980). The circular also included the nomographic weaving procedure developed by Leisch. Circular 212 was published although the two weaving procedures often yielded substantially different results.

The FHWA sponsored an effort to compare the two procedures and to make recommendations for change in the 1985 HCM. Reilly, Kell, and Johnson (1984) reported that, of the two methods in Circular 212, neither was capable of describing weaving section operations and this led to development of another procedure, the JHK procedure.

The Highway Capacity and Quality of Service Committee commissioned a project to resolve this conflict between procedures and develop a revised procedure that was eventually adopted into the 1985 HCM. Roess (1987) reported on that effort. Complete descriptions and definitions of configuration types for weaving sections were now given and defined by the number of lane changes that must be made to successfully complete each weaving maneuver. (*These descriptions are included in the report under methodology on page 20.*) Formulas were derived that predicted if the number of lanes

available would be constrained or unconstrained operations in the weaving section. Weaving capacity was established at 1,800 passenger cars per hour (pcph) for Type A weaves and 3,000 pcph for Type B & C configurations. The maximum flow per lane was established as 1,900 passenger cars per hour per lane (pcphpl), in recognition of the turbulence that exists in weaving sections. Level of service criteria were established. Roess reported that the most controversial fact of this research was the setting of maximum weaving length criteria at 2,000 feet for Type A configuration and 2,500 feet for Type B and C configurations. The author suggested that these limits were based on the fact that operations beyond these lengths were basically isolated merging and diverging actions rather than weaving movements.

Fazio and Rouphail, (1986) examined the three procedures (Leisch, JHK, and 1985 HCM) to propose specific refinements to account for the lane distribution of traffic upstream of the weaving section and the lane shifts traffic would make in the weaving section. Statistical testing of the refined procedure against the three procedures at more than 50 sites nationwide indicated that their changes tended to predict observed average running weaving and nonweaving speeds more closely than with the other procedures. The researchers stated that the 1985 HCM procedure continues to be limited in its application because many locations warranting analysis failed to satisfy the constraints on weaving section capacity or length. The researchers reported that the total number of lane shifts required by drivers in weaving sections affected both weaving and nonweaving speeds. Therefore, the inclusion of lane shift as an independent variable in average running weaving and nonweaving speed models considerably enhanced the predictive ability of the models. The researchers suggested that the proposed models

yielded the highest correlations with actual weaving and nonweaving speeds. The researchers recommended that tying safety characteristics (such as accident frequencies, type, and location) to design and analysis procedures can result in defining lower bounds on section length and the number of lanes for weaving sections.

Researchers at the Institute of Transportation Studies at University of California-Berkeley studied freeway weaving sections in California with simulation models (Skabardonis, Cassidy, May, and Cohen 1989). They described the Integrated Traffic Simulation microscopic model (INTRAS) as well as the modifications and enhancements performed on the model for their study. This study used eight major freeway weaving sections for the application of the model. The sites chosen had various section configurations and design characteristics, such as length, number of lanes, number of approaching freeway lanes, and number of lanes for the on ramp and off ramp. Data for this analysis was collected using video recordings. Six hours of operations were filmed on each site to obtain a range in traffic conditions. The model was used to assess if simulation can predict the operation of weaving sections with reasonable accuracy. It investigated the potential of simulation to augment field data in developing improved methods for the design and analysis of weaving sections. Classifications for the weaving sections were from the definitions provided in the 1985 HCM. The model was applied to the data from the test sites with no adjustments to the default parameters. The model outputs were predicted measures of effectiveness (MOE), including average speed, total travel (veh-mi), average and total travel time, volume, density, number of lane changes, and average and total delay. The model assigned driver/vehicle characteristics randomly and tests performed on a number of data sets indicated that the variation in predicted

speeds was between 1 and 2 percent. Also, testing on length of simulation time indicated that this variation was minimal and that the model results were stable.

The researchers also applied the existing procedures of the *Highway Capacity Manual* and of Leisch to the eight sites for comparison to the simulation method. The research concluded that all the analytical methods underestimated the speeds in the weaving sections, and large differences were noted between sites. Some of the methods had limits for certain geometric and traffic parameters that precluded their application on a number of sites with commonly occurring conditions. INTRAS results for average speeds were close to the field data. The patterns of the simulation results were consistent for the entire range of traffic conditions at the eight sites regardless of the design characteristics and demand patterns. This was not the case with the existing analytical procedures, which produced inconsistent results for data sets gathered from several locations.

Cassidy, Skabardonis, and May (1989) used the same data from the eight sites modeled in Skabardonis et al. (1989) with the six existing methods (HCM-65, Leisch, NCHRP 159, JHK, HCM-85, Fazio) for weaving analysis in an attempt to develop more reliable results for predicted average speeds of weaving and nonweaving vehicles. The existing JHK model and the HCM model were found to be poor predictors for this data. Two types of analysis were done on the data. Regression analysis results were calibrated for all eight sites, but each model was unique and led the researchers to conclude that developing a model to account for all geometric and traffic factors would be difficult. Using a statistical analysis technique developed by Breiman (1984), the researchers built an analysis of the freeway sections without weaving sections, and then compared the

results to analysis output with factors related to the weaving phenomena (e. g. conflicts between weaving vehicles). Factors having the greatest influence on major freeway weaving sections could not be identified because of traffic and geometric variations from location to location. The researchers concluded that the operation of freeway weaving sections might be largely influenced by what is occurring in individual lanes where congestion at freeway weaving sections often occurs as a result of a breakdown in a single lane.

Cassidy and May (1991) proposed a more reliable procedure that evaluates traffic flow behavior in individual lanes of weaving sections by predicting the distribution of vehicles at any location within the right-most lanes of a major weave. The study used empirical data that was gathered by videotaping in the auxiliary lane and the right-most freeway lane of the weaving sections at nine locations. Each weaving section was divided into fixed lengths to measure the volumes, and all weaving and nonweaving movements were extracted. The data was plotted, and the traffic flow parameter that appears to be most clearly influencing the behavior of freeway-to-ramp vehicles was the weaving flow rate. It suggested that, as weaving flows increase, freeway-to-ramp motorists become more anxious to make lane-changing maneuvers over shorter traveled distances. This suggests that lane-changing characteristics are a function of gap availability in conflicting traffic streams.

Depending on the length of the weaving section, empirical charts defined a technique to evaluate the changing lane volumes in the weaving section. Presegregation and lane changing within the weaving section that occurs with a two-lane off ramp might limit the

use of the technique. Using extensive simulation modeling with INTRAS to test the method, the research indicates that weaving section capacity was shown to be 2,200 pcph at any point in the weaving section, and lane-changing capacity was found to range from 1,100 to 1,200 pcph across a single lane line over any 250-foot segment within the weaving section. Where application of this technique yielded higher flow and lane changing values, operational breakdown was expected and the users would consider geometric modifications.

The researchers also found the value of density at capacity to be roughly 46 passenger cars per mile per lane. Compared to the 85 HCM value for basic freeway segments to be 67 pcphpl, this value was expected to be lower because of turbulence created by weaving traffic streams which reduces optimum densities and generates reduced traffic speeds.

Ostrom, Leiman, and May (1993) studied the simulation modeling program called FREWEV that was developed by the Institute of Transportation Studies at the University of California Berkeley to compare alternative designs of major weaving sections. It uses the point flow concept, which the authors report to be more reliable in estimating weaving section behavior in the right two freeway lanes and the ramp auxiliary lane.

