WEAVSIM: A Microscopic Simulation Model of Freeway Weaving Sections

M. ZAREAN AND Z. A. NEMETH

Intense lane-changing maneuvers at weaving sections create turbulences that often lead to congestion. The study of the dynamics of traffic flow at weaving sections thus has the potential to generate benefits. This paper describes a microscopic simulation model, WEAVSIM, developed for such studies. Freeway Data Collection for Studying Vehicle Interaction, a project of the FHWA, produced data sets at weaving sections and other problem areas to facilitate the study of freeway operations and the enhancement of freeway simulation models. Some of these data sets have been used in testing WEAVSIM. The application of the model was demonstrated by a small-scale simulation study of weaving sections.

Weaving sections are those areas of a highway where two or more traffic streams, temporarily traveling in the same general direction, cross each other. Weaving sections are most frequently found at freeway interchanges. The lane-changing maneuvers performed by the weaving traffic introduce frictions and turbulence into the traffic flow that are not usually experienced on basic freeway sections. Therefore, weaving sections are often the cause of recurring congestion problems. In addition, weaving represents a traffic flow situation that is especially difficult to simulate.

An FHWA research study, entitled Freeway Data Collection for Studying Vehicle Interaction, was undertaken to develop a series of data sets on microscopic vehicular traffic flow for several types of potentially problematic geometric configurations (*1*). Several sets of data were collected at weaving sections. The development of the data sets involved digitizing vehicle positions from time-lapse aerial photographs. The data consists of a record of lateral and longitudinal positions of vehicles each second over a one-hour period. The data sets are being made available to researchers who are interested in studying a particular aspect of traffic flow. The data on microscopic vehicle movements were expected to be especially useful in enhancing freeway simulation models.

A comprehensive review of the literature on current freeway simulation models (*2*) reveals that although some general-purpose freeway corridor simulation models, such as INTRAS (*3*), could be utilized to some extent for the study of traffic operations in weaving sections, no specific purpose simulation model has been designed for a detailed study of weaving sections. This paper describes a microscopic simulation model, WEAVSIM, developed specifically for the study of the dynamics of traffic flow at weaving sections. The data sets provided by FHWA were utilized in testing the model.

M. Zarean, Baskerville-Donovan Engineers, Inc., 316 South Baylen Street, Suite 300, Pensacola, Fla. 32501. Z. A. Nemeth, Department of Civil Engineering, The Ohio State University, Columbus, Ohio 43210.

THE SIMULATION MODEL

WEAVSIM is written in SIMSCRIPT II.5 simulation programming language. SIMSCRIPT II.5 is a free-format, English-like programming language which is readable and understandable even by a nonprogrammer who is primarily interested in the system under study and not necessarily in the computer programming. WEAVSIM is thoroughly commented for easy understanding of the logic. The execution time and computer memory requirements of the WEAVSIM program vary considerably with the input volumes. When implemented on AMDAHL/V8, the average real-time/CPU time ratio was approximately 30:1.

In WEAVSIM, vehicles are generated randomly at the system entry points. Each vehicle behaves as an individual entity having a set of attributes which control its progress through the system. These attributes are assigned either stochastically or deterministically. The model is based on a rational description of the behavior of vehicles as they proceed through weaving sections. At each one second of real time, all vehicles are processed through the system using a car-following algorithm, which governs longitudinal movements, and a lane-changing algorithm, which controls lateral movements. Results from various human factor studies have been utilized in the development of the logic. All vehicles are advanced through the system in accordance with their desired speed and destination, influenced by the immediate environment.

The car-following algorithm is a modified version of the so-called "failsafe" approach developed for INTRAS (*2*). This approach is based on a combination of the following three concepts:

1. A following vehicle always seeks a desired safe headway behind a lead vehicle, which is a function of vehicle speed, relative speed, and vehicle and driver type.
2. A following vehicle is able to avoid collision even when a lead vehicle undergoes the most extreme deceleration. This constraint is, however, relaxed during lane-changing maneuvers. Vehicles may accept potentially unsafe positions for a short period of time when engaged in the weaving maneuvers.
3. The desired safe headway is inversely proportional to the driver's maximum speed. This means that a fast driver will maintain a smaller lead-headway than a slow driver, assuming both are traveling at the same speed.

