Conflict Simulation in INTRAS: Application to Weaving Area Capacity Analysis

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Chapter 4 of the 1985 *Highway Capacity Manual* uses weaving and nonweaving speeds as measures of effectiveness (MOEs) to evaluate the quality of service in freeway weaving sections. However, recent research suggests that speed may not be a reliable indicator of traffic performance. Speed and conflict rates [in particular, lane change (LC) and rear-end (RE) conflicts] are tested in terms of their sensitivity to geometric and flow variables. The testing environment is a microscopic simulation model developed for FHWA named Integrated Transportation Simulation (INTRAS), which has been extensively validated on freeway segments throughout the country. For simple one-sided freeway weaving sections, proposed conflict rates were found to be potentially more effective than speeds as an MOE. This finding is demonstrated by a higher sensitivity of the conflict rates MOE compared with the speed MOE to several geometric and flow variables at the weaving section. LC and RE conflict rates were sensitive to changes in the volume-to-capacity ratio (VC), reaching their maximum level for VC in the range 0.9 to 1.0. LC and RE conflict rates were also sensitive to changes in the volume ratio (VR), reaching their maximum level for VR in the range 0.3 to 0.5.

Freeway weaving sections represent a critical capacity link in the freeway system as a result of the complex driving tasks that must take place in the relatively limited roadway space. State-of-the-art capacity analysis methods for such segments are exemplified by the 1985 *Highway Capacity Manual* (HCM) (*1*) and Leisch (*2*) methods, both of which use a set of geometric and traffic flow descriptors to estimate traffic speeds—because lower speeds are associated with poorer levels of service (LOS). However, recent work by Cassidy et al. (*3*) indicated that average speed (weaving or nonweaving) is insensitive to most weaving section parameters, with a considerable amount of scatter in the observed speed data. Their research suggests that new measures of effectiveness (MOEs) may be required to better characterize the operation of freeway weaving segments.

One of the persistent issues in characterizing traffic flow on freeway weaving areas is the quantification of traffic turbulence. Turbulence, in fact, is a microscopic indicator of the magnitude of speed adjustment that is taking place to accommodate weaving maneuvers. What has been avoided so far, and for obvious reasons, are direct measurements of turbulence in favor of proxy macroscopic measures such as speed or speed variations (*4*). The collective modeling experience that is based on the latter approach has been rather disappointing, judged from a purely statistical standpoint, with relatively low correlation coefficients and high standard errors (*5–7*).

A direct quantification of traffic turbulence at freeway weaving sections is attempted. The method, which is based on well-established concepts of traffic conflicts, uses the well-established microscopic traffic simulation model Integrated Transportation Simulation (INTRAS), developed for FHWA as a vehicle to perform the conflict studies (*8*).

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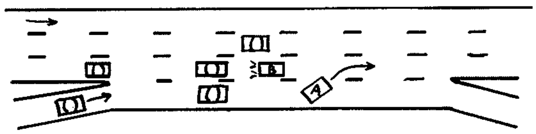
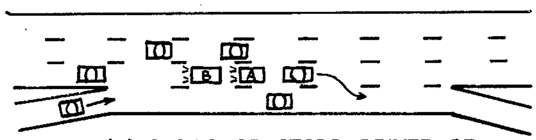
TRAFFIC CONFLICTS AND APPLICATION TO FREEWAY WEAVING SECTIONS

A traffic conflict is an event that has the potential of becoming a traffic accident (*9*). In the past, most if not all traffic conflict studies have involved intersections or their approaches. Research work has shown that strong correlations exist between certain types of conflicts and accidents at intersections (*10–14*). Recently, FHWA issued a report on the procedures required to conduct traffic conflict studies (*15*). The report briefly mentions the possibility of applying the concept of the traffic conflict to nonintersection areas of the transportation network although there has been a lack of validation work at such locations. On freeways, two types of traffic conflicts are evident in the lanes of travel. On the mainline, a driver is either following another vehicle or is in the process of changing lanes. Thus, the two most common types of freeway conflicts are lane change (LC) and rear-end (RE) conflicts. Some not-so-obvious freeway conflicts are the result of head-on collisions, objects on the freeway, and moving violations. These conflicts rarely occur and because of the lack of operational significance under normal operating conditions, further discussion of their nature is precluded.

A traffic conflict caused by a freeway LC is a potential freeway angle or sideswipe accident. This conflict occurs when a vehicle changes lanes and the driver of the vehicle immediately following it in the target lane reacts to avoid a collision by applying the vehicle's brakes, as shown in Figure 1 (top). If this maneuver by the driver is unsuccessful, an angle or sideswipe crash occurs. In an LC conflict, the deceleration of the following vehicle in the target lane will range from coasting deceleration to the maximum deceleration that the vehicle can develop. Coasting deceleration occurs when the driver



VEHICLE (A) CHANGES LANES AND DRIVER OF VEHICLE (B) BRAKES TO AVOID COLLISION.



VEHICLE (A) SLOWS OR STOPS. DRIVER OF VEHICLE (B) BRAKES TO AVOID COLLISION.

FIGURE 1 Lane change (*top*) and rear end (*bottom*) conflict definitions at freeway weaving sections.

removes his or her foot from the accelerator without applying the brakes.

A freeway RE traffic conflict is a potential freeway RE accident. This conflict occurs when a vehicle slows or stops on a freeway and the driver of the following vehicle in the same lane reacts by applying the vehicle's brakes to avoid collision, as shown in Figure 1 (bottom). If this maneuver is unsuccessful, an RE collision occurs. By responding in this manner, the driver is trying to maintain what he or she considers is a tolerable car-following distance. Conflict severity, characterized as minor, moderate, or major, is gauged by the percentage of the maximum deceleration that is applied in a given situation.

In a simple one-sided weaving section, turbulence is mostly concentrated in the auxiliary and rightmost freeway lanes because most drivers perform weaving maneuvers in these lanes, thereby interacting with other vehicles that are entering or exiting the freeway. A secondary cause of turbulence in ramp weaves is caused by nonweaving drivers who seek to avoid the turbulence in the rightmost freeway lanes by changing lanes to the leftmost freeway lanes. By definition, weaving involves a certain amount of lane changing. A small portion, usually under 10 percent of total lane changes (i.e., lane changes caused by drivers performing weaving maneuvers in addition to those of nonweaving drivers) results in LC conflicts. An LC conflict may propagate additional LC and RE conflicts further upstream. Likewise, an RE conflict may result in further RE and LC conflicts upstream. RE conflicts constitute 85 to 95 percent of the total conflicts that occur in ramp weaves.