Wang, Cassidy, Chan, and May (1993) sought to evaluate the capacity of freeway weaving sections and to define the critical region of a freeway weave and a functional value of weaving capacity in this region. The research project used data gathered by video recordings for previous research (Cassidy, et al., 1989) for one Type B major weaving section. The simulation model INTRAS was used to predict flows and lane-changing rates within the weaving section. The researchers gradually increased traffic

volumes sequentially in repeated simulation runs. Simulation was used to identify flow conditions at the advent of congestion. Capacity was defined as the combined value of flow and lane-changing rates that approached the boundary between uncongested and congested operation. Five hours of data at free-flow conditions were gathered to calibrate the model, and 30 minutes of high-flow data was collected and used to validate the model. Empirical data analysis revealed two important considerations: (1), the highest point flows occur in the first 250 feet of the weaving section (the critical region), and (2), the merging and diverging movements create very high flows at a single point (or lane segment) within the weaving section.

The researchers made adjustments to the model and tested the adjustments until the simulation output closely matched observed conditions. The researchers specified an advanced warning sign, adjusted the distribution of vehicles across the upstream lanes, and adjusted the driver type parameters (there were 12 driver types in the model, ranging from very timid to aggressive). The model was run to identify the boundary between uncongested and congested operation and the researchers relied on the error messages that were generated by the program, when vehicles could not execute desired maneuvers as a result of dense vehicle activity, to reflect congested or "breakdown" conditions. Findings were that the capacity of a freeway weaving section is exceeded if the functional flow in the critical region exceeds 5,900 pcph. This rate is the total rate of vehicles that can occupy any portion of the critical region, rather than the through-moving flows. The section is also said to exceed capacity when the total traffic demand exceeds 2,200 pcphpl. The research observed that the highest concentration of vehicular activity occurs near the merge gore, especially as the weave section reaches capacity.

When observed or predicted flows and lane changing rates in the critical region approach or exceed capacity, operational problems can be anticipated.

Roess, McShane, and Prassas (1998) developed updates for the 1985 HCM procedures because the existing procedures were found to be under-estimating average operating speeds of weaving and nonweaving vehicles in many sections for which data had become available for verification. The updates were adopted for the 1997 HCM.

The NCHRP sponsored another study of weaving section operations (Project 3-55(5)) for updating of the fourth edition of the *Highway Capacity Manual* 2000. This project relied heavily on simulation to produce a wide range of data. It developed a new model that substantially differed in its definition of capacity and in its results from previous work in the HCM, and the model was rejected. The Highway Capacity and Quality of Service Committee then sponsored another project to revise existing formulas in the HCM and to incorporate some of the capacity concepts from Project 3-55(5), if possible (Roess and Ulerio, 2000). The project produced improvements including changes for the speeds of weaving and nonweaving vehicles, adjustments to the constants that generate the weaving intensity factors, and an attempt to develop a model for capacity of a weaving section. The researchers used a database of 21 hours of data from 18 different sites gathered in 1983 to come up with constants that would not vary based upon whether the operation is unconstrained or constrained. The new models continue to suggest that capacity is affected by the length of the weaving sections. For Type A configurations there appears to be a great sensitivity to length. Type B and C sections show a small

difference in capacity. (*Definitions in methodology, page 20*) The authors also found that, when higher free flow speeds are achieved, higher capacity values will occur.

Safety

Little research exists that specifically addressed weaving and safety performance. The following presents a limited discussion of safety literature.

Safety, together with capacity, speed, operational flexibility, cost, and level of service, constitute fundamental design criteria. Cirillo (1970) analyzed the effective length of weaving sections, acceleration lanes, and deceleration lanes and the effect on accident experiences of these facilities. Cirillo examined the accident experiences between weaving sections, acceleration lanes, and deceleration lanes from 700 weaving sections in twenty states based on data gathered in the early 1960s.

Cirillo examined sites by average daily traffic (ADT), the length of the weaving section, and accident rates and concluded that for ADT greater than 10,000 vehicles, the provision of longer weaving sections effectively reduced the accident rate. For ADT below 10,000 vehicles, no discernable trend was found. As the percentage of merging or diverging traffic increased, the accident rate also increased regardless of the length of the speed change lanes. The accident rates were substantially higher for acceleration lanes than for deceleration lanes. Cirillo found that the shorter the length of the lane the higher the accident rate regardless of the percentage of merging or diverging traffic. The effect of increasing the length of acceleration lanes appears to be substantial when the percent of merging traffic is greater than 6 percent, and below the 6 percent range improvement was speculative and probably not cost beneficial. Similar results for deceleration lanes

were reported, but the improvement by increasing the length of deceleration lanes was not as great.

Fazio, Holden, and Rouphail (1993) examined ten ramp weaving sections with crash counts and modeled each site in INTRAS, which had rigorously been validated at weaving sections in previous research (Skabardonis, Cassidy, May, and Cohen 1989). The microscopic freeway simulation program would count two types of conflicts: following conflicts, which could lead to rear end crashes, and lane changing conflicts, which could lead to sideswipe or angle crashes. The authors pointed out that conflicts do not have to be associated with crashes to be a good indicator of safety, and that the conflict/crash rate should be examined to strengthen the argument of conflict analysis. The authors concluded that weaving sections with shorter lengths (500 ft. or less) have higher conflicts but lower crash rates. A conflict extracting subroutine could be used with the program to enable the engineer to model proposed freeway facility alternatives to determine which design would be less hazardous.

Summary

The engineering community has been given the tools for weaving section analysis in the *Highway Capacity Manual* that have been developed over many years, and with much attention to accuracy by the Highway Capacity and Quality of Service Committee. Until adequate databases of actual weaving section performances are built, engineers should use the HCM tools carefully, especially in examining sections with predicted and/or observed lower levels of capacity and service. Simulation models hold promise in the

evaluation of weaving sections. Analysis of weaving sections for safety enhancements or improvements is still needed.

METHODOLOGY

In this report we looked at the methods in current practice to evaluate a weaving section. We compared the methods to each other and evaluated their predicted results to the actual performance of a weaving section case study. We offered conclusions on which methods are providing the best solutions for current weaving section analysis.

Definitions

A weaving section for freeway facilities is typically formed where an on ramp is closely followed by an off ramp, and the two are joined by one or more auxiliary lanes. Weaving sections require intense lane-changing maneuvers, as drivers must access lanes appropriate for their desired exit point. Thus, traffic in a weaving section is subject to turbulence in excess of that normally present on basic highway sections. Four types of traffic movements occur on a freeway weaving section: Freeway-to-freeway traffic (a nonweaving movement), freeway-to-off-ramp traffic (a weaving movement), on-ramp-to-freeway traffic (a weaving movement), and on-ramp-to-off-ramp traffic (a nonweaving movement).

Weaving sections were defined by type in the 1985 *Highway Capacity Manual.* A Type A weaving section is where weaving movements of freeway-to-off ramp traffic and on-ramp-to-freeway traffic must make one lane change to execute the desired movement. A Type B weaving section is where one weaving movement may be accomplished without making any lane changes and the other weaving movement requires at most one lane change. A Type C weaving section is where one weaving movement may be

accomplished without making any lane changes and the other weaving movement requires two or more lane changes.

A major weave is defined as a weaving section where three of the weaving sections' entrance and exit legs have at least two or more lanes.

In general, vehicles in a weaving section will make use of available lanes in such a way that all component flows achieve approximately the same average running speed, with weaving flows somewhat slower than nonweaving flows. Occasionally, the configuration limits the ability of weaving vehicles to occupy the proportion of available lanes required to achieve this equivalent or balanced operation. In such cases, weaving vehicles occupy a smaller proportion of the available lanes than desired. When this occurs, the operation of the weaving section is classified as constrained, and nonweaving vehicles will operate at significantly higher speeds than weaving vehicles.

Type B weaving sections are extremely efficient in carrying large weaving volumes, primarily because of the provision of a through lane for one of the weaving movements. Weaving maneuvers can be accomplished with a single lane change from the lane or lanes adjacent to the through lane. Weaving vehicles may occupy up to 3.5 lanes in a Type B section. Such configurations are most efficient when weaving flows compose substantial portions of the traffic stream. Because weaving vehicles may filter through most of the lanes in the segment, nonweaving vehicles tend to share lanes and are generally unable to segregate themselves from weaving flows.