The lane-changing algorithm moves vehicles from one lane to another by first establishing a desire or need for such a move and then searching for and accepting a suitable gap in the adjacent lane. The model assumes that as the ratio of the lane-weaving volume (weaving volume entering each lane) to the total weaving volume increases and, as the weaving vehicles move closer to the exit gore, vehicles become more willing to accept higher risk (i.e., shorter gaps) when engaged in lane-changing maneuvers. The lane changing logic also allows vehicles to look ahead of or behind the adjacent vehicle for appropriate gaps and, if needed, to adjust their speed to improve their position with respect to the available gap. The model performs two types of lane-changing: essential and non-essential. An essential lane-changing is performed by all weaving vehicles as they must change lanes to reach their desired destinations. A non-essential lane-changing is performed if the vehicle wishes to pass a slower vehicle.

In WEAVSIM the system starts empty and idle. Thus, it contends with an initiation bias prior to the steady-state conditions. Based on the observation of average delay and travel time, as a function of simulation time, a "warm-up" period of two hundred seconds was selected for the system to reach the steady-state condition. Buffer lengths are also provided at each end of the weaving section to dissipate the transient at the geometric boundaries. At the upstream end, four hundred feet of the simulated section are treated as the "warm-up" zone. At the downstream end, five hundred feet are used as the "cool-off" zone.

The input modeling of WEAVISM includes the following:

1. Interarrival headways of vehicles are generated using the inverse transformation method of the random deviate generation for a shifted negative exponential distribution with a minimum headway of one second. Interarrival headways are a function of lane volume.
2. Free-flow speeds are sampled randomly from a truncated normal distribution with mean and standard deviations of 60 and 10 mph, respectively.
3. Brake reaction times are generated stochastically from a gamma distribution with mean and standard deviations of 0.745 and 0.073 seconds, respectively.
4. Maximum deceleration/acceleration rates are assigned deterministically based on the vehicle type and speed.
5. Roadway parameters representing the geometry of the simulated section are directly specified.

The standard output of the model includes an echo of the input parameters and statistics on measures of performance describing the operational conditions of the weaving section. Vehicle trajectories, status listing, and a set of statistics on measures of performance are collected at user-specified time intervals. A graphical presentation of these statistics is an optional output of the model.

TESTING

Testing of WEAVSIM involved comparison of the simulated observations with field data provided by FHWA. Data used for this comparison were collected at the Baltimore-Washington Parkway northbound at I-95 in the Washington, D.C., area and at the Harbor Freeway northbound between the Santa Monica Freeway (I-10) and Sixth Street in Los Angeles, California.

Intervals of five minutes were selected from the data sets for comparison. A SIMSCRIPT program was written to read the field data as if they were created by WEAVSIM. To manipulate and analyze the data, this program was properly linked to a statistical analysis system package. This enabled creation of outputs from field data with the same format as those produced by WEAVSIM. This facilitated an easy comparison of the two outputs. The input volume and traffic compositions were also obtained from the data for each time interval and used as input parameters for the simulation model. The geometrics of the model were also adjusted to represent that of the site at which the field data were collected. Although five-minute intervals of data were used, to eliminate possible randomness effect, simulation runs were made for a period of thirty minutes plus a two-hundred-second warm-up time. The outputs were then compared with those obtained from the field data.

The following traffic descriptive parameters were targeted for comparison:

- headway distributions,
- distributions of accepted gaps,
- merging point distributions,
- weaving and non-weaving speed distributions, and
- vehicle trajectories.

