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Development and evaluation of a NFWEAV simulation model for weaving areas under non-freeway condition

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ABSTRACT

Development and Evaluation of a NFWEAV Simulation Model for Weaving Areas under Non-freeway Conditions

by
Wen-min Pan

The development of a microscopic digital computer simulation model representing vehicle interaction at a weaving area under non-freeway condition is presented. Weaving areas are classified into two categories: 1. Weaving caused by merging and diverging of a ramp with an arterial, 2. On/off ramps connecting an arterial with a highway. The principal characteristics of the simulation model are the following: 1) a car following and lane changing model were used to represent vehicle movements; 2) an anti-collision check algorithm was developed for all vehicle movements; 3) driver merging urgency and follower courtesy model were developed for weaving vehicles. The simulation model was validated through field observation using video taping and photogrammetry techniques Comparative analyses between field observations and model predictions are carried out for non-weaving and weaving speed, as well as non-weaving and weaving acceleration. The results indicate that there is no statistically significant difference between the field data and simulation output.

DEVELOPMENT AND EVALUATION OF A NFWEAV SIMULATION MODEL FOR WEAVING AREAS UNDER NON-FREEWAY CONDITION

by
Wen-min Pan

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APPROVAL PAGE

DEVELOPMENT AND EVALUATION OF A NFWEAV SIMULATION MODEL FOR WEAVING AREAS UNDER NON-FREEWAY CONDITIONS

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CHAPTER ONE

INTRODUCTION

1.1 Problem Definition

This study presents a microscopic computer simulation model representing vehicle interactions at a weaving area under non-freeway conditions. The principle characteristics of the simulation model are the following:

- a car following and lane change model were used to represent vehicle movements;
- an anti-collision check algorithm was developed for all vehicle movement;
- driver merging urgency and follower courtesy model were developed for weaving vehicles.

The combinations of facility types, configurations, disturbances, etc., which can exist in non-freeway weaving areas are practically impossible to enumerate. As a consequence, each facility needs to be studied as a separate case. Two different categories of weaving areas are defined as: (1) weaving caused by merging and diverging of a ramp with an arterial, and (2) on/off ramps connecting an arterial with a highway.

This thesis is part of a research project whose scope was the analysis of weaving areas under non-freeway conditions. The project was undertaken by the Center for Transportation Studies and Research, and was funded by Region II Transportation Consortium and New Jersey Department of Transportation (NJDOT). The primary objective of Phase I was the development of an analytical model, and of phase II, the development of a simulation model for analyzing and designing weaving areas on multilane arterial highways (5).

This thesis presents the simulation model developed for analyzing traffic operations in weaving areas on multilane highways which was the primary objective of phase II of the project. Simulation encompasses a model building process as well as the design and implementation of an appropriate experiment involving that model on a computer. The purpose of simulation on a computer is the experiment determination of phenomena which are too complex to study analytically and which may not be conveniently studied empirically. Operation of traffic on weaving areas is a typical complex system.

1.2 Motivation

The operation of weaving area under freeway conditions was treated in many studies, including the 1985 Highway Capacity Manual (HCM) (1). However the 1985 HCM and its previous editions (2,3) contain no treatment of weaving area operations on non-freeway facilities. The committee on Highway Capacity and Quality of Service of the Transportation Research Board, rated the "Effective of Arterial Weaving on Arterial Level Service" of high urgency priority (4). It indicated that although the 1985 HCM treats weaving areas, rural highway, and urban streets, it does not address the problem created on an arterial by ramps and closely spaced intersections which can result in significant lane changing across the arterial over relatively short distances. In addition, most of the studies represented traffic interactions through analytical models which are based on average conditions and fail to capture the true dynamic trajectory of vehicle movements.

The motivation for conducting this study stems from the fact that no models exist to represent traffic flow characteristics for weaving areas on multilane highways. In addition, the development of a simulation model provides transportation engineers with a more powerful tool in analyzing the effect on weaving area operations under various traffic conditions.

1.3 Objectives

The primary objective of this project was the development of a methodology using simulation to analyze operations in weaving areas on multilane and arterial highways. The objectives of this study are the following:

- To develop a simulation model to represent the traffic flow characteristics of weaving areas under non-freeway conditions.
- To validate the simulation model through the field observations
- To compare the simulation model with a recently developed analytical model.

1.4 Overview

Chapter 2 presents the literature review which includes two parts. The first part is a review of weaving area's capacity analysis, including 1985 Highway Capacity Manual, (1) and Fazio's method (6), etc. The second part is a review of simulation model including INTRAS, FRESIM WEAVSIM models, etc. Chapter 3 presents a detailed description of the elements of the simulation model NFWEAV. Chapter 4 presents the traffic flow models which used in the simulation model. Chapter 5 presents the structure of the simulation model, including flow charts of the software package. Chapter 6 presents the verification and evaluation results for NFWEAV. A comparison between the analytical model and the simulation model, and comparison between field data and simulation result are conducted for evaluation purposes. Finally, Chapter 7 presents summary of the thesis, conclusions and future research.

CHAPTER TWO

LITERATURE REVIEW

This chapter presents a literature review on analytical model for freeway weaving sections and some principal simulation models for freeway conditions. Section 2.1 presents the analytical models, and section 2.2 presents simulation models.

2.1 Analytical Models

The history of the development of different models for design and analysis of freeway weaving sections can be traced back to 1950 when the original HCM was published(2). The manual was meant to be a practical guide to the design and evaluation of street and highways in terms of their traffic-carrying capability. A major purpose of the manual was to ensure consistency of procedures in the national program of highway design and construction. These procedures were based on empirical analysis of data collected prior to 1948. In 1953, a major effort was initiated by the U.S. Bureau of Public Road (BPR) to collect additional data for updating the 1950 procedures. As a result, a new weaving design and analysis procedure was published in 1965 HCM (3).

Polytechnic Institute of New York analyzed the 1963 data base collected by the BPR, and additional data collected from 1972 to 1973, A new analysis methodology was proposed and published in National Cooperative Highway Research Program (NCHRP) Report 159(7). The key feature of the methodology was based on the geometric configuration of the weaving area which was a major determinant of operating quality. The Transportation Research Board (TRB) Circular 212: Interim Materials on Highway Capacity was published in 1980 (8). It is a part of the "Freeway Capacity Analysis Procedures" study sponsored by Federal Highway Administration (FHWA). It reformatted and revised Polytechnic's weaving procedure for easier use and understanding.

The JHK & Associates study proposed a simplified method which consisted of two equations; one for the prediction of the average of weaving speed, and the other for the prediction of average speed of non-weaving speed.(9) However this method does not consider any geometric configuration differences or the type of operation (e.g. constrained or unconstrained) In 1984, the NCHRP Project 3-28B team recalibrated the JHK-type equations for the prediction of weaving and non-weaving vehicle speeds in weaving areas for the three basic configurations types taking into account constrained and non-constrained operations. The study results in 12 calibrated equations which are included in the 1985 HCM (1).

2.1.1 1985 HCM

The methodology of the weaving study conducted by JHK & Associates is included in the 1985 HCM. Chapter 4 "Freeway Weaving" of the 1985 HCM discusses and illustrates the development of weaving diagrams and covers basic relationships, level-of-service criteria, and step-by-step procedures for analysis (1). The 1985 HCM defines three weaving area configuration types (A, B, and C). These configurations are based on the minimum number of lane changes required by weaving vehicles as they travel through the section.

- Type A configuration requires that each weaving vehicle performs one lane change in order to execute its desired movements. Ramp-weaving freeway sections are typically of this type.
- Type B weaving areas require vehicles in one weaving traffic stream to execute one lane change, while vehicles in the other weaving traffic stream perform desired movements without changing lanes.
- Type C weaving sections require vehicles in one weaving traffic stream to perform two or more lane changes, while vehicles in the other weaving traffic stream perform their desired maneuvers without changing lanes

Figure 2.1 shows the weaving movements a and b; Table 2.1 shows the configuration types versus number of required lane changes.

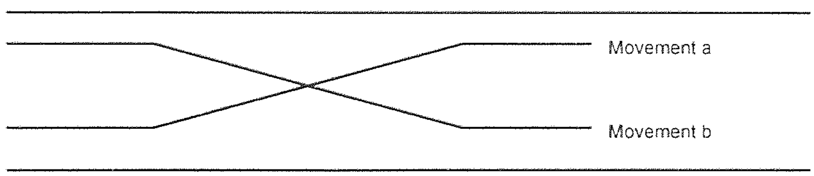

Figure 2.1 Weaving Movements a and b

Table 2.1 Configuration Types Versus Number of Required Lane Changes

No. of required lane changes for weaving Movement b	No. of required lane changes for weaving movement a: 0	1	> =2
0	Type B	Type B	Type C
1	Type B	Type A	
> =2	Type C		

The equation for weaving and non-weaving speeds prediction are calculated from:

$$S_w \ or \ S_{nw} = 15 + \frac{50}{(1 + a(1+VR)^b (V/N)^c / L^d}$$

where a, b, and c are calibrated constants based on operation and configuration.(1) Table 2.2 give the value of these constants.(1)

Table 2.2 Calibration Constants for Speed Prediction in Weaving Areas

Type of configuration	Calibration constants for weaving speed a	b	c	d	Calibration constant for nonweaving speed a	b	c	d
A unconstrained	.226	2.2	1.00	0.90	0.020	4.0	1.30	1.00
constrained	.280	2.2	1.00	0.90	0.020	4.0	0.88	0.60
B unconstrained	.100	1.2	0.77	0.50	0.020	2.0	1.42	0.95
constrained	.160	1.2	0.77	0.50	0.015	2.0	1.30	0.90
C unconstrained	.100	1.8	0.80	0.50	0.015	1.8	1.10	0.50
constrained	.100	2.0	0.85	0.50	0.013	1.6	1.00	0.50

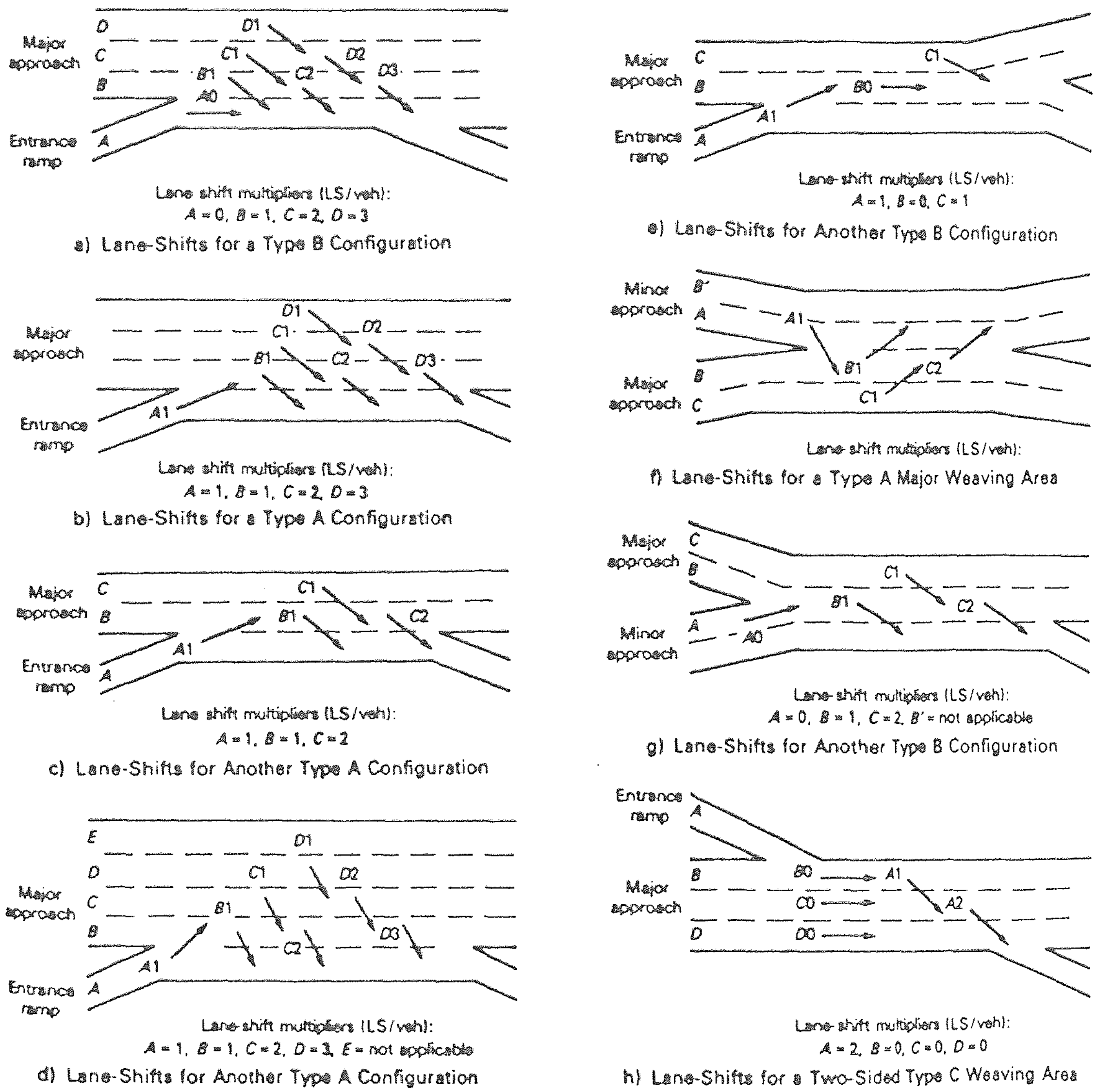

FIGURE Examples of lane-shift determination for the Fazio procedure.
SOURCE: J. Fazio, "Development and Testing of a Weaving Operational Analysis and Design Procedure," Master's Thesis, University of Illinois at Chicago, Chicago, IL, 1985, Figs. 8 and 8.

TABLE Lane-shift equations for the Fazio model

No. of Lanes on Major Entry Leg	No. of Total Lane Shifts for Weaving Vehicles Entering on: Major Leg LS_2	Minor Leg LS_3
1	Bv_2	Av_3
2	$0.934Bv_2 + 0.066Cv_2$	Av_3
3	$0.905Bv_2 + 0.085Cv_2 + 0.010Dv_2$	Av_3
	$LS = LS_2 + LS_3$	

Figure 2.2 Lane Shift for Fazio Model (1)

The level-of-service for weaving and non-weaving traffic is taking from table 2.3 based on the calculated average speed of weaving and non-weaving flow.

Table 2.3 Level of Service Criteria for Weaving Section (1)

Level of Service	Minimum weaving speed(mph)	Minimum non-weaving speed(mph)
A	55	60
B	50	54
C	45	48
D	40	42
E	35	35
F	<35	<35

2.1.2 Fazio's Lane-shift Model

Joseph Fazio suggests a different approach to inclusion of lane configuration in weaving-area analysis methodology (6). The methodology is based on specifically accounting for the number of lane shifts that need to be made by weaving vehicles to successfully complete their desired maneuver. It is based on calibrated lane distribution of entering vehicles in weaving sections. Once the entering lane distribution of entering vehicle is established, the total number of required lane shifts (or lane changes) that have to be made is known, based on the configuration of the section. All volumes are then converted to the peak flow rate by applying appropriate adjustments.

The Figure 2.2 illustrates a number of different configurations. Fazio's equation for prediction of weaving and non-weaving speeds are as follows: (6)

$$S_w = 65 - \frac{50}{1 + (\exp(4.33 - 3.045\ln(1 + MR) - .605\ln(v) - .902\ln(LS / L) + 3.395\ln(1 + LS_3 / V))}$$

$$S_{nw} = 65 - \frac{50}{1 + (\exp(4.11 - 5.08\ln(1 + SR) - 2.019\ln(1 + VR) - 1.523\ln(v) + .916\ln(1 + LS_3 / LS) + 1.07\ln(L)}$$

Variables are defined as follows:

LS: total lane shifts required of weaving vehicles

LS_3: total lane shifts required of weaving vehicles

v: total demand, expressed as a peak flow rate in pcph under equivalent idea conditions

V: total demand, expressed as a full hour volume in prevailing vph

MR: minor leg flow rate; $(v_3+v_4)/v$;

VR: volume ration; v_m/v;

SR: small non-weaving flow ratio; v_4/v

S: average speed of weaving vehicle in weaving area (mph)

S: average speed of non-weaving vehicle in weaving area (mph)

Based on the calibrated average speed levels of service are determined from Table 2.3.

2.2 Simulation Models

2.2.1 System Simulation and Simulation Model

Computer simulation is a technique that permits the study of complex system in the laboratory rather than in the field (10). Computer simulation is the process of designing a mathematical-logical model of a real system and experimenting with this model on a computer. Thus simulation encompasses a model building process as well as the design and implementation of an appropriate experiment involving that model. The experiments, or simulations, permit inferences to be drawn about systems (11-12)

- Without building them, if they are only proposed system;
- Without disturbing them, if they are operating systems that are costly or unsafe to experiment;
- Without destroying them, if the object of an experiment is to determine their limit of stress

In this way, simulation models can be used for design, procedural analysis, and performance assessment.

A. Discrete/Continuous

Models of systems can be classified as either discrete changes or continuous changes. Discrete simulation occurs when the dependent variables change discretely at specified points in simulated time referred to as event times. In continuous simulation the dependent variables of the model may change continuously over simulation time.

B. Macroscopic/Microscopic

Simulation models can be classified as macroscopic or microscopic. Macroscopic models represent traffic in terms of overall parameters such as: traffic volume, average speed and density, or handle the vehicles in groups. This technique is less time consuming and more economical in every respect, however may be unable to describe a complex process adequately. Microscopic models are those which simulate movements of individual vehicles. Each vehicle is represented by a set of variables such as: vehicle type, coordinate, speed and acceleration, etc. When a model together with values specified for all parameters and a particular experiment to be performed on the model are given, dynamic trajectories of variables in the model can provide a detailed understanding of a traffic flow.