Ideally, individual lane changes caused by weaving maneuvers do not result in LC conflicts, nor in upstream LC or RE conflicts. However, the ideal scenario is never sustained in real-world freeway traffic flow. Even on basic freeway segments, minimal background lane-changing frequency often results in some LC conflicts. The additional impact of conflicts caused by weaving adversely affects traffic and increases speed variation in the weaving section. These characteristics essentially define turbulence. Thus, conflicts are adequate descriptors of turbulence. Reducing turbulence (i.e., reducing the abrupt changes in vehicular speeds caused by driver braking) is bound to enhance the safety of the system as well as its operations. Safety is a secondary issue that should be examined in future studies. However, safety effects are briefly described as a means of confirming the model's validity.

ADAPTATION OF INTRAS TO CONFLICT STUDIES

INTRAS (*8*) was selected for adaptation for many reasons. First, to count individual vehicle conflicts, a microscopic simulation program is needed. The capability of INTRAS to control for geometric and volume variables important to weaving sections is another reason. Next, using INTRAS to generate and collect weaving section data is more economical than collecting and processing data from the field. The fact that INTRAS has been rigorously validated at weaving sections gives credibility to its results (*16,17*). Finally, and most important, is the fact that INTRAS uses highly detailed lane change and car-following logic. Such an elaborate simulation provides needed insight and understanding of the complex turbulence relationships in a weaving section.

The INTRAS program structures the freeway network into a series of nodes that are connected by links. Weaving areas of almost any configuration can be modeled by INTRAS. Up to two auxiliary lanes can be modeled in the weaving section. Entering and exiting ramps can also have more than one lane. INTRAS allows the user to input the length of the auxiliary lanes, grade and horizontal curvature of the freeway and ramp links, and number of lanes entering, within, and exiting the weaving section. Inputs that define the amount and mix of traffic in the weaving area are percent or count volume of vehicles entering the weaving section by lane, percent or count of the type of vehicle in the traffic stream, percent or count of vehicles in the weaving section that are exiting, and the origin-destination volume counts. Vehicle attributes produced at every time step include speed, acceleration, lane position, and position within the link. Some vehicle attributes from the previous time step are also stored at every time step.

Originally, INTRAS did not generate average weaving and nonweaving speeds to estimate LOS. The program was enhanced by FHWA so that the volume movements and the speed MOEs appeared in the INTRAS output. In order to extract LC and RE conflict rates from the INTRAS program, algorithms were added so that conflict information appeared in regular INTRAS output reports.

LC algorithms were added where the INTRAS program counts freeway link lane changes, namely, subroutine CHECK. When an LC occurred, separate counts were kept on whether the LC was mandatory or optional, that is, caused by weaving or nonweaving drivers, respectively. Cumulative totals then appear in an INTRAS LC output report. Also, separate counts are conducted on whether all LC and mandatory LC involved a following vehicle in the target lane. In all counting processes for LC and RE conflicts, Vehicle B (see Figure 1) must be situated within the weaving link for the conflict to be counted for the weaving section link. When a following vehicle is present, its acceleration is examined the instant the LC occurs. If the acceleration is greater than zero, a count is added to the acceleration bin in the total LC count report. If the LC was mandatory, a count is also added to the acceleration bin in the mandatory LC count report. If the acceleration of the following vehicle was less than or equal to zero, the deceleration value is divided by the maximum deceleration (d_{max}) of the vehicle to obtain the percentage of d_{max}. In INTRAS, d_{max} is a function of vehicle type. On the basis of this percentage, a count is added to the appropriate bin for percentage of d_{max} in the total LC report. Ten bins for percentage of d_{max} exist in the report; each bin represents a 10 percent range of d_{max}. If the LC is mandatory, the count is also placed in the appropriate bin in the mandatory LC count report.

After all the counts are placed in the correct bins by freeway link, specific count totals are divided by the vehicle-miles of travel (VMT) in the link. INTRAS automatically generates freeway link VMT. These rates are then presented in LC and mandatory LC rate reports.

RE algorithms were added where the INTRAS program updates most freeway vehicle attributes every time step, namely, subroutine FMOVE. At every time step, a check is performed to determine if the subject vehicle and preceding vehicle both exist in the same lane on the link. If they do, three other checks are conducted. One check determines if the lead vehicle is accelerating and the subject vehicle is not in a deceleration cycle. The second check verifies that a vehicle in the adjacent lane is changing lanes between the lead and subject vehicle. The third check determines if the subject vehicle is in the process of changing lanes. If any one of these checks is positive, the event is ignored by the RE algorithms. The three checks ensure that an RE conflict is never counted also as a lane change conflict. LC and RE behavior can be independent of each other; either may occur in isolation. Furthermore, an LC conflict may propagate other LC and RE conflicts. Likewise, an RE conflict may propagate other LC and RE conflicts.

When the three checks are negative, the situation is further evaluated. When the lead vehicle decelerates or stops and the subject vehicle is decelerating, the decelerations of the subject vehicle in the previous and current time steps are stored in each time step and compared until the subject vehicle no longer decelerates. The highest value in this deceleration cycle is then divided by d_{max} of the subject vehicle. This event is then added to the appropriate bin in the RE situation report. If the deceleration cycle extends over two links, the link where the highest deceleration value occurs receives the count.

By placing RE and LC counts in the bins for percentage of d_{max} by freeway link, freeway conflict information can be obtained. RE and LC events in which the deceleration ranged from 2 to 10 ft/sec^2 were considered minor conflicts, 10 to 14 ft/sec^2 moderate, and 14 to 20 ft/sec^2 major. Events with a coasting deceleration of between 0 and 2 ft/sec^2 or that had accelerations were not considered conflicts. Weaving section conflict rates were obtained from the weaving section link where the percentage of d_{max} for d_{max} = 20 ft/sec^2 ranged from 10 to 100 percent. A d_{max} value of 20 ft/sec^2 was used because the original default value for most vehicle types in INTRAS was 21 ft/sec^2. The value of 2 ft/sec^2 for the maximum coasting deceleration was also based on INTRAS default values. The 10 and 14 ft/sec^2 values were based on engineering judgment.

In summary, conflicts are counted in the weaving section as they occur. No distinction is made as to the ultimate cause of a group of conflicts. For example, an LC conflict that causes 3 RE and 1 LC conflicts gives the same count as an RE conflict causing 2 RE and 2 LC conflicts.