The Kolmogrov-Smirnov distribution free test was applied to compare the observed and simulated distributions. The paired t-test was conducted to compare mean values of the observed and simulated speeds and headways. Finally, the F-distribution was applied for the comparison of variances. A complete description of the simulation model, including its testing, is given elsewhere (*3*). Some examples of the comparison of the observed versus simulated data are shown in Tables 1, 2, 3, and 4. A sensitivity analysis of the output to variation in the input variables was also performed with satisfactory results.

In addition, model behavior was tested at extreme traffic conditions by introducing a severe speed disturbance to the leader of a platoon and observing the behavior of the following vehicles. Figures 1 and 2 show the introduction of the speed disturbance and the recovery behavior of the platoon.

The testing results indicate overall that the model reproduces behavior of the real-life system reasonably well.

IMPLEMENTATION

Model implementation is illustrated with a simulation study. The objective of this study is to demonstrate the impact of upstream traffic conditions on some measures of performance (*i.e.*, speed, delay) which describe the operational conditions of the weaving sections.

In one way or another, available analysis and design techniques developed for weaving sections consider the effect of the weaving section length and weaving and non-weaving flow on the operational conditions at these sites. Speeds of vehicles entering the weaving section directly affect the operational conditions within the weaving sections. At the same time, traffic

TABLE 1 COMPARISON OF SIMULATED VS. OBSERVED HEADWAY DISTRIBUTIONS AT THE HARBOR SITE

HEADWAY	lane 1		lane 2		lane 3	
	OBS.	SIM.	OBS.	SIM.	OBS.	SIM.
<= 1.0	0.13	0.07	0.17	0.10	0.21	0.13
<= 2.0	0.57	0.67	0.54	0.60	0.57	0.59
<= 3.0	0.81	0.83	0.78	0.82	0.77	0.81
<= 4.0	0.90	0.87	0.88	0.91	0.87	0.87
<= 5.0	0.94	0.90	0.93	0.94	0.92	0.90
<= 6.0	0.96	0.92	0.95	0.96	0.95	0.93
<= 7.0	0.97	0.94	0.96	0.97	0.97	0.94
<= 8.0	0.98	0.95	0.97	0.98	0.98	0.96
<= 9.0	0.98	0.96	0.97	0.98	0.99	0.96
<=10.0	0.98	0.97	0.97	0.99	0.99	0.97
<=11.0	0.98	0.98	0.98	0.99	0.99	0.98
<=12.0	0.99	0.99	0.99	0.99	1.00	0.98
<=13.0	1.00	1.00	1.00	1.00	1.00	0.99
<=14.0	1.00	1.00	1.00	1.00	1.00	0.99
<=15.0	1.00	1.00	1.00	1.00	1.00	1.00
no. of obs.	302	877	294	950	265	804
MEAN	2.27	2.50	2.39	2.32	2.33	2.68
STD. DEV.	2.44	2.62	2.30	2.19	2.91	2.95
J J(crt)	0.060 0.091		0.070 0.088		0.080 0.096	
t t(crt)	-1.34 -1.96	 +1.96	+0.47 -1.96	 +1.96	-1.68 -1.96	 +1.96
DIFF(Appr.SE)	-.23(.17)		0.07(.15)		-.35(.21)	
F F(crt)	0.933 0.827	 1.198	1.050 0.827	 1.198	0.989 0.817	 1.211