Existing Methods for Weaving Design and Analysis

Weaving sections are one of the more complex traffic operations to analyze. In Washington State, the WSDOT *Design Manual*, Chapter 9, 'Traffic Interchanges', states: "Because weaving sections cause considerable turbulence, interchange designs that eliminate weaving or remove it from the main roadway are desirable. Use C-D roads for weaving between closely spaced ramps when adjacent to high speed highways. But if a weaving section is considered, design weaving sections in accordance with the *Highway Capacity Manual*."

The methodology of the *Highway Capacity Manual* is based on research focusing on freeway facilities. This methodology has evolved over many years of study, as described in the literature section of this report. Software developed with the HCM methods reflects the 1997 update. The software was used for the HCM analysis in this report.

Geometric characteristics required for analysis of weaving sections are: weaving length, configuration (to determine which type of weave and which constant values will be used), and weaving width (number of lanes in the section). Also required are the characteristics of vehicles by type and the distribution in the traffic stream. These numbers are converted to flow rates by the software for the peak 15-minute interval under ideal circumstances.

A chart (Figure 1, follows) in the WSDOT *Design Manual* provides appropriate level of service for design for highway types and roadway terrains.

Highway Type[2]	Rural[1] Level	Rural[1] Rolling	Rural[1] Mountainous	Urban and[1] Suburban
Principal Arterial	B	B	B	C
Minor Arterial	B	B	C	C
Collector	C	C	D	D
Local Access	D	D	D	D

NOTES:

(1) Refer to 610.02 and Chapter 440 for definitions of these area types..

(2) Refer to Chapters 120 & 440 for definitions of these highway types.

TYPE OF AREA AND APPROPRIATE LEVEL OF SERVICE

Figure 610-1

Figure 1-Level of Service from WSDOT Design Manual

The chart method developed by Leisch in 1979 was an alternate method of estimating LOS for weaving sections, based on weaving volume and length of the weaving section. It has been included in the WSDOT *Design Manual* (Figure 940-15) and was compared to the other methods in this study. It is shown on Page 30 of this report.

Simulation Modeling Methods

In the mid-1970s the FHWA began its support to develop a simulation modeling program with reasonable computer usage requirements that would be capable of representing traffic flow in large urban areas containing surface street networks and freeways. FHWA has since supported a series of projects to implement this design and to develop the software. WSDOT tested the INTRAS mainframe simulation models for the FHWA in the 1988-89 time period (Jacobson, 1992). The research modeled an Interstate reconstruction section using the Corridor Flow macroscopic model (CORFLO) and the Freeway Simulation microscopic model (FRESIM). The investigators recommended that

the program be developed for PCs, a preprocessor be created for node and link data entry, improvements be made to decrease the time required to develop and code the highway network, and the time be shortened for debugging the input when errors are found by the program. They also recommended more research to examine the way the model allocates the traffic assignments.

Many of these recommendations have now been incorporated into the PC version of the program. For this project the roadway was modeled in the latest version of FRESIM, the freeway simulation component of the ITRAF model. Among the freeway geometrics that FRESIM simulates are variation in vertical and horizontal alignment and add, drop, and auxiliary lanes. The model also simulates operational features such as lane-changing and driver behavior. Advantages of this model include: a visual simulation of the roadway performance, data that can be compared with the *Highway Capacity Manual*, and an opportunity to test different scenarios.

The output of this model, called measures of effectiveness (MOE's), include average vehicle speed, vehicle stops, delays, vehicle-hours of travel, vehicle-miles of travel, fuel consumption, and pollutant emissions. The validity of these outcomes were evaluated by comparing the predicted results of density and speed to actual traffic performance captured by videotape and speed studies.

FINDINGS: I-5 OLYMPIA FREEWAY WEAVE SECTION CASE STUDY

Operational Analysis (Current Operations)

In the early 1980s, the Interstate freeway system through the Olympia area underwent a major reconstruction, with bridge widening and lanes additions. These changes resulted in significant capacity improvements. The freeway improvements were designed to serve twenty-year traffic projections to the year 1996. The freeway section modeled includes the weaving section that has begun to experience operational problems during peak hours.

The weaving section is a Type B major weave. The right lane of the Interstate freeway (lane 2) is a weaving movement that may be accomplished without making any lane changes. The ramp lane (lane 1) is an added auxiliary lane with options to remain in the drop lane to take the exit or a single lane change to enter the Interstate right lane to continue down the freeway. It is a major weave because it has three of the weaving sections' entrance and exit legs with two or more lanes. (Figure 2)

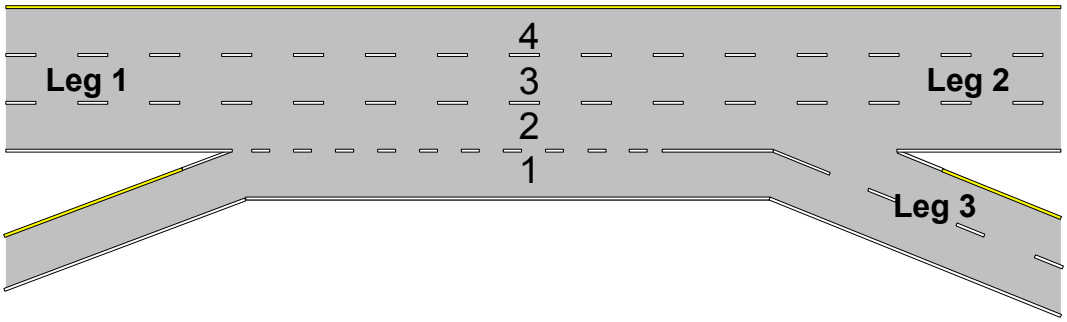

Figure 2-Weave Section Alignment of Case Study

The weaving section as defined by the WSDOT *Design Manual* measured at 1,700 ft. long. (Figure 3)

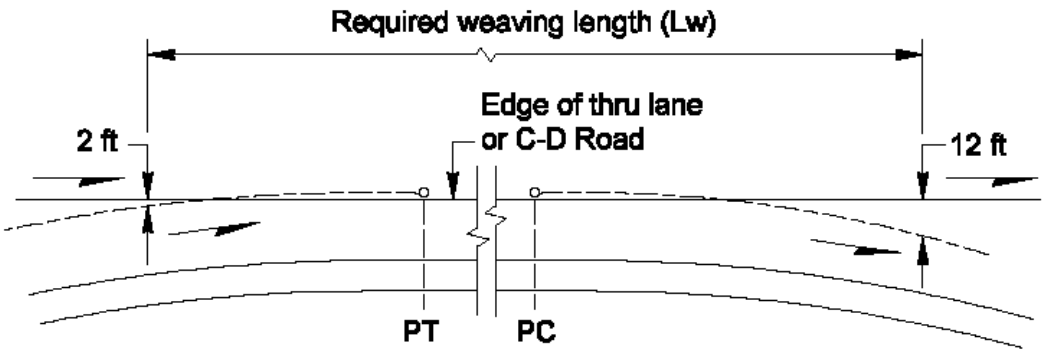

Figure 3-Determining Weaving Length

The weaving section is in a horizontal curve, crest vertical curve combination. It is a horizontal curve to the right with a 1980 foot radius, which falls away with a series of crest vertical curves, the longest of which is 700 feet on a three percent downgrade. The beginning of the weave section is met with an on ramp after a 900 foot painted gore area at an approach taper of 1:50 (1 degree). The ramp is separated from the freeway by concrete barrier. The main line section has an ADT of 56,000 vehicles southbound with an average peak hour of about 5,800 vehicles. Main line splits are 35 percent lane 2 (shoulder lane), 35 percent lane 3 (middle lane), and 30 percent lane 4 (median lane) measured at a permanent station approximately one mile

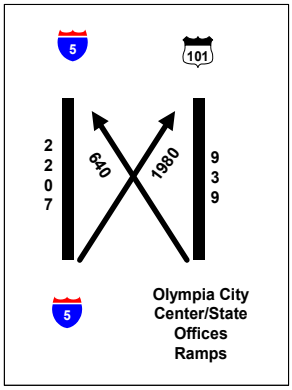

Figure 4-Traffic Movements at Peak Hour in Case Study

upstream of the weaving section. Truck traffic was measured at 15 percent of ADT and at 8 percent of ADT during peak hour.