MODEL VALIDATION

Three validation studies on the model were performed. The first two studies dealt with operational aspects of the model at the macroscopic and microscopic levels, whereas the third was aimed at identifying correlations between simulated conflicts and accidents. The macroscopic study tests the model's ability to predict average space mean weaving and nonweaving speeds by comparing them with speeds from the field. The microscopic study verifies the model capability of maintaining an accurate count of lane change and rear-end conflicts. The safety study tests the model's ability to associate conflict rate to accident rates.

Macroscopic Validation

Data used for the macroscopic level validation of INTRAS were collected in the 1980s under FHWA contract (*7*). Data were collected at three sites and consisted of seven cases (Cases 101, . . ., 107). Each case involved different flow variables. Geometries of the three sites were also coded into INTRAS. All three sites were simple one-sided weaving sections with one auxiliary lane and no lane balance at the exit gore. The sites had three freeway lanes and one ramp lane entering the weaving section and three freeway lanes and one ramp lane exiting the weaving section.

Three INTRAS computer runs per case were performed. Each computer run simulated 15 min of traffic after equilibrium was obtained. The 15-min interval was used for consistency with the 1985 HCM peak period designation. The resulting space mean weaving and nonweaving speeds were then recorded and averaged by case. Once these average weaving and nonweaving speeds were determined, INTRAS average speeds and average speeds observed in the field were compared. The average field space mean speed was subtracted from their INTRAS space mean speed counterparts; the difference was then recorded, as presented in Table 1.

Two-tailed hypothesis tests on the difference between INTRAS speeds and field speeds using the t-statistic were performed. The null hypothesis (no difference in speeds) could not be rejected at a 10 percent level of significance with 6 degrees of freedom. The 90 percent confidence intervals on the average speed difference varied from -0.5 to $+4.7$ mph for weaving speeds and from -4.3 to $+7.5$ mph for nonweaving speeds.

When the field space mean speed was higher than 55 mph, large negative differences occurred for Cases 106 and 107, as indicated in Table 1. These differences are large because of the fact that when the INTRAS program was coded, a desired freeway free-flow speed of 55 mph was specified for all cases in the data base. Had the desired free-flow speed that was coded for Cases 106 and 107 been somewhat higher, these differences would have been reduced.

Microscopic Validation

In the validation test at the microscopic level, both LC and RE conflict counts were tested against individual vehicular

TABLE 1 SPEED VALIDATION RESULTS IN INTRAS

a) Weaving Speeds (SW)

Case #[a]	Avg. Field SW (mph)[b]	Avg. INTRAS SW (mph)	Difference Field-INTRAS (mph)
101	40.9	43.0	-2.1
102	42.3	43.1	-0.8
103	44.4	44.1	0.3
104	47.3	45.7	1.6
105	45.5	42.2	3.3
106	51.7	47.2	4.5
107	55.5	47.3	8.2

b) Nonweaving Speeds (SNW)

Case #[a]	Avg. Field SNW (mph)[b]	Avg. INTRAS SNW (mph)	Difference Field-INTRAS (mph)
101	43.9	53.7	-9.8
102	51.5	51.7	-0.2
103	47.6	52.5	4.9
104	54.9	52.7	2.2
105	43.8	43.4	0.4
106	59.3	48.5	10.8
107	62.8	50.3	12.5

[a]Case 101: Eastbound Interstate 20 from Pryor to Interstate 75/85, Atlanta, Georgia,
Case 102 - 104: Northbound Highway 680 from Rudgear to South Main, Walnut Creek, California,
Case 105 - 107: Northbound Highway 680 from Contra Costa to Oak Park, Pleasant Hill, California.
[b]From Reference (7).

trajectories that were dumped into an external file during the debugging phase. Every observation in this external file had the following vehicular attributes: vehicle identification, vehicle type, link identification, lane identification, time, position in link, speed, absolute acceleration value, acceleration and deceleration flag, preceding vehicle identification, lag vehicle identification, acceleration in previous time step, speed in previous time step, and several vehicular lane change attributes. Also in this file were tags when the LC and RE events were counted (e.g., subject vehicle identification, time, or highest deceleration observed in cycle by link for RE event). After the debugging phase, the counts finally matched what appeared in the vehicular trajectories.

After appearing to perform rationally, the upgraded simulation model was then used to conduct weaving simulation experiments.

Conflict and Accident Correlation

In order to test the two null hypotheses that (a) no correlation exists between RE conflict rates and reported RE crash rates in ramp weaves, and (b) no correlation exists between total LC conflict rates and reported angle and sideswipe collision rates in ramp weaves. Accident rate information for 10 ramp weave sites in a 4-year period (1985 to 1988) was gathered from the Illinois State Toll Highway Authority (ISTHA). Conflict rates were produced from INTRAS by simulating the 10 sites. Appropriate volume movements were determined from annual average daily traffic (AADT) diagrams. Spearman correlation coefficients and hypothesis test results are presented in Table 2.

Results of the hypothesis tests indicated a positive correlation between RE conflict rates and RE crash rates and between total LC conflict rates and angle and sideswipe collision rates for ramp weaves of moderate length at the 97.5 percent confidence level. For short weaving sections, the null hypothesis could not be rejected. Data points (three) were insufficient to conduct hypothesis tests for weaving sites with lengths exceeding 1,900 ft. However, two long sites did have the highest average conflict rates because their ramps connected to other Interstate highways, not to arterials as in the other sites. In other words, high weaving volumes occurred at these sites. In fact, these two sites have been targeted by ISTHA for reconstruction because of known histories of operational and safety problems. The model's ability to identify ramp weaves with known problematic operational and safety histories thus tended to confirm its validity in that aspect.