TABLE 2 COMPARISON OF SIMULATED VS. OBSERVED HEADWAY DISTRIBUTIONS AT THE BALTIMORE SITE

HEADWAY	lane 1		lane 2		lane 3	
	OBS.	SIM.	OBS.	SIM.	OBS.	SIM.
<= 1.0	0.32	0.26	0.16	0.12	0.28	0.16
<= 2.0	0.74	0.71	0.76	0.71	0.68	0.49
<= 3.0	0.90	0.82	0.88	0.87	0.86	0.66
<= 4.0	0.95	0.90	0.93	0.93	0.93	0.74
<= 5.0	0.97	0.94	0.95	0.96	0.96	0.80
<= 6.0	0.99	0.96	0.97	0.98	0.98	0.84
<= 7.0	0.99	0.97	0.98	0.98	0.99	0.88
<= 8.0	0.99	0.99	0.99	0.99	0.99	0.90
<= 9.0	1.00	0.99	0.99	0.99	1.00	0.93
<=10.0	1.00	1.00	1.00	1.00	1.00	0.94
<=11.0	1.00	1.00	1.00	1.00	1.00	0.96
<=12.0	1.00	1.00	1.00	1.00	1.00	0.97
<=13.0	1.00	1.00	1.00	1.00	1.00	0.99
<=14.0	1.00	1.00	1.00	1.00	1.00	1.00
<=15.0	1.00	1.00	1.00	1.00	1.00	1.00
# of obs.	158	480	192	544	85	286
MEAN	1.86	2.03	1.74	1.93	1.84	3.46
STD. DEV.	1.29	1.59	1.44	1.26	1.47	3.42
J J(crt)	0.080 0.125		0.050 0.114		0.200 0.168	
t t(crt)	-1.22 -1.96	 +1.96	-1.73 -1.96	 +1.96	-4.40 -1.96	 +1.96
DIFF(Appr.SE)	-.17(.14)		-.19(.11)		-1.62(.37)	
F F(crt)	0.805 0.768	 1.280	1.147 0.786	 1.254	0.433 0.697	 1.388

TABLE 3 COMPARISON OF SIMULATED VS. OBSERVED SPEED DISTRIBUTIONS AT THE HARBOR SITE

SPEED mph.	WEAVING		NONWEAVING	
	OBS.	SIM.	OBS.	SIM.
<= 15.0	0.00	0.00	0.00	0.00
<= 20.0	0.09	0.16	0.12	0.07
<= 25.0	0.42	0.56	0.46	0.35
<= 30.0	0.81	0.91	0.87	0.61
<= 35.0	0.98	1.00	1.00	0.94
<= 40.0	1.00	1.00	1.00	0.99
<= 45.0	1.00	1.00	1.00	1.00
<= 50.0	1.00	1.00	1.00	1.00
# of obs.	112	339	113	361
MEAN	26.07	24.29	25.44	27.88
STD. DEV.	4.59	4.06	4.61	5.52
DIFF(Appr.SE)	1.78(.46)		-2.44(.57)	
J J(crt)	0.140 0.148		0.260 0.147	
F F(crt)	0.990 0.724	 1.347	1.289 0.719	 1.358

TABLE 4 COMPARISON OF SIMULATED VS. OBSERVED SPEED DISTRIBUTIONS AT THE BALTIMORE SITE

SPEED mph.	WEAVING		NONWEAVING	
	OBS.	SIM.	OBS.	SIM.
<= 15.0	0.00	0.00	0.00	0.00
<= 20.0	0.00	0.01	0.00	0.01
<= 25.0	0.01	0.08	0.04	0.06
<= 30.0	0.23	0.27	0.12	0.17
<= 35.0	0.55	0.56	0.38	0.42
<= 40.0	0.73	0.84	0.76	0.87
<= 45.0	0.88	0.97	0.88	0.99
<= 50.0	0.96	1.00	0.98	1.00
<= 55.0	0.97	1.00	0.99	1.00
<= 60.0	1.00	1.00	1.00	1.00
<= 65.0	1.00	1.00	1.00	1.00
# of obs.	77	239	170	496
MEAN	35.92	33.87	43.70	39.90
STD. DEV.	7.20	6.05	7.03	5.36
DIFF(Appr.SE)	2.05(.83)		3.80(.51)	
J J(crt)	0.090 0.178		0.110 0.121	
F F(crt)	1.013 0.682	 1.416	1.310 0.775	 1.271

disturbances in the weaving section have an impact on arrival speeds of vehicles entering the weaving sections. These impacts, although generally recognized, have not been addressed by any of the current analysis and design procedures.

WEAVSIM is used here to demonstrate the impact of upstream traffic conditions, represented by speed, on operating conditions within the weaving section.