C Deterministic/Stochastic

Simulation models can also be distinguished between probabilistic and deterministic which is based on the model variables. If any random variables are present, the model is classified as a probabilistic model. Random variables must be defined by an appropriate probability function.

2.3 Traffic Simulation

The earliest computer simulation work in highway transportation occurred in the 1950s. Intersection simulation was undertaken by the Road Research Laboratory in the United Kingdom in 1951. The first simulation work in the United States was published in 1953 and reported on intersection and freeway models developed at University of California at Los Angeles. Then intersection simulation by University of Michigan, major arterial simulation at Philco, bus terminal and car-following simulation by Port Authority of New York , and freeway interchange and ramp merging simulation at Midwest Research Institute were developed (13).

The development of simulation grew rapidly during the 1960s and 1970s, and bibliographies were published devoted exclusively to computer simulation models developed for the highway system. Fox and Lehman published a state-of-art article in the Traffic Quarterly in 1967 (14). The University of California at Berkeley published a bibliography identifying selected references of applications of computer simulation to transportation systems (15). By 1981, a Traffic Simulation Conference was conducted by the Transportation Research Board and Sponsored by the U.S. Department of Transportation. Seventy-five persons representing researchers, developers and users attended this conference (16).

Many computer simulation models are available today for analyzing various operating environments of the highway system. The operating environments include signalized intersections, arterial networks, freeway corridors and rural highways. Both microscopic and macroscopic computer simulation models have been developed for each of the operating environments identified above

2.3.1. NETSIM Model

NETSIM is a microscopic simulation model of an urban traffic network (17). It is designed to be applied by the traffic engineer and researcher as an operational tool for the purpose of evaluating alternative network control and traffic management strategies. NETSIM is written in FORTRAN and consists of pre-processor, traffic simulator and post-processor (18). NETSIM's pre-processor is designed to simplify the process of preparing and checking data inputs. It includes a comprehensive set of automatic "diagnostic checks" which are performed on all data inputs. It also provides for the convenient packaging of successive runs based on sequential modification of input conditions. The preprocessor may be operated either independently or may be integrated directly with the main program.

The NETSIM simulator contains the main simulation program. It consists of 60 separate routines, which be linked together in a variety of optional configurations. The simulator requires input as coded descriptions of street networks, together with a pre-specified control plan and a set of input volumes. Its output includes a set of measures of traffic performance, expressed as both link-specific and network-wide values. The NETSIM post-processor consists of a set of standard data manipulation and evaluation routine designed to operate on the outputs of main simulation program to compare the results of two or more simulation runs, construct a "historical" data file summarizing their results, and subject the resultant data set to a standard statistical analysis.

2.3.2 Freeway Corridor Model

There are several models available for freeway corridor. FREQ (19) and FRECON (20) are macroscopic model, the INTRAS is the only microscopic arterial network simulation model.

A. The FREQ Model Family

Since 1968 the FREQ family of freeway models has been developed at the University of California. FREQ is a macroscopic model and is intended to evaluate a directional freeway and its ramp on the basis of ramp origin-destination information (19). Some diversion to parallel alternative is considered for vehicles queued at on-ramps. The strength of FREQ lies in the diversity of traffic impact measures, and the comprehensive range of responses that are included. FREQ uses a linear program to optimize ramp-metering rates.

B. FRECON Model

FRECON is a dynamic macroscopic freeway simulation model developed from Payne's FREFLO model. FRECON can simulate freeway performance under normal and incident conditions (20). The model was developed by Rouphail and written in GASP IV simulation language. The model can generate point detector information for calibration and validation. The model can generate a traffic responsive priority entry control strategy and evaluate its effectiveness. The traffic performance measures include travel times, queue characteristics, delay, fuel consumption and emissions. The input data includes subsection geometric influencing capacity and O-D information.

C. INTRAS

The INTRAS model was developed by KLD and Associates in the late 1970s, and refinements and enhancements have continued through the 1980s. INTRAS stands for INtegrated TRAffic Simulation. The INTRAS model is a microscopic, stochastic, vehicle-specific, time-stepping computer simulation model designed to predict traffic performance for a directional freeway and surrounding surface street environment based on user-specified design, demand and control (21-22).

INTRAS has been developed for use in studying freeway incident detection and control strategies. It is based on knowledge of freeway operations and surveillance system and incorporates detailed traffic simulation logic. INTRAS model contains a realistic surveillance system simulation capability. The ability to visualize vehicle trajectories, and contours of measures of effectiveness (MOE's) in the time-space plane, is included in INTRAS via a digital plotting model. INTRAS also contains a statistical analyses model which permits comparison of MOE's from different simulation runs or field data.

INTRAS model is a highly complex system containing procedures for multi-purpose input processing, diagnostic testing, microscopic traffic simulation, output reporting, statistical analysis, detector output processing and digital plotting.

D. FRESIM Model

The FRESIM model is a microscopic, interval scanning simulation model recently developed (23). This model, although very complex, is a very user-friendly model, which uses the same input/output conventions as the existing TRAF submodels. It is a considerably enhanced and reprogrammed version of its freeway simulation predecessor, the INTRAS model. The enhancement includes improvements, and in most cases, total revisions in areas such as geometric representation, vehicle processing, and operational capabilities of the INTRAS model.

The FRESIM model is now able to simulate more complex geometric and provide a more realistic representation, more efficiently than its predecessor model. FRESIM is capable of simulating more prevailing freeway geometric, which include one to five through-lane freeway mainlines with one to three-lane ramps and one to three-lane freeway-freeway connectors; variations in grade, radius of curvature, super elevation on freeway; lane additions and lane drops anywhere on the freeway; representation of auxiliary lanes; representation of multiple destination lanes and origin-destination trip generation based on off-ramp exit fractions. The FRESIM model also provides realistic simulation of operational features: comprehensive lane-changing model; ramp metering and differences in driving habits. The model generates comprehensive tables of measures of effectiveness: travel time, speed, and traffic flow, which enable a meaningful evaluation of operational situations.

FRESIM has been calibrated and validated using several sets of comprehensive real-world data and has been extensively tested on several complexes and diverse scenarios.

E. CARSIM Model

A CAR-following SIMulation model was developed by Benekohal. It is developed to simulate not only normal but also stop-and-go traffic conditions on freeway (24). The main features of CARSIM are:

- marginally safe spacing are provided for all vehicles
- start-up delays of vehicles are taken into account
- reaction times of drivers are randomly generated
- shorter reaction time are assigned at higher densities
- dual behavior of traffic in congested and non-congested conditions are taken into consideration in developing the car-following logic of model.

The validation of CARSIM has been performed at microscopic and macroscopic levels. At the microscopic level, the speed change pattern and trajectories from CARSIM were compared with those from field data; at the macroscopic level, average speed, density and volume computed in CARSIM were compared with the value from real world traffic conditions. The results were satisfactory.

2.3.3 Weaving Section Model

WEAVSIM model was developed specially for the study of the dynamics of traffic flow at weaving sections by Zarean (25). WEAVSIM is written in SIMSCRIPT II.5 simulation program language. 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 as influenced by the immediate environment.

The car following algorithm is a modified version of the so-called "fail-safe" approach developed for INTRAS (21). This approach is based on a combination of the following three concepts:

- A following vehicle seeks a desired safe headway behind a lead vehicle, which is a function of vehicle speed, relative speed, type of vehicle/driver
- A following vehicle is able to avoid collision even when a lead vehicle undergoes the most extreme deceleration. This constrain is relaxed during lane changing maneuvers. Vehicle may accept potentially unsafe positions for a short period of time when engaged in the weaving maneuvers.
- The desired safe headway is inversely proportional to the driver's maximum speed. This means that a fast driver will maintain a small 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 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 when engaging in lane-changing maneuvers. The lane changing logic allows vehicles to look ahead of or behind the adjacent vehicle for appropriate gaps and, if needed, to adjust their speed to improve the position with respect to available gaps. The model performs two types of lane changing: essential and non-essential. An essential lane changing is performed by all weaving vehicle as they must change lanes to reach their desired destinations. A non-essential one is performed if vehicles wish to pass slower vehicles.

The input modeling of WEAVING includes interarrival headways of vehicles; free-flow speed; brake reaction time, maximum deceleration/acceleration and road geometric parameters. The output of the model includes an each report and statistics on measures of performance describing operational condition of weaving section.

The following traffic descriptive parameters were targeted for comparison:

- headway distributions,
- distributions of accepted gaps
- merging point distributions
- weaving and non-weaving speed distributions
- 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 speed and headways. The F-distribution was applied for the comparison of variances. The test results indicate that the model reproduces behavior of the real-life system reasonable well.

CHAPTER THREE

ELEMENTS OF NFWEAV SIMULATION MODEL

This chapter presents the newly developed traffic simulation model for weaving sections under non-freeway conditions. NFWEAV is an acronym for Non Freeway Weaving simulation model. This chapter presents the discussion of the methodology that is adopted for the development of the NFWEAV model and the selection of the suitable simulation programming language.

Simulation modeling is a description or abstraction of a real system. Computer simulation is a process of designing mathematical-logical models of a real system and experimenting with these models on a computer. The main elements of a simulation model for weaving areas under non-freeway conditions are the following: geometry of weaving sections, behaviors of vehicles and drivers, and interaction of traffic flows. These elements are represented either in static form (geometry) or in dynamic form (vehicle/driver behavior, interaction of traffic flow). The elements of the weaving section operation are described below in detail.

3.1 Description of Weaving Areas

3.1.1. Categories

The geometry of weaving sections has significant effects on the operation of traffic flow. The combinations of facility types, configurations, disturbances, etc., which can exist in non-freeway weaving areas are practically impossible to enumerate. As a consequence, they can not be studied or analyzed in detail. Two different categories of weaving areas are defined as follows:

A. Category I: weaving caused by merging and diverging of a ramp with an arterial

Figure 3.1 shows a typical configuration under this category. Weaving starts where a ramp is merged in to the arterial and stops at the diverging point of another ramp from the arterial. The following factors are important under this category:

- Existence of a crown line
- Lane balance at the diverging point
- Availability of shoulder on each side of the road
- Length of weaving section

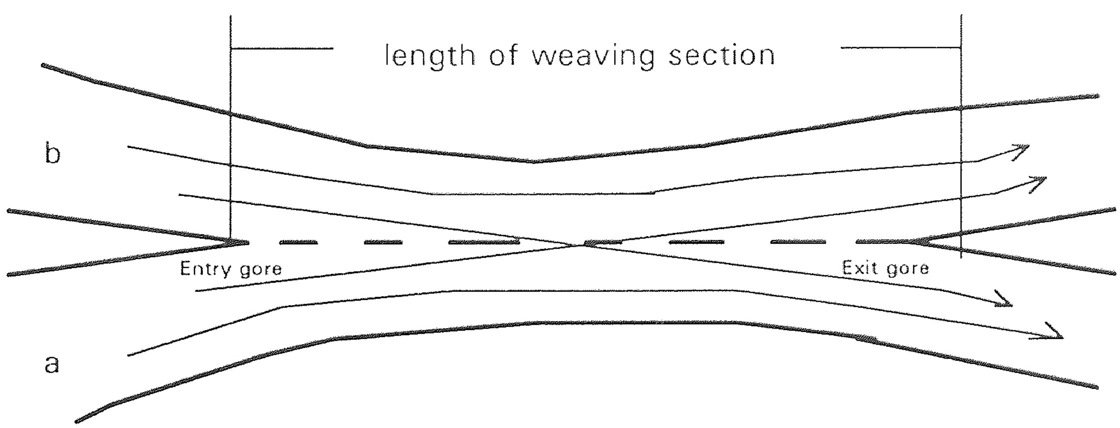

Figure 3.1 Configuration of Category I

B. Category II: on/off ramp connecting an arterial with a highway

Weaving action takes place on a segment of highway between an on-ramp followed by an off-ramp connecting an arterial with the highway. A typical configuration for this category is also shown in Figure 3.2. The basic weaving maneuver takes place as a result of the on-ramp vehicles crossing the path of the off-ramp vehicles. The weaving distance between the on and off ramps is short. The main factors for this category are the following:

- Number of lanes on the arterial/highway
- Existence of shoulder and auxiliary lane
- Availability of sight distance on the-ramp
- the length between the on off ramp gore areas.

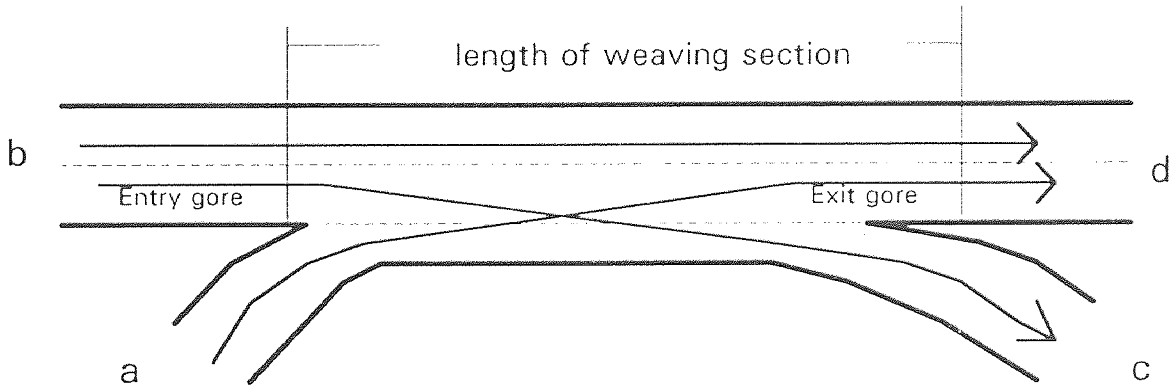

Figure 3.2 Configuration of Category II

3.1.2. Parameters

The parameters for describing geometric characteristics of weaving areas under non-freeway conditions are presented as follows:

A. Weaving length L (ft):

The length of weaving section constrains the time and space in which the driver must make all required lane changes. Length is measured from the merge gore area at a point where the right edge of the freeway shoulder lane and the left edge of the merging lane are 2 ft apart to a point at the diverge gore area where the two edges are 12 ft apart. The maximum length for non-freeway conditions is considered as 600 ft.

B. Weaving width W (ft):

The total width of weaving areas. It is a geometric characteristic with a significant impact on weaving area operations.

C. Number of Lanes N:

The total number of lanes of a weaving area. The number of lane in the weaving section limits the number of potential lane changes that weaving and non-weaving vehicles may make, and therefore influences total lane-changing turbulence in the weaving area. The maximum number of lanes considered in this model is four.

D. Approach angle β (°):

The angle of approach for merging lane affects the speed of the entering traffic, the angle of weaving and the place of weaving.

E. Grade:

The grade for non-freeway weaving areas is limited to ±2% for this study.

F. Friction factor:

The coefficient of friction between pavement and tire surface.

G. Auxiliary lane:

The code indicating a weaving area of category II with or without an auxiliary lane.

An eight-dimensional array RD used to store the geometric parameters is shown in Table 3.1.

Table 3.1 Geometric Characteristics of a Weaving Area

RD(1)	RD(2)	RD(3)	D(4)	RD(5)	RD(6)	RD(7)	RD(8)
Code of Categories RD(1)=1,2; Cat.I, II	Length (ft)	Width (ft)	No.of Lane	Approach Angle (°)	Grade (%)	Friction Factor	Auxilia ry Lane

3.2 Vehicle and Driver Description

To describe the dynamic characteristics of weaving areas, a system state description is a key concept. If it can be characterized by a set of variables, with each combination of variable values representing a unique state of the system, then manipulation of the variable values simulates the movement of the system from state to state.

The behavior of each vehicle/driver is represented by a set of attributes that are stored in a 25-dimensional array ATRIB shown in Table 3.2. The state of an individual vehicle/driver at weaving areas is described by these attributes.

Table 3.2 Attributes of Vehicles

Attributes	Description
Atrib(1)	arrival time
Atrib(2)	origin
Atrib(3)	current lane
Atrib(4)	destination
Atrib(5)	vehicle index
Atrib(6)	vehicle length
Atrib(7)	driver reaction time
Atrib(8)	vehicle weaving status
Atrib(9)	vehicle type
Atrib(10)	speed at the beginning of the scanning interval
Atrib(11)	speed at the end of the scanning interval
Atrib(12)	position at the beginning of the scanning interval
Atrib(13)	position at the end of the scanning interval
Atrib(14)	acceleration
Atrib(15)	animation code
Atrib(16)	travel time
Atrib(17)	weaving vehicle lane changing flag
Atrib(18)	unused
Atrib(19)	gap acceptance
Atrib(20)	flag of vehicle's position in upstream of weaving area
Atrib(21)	driver courtesy factor

Two types of attributes are assigned to the vehicles and drivers: (1) permanent, and (2) temporary. Permanent attributes are those that remain constant throughout the presence of the vehicle in the system. Temporary attributes are updated periodically based on the scan interval. The scan interval used was one second. Following, the permanent and temporary attributes used are presented.

3.2.1 Permanent Attributes

The following attributes are permanent.

- ATRIB(1): a mean time between two vehicles arriving to the system
- ATRIB(2): origin (entry lane) of the vehicle
- ATRIB(4): destination (exit lane) of the vehicle
- ATRIB(5): integer vehicle index assigned sequentially to each arriving vehicle
- ATRIB(6): length of the vehicle
- ATRIB(7): a mean time of driver's break reaction time
- ATRIB(8): status of the vehicle (weaving / non-weaving)
- ATRIB(9): type of the vehicle (passenger car, single unit, combined truck)
- ATRIB(21): a factor to show driver's courtesy for cooperation with a follower

3.2.2 Temporary Attributes

The following attributes are temporary.