TABLE 2 CONFLICT-ACCIDENT RATE CORRELATION RESULTS ON THE BASIS OF 21 CASES ON ILLINOIS TOLLWAYS

Sample Size	Weaving Section Length (feet)	Conflict Type	Mean Simulated Conflict Rate (10^{-2} cpvm)	Mean Observed Acc Rate (100 mvm)	r_s[a]	Significant Correlation at 2.5%
3	1,950 to 2,000	RE	439.9	127.0	+0.50	—[b]
		LC	20.1	96.5	+0.50	—[b]
8	850 to 1,000	RE	82.6	128.0	+0.95	YES
		LC	5.4	85.5	+0.74	YES
10	500 to 650	RE	273.7	67.6	−0.48	NO
		LC	12.0	76.8	−0.61	NO

[a] r_s : Spearman correlation coefficient
[b] Insufficient sample size

SIMULATION EXPERIMENTS

In order to ascertain the basic relationships between conflict rates and speeds on the one hand, and weaving section parameters on the other, parametric analyses on the latter variables were conducted. Table 3 presents a glossary of terms used in these experiments. The simulation experiments were designed to incorporate a good cross section of operating conditions on simple one-sided freeway weaving sections with entrance and exit lane imbalance. One hundred twenty experiments were performed with three replications of each, for a total of 360 runs. In each experiment, a simple one-sided weaving section in an urban area was coded. Traffic in the weaving section was simulated for 15 min from the time equilibrium was attained. Equilibrium occurs when the number of vehicles entering the system is about equal to the number of vehicles leaving the system.

Six variables were selected on the basis of their perceived importance to the operation of freeway weaving sections: L, N, u_r, VF, VRP, and VF%. The desired free-flow speeds of the on- and off-ramps (u_r) were deemed important because of their potential acceleration and deceleration effects on entering and exiting traffic in the weaving section. Their input levels along with default values used in the computer runs are presented in Table 4. After extensive data processing, results of the simulation experiments were then used to conduct univariate analyses. For each observation, VC, VR, R, and NL were determined from the simulation output. Also, additional computer runs were performed to ensure that VR and R were controlled, that is, VR varied for fixed VC and R, and R varied for fixed VC and VR. Because of time constraints, the results reported are limited to cases with $V_2 > V_3$. Furthermore, when studying the effect of other variables, the values of VC, VR, and R were kept fixed at 0.85, 0.3, and 0.35, respectively. In the experiment, seven MOEs were evaluated, as presented in Table 5, using four weaving section variables (VC, VR, R, and NL).

RESULTS

Volume-to-Capacity Ratio (VC) Effect

A scatter diagram of SNW versus VC by length of weaving section revealed an inverse relationship when free-flow conditions prevail with minor speed variance. The sensitivity of SNW to VC increases with decreasing weaving section length. At the 2,000-ft length, the free-flow nonweaving speed ranged from 42 to 52 mph; at 1,400 ft, it ranged from 41 to 54 mph; and for a short weaving section of 800 ft, the range was 38 to 56 mph.

The scatter diagram of SW versus VC indicated poorly defined relationships with extensive speed variance. However, the observations became tighter (speed variance decreased) as the length of the weaving section increased. The fact that a horizontal line could be drawn through the free-flow weaving speed points at two of the three weaving section lengths suggests that free-flow SW is insensitive to VC; the 800-ft length revealed slight sensitivity. The weaving speed variance can best be explained by the traffic flow turbulence caused by drivers performing their weaving maneuvers. Shorter lengths produced more turbulence than longer lengths.

The average lane change and rear-end conflict rates, aggregated by VC range midpoints, were plotted against VC midpoints. A positive relationship is observed in all conflict rates, as shown in Figure 2. As VC increased, so did the rear-end and lane change conflict rates in the weaving section. Rear-end conflict rates were sensitive to VC. Average TRA ranged from 0.06 to 0.32 conflicts per vehicle-mile (cpvm); MRA from 0.04 to 0.26 cpvm; and RRA from 0.25 to 4.75 cpvm.

Volume Ratio (VR) Effect

In examining VR, VC and R were controlled so that their volume effect would not introduce bias in the results. VR is

TABLE 3 DEFINITIONS OF TERMS

Variable	Definition	Units
C	Weaving section configuration.	
cpvm	Conflicts per vehicle-mile	cpvm
d_{max}	Maximum allowable deceleration for vehicle.	ft/s/s
E	Superelevation.	
FLCL	Frequency of lane change logic.	time steps
G	Grade.	%
HC	Horizontal curvature.	
L	Length of the weaving section measured from a point where the entrance gore is two feet wide to a point where the exit gore is 12 feet wide.	feet
LD	Lane distribution of traffic upon entering system.	
LOSw	Level of Service of weaving traffic.	
LOSnw	Level of Service of nonweaving traffic.	
mph	Miles per hour	mph
mvm	Million vehicle-miles	mvm
N	Number of through lanes within the weaving section.	lane
NL	Area of the weaving section, NL = N X L.	lane-feet
PHF	Peak hour factor.	
PTSC	Pavement type and surface condition.	
R	Weaving Ratio, R = min(V2, V3)/VW.	
RN	Random number seeds.	seconds
SD	Early warning exit sign distance.	feet
spvm	Stops per vehicle-mile	spvm
ST	Simulation time measured after equilibrium is attained.	
STS	Simulation time step.	seconds
u_f	Desired free flow freeway speed.	mph
u_r	Desired free flow ramp speed.	mph
V1	Freeway to freeway movement volume.	vph or pcph
V2	Freeway to off-ramp movement volume.	vph or pcph
V3	On-ramp to freeway movement volume.	vph or pcph
V4	On-ramp to off-ramp movement volume.	vph or pcph
V	Total volume, V = V1 + V2 + V3 + V4.	vph or pcph
VC	Volume to capacity ratio, C = 1800 X N.	
VF	Entering freeway volume, VF = V1 + V2.	vph or pcph
VF%	Percent of entering freeway volume that exits, VF% = 100 X (V2/VF).	%
VMIX	Vehicle type mix.	
VNW	Nonweaving volume, VNW = V1 + V4.	vph or pcph
VW	Weaving volume, VW = V2 + V3.	vph or pcph
VR	Volume Ratio, VR = VW/V.	
VRP	Entering on-ramp volume, VRP = V3 + V4.	vph or pcph

a measure of the magnitude of weaving. Simulation experiments for VR > 0.50 were attempted, but given the specific values for VR and R, a higher value for VR could not be attained, because VC would have to be decreased. In this high VR range, the simulation would often stop with the message that no more vehicles could enter by the surface link (i.e., severe congestion). Typically, however, VR < 0.35 for most ramp weaves.

The relationship between the speed MOEs and VR were examined. SNW appears to be insensitive to VR, ranging from 46 mph when VR = 0.1 to 45 mph when VR = 0.5. SW displayed sensitivity when VR > 0.3. The largest speed difference of 16 mph occurred when VR = 0.5. Also noticeable is that the average SW and SNW values when VR is approximately zero correspond to average speed values from the SW and SNW versus VC scatterplots when VC = 0.83.