When two traffic streams merge, the arrival speeds of the two streams are not always compatible. This is the case when the weaving section is formed by an on-ramp which is followed by an off-ramp with a continuous auxiliary lane between the ramps. The arrival speed of the ramp vehicles is influenced by the restrictions of the ramp geometrics and is usually lower than the speed of the freeway vehicles. This difference in arrival speeds directly influences the operational conditions of weaving sections. This study investigates the effect of the difference in arrival speeds of the two merging traffic streams on the speed and delay in the weaving section.

A set of four dependent variables which are indicators of the operational conditions and five independent variables which control the operation through weaving sections has been selected for this study. The dependent variables are weaving and non-weaving speeds and delays. Delay is computed as the difference between the ideal travel time at free-flow speed and the actual travel time for each vehicle. The independent variables are weaving section length, freeway volume, ramp volume, proportion of weaving vehicles to total volume, and difference in arrival speeds (SPDDIF). Three levels of each variable were selected. Using various combinations of the independent variables, a total of 243 experiments were performed. Each simulation experiment was run for a period of forty-five minutes plus a warm-up period of two hundred seconds. Using batch means, with batches of size fifteen minutes, three independent sets of output were obtained from each experiment. These outputs were then subjected to the following multiple regression analysis involving first and second order parameters, as well as one-way interactions:

$$MOP = \beta_0 + \sum_{i<1}^{5} \beta_i X_i + \sum_{i<1}^{4} \sum_{j<i+1}^{5} \beta_{ij} X_i X_j + \sum_{i<1}^{5} \alpha_i X_i^2$$

MOP = Predicted measure of performance,
β_0, β_i, β_{ij} = Estimates of the constants, and
X_i, X_j = Input parameters.

Finally, a stepwise regression approach was employed to derive the best fitting model for each individual measure of performance. The effect of the difference in arrival speeds was illustrated by computing the weaving and non-weaving speeds and delays for various values of this parameter using the regression models. The results are summarized in Table 5. The direct impact of difference in arrival speeds on weaving speeds and delays within the section is demonstrated, with more pronounced effect on weaving traffic than on non-weaving traffic. Values of the weaving and non-weaving speeds computed using the new *Highway Capacity Manual* (HCM) procedures (*4*) are also shown in this table. Although no statistical test was performed, the values predicted by the model seem to be compatible with those produced using the HCM procedures.

SUMMARY

WEAVSIM, a microscopic simulation model of freeway weaving sections was developed, using SIMSCRIPT II.5 simulation programming language. It allows the simulation of traffic flow through a three-lane weaving section of any length and under varying traffic volume conditions. Operational conditions are represented by speed and delay. The intent of this study was neither the development of new freeway weaving