- ATRIB(3): the current lane of the vehicle
- ATRIB(8)-(9): current coordinate of the vehicle at the beginning or the end of the scanning period
- ATRIB(10)-(11): current speed of the vehicle at the beginning or the end of the scanning period
- ATRIB(14): current acceleration of the vehicle at the end of the scanning period

Attributes are generated either stochasticly or deterministicly when a vehicle arrives at 100 feet before the upstream gore point of a weaving area.

3.3 Traffic Flow Description

This section presents the principle characteristics that are needed to represent the traffic flow at weaving sections. These characteristics are the following: (1) arrival flow pattern, (2) traffic flow description. The arrival flow pattern and interaction behavior of vehicles in weaving areas under non-freeway conditions are modeled as follows.

3.3.1. Arrival Flow Pattern

The principle components that identify the arrival flow pattern at weaving areas are the following: Arrival headway and speed, traffic composition, and proportion of weaving vehicles in a traffic stream.

A. Arrival headway

The distribution of vehicle headway has been the subject of research for a number of years (10). Negative exponential, Pearson type III, lognormal distribution are used for headway distribution. The research conducted by Minjie Mie indicated that lognormal distribution is suitable for heavy traffic or the traffic in a car following state.

The arrival headway distribution $H_a(t)$ in NFWEAV is considered to be a log-normal (5), and it is shown in Equation 3-1.

$$H_a(t) = \frac{1}{\sqrt{2\pi}\sigma_h t} \exp\left(-\frac{(\ln t - \mu_h)^2}{2\sigma_h^2}\right) \tag{3-1}$$

μ_h, σ_h: mean and standard deviation (STD) of arrival headway t.

For simulation purposes, Arrival Headway Statistics (AHS) in the model is described as a matrix AHS(4,5); in which four (4) represents the maximum number of lanes, and five (5) represents the statistical values, that is, minimum, maximum, mean, mode and standard deviation of arrival headway for each lane. The minimum headway is 0.6 sec, and the maximum, 12 sec. The mean value changes according to the specific condition.

B. Arrival speed

Numerous investigators have used normal distributions to represent speeds (10,13). The arrival speed $S_a(v)$ in the NFWEAV model has a normal distribution shown in Equation 3-2.

$$S_a = \frac{1}{\sqrt{2\pi\sigma_v v}} \exp\left(-\frac{(v-\mu_v)^2}{2\sigma_v^2}\right) \qquad (3\text{-}2)$$

μ_V, σ_V: mean and STD of arrival speed v.

The Arriving Speed Statistics (ASS) for the two approaching legs are stored in a 2x5 matrix ASS. Two (2) reflects the two entrances A and B of a weaving area, and five (5) indicates the same meaning mentioned in the arrival headway. According to surveys conducted in this research (8), the default value are the following: the mean of arrival speed is 35 mph, a minimum of 15 mph, and a maximum of 50 mph.

C. Traffic composition

Vehicles in the model are classified into three types: Passenger Car, Single Unit and Combined Truck. A three-dimension array VT is one that describes the composition of a traffic flow in weaving areas. Default values VT(1), VT(2) and VT(3) for this model are 0.92, 0.05, 0.03 for passenger car, single unit and combination truck, respectively. The length for different types of vehicles are 19, 39 and 59 ft, respectively (26).

D. Weaving volume ratio

Proportions of weaving vehicles in a weaving area vary from 0 to 100% according to different operation conditions. A Weaving Division (WD) matrix WD(2,2) describes the proportion of non-weaving and weaving vehicles for each leg.

WD(i,j): i = 1,2 denote entering approach A or B, and

j = 1, 2 denote proportion of weaving or non-weaving vehicles in approach.

3.3.2 Traffic Flow Description

Traffic flow description is required for governing the movement of vehicles in the model. Vehicles operating in weaving areas are designated as entities which have multi-attributes, and engage in different type of activities such as moving maneuver or merging action. The aim of a simulation model is to reproduce the activities that the entities engage in, by different traffic flow models, such as, car-following model or lane changing model. The next chapter presents the traffic flow models which are used for the NFWEAV model.

CHAPTER FOUR

TRAFFIC FLOW MODELS

This chapter presents the newly developed traffic simulation model for weaving sections under non-freeway conditions. Traffic flow models are the core of the NFWEAV models. Two traffic flow models are required for governing the movement of vehicles at weaving areas. Longitudinal movements of the vehicles are determined by a leading vehicle movement or a car following algorithm, and lateral movements of the vehicles are determined by a lane changing model.

4.1 Longitudinal Movement Model

4.1.1 Leading Vehicle Movement

A leading vehicle is the first vehicle in a platoon. The behavior of leading vehicles affects the operation in a weaving area because of a much shorter length (less than 600 ft) existing under non-freeway weaving areas. According to the survey conducted in this study (8), the number of vehicles in a platoon usually varies from 3 to 8, whereas the portion of the platoon occupied by the leading vehicles varies from 33% to 12%. The leading vehicle usually attempts to increase its acceleration at the maximum possible rate which depends on the type and speed of vehicles as shown in Table 4.1 (26).

Table 4.1. Maximum Acceleration Rate (m/h/s) of Vehicles

Vehicle Type	Speed Change														
	0-15 mph			15-30 mph			30-40 mph			40-50 mph			50-60 mph		
	0%	2%	6%	0%	2%	6%	0%	2%	6%	0%	2%	6%	0%	2%	6%
Pas.car	4.7	4.6	4.2	4.2	4.0	3.7	3.8	3.5	3.4	2.8	2.7	2.5	1.9	1.7	1.5
S. U.	2.0	1.6	0.7	1.0	0.6	0	0.6	0.6	0	0.2	0.2	0	0	0	0
C. T.	2.0	1.6	0.7	0.8	0.6	0	0.4	0.3	0	0	0	0	0	0	0

However the increasing in a vehicle's acceleration in the NFWEAV model is subject to the different non-freeway operation situations. The operating acceleration of leading vehicles adopted in NFWEAV model is calibrated in Chapter 6.

4.1.2 Car Following Model

Car following behavior is a very important aspect in the study of traffic flow characteristics. The interaction of vehicles within a single stream of traffic is based on car following behavior. The car following models are in the forms of stimulus-response equations, where the response is the reaction of a driver to the motion of the vehicle immediately preceding him/her in the traffic stream. The response of successive drivers is to accelerate or decelerate in proportion to the magnitude of the stimulus at time t which is begun after a time lag T. The basic principle of this model is of the form (10):

Response (t +T) = Sensitivity * Stimulus (t)

For convenience, the symbols used in car-following models study in this project are the following:

- $A_f(t+T)$: acceleration of the follower at the end of this interval;
- $V_l(t+T)$: velocity of leader at the end of this interval;
- $V_l(t+T)$: location of leader at the end of this interval;
- $V_f(t)$: velocity of follower at the beginning of this interval;
- $X_f(t)$: location of follower at the beginning of this interval;
- L length of leading vehicle
- T scanning time
- α, k, b, w, m: constants

Following, some commonly used car-following model are presented:

A. Linear model:

The basic car-following model is a linear model shown in Equation 4-1(10)

$$A_f(t+T) = \lambda\,(V_l(t)-V_f(t)) \tag{4-1}$$

The linear model is useful because of its simplicity and its susceptibility to stability analyses. This model has one shortcoming: the reaction of the follower is a function only of the relative speed of the two vehicles and is independent of the spacing of the vehicles.

B. General model

Gazis proposed a more general expression for the car-following model which is given in Equation 4-2 (10).

$$A_f(t+T) = \alpha \frac{V_f^{k}(t+T)}{[X_l(t)-X_f(t)]^m}\,[(V_l(t)-V_f(t)] \tag{4-2}$$

This model indicates that the spacing, related speed of the two vehicles and the speed of the follower all reflect the stimulus for a response. For applications, there are several car-following models used in different situations such as TEXAS (27), NETSIM (17), PITT (21) shown in the following equations:

C. TEXAS model (27):

$$A_f(t+T) = \alpha \frac{(V_l(t)-V_f(t)]^k}{(X_l(t)-X_f(t))^m} \tag{4-3}$$

The acceleration in TEXAS is not only related to the difference of the speed of the leader and follower, but also affected by the difference of gap between the leader and follower. This car following model is used in the intersections of urban roads.

D. NETSIM model:

This model consists of a spacing algorithm which provides for collision avoidance when the leading vehicle decelerates suddenly to a stop. The algorithm is given by Equation 4-4 (17).

$$A_f(t+T) = \frac{7[X_l(t+T)-X_f(t+T)-V_f(t)-L_l]+1/3(V_l(t+T)^2-2V_f(t)^2)}{(V_f(t)+3)} \tag{4-4}$$

E. PITT model:

The PITT car following relationship is that a following vehicle will attempt to maintain a space headway and sensitive to the operation conditions. The algorithm is shown in Equation 4-5 (26):

$$A_f(t+T) = \frac{2[(X_l(t+T)-X_f(t)-L-10-V_f(t)(k+T)-bk[V_l(t+T)-V_f(t)]^2)]}{(T^2+2Tk)} \tag{4-5}$$

$$b = \begin{cases} 0.1 \\ 0. \end{cases} \quad \text{if} \quad \begin{cases} V_l(t+T)-V_f(t) < 10 \text{ fps} \\ V_l(t+T)-V_f(t) > 10 \text{ fps} \end{cases}$$

k is a sensitivity factor.

The term $2[(X_l(t+T)-X_f(t)-L-10-V_f(t)(k+T)-bk[V_l(t+T)-V_f(t)]^2)$ reflects a desired safe space headway, and k is a sensitivity factor which is a function of driver type, regulates maximum lane capacity since it determines the average headway at high volume.

The PITT car following algorithm is adopted by INTRAS and FREESIM models. The modified PITT model is also adopted by WEAVSIM simulation model.

F. NJIT Model

The TEXAS and NETSIM models have been successfully applied in urban street intersections or networks. The PITT model is good for freeway conditions. However, none of those model can be used for weaving areas under non-freeway conditions.

The main feature of operation at weaving areas under non-freeway conditions is that the speed of vehicles is lower than that at freeway situation. Figure 4.1 shows that the followers in PITT model keep decelerating when the leading vehicle is slightly faster, this will forces the follower to stop easily at non-freeway weaving areas. The horizontal axis DV in Figure 4.1 presents the difference of speeds between the leader and follower, and DV is greater than zero if the leader is faster.

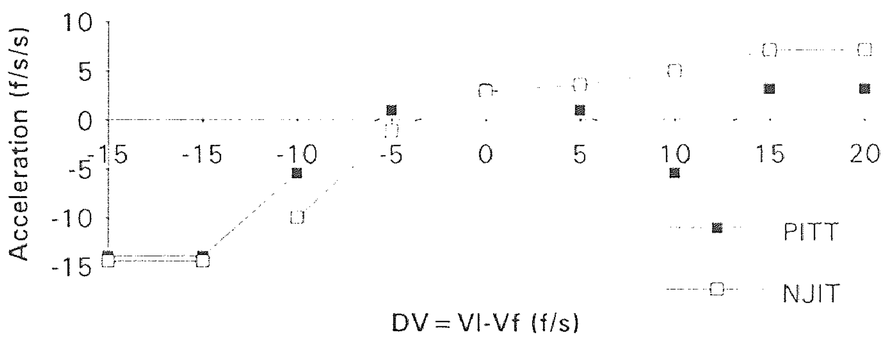

Figure 4.1 Comparison of PITT and NJIT Model

To avoid the problem, the NJIT car-following model shown in Equation 4-6 is specially developed for weaving areas under non-freeway conditions. It is also a modification of the PITT model.

$$A_f(t+T)=\frac{2[(X_l(t+T)-X_f(t)-L-10-V_f(t)(k+T)+bk|V_l(t+T)-V_f(t)|\,|V_l(t+T)-V_f(t)|\,]}{(T^2+2Tk)} \qquad (4\text{-}6)$$

here b and k will be calibrated

Here the desired space headway H_d of the follower in the NJIT model is given by $H_d=L+10+V_f(t)(K+T)+bK(V_l(t+T)-V_f(t))|V_l(t+T)-V_f(t)|$. The absolute value of $(V_l(t+T)-V_f(t))$ assures that H_d should be larger when the following vehicle is faster, and vice versa. Figure 4.1 shows the difference of acceleration between PITT and NJIT models. Acceleration increases in the NJIT model when leader is faster (DV:0-10 mph).

4.2 Lateral Movement Model

Interaction of two separate traffic streams constitute one of the most important aspect of traffic operation. This interaction, in case of weaving area operation, takes place when a driver changes lane, merges into a traffic stream (on ramp merge), or two traffic streams merge (lane balance at weaving sections). Merging movements of vehicles in weaving areas are governed by lane changing models. Lane changing maneuvers associated with weaving areas under non-freeway conditions are much more aggressive because of restrictions due to relatively short lengths of weaving sections.

Inherent in the traffic interaction associated with these basic maneuvers is the concept of gap acceptance. Figure 4.2 shows that certain terms related to the concept of gap acceptance are defined below (10):

Gap: it is defined as a major stream headway that is scanned by a minor stream driver waiting to complete a certain maneuver.

Lag: it is the time interval between the arrival of a minor stream vehicle and the arrival of a major stream vehicle at a reference point where the two streams either cross or merge.

Critical gap: it is an acceptance threshold and defined as the minimum size of an acceptable headway in the main stream traffic which is considered to be sufficiently large to allow a driver in the minor stream of traffic to merge or cross.

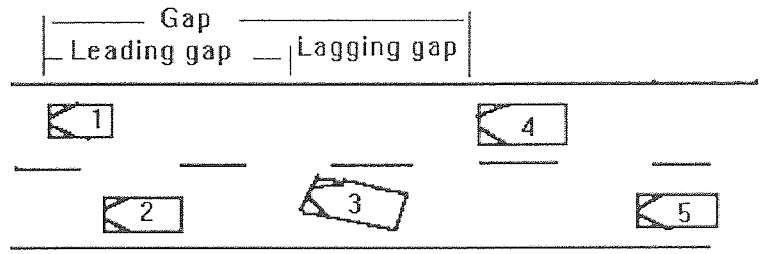

Figure 4.2 Vehicle Lane Changing Diagram

In general, the merging process is influenced by the following variables: headway, gaps, lags, the speed of the major stream vehicles, speed of the merging vehicles, relative speed, major-stream flow, and minor stream flow. In addition to that, the gap acceptance phenomenon is influenced by the critical gap, percent of ramp vehicles delayed, mean duration of static delay accepting gap, mean length of queue, and total waiting time on the ramp. The merging mechanism is as follows: A merging action is initiated if a safe gap is available. When a merging vehicle fails to merge, it stays in its original lane until there is a larger safe gap available. Models are distinct for the two different weaving section categories: Category I is a normal crossing of traffic streams without traffic control devices. Category II is a normal gap acceptance operation of ramp traffic with the main stream. Four modules were developed to present the merging movements in the NFWEAV model which are presented below.

4.2.1 Lane change logic

In order for vehicles to perform lane changing movements in Category I, an acceptable leading and lagging gap shown in Figure 4.2 must be available in the target lane. An acceptable leading gap must assure avoidance of collision occurring during the merging maneuver when the leader in the target lane is assumed to immediately decelerate with the maximum deceleration. The condition also applies to the lagging acceptable gap.

4.2.2 Gap acceptance

There is a different scenario of vehicle merging movements in Category II. It is assumed that each driver has a consistent behavior. he/she has a fixed threshold and accepts any gap greater than the threshold whilst rejecting all gaps which are smaller. Different thresholds apply to different drivers in the model. Motorists in weaving areas under non-freeway conditions usually tend to accept much smaller gaps than driver traveling on freeways. The following gap acceptance formula was used (28).

$$gap_{acp} = (11.325 + \log [r / (1-r)]) / 0.1188 \qquad (4\text{-}9)$$

here gap_{acp} is an accepted gap in feet, and r is a pseudo random number uniformly distributed between 0 and 1

In Category II, most of merging activity occurs near the entrance of weaving areas. Drivers have to wait on the on-ramp until an acceptable gap for merging is available. Therefore, there is often a queue in the on-ramp approach in weaving areas, and the operation speed is also lower than the one in Category I.

4.2.3 Follower courtesy

A follower courtesy sub-model was developed for lane changing which provides for some of the drivers in the target stream to cooperate by allowing a vehicle to merge in front of them. Figure 4.2 shows that the vehicle #3 tries to merge to the target lane, and two successive vehicles #1 and #4 are in the target lane. Suppose that the first merging attempt was unsuccessful because of lack of an acceptable lag gap. Then the follower (vehicle #4) might decrease its acceleration (ACC) to a smaller acceleration (ACC_{co}) to provide a bigger lagging gap for the merging vehicle #3, that can again try a lane changing maneuver. The follower courtesy sub-model offers an opportunity for a subsequent attempt to merge if an acceptable lag gap is available at that time.

A two-dimensional array FC is used to describe the behavior of drivers. The follower courtesy code is generated by a random number generator that is uniform distribution. The default values FC(1) and FC(2) in the model are 0.4 and 0.6. These two values represent the percentages of drivers willing to cooperate or not.

$$ACC_{CO} = ACC\ (1\text{-}K_{AC}\ FC(i)) \tag{4-10}$$

$$FC(i) = \begin{cases} 0.25, & i=1, \text{ for those followers willing to cooperate;} \\ 0, & i=2, \text{ otherwise.} \end{cases}$$

$K_{AC} = 1, -1$, when ACC is greater or less than 0, respectively.