As part of the original design, design speed through the weaving section was set at 60 mph. The design configuration was chosen to avoid environmental takes, railroad right-of-way encroachments, and their cost consequences. The peak hour weaving volumes shown in Figure 4 were gathered during the analysis period.

Design Analysis (Predicted Operation)

The weaving section was analyzed using three methods, the ITRAF Simulation Model, the *Highway Capacity Manual*, and the Leisch method (Figure 940-15 of the WSDOT *Design Manual*).

ITRAF Simulation Modeling

The first step in building the simulations is to develop the alignment. The configuration through the weaving section is a Type B major weave, with one lane of ramp traffic entering from the right joining with the three freeway lanes. The exit ramp is a two-lane configuration with the choice lane being the right lane of the freeway. The current configuration and four alternatives were developed for comparison.

Geometric data of the roadway section was extracted from the WSDOT highway route log and a WSDOT risk database. Additional data, such as coordinates, vertical curves, ramp locations, and gore lengths, were gathered from as-built contract plans.

Counters were placed in all thirty-nine ramps in the ten-mile corridor to collect the traffic volume and turning movement data. Data was gathered during a one-week period in January 1999. The permanent counters provided the entering/exiting volumes,

composition of the transportation fleets (cars, carpools, trucks, and buses), and operating speeds. A week with no holidays or special events was chosen for data gathering to avoid the probability of seasonal flux in the traffic volumes. After evaluating the traffic data, the Wednesday afternoon peak hour counts were used to reflect the heaviest traffic flows (Friday flows were not gathered at this time).

See Appendix A-Nodes and Volume Data for the geometric and traffic data that were used to build the model. See Appendix A-Network Diagrams for the corridors and see Appendix A-SB Weave Section for the case study area.

Alternative scenarios for the roadway were then developed to test different solutions.

(1) The first alternative was developed with barrier to separate ramp-to-ramp traffic from the freeway traffic through the weaving section. FRESIM was used to model the option to separate the lanes with barrier. This alternative created a weaving section without ramp to ramp traffic (Figure 2).

(2) The second alternative involved adding a fourth lane to the freeway beginning upstream and continuing through the weaving section.

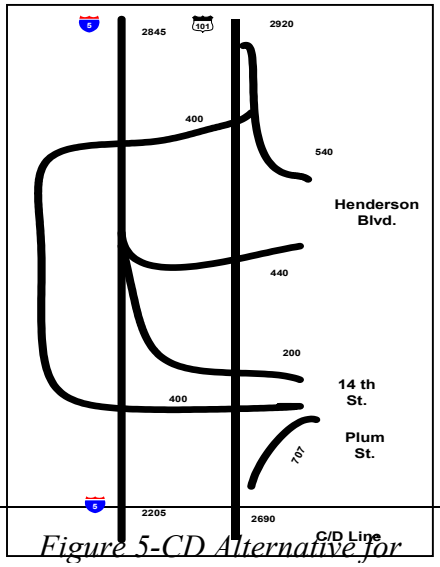

Figure 5-CD Alternative for Case Study Section

(3) The third alternative was a Collector/Distributor system to segregate the exiting traffic flows of city center and SR 101, from the Interstate and provide a merging area for the ramp traffic. (Figure 5) For the CD line, the model required developing a subnetwork

with the surface street network program (NETSIM) in addition to the FRESIM model. A two-lane, CD line was needed to handle the volumes of the traffic that would exit at the two interchanges.

(4) Alternative four was developed using ramp metering.

Construction costs for the different alternatives were not compared in this review.

Speed and density outputs generated by the FRESIM model comparing individual segments of each alternative are included in Appendix B-Simulation Model Outputs.

The Highway Capacity Manual Method

Specific characteristics are required to generate analysis with the HCM software (data for the existing alignment included in parenthesis):

Type of section (B), length of section (1700 ft.), number of lanes (4), free-flow speed (60 mph), terrain (Grade), grade (-3%), length (0.32 mi.), volume for weaving and nonweaving traffic (see Table 2, page 43, in vph), and traffic composition (10% trucks).

The existing condition and each alternative were examined with the HCS software.

The Leisch Method

From the *Design Manual* (Figure 940-15) in the Traffic Interchanges section developed by Leisch (1983), the weaving section estimates a LOS between D and E. (Peak 2,600 pcph and 1,700 feet length). All the alternatives were examined with the chart and included in table 1, Comparison of Methods, page 31.

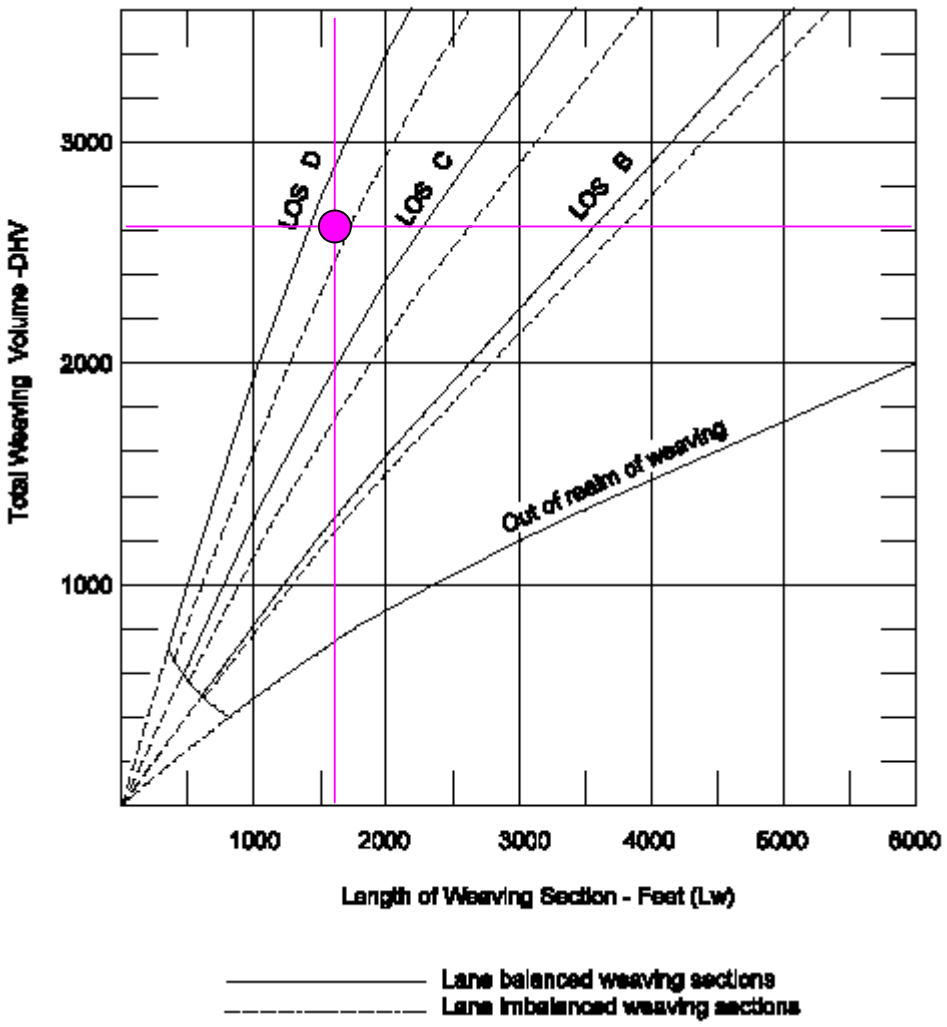

Figure 6 Estimating LOS with the Leisch Method

Comparison of Analysis Tools for Alternatives

Alternative #	Analysis	ITRAF Simulation Model		HCM 1997		Leisch Method
		Speed	LOS	Speed Weaving/ Non-Weaving	LOS	LOS
	Existing roadway	27	F	39/37	E	D
1	Remove ramp to ramp traffic with barrier	35	E	40/40	E	C
2	Add a lane to freeway	27	E	41/42	C	D
	Alternative 3 Collector/Distributor					
3a	CD alternative-freeway section	53	C	55	B	N/A
3b	CD alternative-CD line section	38	C	50	C	N/A
3c	CD alternative-Weave effects upstream at Pacific	54	B	58	B	C
	Alternative 4 Ramp Metering					
4	Ramp metering at 14th/Henderson (4 seconds)	32	D	40/40	D	C