The relationship between lane change conflict rates and VR is shown in Figure 3. This direct proportional relationship confirms theory and is an important finding. Evidently, as VW increases, more lane changes take place and so does the probability of lane change conflicts. The rear-end conflict rate relationship also indicates sensitivity to VR, especially when VR > 0.3, as in Figure 3. Lane change and rear-end conflict rates are their maximum values when DSPD assumes its largest value.

Weaving Ratio (R) Effect

Weaving ratio R measures the degree to which the weaving section functions as a weaving section, that is, the interaction between entering and exiting drivers. When weaving movements V2 and V3 are equal (R = 0.50), the weaving section is performing strictly as a weaving section (i.e., weaving is maximized). If V2 or V3, but not both, are zero (R = 0), the weaving section operates either as an off-ramp junction or an on-ramp junction. If V2 and V3 both are zero, the weaving section behaves like a basic freeway segment. In experimenting with R, both VC and VR were kept constant so that their volume effect would not introduce distortions in

TABLE 4 EXPERIMENTAL DESIGN

Variables	Input/Output	Level(s)
L^a	I	800, 1400, and 2000 feet
N^a	I	3, 4, and 5 lanes
RN^a	I	Three 8-digit prime numbers
u_r[a]	I	30 and 50 mph
VF^a	I	2400, 4800, 7200 pcph
VF%[a]	I	10, 20, 30 %
VRP^a	I	100, 600, and 1200 pcph
C	I	Ramp weave, lane imbalances
d_{max}	I	20 feet per second per second
E	I	Zero
FLCL	I	Two time steps
G	I	Level
HC	I	None
LD	I	Uniform
PHF	I	One
PTSC	I	Dry asphalt pavement
R	O	
SD	I	0.5 mile
ST	I	15 minutes
STS	I	One second
u_f	I	55 mph
VC	O	
VMIX	I	50% high perf. pass. cars, 50% low
VR	O	

[a]Variables studied.

TABLE 5 SUGGESTED WEAVING SECTION MOEs

MOE	Description
MRA[a]	Total mandatory lane change conflict rate in cpvm.
MRDJ	Moderate and major mandatory lane change conflict rate in cpvm.
MRJ	Major mandatory lane change conflict rate in cpvm.
RRA[a]	Total rear-end conflict rate in cpvm.
RRDJ	Moderate and major rear-end conflict rate in cpvm.
RRJ	Major rear-end conflict rate in cpvm.
S1	Average space mean speed of freeway to freeway movement traffic through weaving section length in mph.
S2	Average space mean speed of freeway to off-ramp movement traffic through weaving section length in mph.
S3	Average space mean speed of on-ramp to freeway movement traffic through weaving section length in mph.
S4	Average space mean speed of on-ramp to off-ramp movement traffic through weaving section length in mph.
S	Average space mean speed of all traffic through weaving section length, S = (V1/V) S1 + (V2/V) S2 + (V3/V) S3 + (V4/V) S4 in mph.
SW[a]	Average space mean speed of weaving traffic through weaving section length, SW = (V2/VW) S2 + (V3/VW) S3 in mph.
SNW[a]	Average space mean speed of nonweaving traffic through weaving section length, SNW = (V1/VNW) S1 + (V4/VNW) S4 in mph.
DSPD[a]	Difference in nonweaving and weaving speed, DSPD = SNW − SW in mph.
SR	Stop rate in spvm.
TCR	Total lane change conflict count to total lane change ratio (%).
TRA[a]	Total [Mandatory + Optional] lane change conflict rate in cpvm.
TRDJ	Moderate and major lane change conflict rate in cpvm.
TRJ	Major lane change conflict rate in cpvm.
TTRA[a]	Total lane change and rear end conflict rate, TTRA = TRA + RRA, in cpvm.

[a]Measure of effectiveness examined in this paper.

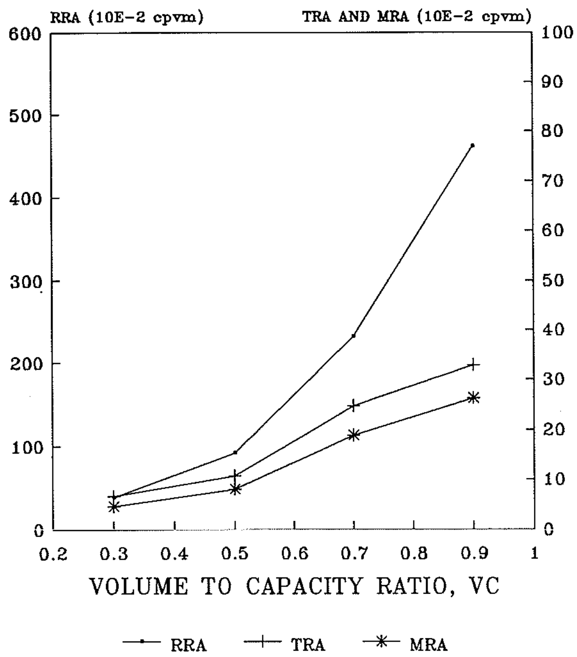


FIGURE 2 Conflict rates versus VC for a simple one-sided weaving section (n = 120).

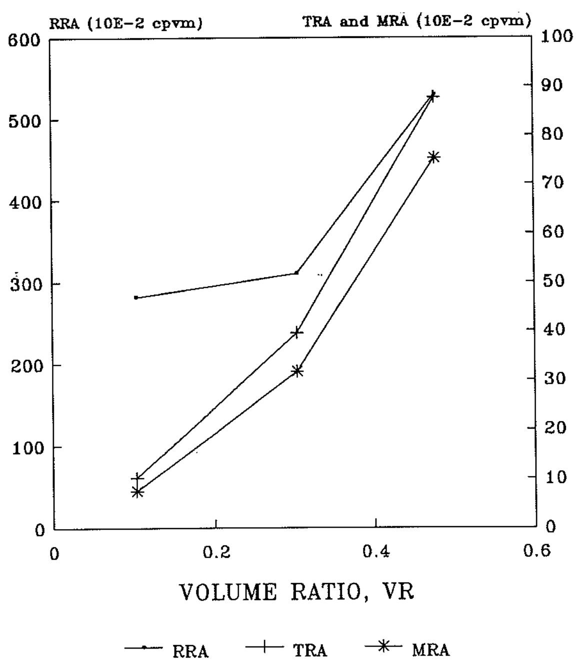


FIGURE 3 Conflict rates versus VR for VC = 0.83, R = 0.35, V3 ≤ V2, and n = 9.