4.2.4 Driver merging urgency

A driver merging urgency sub-model was developed for lane changing maneuvers. A weaving section in Category I is divided into three sections as shown in Figure 4.3. The urgency codes are different for the drivers depending upon the location of the vehicles. Drivers continue to move, according to the leading vehicle or car-following algorithm, when they fail to merge in the first section. They have to decelerate in order to attempt a merge to the target lane when they are in the second section of a weaving area. The deceleration rates for the vehicles failing to merge in section 2 are calibrated later. They would be forced to decelerate with the maximum deceleration rate, and to wait for completing a merge activity in the last section of a weaving areas. Otherwise, they will be unable to reach their destinations.

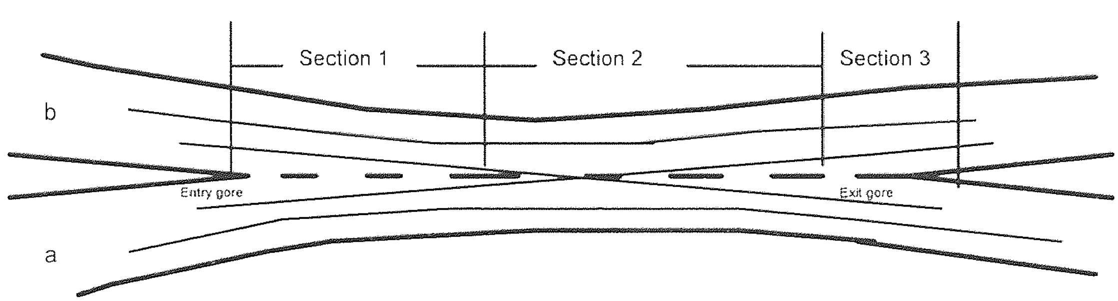

Figure 4.3 Diagram of Weaving Sections

The drivers in Category II are more urgent to take merging activity. They decelerate the speed when they fail to merging even at the beginning. A queue is often accumulated at the on-ramp entrance when the lead-vehicle fails to merge..

4.3 Non-Collision Constraints

All vehicle movements must adhere to certain restraints in order to avoid collision. Following vehicles can stop safely behind the leader under the following basic conditions:

- Leading vehicle decelerates to a stop at the maximum emergency deceleration.
- Following vehicle starts at a reaction time Rt later and decelerates to a stop behind the leader at a deceleration rate within the maximum emergency deceleration limit.

Three rules used to guarantee the non-collision constraints are the following:

A. Case I

This case presents a scenario in which the follower's speed is less than or equal to the speed of the leading vehicle (Eq. 4-11). The drivers in a platoon must maintain a space of at least equal to their reaction distance plus the length of the leader (Eq. 4-12),

$$\text{If} \quad V_l(t+T) \geq V_f(t+T) > 0 \qquad (4\text{-}11)$$

$$X_l(t+T) - X_f(t+T) \geq L + R_t \; V_f(t+T) \qquad (4\text{-}12)$$

where R_t is a reaction time.

The following Equation is from Eq. 4-12 according to Newton's law,

$$X_l(t+T) - X_f(t) - V_f(t)T - 1/2 \, A_f(t) \, T^2 \geq L + R_t \; [V_f(t) + A_f(t)T]$$

$$A_f(t) \leq A_{f,max} = \frac{[X_l(t+T)-X_f(t)-V_f(t)(R_t+T)-L]}{(T(R_t+T/2))} \tag{4-13}$$

For case I, the constraint is

$$V_l(t+T) \geq V_f(t) + A_f(t)T > 0 \tag{4-14}$$

or

$$[V_l(t+T) - V_f(t)] /T \geq A_f(t) \geq -V_f(T) / T \tag{4-15}$$

B. Case II

This case presents a scenario in which the follower's speed is higher than or equal to the speed of the leading vehicle (Eq. 4-16).

$$\text{if} \quad V_f(t+T) \geq V_l(t+T) > 0 \tag{4-16}$$

Drivers have to increase the space between vehicles in a platoon when their speed are higher then the speed of the leaders. The space is the reaction distance plus the length of the leader and plus the deceleration distance (Eq. 4-17).

$$X_l(t+T)-X_f(t+T) \geq L+R_tV_f(t+T)+\frac{(V_f^2(t+T)-V_l^2(t+T))}{(2DCC_{max})} \tag{4-17}$$

where DCC_{max} is a maximum deceleration rate of vehicles. According to Newton's law, the following Equation is found from Eq. 4-17

$$X_l(t+T)-X_f(t) - V_f(t)T - 1/2\ A_f(t)\ T^2$$

$$\geq L+R_t[V_f(t)+A_f(t)T]+\frac{(V_f^2(t)+2V_f(t)A_f(t)T+A_f^2(t)T^2-V_l^2(t+T))}{(2DCC_{max})} \tag{4-18}$$

$$A_f t) \leq A_{f,max} = \frac{-B + (B^2 + 4C)^{1/2}}{2} \tag{4-19}$$

$$B = \frac{2DCC_{max}}{T} \left(\frac{(V_f(t)}{DCC_{max}} + R_t + T/2 \right) \quad (4\text{-}20)$$

$$C = \frac{2DCC_{Max}}{T^2} \left(X_l(t+T) - X_f(t) - V_f(t)^*(R_t + T) - L - \frac{(V_f^2(t) - V_l^2(t+T))}{2DCC_{Max}} \right) \quad (4\text{-}21)$$

For case II, the constraint is

$$V_f(t) + A_f(t)T \geq V_l(t+T) > 0 \quad (4\text{-}22)$$

$$\text{or } A_f(t) \geq (V_f(t+T) - (V_f(t)) / T \geq -V_f(t) / T \quad (4\text{-}23)$$

C. Case III

This case presents a scenario in which both follower and leader are stopped. (Eq.4-24).

$$\text{if } \quad X_l(t+T) = X_f(t+T) = 0 \quad (4\text{-}24)$$

Drivers should keep a space greater than or equal to the length of the leading vehicle in the case when both vehicles are stopped.

$$X_l(t+T) - X_f(t+T) \geq L \quad (4\text{-}25)$$

Then,

$$X_l(t+T) - \left(X_f(t+T) + \frac{0 - V_f^2(t)}{2A_f(t)} \right) \geq L \quad (4\text{-}26)$$

$$A_f(t) \leq A_{f\ max} = - \frac{V_f^2(t)}{[2(X_l(t+T) - X_f(t) - L)]} \quad (4\text{-}27)$$

For case III, the constraint is :

$$V_f(t) + A_f(t)T \leq 0 \quad (4\text{-}28)$$

$$\text{or } A_f(t) \leq -V_f(t)/T \quad (4\text{-}29)$$

Overriding a car following model, Expression 4-13, 4-19 and 4-27 are the constraints which determine the maximal acceleration of the follower to prevent collisions when vehicles are undertaking maximum emergency deceleration.

4.4 Level Of Service at Weaving Areas under Non-Freeway Conditions

The primary criteria of the Level of Service (LOS) for weaving areas under non-freeway conditions are weaving and non-weaving speeds shown in Table 4.2 (8).

Table 4.2 Criteria of LOS for Weaving Areas under Non-freeway Condition

LOS	CATEGORY I		CATEGORY II	
	S_W	S_{NW}	S_W	S_{NW}
A	42 mph	45mph	>38mph	>50mph
B	38mph	40mph	33mph	45mph
C	33mph	35mph	30mph	40mph
D	30mph	30mph	25mph	35mph
E	25mph	25mph	20mph	25mph
F	<25mph	<25mph	<20mph	<25mph

The LOS criteria are developed in the analytical model in the first phase of the project (8) and established for basic and ramp weaves, separately. The criteria are embedded in the NFWEAV model, and the Level of Service can be directly determined according to the simulation results.

The criteria of LOS for weaving areas under non-freeway conditions were calibrated according to the data collected from fourteen sites. To let this result being universal for all type of weaving sections under non-freeway conditions, more data collection are needed. The next chapter presents the structure of the NFWEAV simulation model.

CHAPTER FIVE

NFWEAV SIMULATION STRUCTURE

Simulation encompasses a model building process as well as the design and implementation of an appropriate experiment involving that model on a computer. The purpose of simulation on an electronic computer is the experiment determination of phenomena which are too complex to study analytically and which may not be conveniently studied empirically in the real-life situation. Operation of traffic on weaving areas is a typical complex system. Intense lane-changing maneuvers at weaving sections create turbulence that often lead to congestion.

Simulation models can be classified as either discrete events or continuous, depending upon whether variables change discretely at specified points or continuously over simulation time. Simulation models can also be classified as either macroscopic or microscopic ones. To analyze weaving areas in more detail, the model considers individual vehicles rather than the traffic stream at specified time point, e.g. every second. Therefore, a stochastic, microscopic, and discrete event simulation technology is chosen for this purpose.

The selection of a simulation language is a decision that has a major impact upon the ultimate success of a simulation analysis. To make a proper selection, one needs to understand how the simulation language seeks to facilitate the process of transforming a logical model into acceptable computer code, and the specific language features available to support model development and experimentation. In addition, there are many pragmatic considerations in the selection of a language such as ease of learning, the ability to run on many different computers, and the scope of problem addressed.

5.1 SLAM II Simulation Language

Although a simulation model can be programmed using a general purpose language, such as BASIC, FORTRAN, C language, the SLAM II (Simulation Language for Alternative Modeling) simulation language was chosen.

SLAM is an advanced FORTRAN based simulation language developed by A. Alan B. Pritsker. SLAM II provides the user with a set of subroutines for performing all file manipulations which are commonly encountered in discrete event simulation. Statistic collection of the variables of interest is readily available in SLAM subprograms. SLAM also provides functions for graphics and animation (10).

5.2 Event Orientation Technique

In simulation terminology, vehicles operating in weaving areas are designated as entities which have 25 attributes shown in Table 2, and engage in different types of activities such as moving maneuver or merging action in a discrete event system. The aim of a discrete simulation model is to reproduce the activities that the entities engage in. The state of a system is defined in terms of the numeric values assigned to the attributes of the entities. Therefore, the simulation is a dynamic portrayal of the states of a system over time.

An isolated point in time when the state of the system may change its state is called an event time. In discrete simulation, the state of the system can be changed only at event times. Three different world views are available in SLAM II: event orientation, activity scanning orientation and process orientation. An event orientation technique is used in the NFWEAV model development.

A vehicle as an entity, arriving in a weaving area is an event. To scan a weaving area second by second for monitoring the change of the state of the system, "scanning at every second" is chosen as another event. The objective of the model is to determine the event that can change the state of the system and tend to develop the

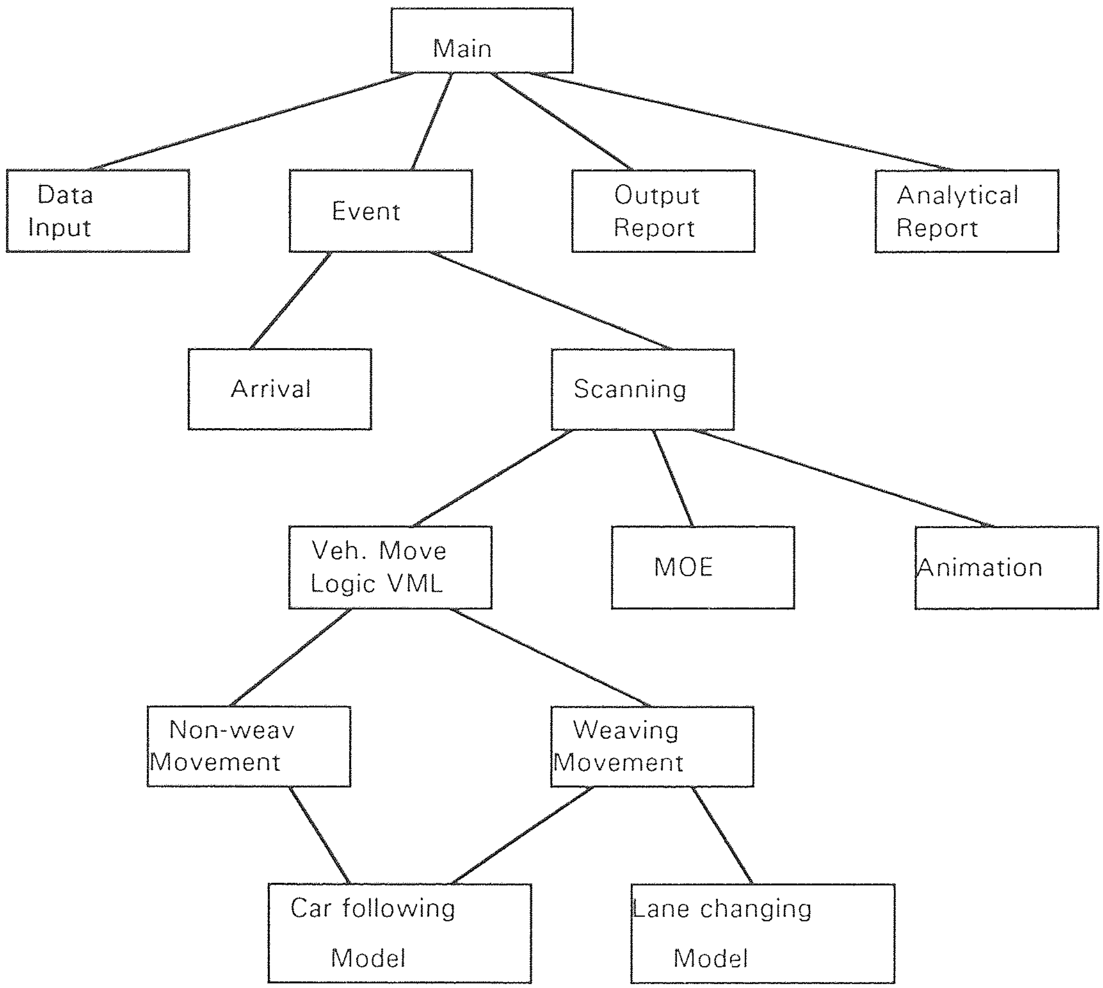

Figure 5.1 The Module Structure of NFWEAV

logic associated with each event type. An event calendar NCLNR in SLAM II is used for maintaining the time-ordered sequence of entity (vehicle) arrival events. Storage arrays NSET and QSET are employed by the SLAM II for storing both events and entities with their attributes.

5.3 NFWEAV Simulation Model Structure

To simulate weaving areas under non-freeway conditions using SLAM II, user input FORTRAN subroutines should be coded for each discrete event. However, SLAM II provides a set of FORTRAN programs for performing all commonly encountered functions such as event scheduling, SCHDL; file manipulation: FILEM, RMOVE, COPY; and statistic collection: COLCT and random number generation. The SLAM II processor completely relieves the user of the responsibility for chronologically ordering the events on an event calendar. The user simply schedules events such as arrival and scanning to occur, and SLAM II causes each event to be processed at the appropriate time in the simulation. A module structure of user input subroutines as shown in Figure 5.1 is used for programming of the simulation model. Following, a description of the NFWEAV program written in SLAM II is presented.

5.3.1 Main Program

The main program is used to access all SLAM II executive subroutines, to dimension the storage array NSET/QSET the length of which is 24000 in this model, and to denote the unit numbers for the periphery devices of the computer as the following:

- NCRDR: 5 input reader unit
- NPRNT: 6 line printer unit
- NTAPE: 7 temporary scratch file unit

5.3.2 Subroutines INTLC

At the beginning of each simulation run, the SLAM II processor calls subroutine INTLC to set initial conditions and schedule initial events.

A. Read all non-SLAM data:

Read VT(3), VEH(3,3), RD(8), WD(2,2), IDS(8), AHS(4,5), ASS(2,5), RTS(1,5), ACS(3,5), DCS(3,5) which description are in Table 5.1;

Table 5.1 Input Parameters

Array/Matrix	Description
VT(3)	Vehicle Type: Pas.; S.U.; C. T.
VEH(3,3)	Length, width & hight of 3 type of vehicles
RD(8)	Road Characteristics
WD(2,2)	% of weaving, non-weaving veh. for 2 entries
IDS(8)	Code for random number generators
AHS(4,5)	Arrival headway for at last 4 lanes
ASS(2,5)	Arrival speed for two entrance
RTS(1,5)	Driver reaction time
ACS(3,5)	Leading vehicle's Acceleration
DCS(3,5)	Deceleration of vehicles failed to merge

B. Set initial vehicles into a weaving area:

The attributes of the initial vehicles are stored in the file #1;

C. Schedule initial events for arrivals and scan

5.3.3 Subroutine EVENT(IX)

The SLAM II processor chronologically orders the events on an event calendar NCLDR. Events are scheduled by calling subroutine SCHDL(KEVNT,DTIME,A),

- KEVNT: the event code of the event being scheduled;
- DTIME: the time unit from the current time that the event is to occur;
- Matrix A: the buffer array that passes the attributes of the event.