Table 1-Comparison of Analysis Tools on Alternatives

Examination of Significant Factors in Weave Section Operations

Speed and Geometrics

While numerous variables can impact the weaving section's operational abilities it is clear that design speed interactions can positively or negatively impact performance. The lowered design speeds for this section arguably produce lower levels of service due to increased decision-making demands. The ITE Handbook of Traffic Engineering Fifth Edition states "restricted design speeds affect operations and level of service by forcing drivers to be more careful in reacting to the harsher horizontal and vertical *alignments*, and to travel at somewhat reduced speeds. In extreme cases, the capacity of multilane facilities may be reduced when lower design speeds are employed."

As stated earlier in this report, the original design speed was restricted to 60 mph because of environmental takes, railroad right-of-way encroachments, and their cost consequences.

Figure 7-Approaching the Weaving Section

This freeway section includes a horizontal curve, crest vertical curve combination upstream of the weaving section. The horizontal and vertical alignments complicate the lane changing maneuvers that are required of drivers in this section. The curve interaction constricts the travel speeds of the freeway traffic and provides the drivers with a poor view of the weaving section ahead of them. In addition, drivers on the freeway cannot see approaching traffic from the ramps on the right because traffic

enters from a raised structure next to the roadway. This contributes to the queuing in the main line right shoulder lane (lane 2) during peak operations (Figure 7).

Counts used in compiling the splits substantiate that volumes and lane splits mentioned on page 26 and used in the HCM confirmed that volumes had not significantly changed over the period of time of the research project. This is further explained in the validation section later in this report. The percentages indicate that main line drivers have a tendency to opt for the right lane of the freeway as they approach this weaving section to protect their ability to make the exit, even in instances of queuing. Peak hour volumes average 4,200 vph in the main line (lanes 2, 3, and 4) with 1,500 vph in lane 2 only, and 1,580 vph on the ramp (lane 1), for a total of 5,780 vph.

While this research did not determine origins and destination of drivers, it can be speculated that there are large proportions of drivers on pass-through trips to the coastal and Olympic National Park areas. In these cases, these drivers will be freeway-to-ramp vehicles in the weave section that wish to exit. These drivers are apt to choose the right lane of the freeway as they approach the weave section to protect their ability to make the exit. (Accidents have the potential to increase when the congestion occurs in the weaving section and slows to below freeway speeds. This also creates rolling slowdowns in areas on the main line before the line of sight of the weaving section.

The ramp traffic is a combination of two ramps that merge together before they arrive at the weaving section. The traffic volume approaching from City Center (Figure 9) is double the traffic volume approaching on the 14th Street ramp. The 14th Street traffic

comes down a long vertical grade (Figure 8) and the City Center traffic comes up a grade. This merging action slows the ramp traffic speeds considerably (10).

Figure 8-14th St./State Capitol Ramp

Figure 9-Henderson/City Center Ramp (looking back)

The weave section then begins after a 900 foot painted gore area. The ramps merge with an approach taper of 1:50 (1 degree).

Figure 10-14th St/State Capitol. Ramp on left, Henderson/City Center Ramp on right

Figure 11-Ramps merge and gore area of the weaving section

After merging together, the ramp traffic proceeds toward the weaving section, and can be affected during congested operations by freeway traffic cutting through the gore area into the ramp lane in an effort to slip by the turbulence and congestion of the right freeway lane (Figure 11). Research by Cassidy (1991) showed that 5-10 percent of the freeway-to-ramp weaving movement will do this in a congested weave section.

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Signing

Informational signing and lane choice play a critical role to drivers. Reviewing the placement of signing and delineation may provide operational improvement of this section. It is the opinion of the authors of this report that signing and delineation is not provided at the most beneficial decision points for the freeway and pass through traffic, contributing to the congestion in the right lane of the freeway.

Figure 12-Advance Signing #1

Figure 12 shows the first sign notifying the driver that the exit is ahead, located on the right side of the three-lane freeway section. Placement at this location does not clearly indicate actions and decisions that lie ahead.

Figure 13-Add Lane Signing #2

The signing and channelization shown in Figure 13 illustrate that an add lane is joining on the right. Yet the pavement marking may suggest to drivers that moving through the gore area is an appropriate maneuver.

Figure 14-Overhead Signing #3.

About one-third (600 feet) through the weaving section an overhead sign extends from the shoulder, but is misaligned with the roadway. At this point, drivers still cannot see the exit. Much of the ramp-to-freeway weaving traffic merges in this area to escape the exit only lane. Many freeway-to-ramp drivers mistakenly take this sign to mean that they need to be in the auxiliary lane to exit.

Figure 15-Overhead Signing #4.

With 500 feet left in the weaving section, signing and delineation allow the drivers to see their exit clearly. Most of the weaving has already been completed by this point.

Peak Hour

At peak hour, the right lane of the freeway (lane 2) approaches capacity and the available gaps for merging vehicles from the on-ramp are reduced. The traffic in the right lane slows and queues under these conditions. The queuing constrains the performance on the roadway and initially results in wider differences in speed between weaving and

nonweaving operations upstream of the weaving section. As the backup lengthens, traffic congestion is increased when these slowed vehicles move left into lane 3 to go around the congestion. During the peak hour only, an incident occurs about every other month. If incidents are avoided, these movements usually cause slowdowns in all the lanes and the weaving and nonweaving speeds level out. Friday volumes can create two-mile backups with queuing in all the lanes.

Safety Analysis

Actual Accident History

In order to evaluate the safety aspects of the Olympia weave section, accident data from the three-year period of 1994-1996 was extracted. Accidents were examined by collision type and severity. Accidents were charted by location and type. A two-mile section was analyzed upstream and downstream of the weave section.

The weave section lies between MP 104.6 and 104.9 in the following charts.