the results. Additionally, V3 is kept less than or equal to V2 because of the constraints mentioned previously. Thus, diverging maneuvers govern the operation. Merging or diverging maneuvers dominate when R is near zero and VW is greater than zero. Weaving maneuvers dominate when R approaches its maximum value of 0.5. The midrange is 0.25. Thus, weaving controls when $R > 0.25$. SW, SNW, TRA, MRA, and RRA were all found to be insensitive to R when weaving controls (i.e., $R > 0.25$). Insensitivity of conflict MOEs is evident from Figure 4. When R < 0.25, SNW is insensitive to R, whereas SW, TRA, MRA, and RRA are slightly sensitive. When the entire range of R is examined, all conflict rates attain their maximum values when diverging maneuvers control (i.e., $0 \leq R < 0.25$). This situation is also the range where the largest speed difference is observed.

Also noticeable in the relationship of speed versus weaving ratio is that SW and SNW approach their average values determined from SNW and SW versus VC scatterplots at VC = 0.83 as R approaches 0.5. Similarly, lane change conflict rates stabilize as R approaches 0.5. TRA and MRA values at high R values correspond to values in Figure 3 at VR = 0.3. Likewise, RRA stabilizes at 324 cpvm when R = 0.45. This result corresponds to the RRA value in Figure 2 when VC = 0.83.

Weaving Section Area (NL) Effect

Geometric variables N and L are multiplied to represent the area of the weaving section. The scatter diagram of SNW versus NL revealed that free-flow, nonweaving speed is insensitive to the length of the weaving section as well as to the number of lanes within the weaving section. Average free-flow SNW only ranged from 46 to 53 mph through the entire NL spectrum. SNW appears to be independent of the area of the weaving section.

The scatter diagram of SW versus NL revealed a slightly different picture. Free-flow SW marginally increases as L increases and is insensitive to N because of the shallow slopes of the L lines. Overall, average free-flow SW ranged between

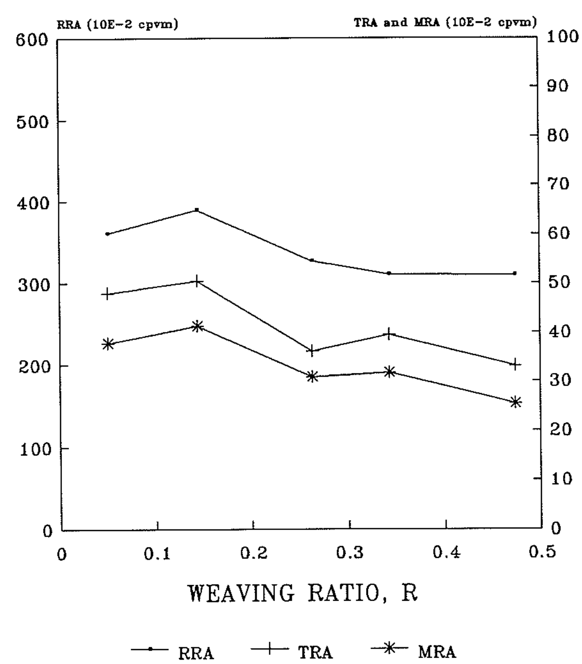


FIGURE 4 Conflict rates versus R for VC = 0.83, VR = 0.3, V3 ≤ V2, and n = 15.

40 and 50 mph when NL varied from 2,200 to 10,200 lane-ft. Thus, SW is slightly sensitive to NL.

Speed difference (DSPD) is plotted against NL in Figure 5. DSPD appears to be sensitive to N, especially at weaving sections with short lengths. As N increases, DSPD increases. This relationship is reasonable because most weaving is concentrated in the rightmost freeway lane and auxiliary lane. With more freeway lanes, nonweaving traffic has more opportunity to avoid the weaving turbulence in the rightmost lane (i.e., to separate from the weaving traffic). This separation increases the speed difference with weaving traffic, and its effect is more pronounced when weaving takes place in a short distance. Weaving sections should be designed such that DSPD is minimized and SNW and SW are maximized. The practice of minimizing DSPD is based on the theory that minimizing the average speed difference decreases accident severity. The practice of maximizing SNW and SW is based on the belief it will reduce travel time and improve operations. In Figure 5, DSPD is minimal when $N = 3$ for $L = 800$ ft, $N = 3$ or 4 for $L = 1{,}400$ ft, and $N = 4$ for $L = 2{,}000$ ft. The shallow slopes of the $N = 4$ and 5 lines indicate that DSPD is not sensitive to L.

The scatter diagrams of the conflict rates versus NL also portray a similar picture. One plot is chosen to be representative of the lot. Figure 6 shows the scatter diagram of the total lane change conflict rate versus NL. Clearly, TRA is sensitive to N when the length is short and is sensitive to L when N is large. The pattern of lines that appears in the scatter diagram is similar to the DSPD pattern in Figure 5. Figure 6 indicates that TRA is minimal when $N = 3$ for $L = 800$ ft, $N = 3$ for