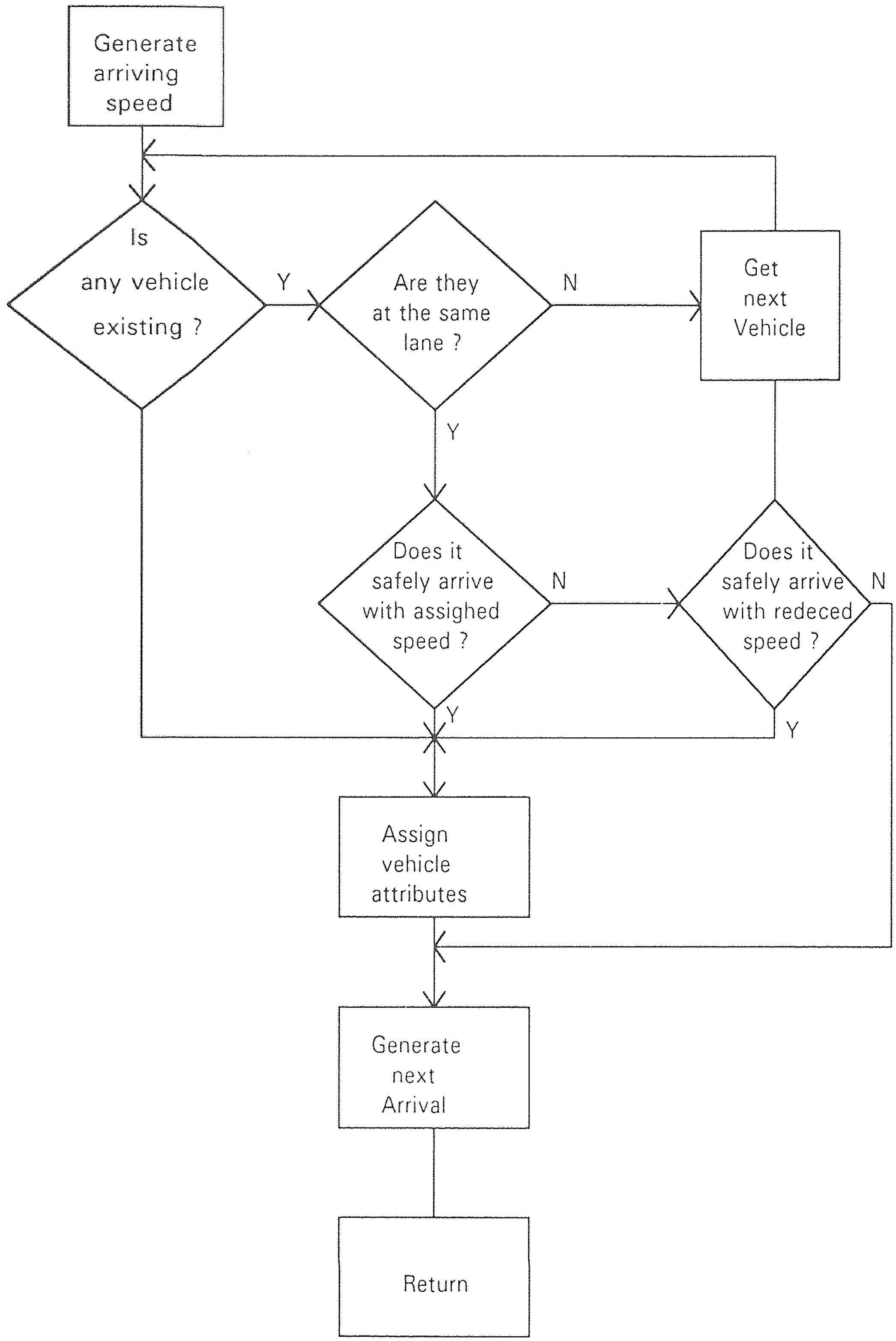

Figure 5.2 The Flow Chart of Subroutine ARV

Main events are arrivals in different lanes and scanning in the NFWEAV model. This is called by the time-keeping mechanism in the SLAM II routine which controls the scheduling of the following events:

- IX=1, 2, 3, 4: Arrivals of vehicles in lane 1, 2, 3, 4, respectively,
- IX=5 Scan event to update the state of all vehicles in a weaving area.

5.3.4 Subroutine ARV(IX,KK)

All vehicles arriving in the system from upstream are processed in the subroutine. IX reflects the lane in which a vehicle arrives, KK is an index for arriving vehicles. Figure 5.2 shows a flow chart of ARV(IX,KK). The main function is as follows:

A. Generate two attributes: speed and reaction time, and check safe arrival.

At first, generate only two attributes: speed and reaction time that are created by random number generator based on the field data distribution. The speed is stored at a 2X5 matrix ASS, and The reaction time, a five-dimensional array RTS. Then check if the vehicle can have a safe arrival with its assigned speed at the approach to the weaving area. If the safe arrival check can be met, go to step B. Otherwise, this entry is aborted, and the vehicle arrival time should be delayed by a scan unit of time.

B. Generate all other 23 attributes for a arriving vehicles.

All attributes of a vehicle as shown in Table 3.2 are generated stochastically or deterministically after it enters an approach of a weaving area. Then the attributes of the arrival vehicle will be filed into the file #2.

C. Generate next arrival event.

The next arrival event is scheduled by calling subroutine SCHDL(IX,ET,A), where IX is the event code for the lane, and ET is an arrival headway generated by a random number also based on field data distribution which is stored in a arrival headway AHS.

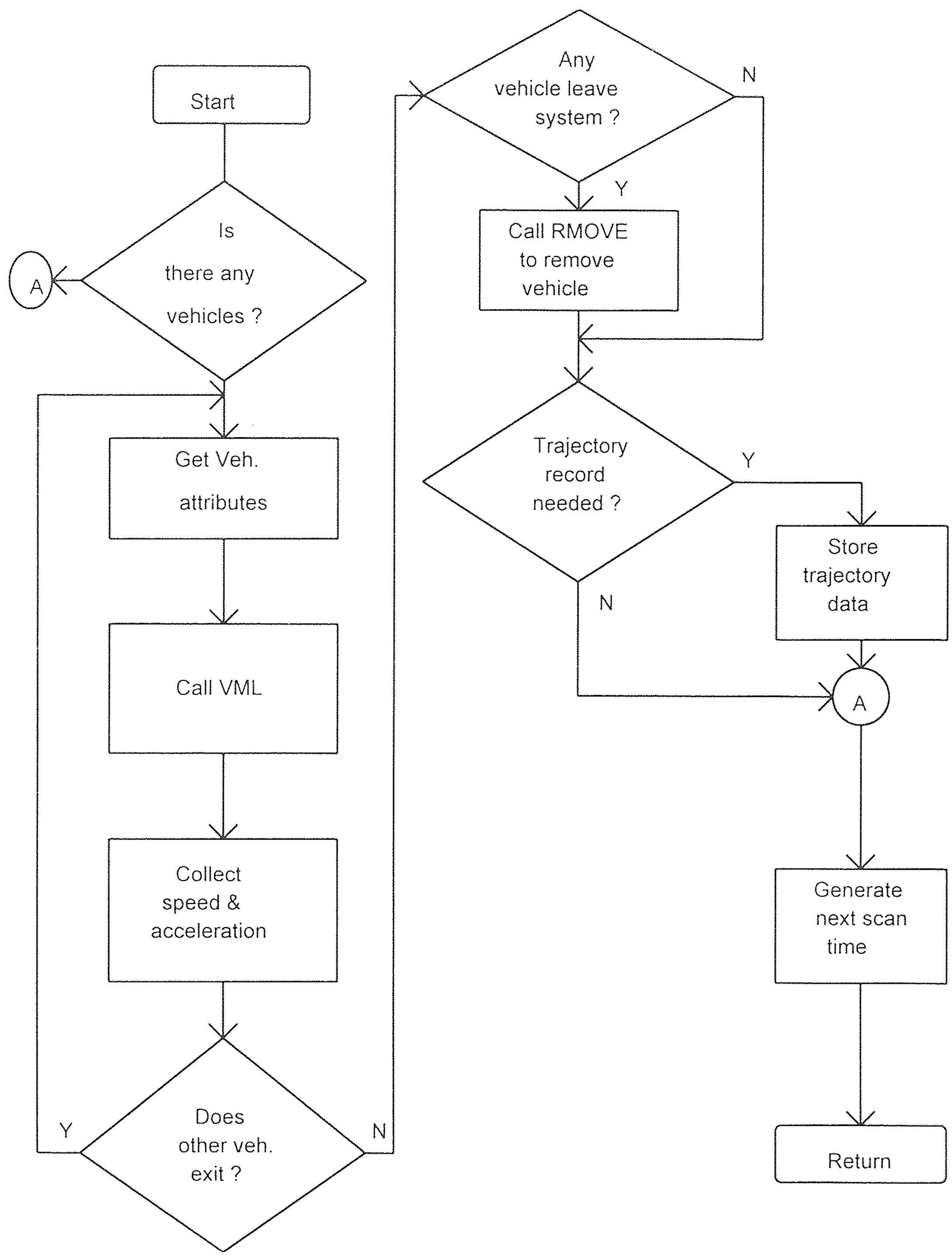

Figure 5.3 The Flow Chart of Subroutine SCAN

5.3.5 Subroutine SCAN

A SCAN module is the core of the simulation programming, and the scanning period is set as 1 second. Each entity is processed through the weaving section by defining the changes that occur, and by updating its attributes at the scan time.

The flow chart for SCAN is shown in Figure 5.3. There are four functions in the SCAN subroutine:

A. Scan and update the state of the system.

During each scanning time, all vehicles are processed by calling subroutine VML which will change the state of the system according to the logic associated with the events. The rank of the entities in file #2 are based on the positions of vehicles. The processing will start with the vehicle closest to the exit point of a weaving area. Then the attributes of all vehicles in the weaving area are updated, and two of those attributes: speed and acceleration are collected by calling SLAM II subroutine COLCT(speed, K1) and COLCT(acc, K2). K1 and K2 are the codes for speed and acceleration collection.

B. Check and remove vehicles that have passed the weaving area.

Check if any entity has already passed the weaving area. If it does, remove it by calling SLAM II subroutine RMOVE(1, 2, A), where the numbers 1 and 2 represent the first vehicle in file #2. The first vehicle will be moved out if it has passed the weaving area. Then the travel time and delay will be collected. This judgment also applies to the next vehicle, which now becomes the first one after its leader left.

Travel time and delay will be collected by calling the SLAM II subroutine COLCT(Time, K3) and COLCT(Delay, K4). K3 and K4 are the codes for time and delay collection.

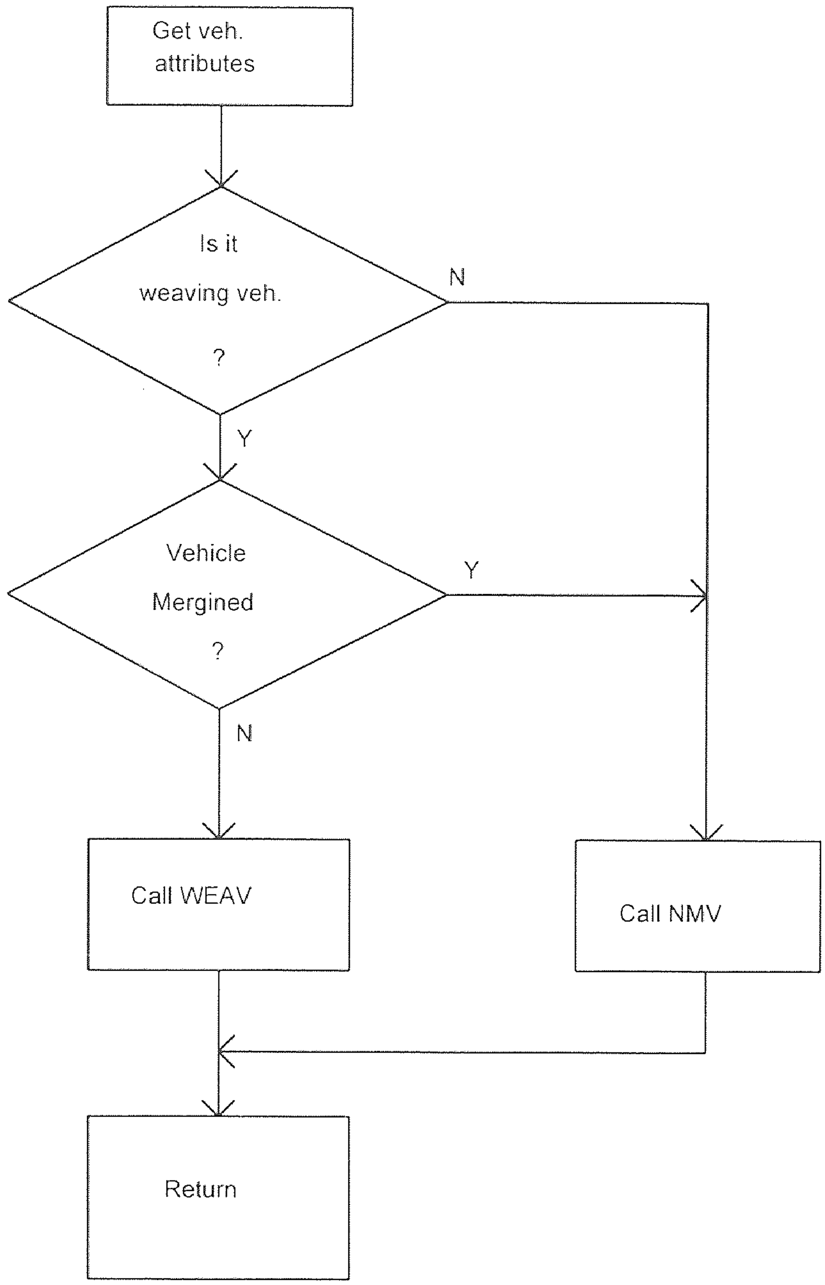

Figure 5.4 The Flow Chart of Subroutine VML

C. Record trajectory if needed.

Test if trajectories of vehicles should be stored; call subroutine VTR if it is needed

E. Generate next event SCAN

The next event SCAN is scheduled by calling SLAM II subroutine SCHDL(5,1,A), where 5 denotes the code of the scan event, and 1 means one second scanning time gap.

5.3.6 Subroutine VML

This subroutine is called from SCAN. A vehicle movement logic VML Module is the main logic associated with all movements. It governs the non-weaving and weaving vehicle movements to the different routines by calling subroutine NWV or WEAV. The movement of weaving vehicles which have not merged to the target lane are controlled by subroutine WEAV, which is controlled by a lane change logic. Otherwise movements are controlled by subroutine NWV, car-following logic, or by subroutine ACLD, a leading vehicle movement role. Figure 5.4 shows the logic for subroutine VML.

A. Test the weaving status ATRIB(8), then a logic decision is made:

- Call subroutine NWV, if ATRIB(8) = 0
- Do further logic decision making, if ATRIB(8) = 1

B. Test if a weaving vehicle has already finished a merging maneuver

ATRIB(17) is a flag for weaving vehicle lane changing activity.

- Call subroutine WEAV, if a vehicle does not change the lane; ATRIB(17) =0
- Call subroutine CARF if a vehicle has changed a lane already; ATRIB(17) =1

5.3.7 Subroutine NWV

This is the main subroutine to determine which logic should be used to process changes in state for all non-weaving vehicle movements. It is called from subroutine VML.

A. Call subroutine CARFL

Call car-following model CARFL, if the vehicle is a follower.

B. Call subroutine ACLD

Call a leading vehicle logic ACLD, if the vehicle is a leader.

States of vehicles such as speeds and positions for non-weaving movement are changed according to Newton's law after accelerations are determined by different logic.

$$V(t+T) = V(t) + A(t)\ DT$$

$$X(t+T) = X(t) + V(T)\ DT + 1/2\ \ A(t)\ DT^2$$

X(t), X(t+T) are coordinates, V(t) V(t+T); speeds; A(t) are acceleration, and T is the scanning time period.

All updated attributes are filed into the file #2 again.

5.3.8 Subroutine CARFL(ILD, ACM)

This subroutine consists of three car-following algorithms for the NFWEAV model. The BASIC, PITT and NJIT car-following models are selected when code NCAF is set as 1, 2 or 3, respectively. Non-collision constraints have to be satisfied.

5.3.9 Subroutine ACLD(V_f, ACCM)

Accelerations of leading vehicles are determined in this subroutine according to the leading vehicle movement logic.

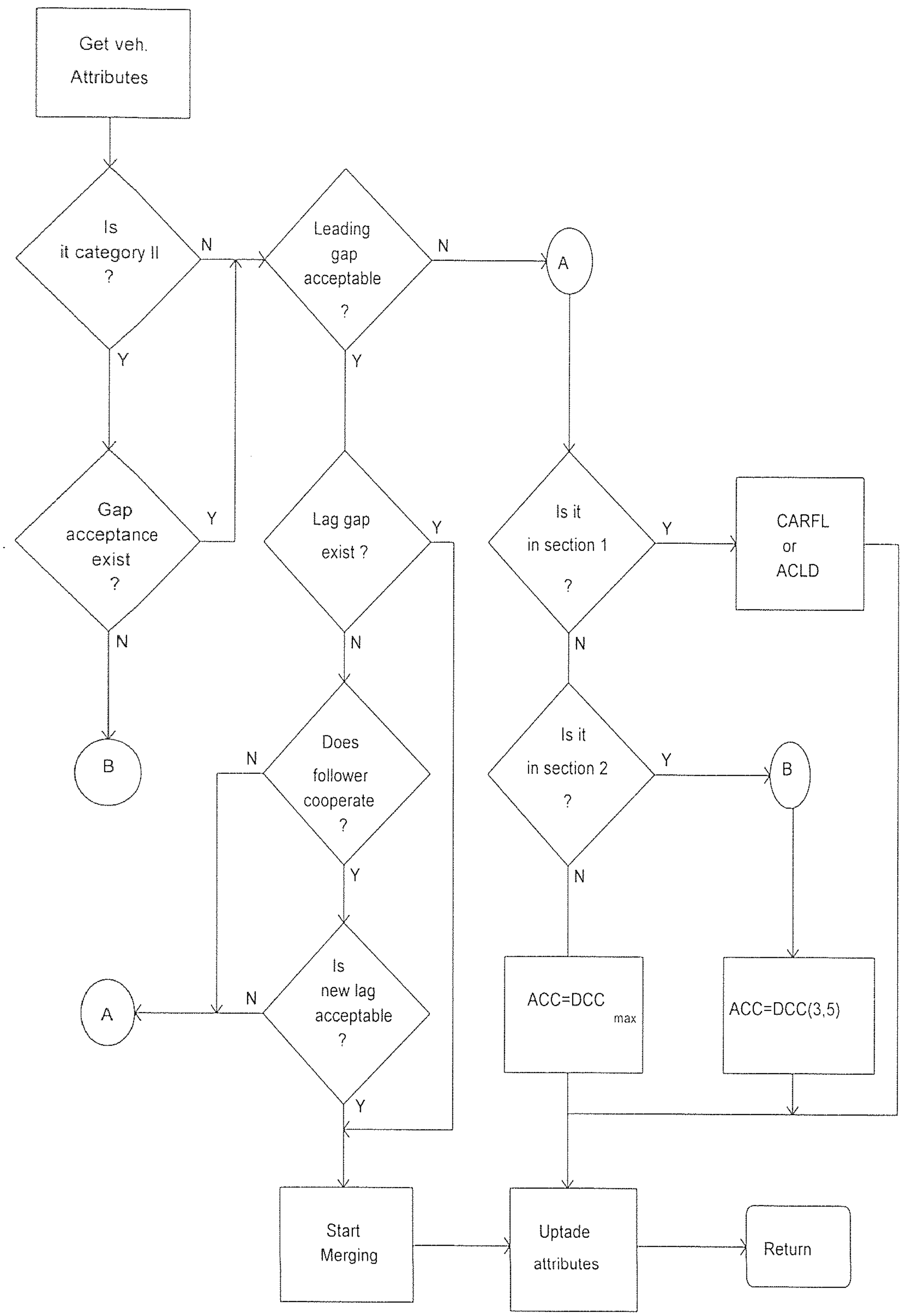

Figure 5.5 The Flow Chart of Subroutine WEAV

5.3.10 Subroutine WEAV

This is a main subroutine to process a change in states for weaving vehicle movements by lane changing logic. The flow chart of subroutine WEAV is shown in Figure 5.5.