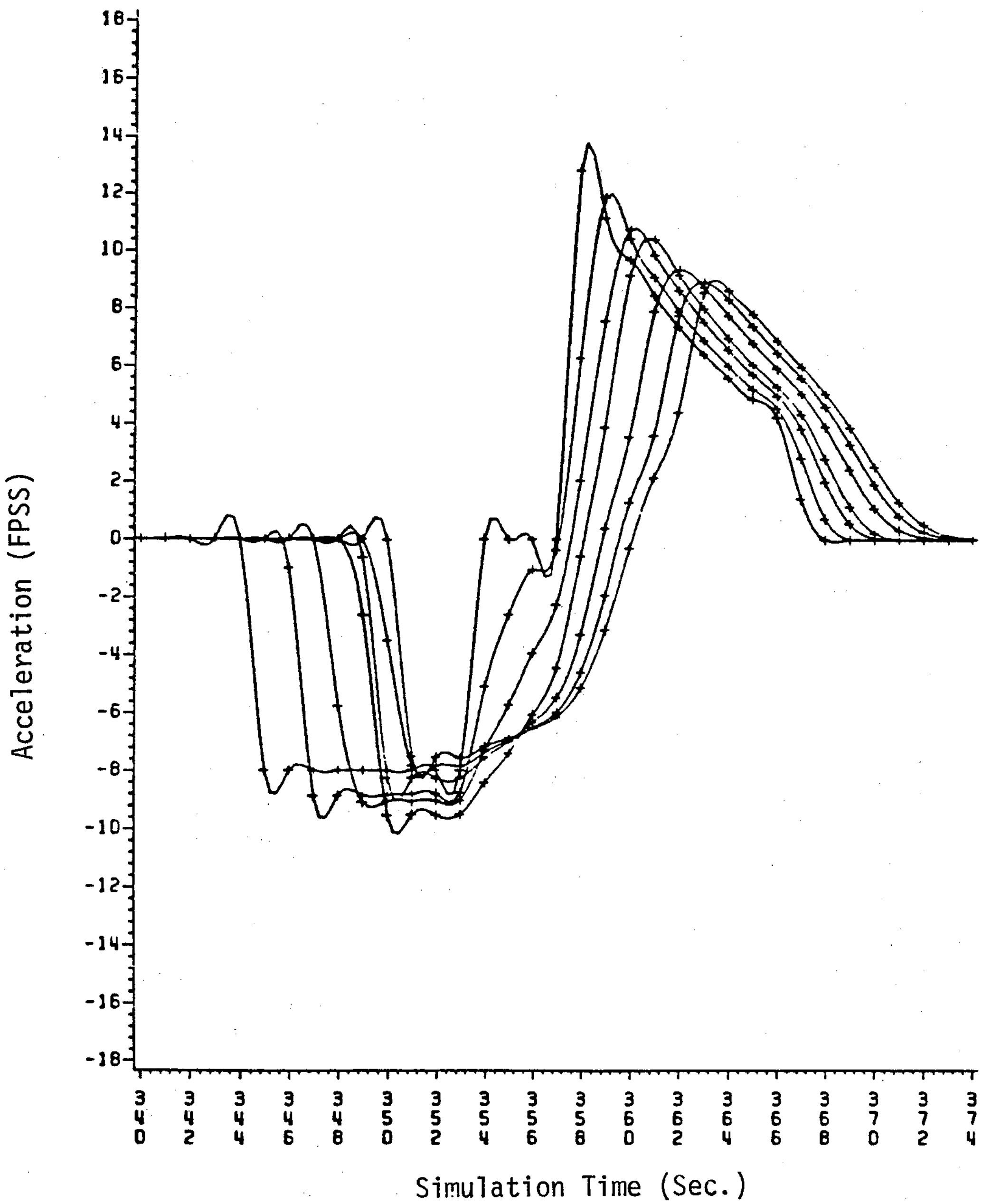

FIGURE 1 Acceleration changes during a speed disturbance.