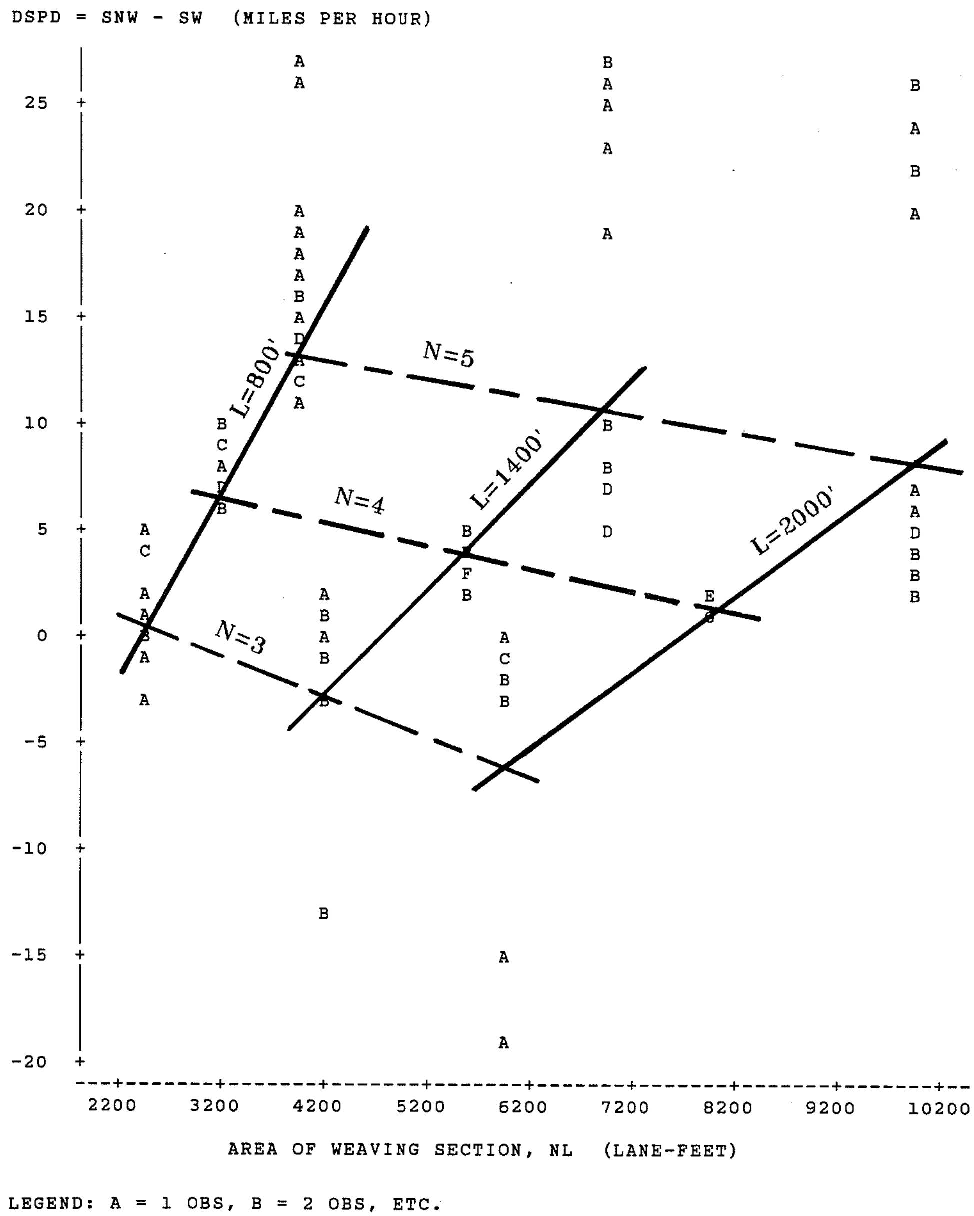


FIGURE 5 Plot of DSPD * NL.

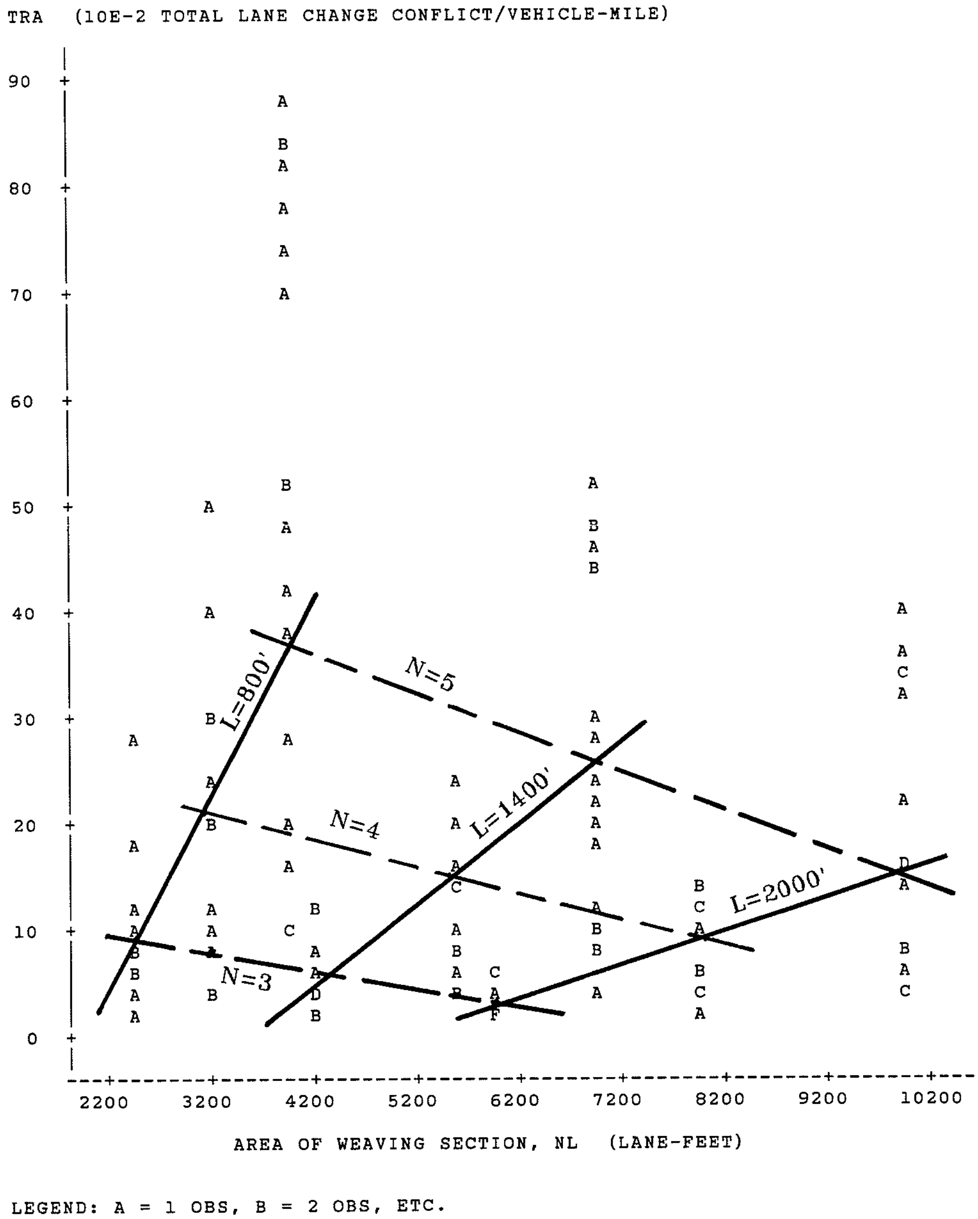


FIGURE 6 Plot of TRA * NL.