A. Check which category the weaving area is.

If this is in category I of a weaving area, then go to step B. For category II, check if an acceptable gap is available. If yes, go to step B. Otherwise, a vehicle in category II failed to merge, and go to step F.

B. Check if a leading gap acceptance is available.

Check if there is an acceptable leading gap for vehicles which are in the category I. If yes, go to step C, otherwise, they fail to merge, and go to step F.

C. Check if a lag gap acceptance is available.

Check if there is an acceptable lag gap available for vehicles which passed the leading gap check. If not, go to step D. Otherwise, a merging maneuver can be initiated, and go to step G.

D. Check if the follower cooperates.

When an acceptable lag gap is not available, check if the follower cooperates. If yes, go to step E. Otherwise, the vehicle fails to merge, go to step F.

E. Check if a new lag gap is acceptable for a safe merge.

The follower who is willing to cooperate will decrease his/her acceleration. If the new gap is acceptable, a merging maneuver is initiated, and go to step G. Otherwise go to step F.

F. Vehicles which fail to merge moves according to different urgency codes.

G. All attributes of vehicle for weaving movement are renewed and filed to file #2.

5.3.11. Subroutine MTEST

Check if a safe leading or lagging gap is available.

5.3.12 Subroutine LOS

This is a subroutine to determine the Level of Service of the operation condition. A criteria which developed according to the analytical model in the phase I is used.

5.3.13 Subroutine of OTPUT

This subroutine is a user developed output file to analyze the simulation results. Input echo report, Measures of Effectiveness, and Level of Service are the contents of the report. Measures of effectiveness are the output of the simulation results. Statistical analyses for non-weaving and weaving speed, delay, and travel time are displayed in tables and graphical forms in intermediate or summary report.

5.3.14 Function SF

The function FS generates random numbers based on seven distribution functions available in the model. The distributions are the follows: Normal, Log normal, Erlang, Poisson, Uniform, Exponential and Beta which are coded from 1 to 7. An eight dimensional array IDS is used for storing the statistic code for different purposes. The detail information is: four for arrival headway, which is lognormal distributed; two for arrival speed, normal distributed; one for driver reaction time, beta distributed; three for leading vehicle accelerations, normal distributed; and three for deceleration of vehicles which fail to merge in section #2 of a weaving area, normal distributed, respectively. The input data consists of five parameters in the following order: minimum, maximum, mean, mode and standard deviation for each distribution.

Callable Subroutine	Calling Sub routine							
	INTLC	EVENT(IX)	ARV(IX,KK)	SCAN	VML	NMV	WEAV	VTR
SCHDL(No,Time,Atrb)	X		X	X				
COPY(Nrank,Ifile,A)			X	X	X			X
COLCT(Z,ICLCT)			X	X			X	
RMOVE(Nrank,Ifile,A)				X		X	X	
FILEM(Ifile,A)			X			X	X	
ARV(IX,KK)		X						
SCAN		X						
VML				X				
NMV					X			
CARFL						X	X	
ACLD(Vf,Accm)						X	X	
DC(Vf,Accm)							X	
WEAV					X			
MTEST							X	

Table 5.2 Subroutine Call Cross Reference Chart

5.3.15 Common Block

There are two types of variables: SLAM II variables and user-defined variables available in the SLAM II. The values of SLAM II variables are transferred between the SLAM II processor and user-written subroutine through the COMMON block named SCOM1. The user-written common blocks are USER1, USER2, USER3, USER4, and USER5.

The subroutines call cross reference chart is shown in Tables 5.2.

The animation module offers additional options to enhance the function of the software package. A dynamic characterization of the state changes can be presented visually as a form of animation. To obtain an animation, it is necessary to diagram a weaving area which represents the system and icons which represent the vehicles in the weaving area. The SLAM II provides the tool for users to convert either system data or simulation data into a form which portrays the state change on a facility diagram.

5.4 Animation Model

Simulation is a dynamic portrayal of states of a system. The state changes of a system that occur over time can be traced during simulation running period. A dynamic characterization of the state changes can be also presented visually as a form of animation in which icons move, and are added or deleted from the picture. In fact, an animation is a dynamic presentation of the changes in state of the system over time.

To obtain an animation in the model, a weaving area is diagrammed by creating background screen. A symbol table is built to present the vehicle running in the weaving area. The style, shape and color of a vehicle can be designed arbitrarily. Location reference point (LRP) is a number identifying a specified pixel location in the background. Then the coordination's of these points are recorded.

Coordinates of vehicles are updated in each scanning time period. Place or move the symbols in the desired location reference point LRP, a dynamic portrays of states of the system is displaying visually as a form of animation.

5.5 NFWEAV Input Module

To ensure that the application software package NFWEAV is really user friendly. There is a menu for the user to choose one of the following three functions: to create a user input data file; modify a user input data file, or running SLAM. An input module was specially developed for data input. The geometric and traffic data are input item by item from the screen. The program is written in PASCAL. The input screen is shown in Figure 5.6

Geometry Data
Weaving area site name: Category: Length(ft): Width(ft): No. of lanes: Grade(%): Friction factor: With/without Auxiliary lane:

Traffic data				
Composition:	PC		SU	CT
Arrival Volume	NW from A-C	WV from A-d	NW from B-D	WV from B-C
Arrival speed	From A		From B	

[ESC] to exit   [CR] to continue   [F2] for default data

Figure 5.6 Data Input Diagram

CHAPTER SIX

MODEL VERIFICATION AND VALIDATION

Model verification and calibration are two important tasks in developing a traffic simulation model NFWEAV. Verification is usually defined as ensuring that the model behaves as intended, and validation is usually defined as determining that an adequate agreement exists between the entity being modeled and the model for its intended use (30). Traffic simulation models have unique characteristics because of the interaction among the drivers, vehicles and roadway. The effects of interaction on traffic flow should be considered in detail in verification and validation of the model. To provide some degree of consistency and ensure the reliability of the model, an approach for verification and validation of traffic simulation model is developed in this paper.

In order to obtain a high model-confidence, it is necessary to compare the behavior of the model and the behavior of the system under different experimental conditions. If the input-output pairs of the model and the system are in sufficient agreement for various experimental frames, the model is considered valid for those experimental frames. Sargent (30) suggests that model verification and validation should consist of conceptual validation, computerized validation, operational validation and data validation.

6.1 Model Verification

Verification ensures that the model behaves as the experimenter expects. Conceptual model validation and face validity are the main tasks for model verification. They are used to ensure that assumption of models is right, logic of model flowchart is correct, and the input-output relationship is reasonable. For computerized model verification, behaviors of different types of specific entities are traced through the computerized model to ensure that logic of the model and computer program are correct.

6.1.1 Face Validity

Face validity is asking people knowledgeable about the system whether the model is reasonable. Six questionnaire sheets of "Investigation of Vehicle Behaviors in Weaving Area" was distributed to transportation engineering's professionals for this purpose. The questionnaires are presented as follows:

A. How do weaving vehicles make their way into their respective target lanes in non-freeway conditions?

(a) reaction:

• acceleration • deceleration • uniform speed

(b) lane change time

• one second • two seconds • three seconds

(2) What is the response of weaving vehicle driver to try to reach the respective target lane when an adequate gaps is not available?

(3) What percentage of drivers in the main stream "cooperates" to allow a vehicle to merge in front of them?

(4) What is the difference of driver behaviors in a merging gore area for weaving areas of Category I and Category II?

(5) What is the difference of behaviors for vehicles in Category II with and without an auxiliary lane?

(6) What is the influence of the width of lane in weaving areas to the operation of drivers?

(7) What is the most important MOE for traffic operation in weaving areas under non-freeway conditions?

The returning investigation sheets are very helpful in verifying the traffic model to ensure that the assumptions and logic of model are reasonable.

6.1.2 Conceptual Model Validation

Conceptual model is developed through an analysis and modeling phase. It is used to ensure that the logic of model flowchart is correct, and the input-output relationship is reasonable. There are two basic approaches to be used: static and dynamic testing. The program is debugged to eliminate any coding errors and programming problems. The behavior of different types of specific entities in the model are traced. The logic of different components of the model, such as car following and lane changing models, is carefully reviewed. Acceleration and deceleration patterns have been examined.

A. Leading vehicle acceleration pattern

Typical vehicle acceleration rates vary by grade of facilities, type and speed of vehicles. The acceleration rates of vehicles in weaving areas under non-freeway conditions are subject to different operating situations. The model calibration is performed using field data for fine tuning of variables in the model. The operating acceleration rate for the leading vehicle adopted in NFWEAV model was calibrated as an uniform distribution whose maximum and minimum values are shown in Table 6.1.

Table 6.1. Operation Acceleration Rate at Weaving Areas under Non-freeway Conditions

Vehicle Type	Speed Range											
	< 20 mph				20-50 mph				> 50 mph			
	0%		2 %		0 %		2 %		0 %		2 %	
	max	min	max	min	max	min	max	min	max	min	max	min
Pas.car	4.7	3.5	4.5	3.0	3.7	2.0	3.5	2.0	2.0	1.0	0.8	0.3
S. U.	2.0	0.5	1.6	0.5	1.5	0.5	1.2	0.5	1.0	0.	0.5	0.
C. T.	2.0	0.5	1.6	0.5	1.5	0.5	1.2	0.5	1.0	0.	0.5	0.

B. Dynamic test of car-following model

The NJIT car following model was dynamically tested by simulating traffic flow in a single lane. The SLAM[13] continuous simulation language was used for this purpose. It was assumed that a platoon of vehicles was initially traveling within a lane at a constant speed of 60 fps. Then the leading vehicle was disturbed by applying an acceleration of -8 fpsps for 5 seconds, a zero acceleration for 2 seconds, and an acceleration of 8 fpsps for 5 seconds.

Figure 6.1 shows the responses of the first three vehicles in the platoon. The followers have good oscillatory characteristics, and their movements are stable.

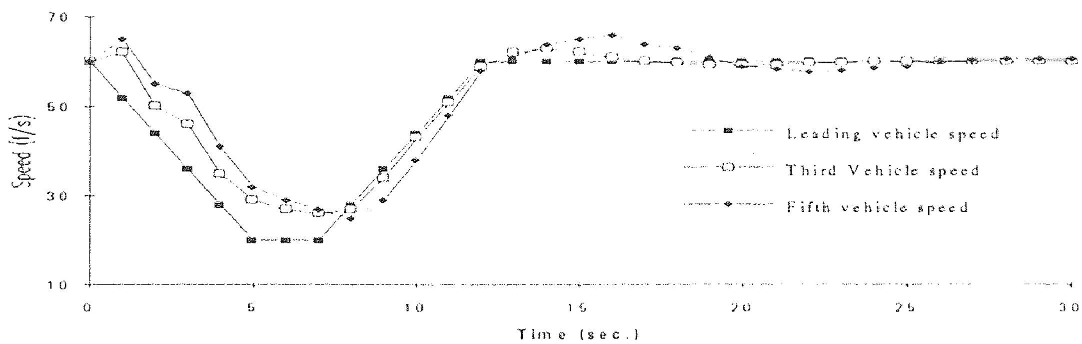

Figure 6.1 Dynamic Test of NJIT model

C. Lane Change Pattern

Lane changing behavior is a principal characteristic for weaving area analysis. As mentioned before, lane changing maneuver in weaving areas of Category I is a normal crossing of traffic without traffic control devices. Acceptable leading and lagging gap patterns are verified by the merging point distribution. Figure 6.2 shows the comparison of merging point distribution patterns of field data and simulation results for the site at Long Island Expressway Exit 30N at 8:10 a.m..

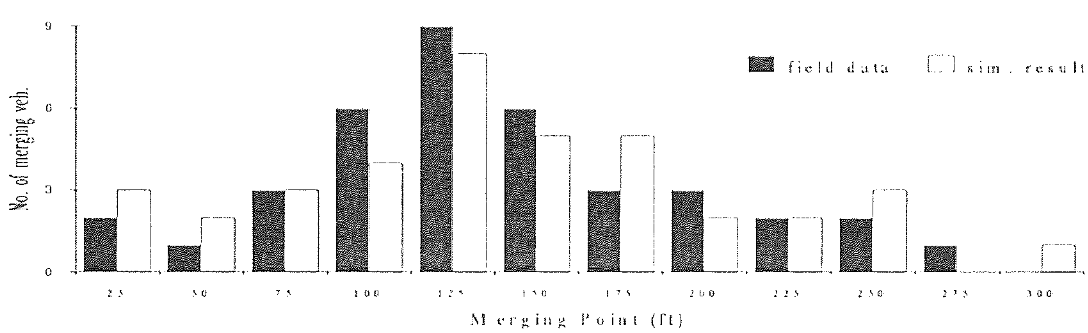

Fig. 6.2 Comparison of Merging Point Distribution between Field Observation and Simulation Result for Category I

Lane changing maneuver in category II is a normal gap acceptance operation of ramp traffic with the main stream. The lane changing patterns heavily depend on the geometric character. A site in Category II with or without auxiliary lane reflects different behaviors. The weaving operation in Category II without an auxiliary lane is in more critical situation. There is a long queue to wait for merging. Figure 6.3 shows the merging point distribution of Category II, where most of the weaving vehicles have to merge at the entrance gore area. The distributions in Figure 6.2 and 6.3 are different, where more vehicles in category II tend to merge earlier.

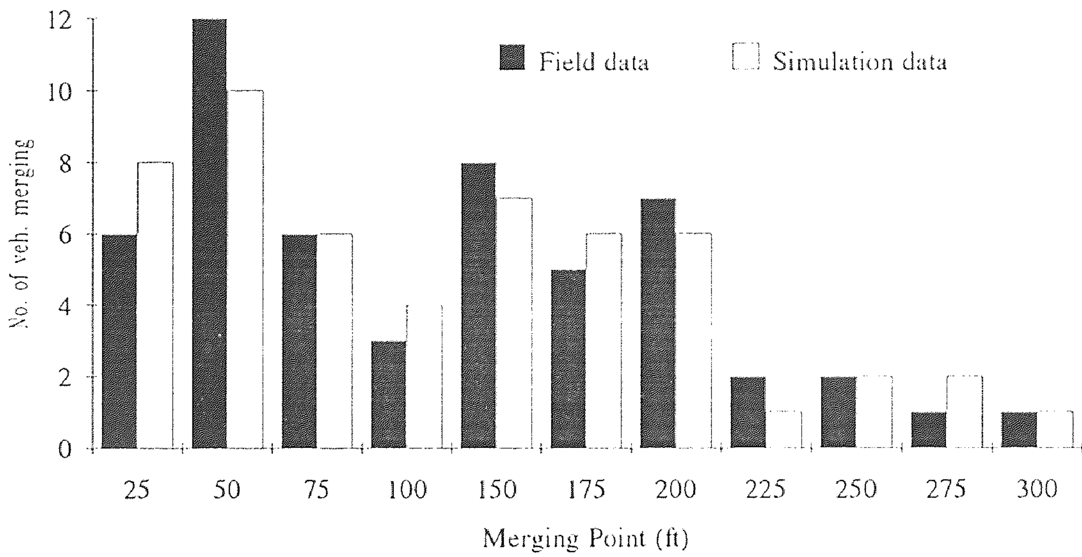

Fig. 6.3 Comparison of Merging Point Distribution between Field Observation and Simulation Result for Category II

D. Deceleration rate pattern for weaving vehicles failed to merge

Lane changing maneuvers associated with weaving areas under non-freeway conditions are much more aggressive because of restrictions on the relatively short length of weaving sections. A driver merging urgency sub-model developed in NFWEAV is also calibrated. The deceleration rates for weaving vehicles which fail to merge in section II and section III of a weaving area are calibrated, and shown in Table 6.2.