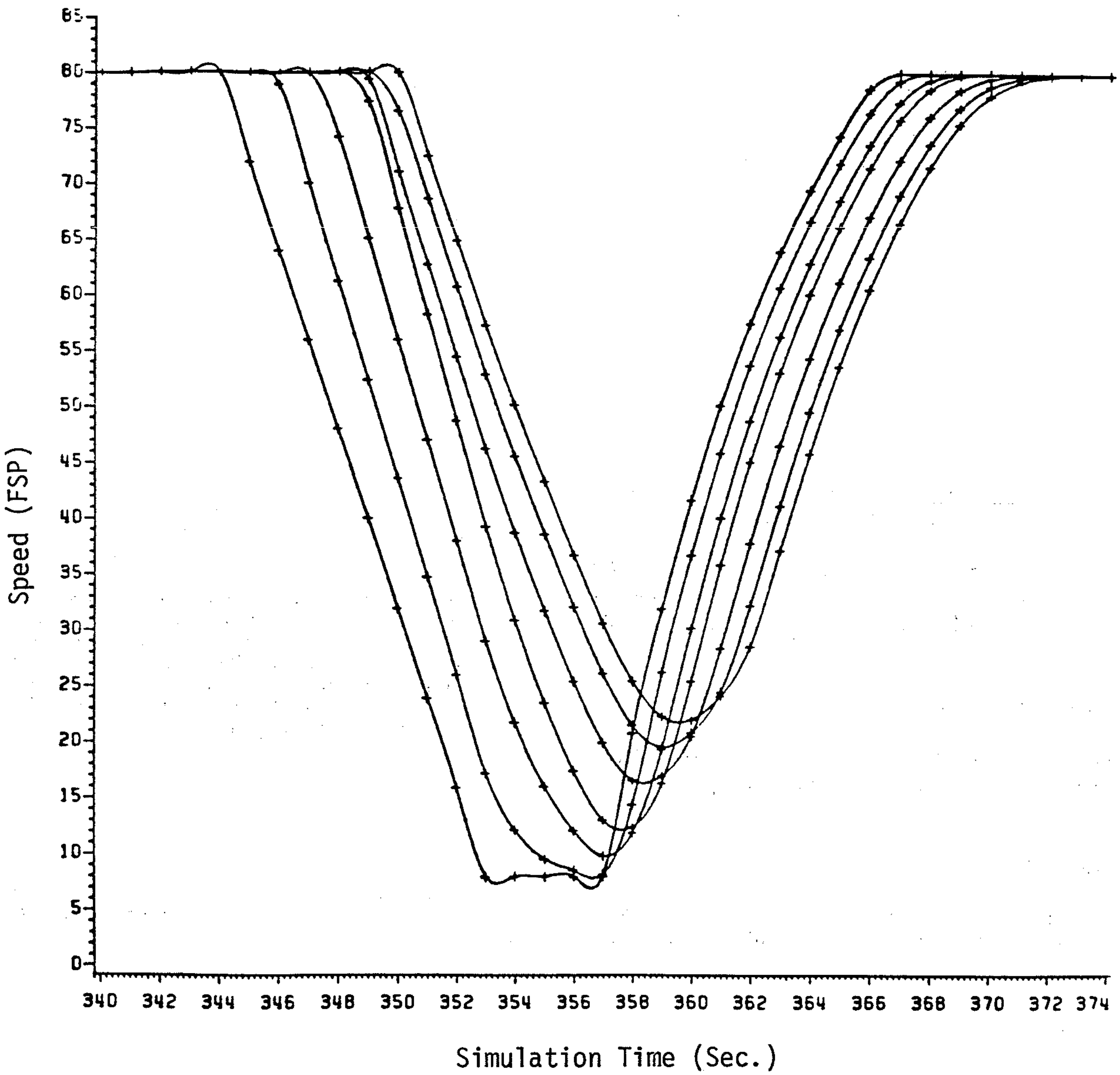

FIGURE 2 Platoon recovery during a speed disturbance.

TABLE 5 SPEEDS AND DELAYS FOR VARIOUS VALUES OF SPEED DIFFERENCE

	SPEED (MPH)		DELAY (SEC./VEH./MILE)	
SPDDIF	WEAVING	NON-WEAVING	WEAVING	NON-WEAVING
0	37.07	40.86	24.89	17.89
10	32.78	38.49	29.19	20.08
20	28.11	36.12	34.18	22.35
HCM	34.50	42.00	N/A	N/A

CONDITION:

Weaving Section Length = 1000 FT.
Ramp (Minor Entrance) volume = 794 VPH
Mainline (Major Entrance) Volume = 2483 VPH
Proportion of Weaving Vehicles = 0.55

Mainline arrival speeds were sampled from a truncated normal distribution with mean and standard deviations of 60 mph and 10 mph, respectively.
Ramp arrival speeds were sampled from a truncated normal distribution with mean and standard deviations of (60 mph - SPDDIF) and 10 mph, respectively.

section design procedures nor the modification of current procedures, but to develop a tool which might provide the means for such endeavor.

The availability of microscopic data sets from the FHWA permitted the testing of the model. The results of the test indicate that the model is capable of producing realistic results.

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