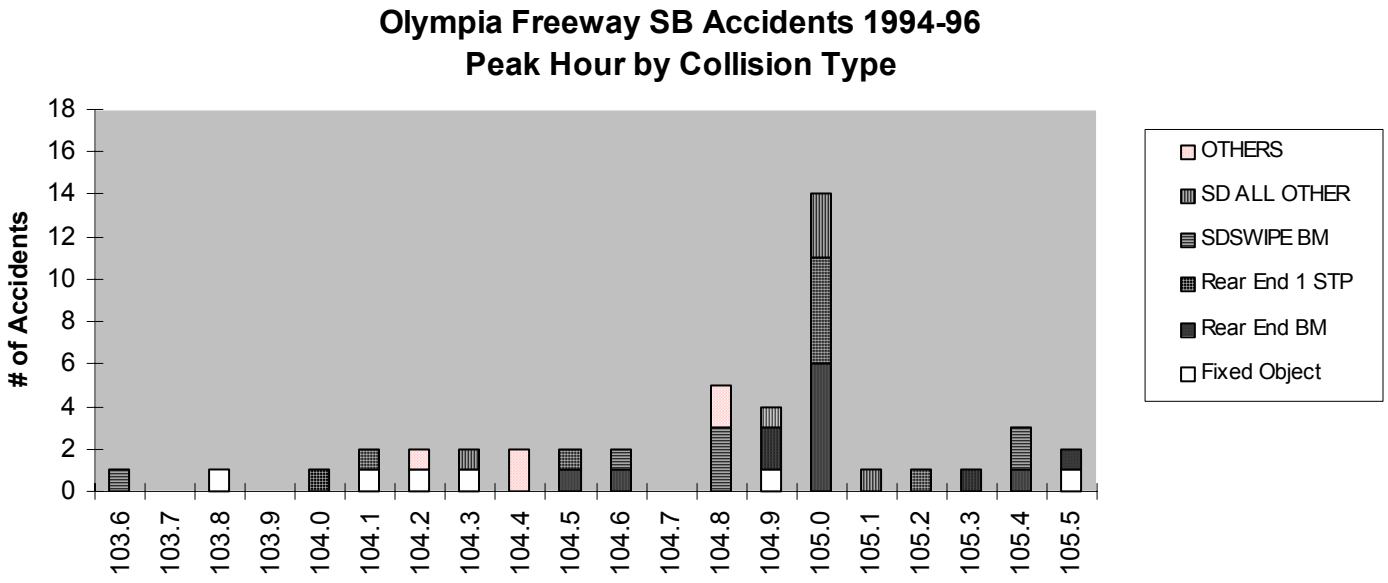

Figure 16-Peak Hour Accidents by Collision Type

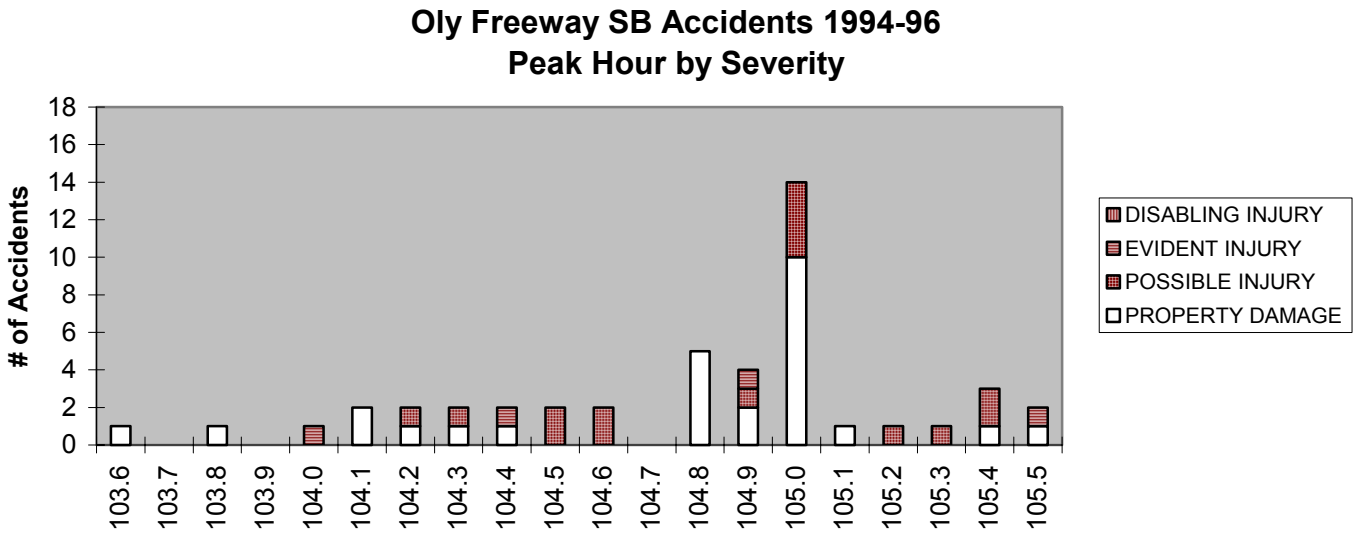

Figure 17-Peak Hour Accidents by Severity

The predominant accidents recorded during the peak hours were rear enders occurring upstream of the weaving section, reflecting congestion caused by queuing traffic from the weaving section. These accidents occur at lower speeds, with sudden stops in the flow of traffic. Accidents occurred during the peak hour every 52 days, on average, in this two-mile section of the corridor.

During off-peak hours, there is an increased incidence of sideswipe accidents and rear end accidents through the weaving section, similar to accident occurrences in nonweaving sections. Speeds are increased through the weave section for the freeway traffic as well as for the ramp traffic, which can use the long ramps to generate speeds that are greater than the freeway speeds. Most incidents are occurring at the weave in the right lane of the freeway, where ramp lane changing and merging conflict with freeway traffic. Accidents are also more severe because the vehicles are traveling at higher

speeds. This also leads to a slightly increased level of fixed object collisions from drivers avoiding collisions with slowing or stopped vehicles and running off the roadway.

The following charts include peak and off-peak accidents, where accidents are occurring about one every eight days.