Table 6.2. Deceleration Rate (m/h/s) of Vehicles in A Weaving Area under Non-freeway Conditions

vehicle	<20 mph	20 - 50 mph	>50 mph
Pas. car	-3.0 -2.0	-5.0 -3.0	-8.0 -5.0
S.U.	-2.5 -0.5	-2.5 -0.5	-6.0 -4.0
C.V.	-2.0 -0.5	-4.0 -2.5	-5.0 -3.0

6.1.3 Sensitivity Study of Parameter K and Constant b

Sensitivity analysis is made of changing the input and internal parameters of a model to determine the effect upon the model and its output. Sensitivity factor k is sensitive and causes significant changes in the behavior of the model. It should be made sufficiently accurate prior to using the model. A set of values of K is taken for different types of vehicles. The default values of K under normal conditions used in this model are 2.0, 2.15, 2.3 for Passenger Car, Single Unit and Combined Truck, respectively. It varies according to different geometric and traffic conditions. The sensitivity study of the simulation model to the sensitivity factor K has been conducted by a regression analysis between weaving speed of field observation and simulation results. To reduce the effect of the random number seed in the simulations each series is repeated six times with different random seeds. The results of these NFWEAV runs are measured by the slopes a of the fitted straight lines and r values of the speed, and shown in Figure 6.4. here, a is equal to 0.892, and r, 0.83. The constant b is calibrated as 0.1.

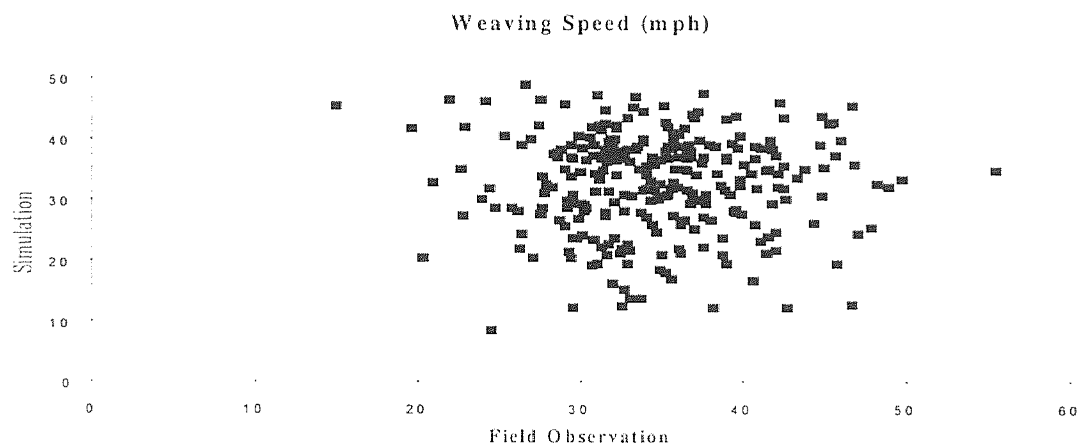

Figure 6.4. Regression Analysis of Sensitivity Study

6.1.4 Analytical Model Comparisons

A comparison is conducted between the simulation model and the analytical one which was developed in Phase I. The analytical models which shown in Equation 6-1, 6-2, 6-3 and 6-4 were calibrated by using the Statistical Analysis Software package **SAS** on a mainframe computer. Multiple regression models were developed for predicting non-weaving and weaving speeds. The non-weaving and weaving speed prediction models have R-square value of .84 and .71, respectively (8).

$$S_w = 15 + \frac{35}{1 + 0.003\,(1+VR)^{.176}\,(V\,/\,N)^{1.67}\,/\,L^{0.6}} \qquad (6\text{-}1)$$

$$S_{nw} = 15 + \frac{35}{1 + 0.003\,(1+VR)^{6.22}\,(V\,/\,N)^{1.79}\,/\,W^{2.86}} \qquad (6\text{-}2)$$

The analytical models for Category II are the follows:

$$S_w = 15 + \frac{25}{1 + [\,16\,(1+VR)^{4.82}\,]\,/\,[\,W\,(L\,/\,V)^{1.47}]} \qquad (6\text{-}3)$$

$$S_{nw} = 15 + \frac{40}{1 + [3.26\ 10^7 (1+MR)^{11.96}\,]\,/\,[1+VR)^{3.14}\,W^{2.86}]} \qquad (6\text{-}4)$$

The comparison between analytical model and simulation model result is shown in Figure 6.5. A Z-test was used at 1-percent level of significance to test the equality of two population variances, the result is satisfied.

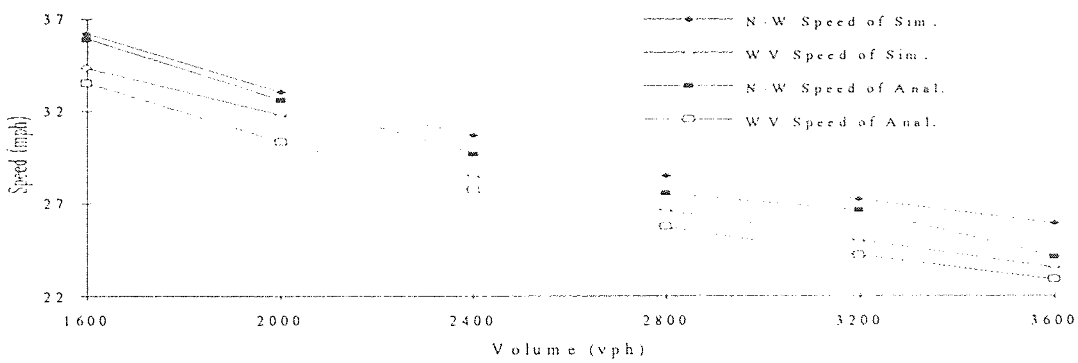

Figure 6.5 The Comparison of Analytical and Simulation Model

6.2 Model Validation

6.2.1 Data Collection

The field data for NFWEAV model was collected during the peak traffic hour in Fall of 1992. Four sites located in New Jersey and New York regions are chosen for the pilot study. Video taping and photogrammetry techniques are used for data collection and reduction [19]. Video taping was performed using two camera platforms mounted on the roof of a research van, which provided up to 18 feet of elevation from the ground. A video image processing board and an image processing function library is installed in a PC-based microcomputer to perform the photogrammetric measurement that produces coordinates (x, y) of vehicles which were processed by digitizing vehicles one by one for each image frame of the video tapes. A current lane placement of a vehicle can be determined by x, and a longitudinal position of vehicle can be obtained directly from y. Speed and acceleration can be calculated by differentiating of the coordinates. The field data provided a complete record of spacing, longitudinal positions, velocities, travel times and merging points for individual vehicles.

6.2.2 Field Data Test

For the model validation, there are two different types of field data test conducted. One set of data are processed by Imaging Processing technique, and other one, directly from video tape reading. For operational validity, statistical hypothesis testing is made to determine if the pertinent characteristics of the model adequately represent the problem entity for the intended use of the model.

A. Comparison with the field data from image processing technique.

The data are taken for 60-90 seconds per five minutes. The sampling size is large enough to be considered as normally distributed. The sites which can offer imaging processing data are listed in Table 6.3.

Table 6.3 Sites for Data Collection

Date	Name of Sited
12/31/91	*.Long Island Expressway Exit 30N, Long Island, New York
9/15/92	* Entrance weaving area of Newark International Airport
10/24/92	* 17 Route 4 W & Route
2/27/92	* NCV

To generate the simulation data base, six runs were performed for each experiment using different random seeds. The following statistical distributions were formed per experiment by aggregating the results of the six simulation replicates:

- Weaving and non-weaving speed; Six distributions were formed, each representing one five minutes time period.
- Weaving and non-weaving acceleration; A single distribution was created per experiment.

The following statistical tests were used for model validation.

- Z-test for differences between field and simulation population means

For large samples of speed and acceleration in one 5-minute interval , the Z-test, normal approximation method, was used to test for the differences between field observations and simulation results. Basic assumptions are both populations are normally distributed, and the values of both population variances σ_1^2 and σ_2^2 are known. The null hypothesis H_0 is

Table 6.4 Statistic Analysis for Weaving Speed

Anova: Single-Factor

Groups	Count	Sum	Average	Variance		
Field	273	9470	34.69	35.07		
Sim.	380	12929	34.02	63.42		
Source of Variation	SS	df	MS	F	P-value	F criteria
Between Groups	70.83	1	70.83	1.374	0.242	6.674
Within Groups	33578	651	51.58			
Total	33648	652				

z-Test: Two-Sample for Means

	Field	Sim.
Mean	34.69	34.0
Known Variance	35	63
Observations	273	380
Hypothesized Mean Difference	0	
z	1.231	
P(Z < =z) one-tail	0.055	
z Critical one-tail	2.576	
P(Z < =z) two-tail	0.109	
z Critical two-tail	2.326	

F-Test: Two-Sample for Variances

	Field	Sim.
Mean	34.69	34.02
Variance	35.08	63.42
Observations	273	380
df	272	379
F	1.808	
P(F < =f) one-tail	1E-07	
F Critical one-tail	1.157	

Table 6.5 Statistic Analysis for Non-Weaving Speed

Anova: Single-Factor

Groups	Count	Sum	Average	Variance		
Field	107	3504	32.75	85.4		
Sim.	79	2452	31.04	24.6		
Source of Variation	SS	df	MS	F	P-value	F criteria
Between Groups	133	1	133	2.23	0.137	6.775
Within Groups	10975	184	59.55			
Total	11108	185				

z-Test: Two-Sample for Means

	Field	Sim.
Mean	32.75	31.04
Known Variance	85	24.7
Observations	107	79
Hypothesized Mean Difference	0	
z	1.626	
P(Z < =z) one-tail	0.026	
z Critical one-tail	2.576	
P(Z < =z) two-tail	0.052	
z Critical two-tail	2.326	

F-Test: Two-Sample for Variances

	Field	Sim.
Mean	32.75	31.04
Variance	85	24.7
Observations	107	78
df	106	77
F	3.437	
P(F < =f) one-tail	2E-08	
F Critical one-tail	1.1427	

Hypothesis H_0: $\mu_1 = \mu_2$

Test Statistics: $Z = \dfrac{\bar{x} - \bar{y} - (\mu_1 - \mu_2)}{\sqrt{\dfrac{\sigma_1^2}{n_1} + \dfrac{\sigma_2^2}{n_2}}}$

A 5-percent level of significance was chosen in designing the hypotheses test.

- F-test for differences between the field and simulation population variances.

To test the equality of two population variances (or standard deviations), The F test was used. The assumptions are that the both populations are normally distributed as $N(\mu_1, \sigma_1^2)$ and $N(\mu_2, \sigma_2^2)$, with sample sizes n_1 and n_2, respectively. The hypothesis H_0 and test statistic is as the follows: A two-side F-test at 5-percent level with (n_1-1, n_2-1) degree of freedom was used.

Hypothesis H_0: $\sigma_1^2 = \sigma_2^2$

Test Statistic: $F = \dfrac{S_1^2}{S_2^2}$

- ANOVA and F-test for differences between the field and simulation population variances

To test the equality of two population variances (or standard deviations), ANOVA and F test were used. The assumptions are that the both populations are normally distributed as $N(\mu_1, \sigma_1^2)$ and $N(\mu_2, \sigma_2^2)$, with sample sizes n_1 and n_2, respectively. A level of significant of one percent was used with (n_1-1, n_2-1) degree of freedom for each population, respectively.

Sampling of speed and acceleration in five minute intervals were used for the hypothesis test. For large samples, it was hypothesized that there was no difference between field observation and simulation results. Tables 6.4 and 6.5 show the statistics of results for weaving and non-weaving speed.

Table 6.6 Statistic Analysis for Weaving Acceleration

Anova: Single-Factor

Groups	Count	Sum	Average	Variance		
Sim.	223	98.5	0.442	26.5		
Field	223	62.98	0.282	31.19		
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.832	1	2.832	0.098	0.754	6.692
Within Groups	12806	444	28.84			
Total	12809	445				

z-Test: Two-Sample for Means

	Sim	Field
Mean	0.442	0.28
Known Variance	26.5	31.2
Observations	223	223
Hypothesized Mean Difference	0	
z	0.313	
P(Z < =z) one-tail	0.189	
z Critical one-tail	2.576	
P(Z < =z) two-tail	0.377	
z Critical two-tail	2.326	

F-Test: Two-Sample for Variances

	Sim	Field
Mean	0.44	0.28
Variance	26.5	31.2
Observations	223	223
df	222	222
F	1.177	
P(F < =f) one-tail	0.113	
F Critical one-tail	1.188	

Table 6.7 Statistic Analysis for Non-Weaving Acceleration

Anova: Single-Factor

Groups	Count	Sum	Average	Variance		
Sim.	107	108.6	1.01	23.95		
Field	61	-32.98	-0.54	20.37		
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	93.98	1	93.98	4.147	0.04	6.79
Within Groups	3762	166	22.7			
Total	3856	167				

z-Test: Two-Sample for Means

	Sim	Field
Mean	1.015	-0.54
Known Variance	23.95	20.4
Observations	107	61
Hypothesized Mean Difference	0	
z	2.082	
P(Z < =z) one-tail	0.009	
z Critical one-tail	2.576	
P(Z < =z) two-tail	0.019	
z Critical two-tail	2.326	

F-Test: Two-Sample for Variances

	Sim	Field
Mean	1.015	-0.54
Variance	23.95	20.4
Observations	107	61
df	106	60
F	1.176	
P(F < =f) one-tail	0.248	
F Critical one-tail	1.477	

Table 6.6 and 6.7 show the statistical results for weaving and non-weaving accelerations. The level of significant is one percentage. Tables 6.8 shows the test of differences of non-weaving and weaving acceleration of field observations and simulation predictions. The ANOVA test tests the differences of population variances between the field observations and simulation results. The Z test tests the difference of population mean between field and simulation. "F" indicates that the hypothesis was rejected, whereas "P" indicates that the hypothesis was not rejected.

Table 6.8 Evaluation for Weaving and Non-weaving Speed at LIE Exit 30N

	Weaving	*Speed*			*Non-*	*weaving*	*Speed*	
Time	*Field*	*Sim.*	*ANOVA*	*Z-test*	*Field*	*Sim.*	*ANOVA*	*Z-test*
7:50	29.1	32.74	F	F	30.3	32.8	F	F
8:00	33.6	33.3	P	P	32	32.6	P	P
8:10	34.7	33.8	P	P	31	31.8	P	P
8:20	34	33.4	P	P	33	32.8	P	P
8:30	33.1	32.9	P	P	29.4	31.1	F	F
8:40	34.2	33.9	P	P	33.4	32.7	P	P
8:45	35.4	33.5	F	F	33	32.6	P	P
8:55	35.1	33.3	P	F	34.2	33.7	P	P

The results are very favorable as in most cases the null hypotheses was not rejected. The Z-test shows that only three weaving speed and two non-weaving speed's means have significant difference for each eight five-minutes interval. The ANOVA test shows that only two weaving speeds and one non-weaving speeds variance have significant differences for each eight five-minutes interval.

B. Comparison with Field Data Directly Read from Video Tape

Ten sites such as Exit 30 of Long Island Expressway, entrance of the Newark Airport, Route 20 and 80, Exit 10 of Great Central Parkway, Route 17 North and Route 4; and Route 4 East and Route 17, etc. were used to collect data specifically for this comparison. Four sites are category I, basic weaving occur in the 2-lane weaving areas. The longest weaving section is 436 ft, which is in Exit 10 of Great Central Parkway. The shortest weaving section for this test is just 210 ft, which is in Market Street, Route I-80 and I-20. For Category II, sometimes there are 3 or 4 lanes in weaving areas. One or two lanes are just for non-weaving vehicles. The lengths are shorter and the minor approach angle are wider. The maneuver of weaving and non-weaving vehicles in this category are more complicated.

The sample size is much smaller for this test, so one factor t-test is used for the statistic analysis. A five percent level of significance was chosen in designing the test of hypothesis. Appendix A shows the detail of results of the hypothesis testing for each test site. A summary of the six test sites is shown in Table 6.9 are the .

Table 6.9 Test of Hypothesis for NFWEAV

Site	Category	Validated Variable	T - Test No.of reject/total
Exit 30N of Long Island Expressway.	I	WV Speed	3 / 22
7:05-8:50 AM		NW Speed	5 / 22
Newark International Airport Entry	I	WV Speed	5 / 24
4:00-5:55 PM		NW Speed	6 / 24
Route Marker, I-80 & I-20	I	WV Speed	8 / 21
8:15-9:55 AM		NW Speed	4 / 21
Exit 10 of Great Central Parkway N.	I	WV Speed	5 / 24
6:40-8:35 AM		NW Speed	
Route 17 South & Route 4	II	WV Speed	7 / 24
2:30-4:35 PM		NW Speed	11 / 24
Route 4 East. & Route 17	II	NW Speed	9 / 23
7:05-8:55 Am		WV Speed	9 / 23

There are three sites for category I, two for category II. About one hour was taken for evaluation purpose for each site. The result is presented by the ratio of number of test rejected and total number of test. For example, three of weaving speed hypothesis testing were rejected from total twenty two tests for Long Island Expressway Exit 30N site, and five of non-weaving speed were rejected from total twenty two tests.

The evaluation shows that the model is acceptable in most Category I cases, the null hypotheses could not be rejected. The results for Category II are also satisfactory, although not as good as that in Category I.

CHAPTER SEVEN

SUMMARY AND CONCLUSIONS

7.1 Summary

The operation of weaving areas under freeway conditions has been treated in many studies, including the 1985 Highway Capacity Manual, however the 1985 HCM and others contain no treatment for weaving areas under non-freeway conditions. This study presents a microscopic computer simulation model NFWEAV representing vehicle interactions on weaving areas under non-freeway conditions. The simulation model NFWEAV is found to be a useful tool for the study of a weaving area under non-freeway conditions. It has been implemented in a microcomputer IBM/PC 386.