$L = 1,400$ ft, and $N = 3$ or 4 for $L = 2,000$ ft. This result further illustrates the relationship that exists between the macroscopic DSPD measure of effectiveness and its microscopic counterpart, namely, the conflict rate.

CONCLUSIONS

General Findings

Table 6 presents the results of the sensitivity analyses. Overall, the speed MOEs were not strongly sensitive to most operational variables encountered in the study of weaving sections. This conclusion confirms the work of previous research (*3*). Conflict rate MOEs that indicate high overall sensitivity are TRA, MRA, and RRA. Thus, these conflict rate MOEs appear to be better descriptors of the complex traffic operations in simple one-sided ramp weaves than the speed MOEs. Further, a positive association was detected between the microscopic conflict rates and the speed difference, that is, high conflict rates were observed when the DSPD was large.

An important finding was that conflict rates and speed differences increased significantly when the volume ratio increased from 0.3 to 0.5 for fixed VC and *R*. Another finding was that conflict rates and weaving speed were marginally sensitive to the weaving ratio when it varied between 0.05 and 0.25 for fixed VC and VR.

Using the weaving and nonweaving speed range criteria in Tables 4 to 6 of the HCM (*1*), the relationship between total conflict rate and the two LOSs, LOS_w and LOS_{nw}, is shown

TABLE 6 SENSITIVITY ANALYSES SUMMARY

MOES	Parameters[a]				
	VC	VR	R[b]	L	N
SW	N	Y	N	S	N
SNW	S	N	N	N	N
DSPD	N	Y	N	N	Y
TRA	Y	Y	N	Y	Y
MRA	Y	Y	N	Y	Y
RRA	Y	Y	N	Y	Y

[a]Legend: Y = Exhibits moderate to high sensitivity,
S = Exhibits slight to moderate sensitivity, and
N = Exhibits no sensitivity.
[b]For R $\geq$ 0.25

in Figure 7. In general, conflict rates did not increase significantly when LOS_w and LOS_{nw} were at Level C or better, when vehicular headways for weaving and nonweaving traffic are sufficiently large to accommodate lane changes and rear-end situations with a minimal level of conflicts. As LOS_w varies from D to F, lane change and rear-end conflict rates increase sharply. When LOS_{nw} varies from D to E, conflict rates increase sharply; however, when the level changes from E to F, a decrease in the conflict rates occurs. This slight decrease in the conflict rate when LOS_{nw} is F cannot be accounted for by variation in the data (in fact, the coefficients of variation for the conflict rate at LOS_w F and LOS_{nw} F are 0.12 and 0.11, respectively). The observation that the total conflict rate increases at LOS F for weaving traffic and decreases for nonweaving traffic clearly emphasizes the inherent natures of weaving and nonweaving traffic. By definition, weaving traffic must change lanes regardless whether the prevailing condition is free-flow or forced-flow. For nonweaving traffic, drivers do not necessarily have to change lanes. The propensity of nonweaving drivers to change lanes decreases in forced-flow conditions because one lane of traffic is just as congested as the next. This abatement in the nonweaving driver's desire to change lanes may have resulted in a slight drop in the total conflict rate. In summary, TTRA appears to be a consistent indicator of weaving LOS, but not for nonweaving LOS.

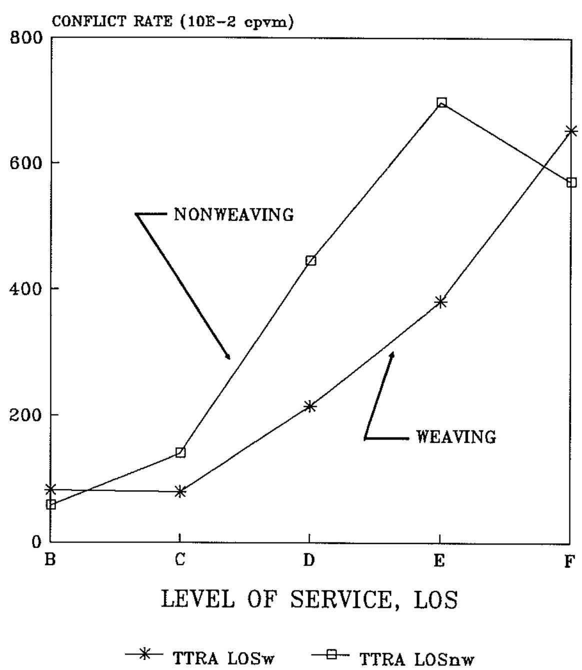


FIGURE 7 Overall conflict rate versus LOS for a simple one-sided weaving section (n = 120).

Application

In order to apply conflict rate data in the operational analysis of ramp weaves, the following procedure is suggested:

1. Count RE and LC conflicts (e.g., brake light indications) that occur within the weaving section during the peak 15-min period.
2. During the same 15 min, count the number of vehicles entering the weaving section from the freeway and on-ramp.
3. Calculate the conflict rate using the following equation:

$$\text{Conflict rate} = \frac{\text{15-min conflict count}}{\text{15-min count volume} * L/5280} \quad (1)$$

4. Determine weaving and nonweaving LOS for the simple one-sided weaving section from Figure 7.

For example, a conflict rate of 4 cpvm is calculated from the counts and geometric information. In Figure 7, draw a horizontal line from the conflict rate value on the vertical axis to intersect with the nonweaving and weaving lines. For weaving traffic the LOS is E and for nonweaving traffic the LOS is D. Figure 7 should not be used to analyze operations at

LOS A or B because of conflict rate insensitivity at such operations.

RECOMMENDATIONS

The possibilities of using freeway conflict rates as an MOE to quantify safety and operations are many. One topic for future study includes the application of conflict rates to other weaving section configurations. Another topic is the study of how conflict rates vary within other freeway components (e.g., basic freeway segments and ramp junctions). More work should be conducted in field testing of conflict rates versus speeds, volumes, or densities, instead of relying on just simulation modeling. Further investigation of using a macroscopic speed differential as a weaving and nonweaving LOS measure is needed. More work in relating turbulence at the microscopic versus macroscopic terms is essential. Ergonomic studies of what is considered minor, moderate, or major conflicts from the driver standpoint are also recommended. Another area for future study is the effect that different geometries have on conflict rates (e.g., speed change, lane length, ramp curvature, and grades). Finally, further tests involving associations between freeway conflict rates and accident rates are recommended.

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