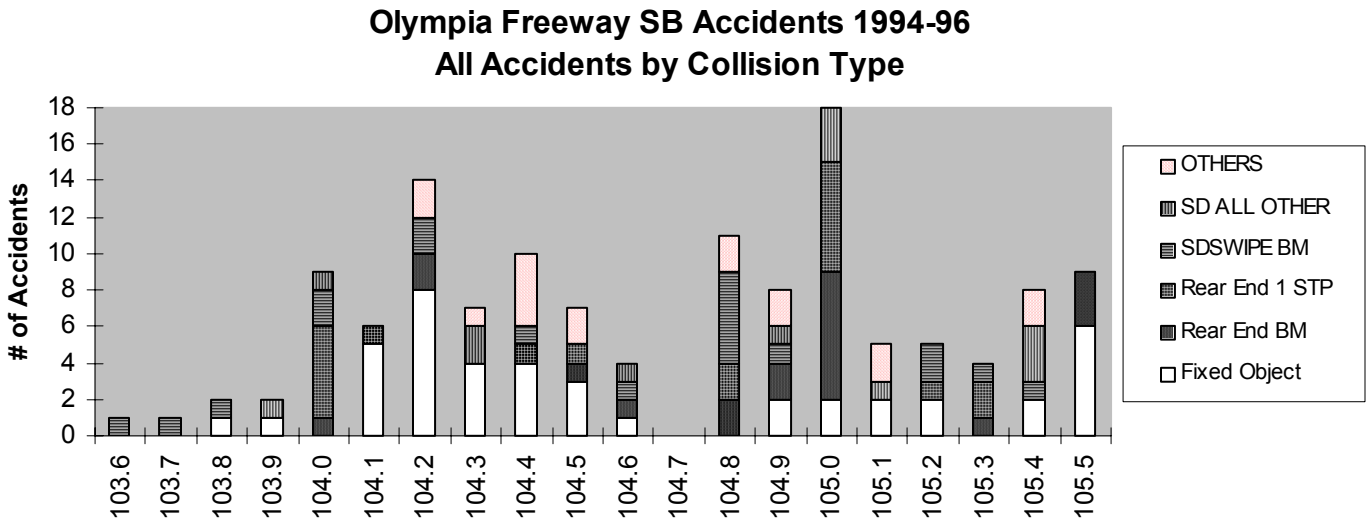

Figure 18-All Accidents by Collision Type

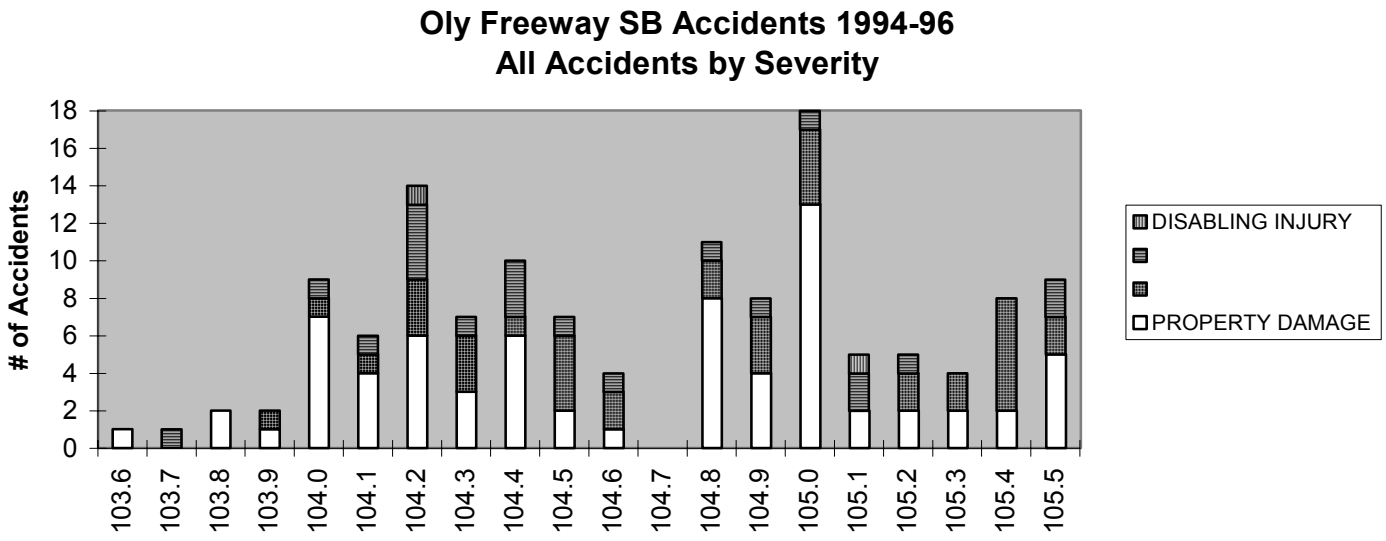

Figure 19-All Accidents by Severity

Safety Impacts of the alternatives

Alternative 1-Remove the ramp-to-ramp traffic from the weave section.

This alternative eliminates about two-thirds of the traffic in the auxiliary lane by adding an exit only lane for the ramp-to-ramp vehicles at the beginning of the weave section. This marginally improves the speeds of the weaving vehicles, and only if the auxiliary lane exists through the weaving section, allowing for two lanes off in addition to the exit only lane.

Two-thirds of the rear enders and one-third of the sideswipes occur in the auxiliary lane through the weave section. This alternative would eliminate two thirds of the volume in the auxiliary lane and would provide a forty percent reduction in these types of accidents. Also, congestion-caused rear-end accidents that were occurring upstream in the right lane of the freeway would be reduced by twenty-three percent.

Alternative 2-Add a lane to the existing freeway

For this alternative to be successful, significant changes to the geometrics of the weave section would be required to make the additional space useful for lane changing. The HCS analysis predicts an improvement to the level of service of C for these volumes. The freeway traffic would operate at higher speeds than the ramp traffic, and an increase in sideswipe accidents would probably be expected. However, the alternative would reduce rear end accidents caused by congestion on the freeway, with an estimated improvement of thirty percent.

Alternative 3-Provide a collector/distributor to remove the SR 101 traffic

This alternative would eliminate most sideswipe accidents and rear enders during peak hour operations by removing the weave section. The LOS of the freeway would improve from E to C. Rear end accidents caused by queuing on the freeway would be reduced by eighty percent.

Because the horizontal and vertical alignment of the roadway through the section would be flatter and straight, much better sight distance would exist for traffic movements. However, designing enough capacity for the volume of traffic that would access the CD would be an issue. More traffic moves to the SR 101 and City Center and State Capital exits than remain on the freeway southbound. The ramp traffic would need to be provided auxiliary lanes to separate it from the large volume of SR 101 vehicles.

Alternative 4-Ramp metering

Ramp metering would space out the traffic merging into the freeway lane and using the auxiliary lane. Reducing the flow of traffic by half during the peak hour would improve the flow of the freeway from LOS E to LOS D. Rear end accidents in the weave section and on the freeway during the peak would be reduced by forty percent, and sideswipe accidents in the weave section would be reduced by fifty percent. Traffic would back up on the ramp during the peak hour, which may lead some local traffic to use alternative routes.

Calibration of the Model Input

The original project was developed in the ITRAF model with input of topography, roadway geometrics, traffic volumes, and turn movements. Default values for motorist behavior and transportation fleet splits (cars, carpools, trucks, and buses) were used. In the initial analysis of results generated by the project, the model did not reflect the existing congestion conditions well. A number of items were reviewed to analyze the results. The geometrics, turn movements, and topography elements were checked for accuracy. Data for random days was examined for speeds, transportation fleet splits, and volumes.

Free Flow Speeds

Actual speeds were examined to calibrate the free flow speeds in the model. The numbers were also compared to the model's predicted output. These numbers would be expected to be slightly different because the corridor was modeled with peak hour volumes only. From these observations the free flow speed of 65 mph was adopted for the analysis. This speed is also the default free flow speed of the simulation model.

Permanent Location	Date	Nodes	Modeled Free Flow Speed	ADT Actuals from Permanent Stations	Model Predicted (at peak)
Marvin Road	1/13/99	2-4	65	64.8	61.53
	3/9/99		65	65.5	
	8/2/00			65.2	
Boulevard Road	3/9/00	25-26	65	62	54.25
	5/2/00		65	60	

Table 2-Free Flow Speed Comparison at the Permanent Locations

Free Flow Speed through the weaving section

A floating car study was done to evaluate the free flow speeds through the weaving section. The study indicates a significant lane speed variance, as noted in table 3. It was difficult for the researchers to reach the weave section unimpeded by traffic movements, especially in the right lane.

Floating Pass #	Lane 4	Lane 3	Lane 2	Average
	Speed in MPH			
1			50	
2			51.4	
3	63.8			
4		61		
5		61		
6	66.9			
Average	65.35	61	50.7	59.0

Table 3-Free Flow Speed through the Weaving Section

Traffic movements in advance of the weave section seemed to cause the most congestion in the right lane. Drivers move to the right lane before the short horizontal curve and stay there to position themselves for the weaving section.

Based on the free flow speeds observed in Lane 4 through the weave section and the design speed information, a free flow speed of 60 mph was adopted for the weave section in the models. This matches up with the design speed of 60 mph that was discussed on page 27.

Vehicle Type Specifications

The axle classification for truck traffic was available from the first permanent station of the corridor.

Percentage of Trucks	Single	Semi w/med load	Semi w/full load	Double-bottom trailer
Model Default-10 % trucks	31%	36%	24%	9%
Actuals-approx. 14% of all vehicles ADT	32%	45%	11%	12%
Peak hour (3-7pm)-approx. 8% of all vehicles	40%	50%	7%	3%

Table 4-Vehicle Type Specifications for the Simulation Model

Because of the small sample of data, the default values were used.

Validation of the Model Output

Volume Checks

Eighteen days of daily peak hour volumes were averaged to evaluate the validity of the traffic volumes used in the modeling. The data is included in Appendix C-Volume Checks. The average compared closely to the volumes that were used in the modeling.

The average peak hour speeds were also consistent with average daily speeds noted in the calibration section.

Location	Average Peak Volume (18 days)	Modeled Volume	Average Speed
Marvin Road-beginning of section	3441	3461	65.1
Boulevard Road-upstream of weaving section	4714	4892	59.5

Table 5-Traffic Volumes for the Simulation Model

Lane dispersions

The model results were compared to the actual performance of a segment of the roadway recorded with videotape. The videotape section corresponded to a section included in the model. This section was recorded during an evening commute soon after the traffic counts were taken. Counts of the traffic density in each lane at one-minute intervals were taken from the video and model. Eleven counts were made and the raw data counts are included in Appendix C-Model and Video Counts.