Weaving operation under non-freeway conditions is characterized by lower speed and much more aggressive merging maneuvers because of restrictions due to the relatively shorter length of weaving section. The traffic models developed in NFWEAV includes NJIT car following, lane changing, follower courtesy, driver merging urgency model and anti-collision check algorithms, which reflect a different scenario of driver behaviors and traffic operation situations from those on freeway conditions.

A SLAM II simulation language was chosen for the simulation purpose. An event orientation technique was used in the NFWEAV model development. The simulation approach makes it possible to study in detail the dynamic traffic responsiveness of weaving operations under non-freeway conditions. A graphic and animation output visually present the dynamic characterization of the weaving section operation under non-freeway conditions. The Level of Service criteria developed in phase I of the project were stored in the library of the NFWEAV, and the simulation result predicted the LOS for user's weaving area capacity analysis.

Extensive testing was conducted in order to verify and validate the NFWEAV model. Data collection and reduction were conducted by video taping and photogrammetry techniques from fourteen sites in the New York and New Jersey region. Comparative analyses between analytical and simulation model, as well as analysis between field observation and model predictions were conducted.

7.2 Conclusions

The principal contribution of this thesis was the development of a microscopic computer simulation model NFWEAV for analyzing traffic operations on weaving areas under non-freeway conditions. The principal components that characterize NFWEAV are the following:

- NJIT car following model was developed for the particular scenario of weaving operations under non-freeway conditions with relatively shorter length and more aggressive merging maneuvers. It is a modification of PITT model which sometimes forces the followers to stop easily at non-freeway weaving areas. The desired safe headway space in NJIT model is larger when the follower is faster, and vice versa to avoid the problem caused by PITT model.
- A lane changing model was also developed for weaving maneuvers. A follower courtesy model was conducted to describe the different behavior at much heavier weaving maneuver situation. A driver merging urgency model described the forced merging behaviors at the relatively shorter weaving sections.
- An animation model was conducted in NFWEAV model to visualize the dynamic portray of the system simulation of weaving operation under non-freeway conditions.

The NFWEAV model underwent through extensive testing. The principal results of the verification and validation are the following:

- The NJIT car following model was dynamically verified: the result shows that the followers have good oscillatory characteristics; their movements are stable.
- The lane changing model was verified by merging pattern which described by the merging point distribution along the weaving section for both Category I and Category II in weaving areas under non-freeway conditions.
- A comparison between the analytical model and simulation model was conducted, showed no significant difference.
- A comparison between the simulation results and field observations was conducted. The evaluation shows that the model is satisfactory, and in most Category I cases, the null hypotheses could not be rejected. The results for Category II are also acceptable, although not as good as that in Category I.

More than 14 sites were video taped for model verification and validation purpose, however only the data from six sites could be used. The main deficiencies of the digitizing procedure are the following:

- The geometry factor, such as shorter length, larger approach angle of weaving sections; and traffic factor such as heavy traffic flow or huge combined truck, form obstacles to choose a accurate digitizing target.
- Clear and accurate reference points for digitizing are not available in some sites.
- Human behavior, such as fatigue and/or carelessness also cause deficiency.

7.3 Future Research

The model calibration and evaluation were conducted under limited conditions. Most of the sites are located in the New Jersey and New York state. The configuration of facilities, traffic operation conditions are limited. The method of the data collection, especially the reliability and accuracy of the imaging processing method needs to be improved. The model will be widely used if robust statistical testing of more sites can be conducted to validate the model under a wider spectrum of facility types.

APPENDIX A

Table A-1 Test at Exit 30N on Long Island Expressway

Time	Weaving Speed					Non-Weaving Speed				
	Field		Simulation		T test	Field		Simulation		T test
	Mean	*Std*	*Mean*	*Std*		*Mean*	*Std*	*Mean*	*Std*	
7:05	40.01	4.25	40.04	7.57		45.05	2.54	39.54	9.54	f
7:10	39.01	6.64	40.66	8.06		38.44	5.30	41.00	9.53	
7:15	37.80	5.31	36.55	7.31		35.30	4.34	35.27	9.31	
7:20	40.00	6.68	40.97	7.43		38.28	4.41	41.93	8.53	
7:25	35.50	7.38	40.19	7.68	f	36.06	5.29	39.30	9.48	
7:30	37.52	6.75	38.00	8.54		37.13	5.49	34.14	11.42	
7:35	39.80	5.88	39.14	7.84		39.27	4.87	37.84	10.21	
7:40	37.54	6.93	38.76	7.80		39.13	8.00	39.02	9.97	
7:45	35.11	6.82	31.58	9.05	f	33.63	6.15	25.31	10.38	f
7:50	37.09	8.03	39.36	7.98		34.56	6.50	38.33	9.38	
7:55	36.07	6.78	37.17	7.97		36.26	3.88	35.42	9.56	
8:00	38.33	5.93	38.48	7.47		36.83	4.27	37.98	10.59	
8:05	34.38	7.04	36.23	7.76		31.89	6.06	33.14	9.41	
8:10	38.65	6.31	39.60	7.95		37.24	7.38	37.55	9.39	
8:15	36.20	6.58	32.81	8.34	f	34.00	6.65	27.17	10.04	f
8:20	35.21	7.84	36.73	8.19		40.10	2.51	34.61	10.46	f
8:25	36.29	6.59	37.73	8.38		38.50	3.58	34.10	10.69	f
8:30	33.97	8.13	33.65	8.10		31.64	8.56	28.76	10.36	
8:35	37.13	7.28	37.06	8.11		34.89	6.30	34.12	10.26	
8:40	40.85	7.33	40.85	7.42		40.29	5.27	41.00	9.41	
8:45	38.62	7.05	39.45	7.69		36.04	8.40	38.86	9.64	
8:50	43.57	7.13	42.95	7.56		40.01	5.18	43.45	8.38	

*length: 302 ft   width: 30 ft
*No. of lanes: 2   minor approach angle: 20

Note: f means the t-test is failed in this 5-minute period.

Table A-2. Test at Newark International Airport (Category I)

Time	Weaving Speed					Non-Weaving				
	Field		Simulation		T-test	Field		Simulation		T-test
	Mean	*Std*	*Mean*	*Std*		*Mean*	*Std*	*Mean*	*Std*	
4:00	37.81	5.60	35.18	6.65	f	43.04	5.07	36.34	7.37	f
4:05	36.40	4.16	35.41	6.76		36.81	5.23	37.22	8.72	
4:10	34.68	5.04	34.82	7.09		36.26	3.75	36.37	8.34	
4:15	36.15	6.13	34.44	6.73		37.44	4.56	35.10	8.62	
4:20	34.36	5.45	35.80	6.19		35.09	5.50	35.43	8.18	
4:25	34.90	5.04	33.93	7.35		36.48	3.56	33.63	10.31	
4:30	33.81	3.68	34.77	7.33		34.32	5.46	35.69	9.66	
4:35	33.80	5.76	33.35	6.78		36.20	3.94	34.41	9.56	
4:40	34.48	5.29	33.02	6.76		38.25	4.56	34.67	8.99	f
4:45	33.11	5.86	34.19	7.41		32.58	2.98	35.52	9.25	f
4:50	34.30	4.54	32.42	7.35	f	33.99	5.46	33.28	9.52	
4:55	34.23	4.84	34.86	7.40		34.18	5.87	34.91	10.32	
5:00	35.02	5.45	33.64	6.97		34.94	4.35	35.13	9.20	
5:05	34.10	5.03	33.03	7.05		36.10	4.12	35.25	9.01	
5:10	32.55	4.72	32.34	7.41		34.49	4.53	32.14	9.97	
5:15	33.12	4.06	34.30	6.56		33.72	4.67	32.63	9.11	
5:20	32.72	5.57	34.32	6.64		35.33	3.75	36.74	8.45	
5:25	33.48	3.98	37.37	6.00	f	34.85	2.14	37.26	7.04	f
5:30	32.93	4.68	34.98	6.84	f	33.82	3.11	35.41	8.55	
5:35	33.37	3.75	33.60	7.06		34.46	4.53	34.71	9.22	
5:40	33.93	5.45	34.10	7.17		35.31	5.87	35.31	9.08	
5:45	33.06	3.46	33.66	6.83		35.28	3.86	34.32	9.47	
5:50	33.37	3.72	34.11	6.64		36.59	2.45	34.24	8.99	f
5:55	33.38	5.68	36.54	6.22	f	35.89	2.74	38.18	7.5	f

length: 310 ft
No. of lanes: 2

Note: f means the t-test is failed in this 5-minute period.

Table A-3. Test at Market St. I-80 and I-20 (Category I)

Time	Weaving Speed					Non-Weaving				
	Field		Simulation		t test	Field		Simulation		t test
	Mean	*Std*	*Mean*	*Std*		*Mean*	*Std*	*Mean*	*Std*	
8:15	28.15	5.65	38.42	6.57	f	31.97	1.80	30.59	9.34	
8:20	33.12	8.84	30.76	6.64		35.84	5.34	32.14	7.95	
8:25	32.34	7.45	32.98	6.67		31.46	4.54	32.61	6.68	
8:30	32.49	6.12	31.95	6.63		35.59	6.19	33.33	6.95	
8:35	33.30	6.23	32.58	6.23		33.62	4.65	33.97	7.05	
8:40	31.54	6.41	32.90	6.61		34.02	6.36	33.49	7.71	
8:45	30.50	8.22	29.72	6.73		28.86	9.49	30.49	8.52	
8:50	34.27	7.77	34.07	6.08		36.13	8.12	35.27	7.63	
8:55	34.20	8.24	29.85	6.83	f	33.25	7.84	32.00	7.90	
9:00	31.74	6.64	29.32	6.90	f	36.42	4.90	30.17	8.54	f
9:05	30.54	6.96	32.60	6.76		29.85	8.30	31.07	8.62	
9:10	33.89	6.51	31.36	6.62	f	32.29	6.28	31.08	7.87	
9:15	32.18	5.61	32.71	6.88		31.50	4.86	31.90	8.79	
9:20	32.32	7.76	33.95	6.14		30.27	5.48	34.61	6.92	f
9:25	32.99	4.42	27.10	6.96	f	31.08	4.85	27.06	9.06	
9:30	34.69	5.46	33.36	6.15		31.61	6.18	33.85	7.67	
9:35	28.63	6.21	27.98	7.33		36.19	2.44	29.04	8.53	f
9:40	32.83	6.97	32.92	5.77		29.75	7.09	30.25	8.72	
9:45	35.36	5.81	26.99	7.27	f	36.29	4.37	29.29	8.53	f
9:50	32.31	7.59	27.57	7.33	f	33.31	7.50	29.53	8.10	
9:55	34.25	7.07	30.85	7.03	f	35.32	7.35	34.66	7.60	

Length: 210 ft   Width: 31 ft

No. of lanes: 2   Minor approach Angle: 15

Note: f means the t-test is failed in this 5-minute period.

Table A-4. Test at Exit 10 of

Great Central Parkway (Category I)

Time	Weaving Speed				
	Field		Simulation		T-test
	Mean	*Std*	*Mean*	*Std*	
6:40	36.81	5.50	37.44	7.58	
6:45	35.62	2.80	35.77	8.06	
6:50	35.96	4.28	35.84	7.32	
6:55	35.96	4.86	37.61	6.46	
7:00	36.93	4.93	36.07	6.36	
7:05	36.42	3.56	34.99	6.87	f
7:10	37.74	4.32	38.62	7.18	
7:15	39.01	5.08	38.52	6.92	
7:20	36.68	5.78	36.51	7.04	
7:25	36.48	7.84	35.85	7.68	
7:30	40.00	4.32	41.28	6.23	
7:35	37.03	3.75	38.94	7.13	f
7:40	39.46	6.43	38.30	7.26	
7:45	38.34	4.49	37.93	7.35	
7:50	30.63	6.57	36.06	7.41	f
7:55	34.10	4.57	36.06	7.46	
8:00	38.33	5.11	37.94	6.56	
8:05	35.85	5.04	37.37	6.00	
8:10	36.16	3.64	38.55	7.40	f
8:15	36.93	3.55	37.48	7.60	
8:20	36.46	4.63	37.62	7.94	
8:25	36.34	5.94	33.66	6.83	f
8:30	37.27	4.63	36.09	7.42	
8:35	37.81	6.26	35.99	7.15	

Length: 436 ft — Width : 34 ft

N0 of lanes: 2 — Minor Approach Angle: 30

Note: f means the t-test is failed in this 5-minute period.

Table A-5. Test at Route 17 South and Route 4 (Category II)

Time	Weaving Speed					Non-Weaving				
	Field		Simulation		T-test	Field		Simulation		T-test
	Mean	*Std*	*Mean*	*Std*		*Mean*	*Std*	*Mean*	*Std*	
2:30	20.27	4.64	20.12	7.17		23.30	5.67	21.54	6.77	
2:35	20.30	4.93	20.00	7.72		23.34	5.34	19.60	7.11	f
2:40	21.46	4.41	20.04	6.58		22.03	5.21	23.35	5.86	
2:45	19.17	3.81	19.87	7.76		19.48	4.71	18.51	6.21	
2:50	18.40	4.54	19.71	7.22		17.45	5.05	17.18	6.88	
2:55	18.92	4.63	20.85	7.68	f	21.53	6.01	19.56	5.97	
3:00	20.50	4.88	19.11	7.69		21.03	5.34	17.79	6.68	f
3:05	21.72	4.44	21.56	7.16		28.07	5.43	21.54	6.23	f
3:10	22.34	5.09	19.51	7.57	f	30.04	6.01	31.03	6.56	
3:15	22.44	7.03	20.24	7.47		29.51	5.76	30.51	6.12	
3:20	21.50	5.53	20.96	7.33		29.14	5.88	30.27	5.55	
3:25	23.20	3.45	21.73	8.38		27.40	6.05	25.70	6.38	
3:30	21.27	4.87	21.34	8.28		26.29	5.87	25.37	7.15	
3:35	24.00	6.01	22.29	7.58	f	23.82	6.53	26.43	6.43	f
3:40	22.39	4.76	20.99	7.51		22.64	4.12	25.51	6.52	f
3:45	23.51	4.92	21.47	7.83	f	23.73	4.06	25.61	6.96	f
3:50	22.45	4.46	20.49	6.66	f	25.88	5.05	29.63	7.03	f
3:55	23.14	4.39	22.37	7.08		33.33	4.32	34.56	6.50	
4:00	24.61	4.96	19.89	8.47	f	31.41	5.04	29.99	6.78	
4:05	22.38	5.08	20.35	7.27		28.50	4.33	33.43	6.26	f
4:10	22.01	6.35	22.08	8.59		24.82	4.76	24.31	6.66	
4:15	22.23	4.77	22.55	7.79		26.16	3.78	28.29	7.15	f
4:20	21.19	5.56	19.67	7.66		24.78	4.37	29.86	6.74	f
4:25	23.33	4.97	20.50	7.60	f	23.90	4.98	26.85	7.51	f

length: 246 ft width: 22 ft

No. of lanes: 3 minor approach angle: 40

Note: f means the t-test is failed in this 5-minute period.

Table A-6. Test at Route 4 East and Route 17 (Category II)

Time	Weaving Speed					Non-Weaving				
	Field		Simulation		T-test	Field		Simulation		T-test
	Mean	*Std*	*Mean*	*Std*		*Mean*	*Std*	*Mean*	*Std*	
7:05	31.72	4.30	31.05	7.13		46.66	5.96	45.14	6.89	
7:10	32.36	3.74	32.05	6.87		46.49	5.97	45.14	6.95	
7:15	33.06	4.08	31.90	7.50		47.20	5.10	46.48	7.23	
7:20	32.04	4.24	28.36	7.98	f	46.33	4.17	44.93	7.48	
7:25	31.78	4.68	30.99	7.34		44.94	4.63	42.86	7.58	f
7:30	30.54	4.86	27.59	7.20	f	43.12	5.54	41.86	5.45	
7:35	29.55	6.57	27.81	7.18		41.80	5.25	39.89	5.37	
7:40	30.74	3.90	27.57	7.82	f	40.91	5.28	39.38	5.56	
7:45	29.30	4.37	28.52	8.05		40.81	5.88	35.52	4.95	f
7:50	29.66	3.66	24.14	7.18	f	39.30	6.12	34.18	5.41	f
7:55	29.14	5.03	29.23	7.88		39.05	6.46	33.19	5.78	f
8:00	29.05	3.70	29.02	7.22		36.68	8.89	34.19	5.24	f
8:05	29.03	4.23	27.83	7.52		36.52	6.72	33.14	5.81	f
8:10	28.95	3.83	26.11	7.23	f	34.23	7.93	32.43	5.09	
8:15	27.10	4.73	27.03	8.41		27.93	3.19	31.51	5.21	f
8:20	30.32	4.10	29.66	8.13		30.78	3.95	29.61	5.91	
8:25	26.45	7.04	21.45	7.38	f	29.49	3.78	29.54	6.81	
8:30	28.03	4.19	23.63	7.48	f	28.15	4.81	29.05	5.49	
8:35	29.91	4.39	25.27	7.11	f	34.79	6.07	30.97	5.44	f
8:40	26.85	5.08	26.90	7.54		29.63	3.28	27.93	6.52	f
8:45	27.70	3.99	25.68	8.21	f	30.22	5.05	29.17	5.58	
8:50	27.68	5.56	26.56	8.35		29.89	4.71	30.90	6.25	
8:55	27.75	4.97	26.91	6.75		27.30	5.61	28.43	5.93	

length: 259 ft
width: 23 ft
No. of lanes: 4
minor approach angle: 30

Note: f means the t-test is failed in this 5-minute period.

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