Video Counts	Average Vehicle Density for a 545 foot section				
Date/Time	Lane 4	Lane 3	Lane 2	Lane 1	Total
3/9/99	2.9	3.7	6.4	5.8	18.8
Std Dev.	1.76	1.35	2.01	2.04	
Average Densities per lane through section- peak Hour	(18.8 v)(5280ft/mi)/ (4 Lanes)(545 ft)=				45.5

Table 6-Actual Lane Densities of the Weaving Section

Predicted from Model	Average Vehicles contained in section [545 feet]				
Date/Time	Median Lane	Middle Lane	Right Lane	Ramp	Total
Peak Hour	2.1	2.7	8.4	5.2	18.4
Std Dev.	1.70	1.49	3.20	1.94	
Average Densities per lane through section- peak Hour					48.7

Table 7-Model Predicted Lane Densities of the Weaving Section

The densities estimated from the videotape and from the model are somewhat comparable, but the results from the model could not be shown to be statistically valid with the limited data available in this research.

CONCLUSION AND RECOMMENDATIONS

A case study of a weaving section was undertaken to evaluate the ongoing efforts to improve weaving analysis, to test the ITRAF simulation program on a complex weaving section, and to analyze site related issues for a failing weaving section on SR 5 in Olympia, Washington. The literature search revealed that the *Highway Capacity Manual* methodology has been under continuous examination and modification since its inclusion in 1950. These modifications have led to the current methodologies contained in the 1997 HCM but have never been considered to accurately portray many in-field conditions. Methods used in the analyses are contained in the 1997 HCM and the FHWA's Traffic Software Integrated System (ITRAF) with the FRESIM model. Predicted outcomes of the simulation modeling program and the *Highway Capacity Manual* were compared for the weaving section case study for both actual characteristics and design alternatives for the weaving section. With its output, the simulation model allowed for evaluation of the interaction of many of the geometric aspects of the freeway weaving section. It produced predicted speeds that were lower than the HCS method on the existing condition and all alternatives. The model also allowed the ability to evaluate the congestion occurring in individual lanes with the visual simulation program. Although the results from the model could not be shown to be statistically valid, they appeared to reflect the existing roadway conditions and showed a consistency in the alternatives.

Previous safety research specific to weaving sections was limited. For the Olympia case study presented, a three-year period of accidents was examined. The predominant accidents that occurred during peak hour were rear enders, occurring upstream of the

weaving section as drivers react to congestion caused by queueing of traffic in the weaving section or weaving vehicles held up on the ramp as they seek a gap to merge onto the freeway. At lower volumes at off-peak hours the weaving section showed an increased incidence in sideswipe accidents and rear end accidents in Lane 1, the add lane of the freeway.

The *Highway Capacity Manual* remains the ultimate resource for clear definitions and procedures to examine freeway weaving sections. Researchers continue to try to improve the existing procedures of the HCM methods to reliably predict how weaving sections will operate. Results have been limited by the data available for examination and have been difficult to be judged statistically adequate in many cases. The latest effort to modify the methods in the *Highway Capacity Manual* for the 2000 edition reflected this data problem, although incremental changes have been developed that are expected to improve predictions.

Simulation models are increasingly used to analyze complex traffic flow patterns and operations and appear to be effective, as reflected in the results of this research project. The ITRAF simulation-modeling program was labor intensive, requiring significant editing and review for each change entered in the project file. A high degree of effort was required to develop, enter, and debug the geometric data through the preprocessor program. The engineers needed significant training to learn how to use the program. A new version of the program was released during the course of this study, which required a few adjustments to input files but was found to be more user friendly.

Output in the graphic viewer of the simulation program reflected the disparity of speeds and slowdowns from congestion in Lane 2 of the weaving section that was confirmed in field reviews and a floating car study. The density output of the model was converted to LOS using the HCM criteria for comparison to the LOS generated by the HCM software. Speeds are presented as an average speed for a link by the model, which are not directly comparable to the *Highway Capacity Manual* output of weaving and nonweaving speeds. Engineering judgment is needed to compare the two methods, especially for speed.

Four alternatives were modeled for the section and the outputs were compared to densities and speeds from the 1997 *Highway Capacity Manual* software. The model-predicted speeds were lower than the HCS method for the existing condition and all alternatives, which also generated different LOS based on their values. The results appeared to reflect the existing roadway conditions well, although the results from the model could not be shown to be statistically valid with the data available in this research.

Traffic volumes through the weaving section are reaching the capacity limits for a Type B weaving section during peak hour periods. The roadway section has certain geometric elements that affect driver expectancy and judgments. The horizontal and vertical curve combination results in slower speeds, contributing to the congestion already occurring because of capacity problems through the section. One alternative was examined that removed all the nonweaving ramp traffic from the weaving section. A second alternative examined a collector-distributor line to remove the weaving section from the freeway. A third alternative added an additional freeway lane through the weaving section. A fourth alternative examined ramp metering to control the gaps of vehicles approaching from the

on-ramp. The collector/distributor alternative was shown to hold the most promise for operational improvements in the case study section. Costs were not examined in the research for any of the alternatives. Future traffic projections will also need to be considered in the design of improvements for the section. The operational analysis suggested that better signing and lane markings for driver notification can improve the flow through the weaving section.

This project generated promising results as the simulation program appeared to represent the actual lane-by-lane traffic operation quite well. The alternatives modeled seemed to provide consistent results when compared with the *Highway Capacity Manual* procedures. The model findings suggest that the validity of HCM is indeed questionable when the geometrics are complicated. However, further modeling projects with the ITRAF program are recommended to generate more confidence with the results before policy recommendations are made in the use of the ITRAF simulation models for project design in the future.

This research recommends that weaving sections be analyzed for their impacts to overall operations to a freeway. Previous research, as well as this study, clearly indicates the impacts that weaving sections performances have on the entire freeway system. No longer is it acceptable to solely review weaving as a localized phenomenon. Current policy for weaving section design will continue to emphasize engineering judgment when using the HCM methodology and/or modeling analysis programs, especially with geometric complications. On-site examinations of weaving sections should be conducted

to ensure appropriateness when considering modeling with the ITRAF software. Also, future research is still needed to further examine the safety impacts in weaving sections.

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APPENDIXES-CONTENTS

Appendix A: MODELS

NODES AND VOLUME DATA

SB MODEL…….……A1
NB MODEL……A3
SB WEAVE SECTION…… ……A5
SB CD LINE……A6

NETWORK DIAGRAMS

SB MODEL…….....A7
NB MODEL……..……A17
SB WEAVE SECTION…….....……..A31

Appendix B: ANALYSIS RESULTS

HIGHWAY CAPACITY MANUAL OUTPUTS

HCM-EXISTING…… ……...B1
HCM-ALTERNATIVE 1-BARRIER…… ……....B2
HCM-ALTERNATIVE 2-ADD A LANE TO FREEWAY…… ……..B3
HCM-ALTERNATIVE 3-CD LINE…… ……..……..B4
ALTERNATIVE 3-FREEWAY SECTION……..…… …..……..B5
ALTERNATIVE 3-UPSTREAM ANALYSIS……..…….. ……..B6
HCM-ALTERNATIVE 4-RAMP METERING…… …….……..……B7

SIMULATION MODEL OUTPUTS

SBFLOW-EXISTING……..... B8
SBBARRIER-ALTERNATIVE 1-BARRIER……..…….. ..... B8
SBCD-ALTERNATIVE 3-CD LINE……..... B8
METERING-ALTERNATIVE 4-RAMP METERING (10 SECOND DEFAULT)…..... B9
METERING-ALTERNATIVE 4-RAMP METERING (4 SECOND DELAY ONLY).. ..... B9
SBFIVELANES-ALTERNATIVE 2-ADD A LANE TO FREEWAY…… B9

Appendix C: VALIDATION OF THE MODEL

VOLUME CHECKS

MARVIN ROAD PERMANENT STATION…… C1
BOULEVARD ROAD PERMANENT STATION…..……..... C2
MODEL AND VIDEO COUNTS……..... C3