

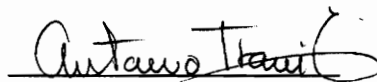
**RAMP CONTROL STRATEGIES AND GEOMETRIC DESIGN  
IMPLICATIONS OF HIGH-SPEED AUTOMATED TRANSPORTATION  
SYSTEMS**

by

Venkata Giri Nanduru

Thesis submitted to the faculty of the  
Virginia Polytechnic Institute and State University  
in partial fulfillment of the requirements for the degree of  
Master of Science  
in  
Civil Engineering

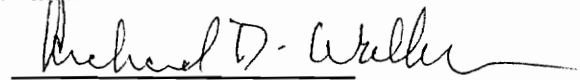
APPROVED:



Dr. Antonio A. Trani, Chairman



Dr. Donald R. Drew



Dr. Richard D. Walker

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Dr. Antonio A. Trani (Chairman)

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(ABSTRACT)

In recent years, the field of transportation engineering has witnessed the emergence of technological innovations linking several different application areas like human factors, computer science, communications and operations research. This research deals with automatic freeway traffic operations including ramp guidance and merging which is an important aspect of Intelligent Vehicle Highway Systems (IVHS) Technology. An existing traffic flow model is utilized to generate a non-overtaking, continuous traffic stream with automatic acceleration/ deceleration characteristics of the smart cars to fulfill the needs of a high-speed flow under controlled headway and optimized density conditions.

The orientation, shape, and geometry of such ramps on a high-speed highway system is investigated. It is proposed that the angle between the ramp and highway

would be very acute and lane changes from acceleration lane to the cruising lane would follow a smooth trajectory. The curve would be composed of two circular curves of large radii of curvature or two spiral curves in succession.

The adequacy of the existing geometric design specifications are questionable, not only for the merging section, but the entire stretch of the "smart highway". The introduction of intelligent highway network extensively in rural areas could necessitate a complete rethinking about highway geometric design standards. An alternate method of geometric design requirements is undertaken to explore the applications of vehicle aerodynamics' principles to the highway design, which is perceived to be essential under the high-speed conditions. The results obtained can be compared to those of the conventional geometric design formulae to yield a comparison. Though the principal aim of this research is to serve the highways, it has applicability to other forms of high-speed, controlled guideway transportation systems also.

*To my parents, brothers, and sister-in-law*

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I will forever be grateful to my father, a professor himself, not only for his encouragement and financial support for my graduate studies but also for instilling in me, an urge for higher education. I am also deeply indebted to my mother and to my brothers for being a constant source of inspiration and moral support, especially during my challenging days at Blacksburg.

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# 1 INTRODUCTION

## 1.1 Background

In the past few decades, highway transportation in the United States made a vital contribution to its magnificent progress to become an industrial, economic and military superpower in the world. The construction of the Interstate Highway System in 1960's and 1970's, lead to an unprecedented quality improvement of travel and served as a foundation for the technological and industrial complex of this nation. In light of these facts, increased attention is being paid towards the Interstate Highway System, which is considered by many as the greatest Civil Engineering accomplishment of this century (Mannering et al., 1990). The Intercity travel covering long distances, has been monopolized to a large extent by the Interstate Highway System.

Highway travel by Americans is several times that of any other developed nation, computed as vehicle-miles per capita. According to statistics, the total vehicle-miles travelled by an American was 8,241 in 1988, which was 22% more than the figure in 1980. Total annual vehicle-miles travelled was 817,557 millions in rural areas in 1988, which showed an increase of 41.2% over the preceding 8 year period. This indicates a rapid rise in highway usage, causing great deal of anxiety not only among the transportation professionals and state departments of transportation, but also the policy

makers and the general public. Again, the Interstate Highway System accounts for 21.7% of the total travel inspite of possessing only 1.2% of the total length of highways in United States as against local roads which carry 13.6% of traffic with as much as 68.6% of the total roadway length.

The accomplishments of the freeways had such a profound effect on the American way of life that a phenomenal growth in traffic demand followed it, creating an era of "Transportation Systems Management" (TSM), during the 1970's and 1980's. The volume of urban traffic grew by about 5% per year in the 80's. By 2005, continuation of such a growth rate can result in a fivefold increase in congestion levels, seen today. Mere addition of the freeways is not a viable solution any more because of the complexities involved including the displacement of urban populations, environmental affects, adverse public reactions and the expenses of real estate and construction. Also, an indefinite expansion of the right of way leads nowhere. Traffic accident data points towards a rise in the number of traffic hazards and fatalities inspite of determined effort from law enforcement and public service agencies to the contrary. Focus is on controlling the demand by innovative improvements as part of Transportation Systems Management (TSM) methods such as on-site diversion strategies at the bottleneck spots and improvements of the transportation systems, pavement, and geometry of the right-of-way. Emphasis is being laid on encouraging mass transit and separate lanes for High Occupancy Vehicle lanes (HOV lanes), optimal diversion strategies and restrictions on

parking and peak period travel. The latest TSM strategies are in the direction of development and implementation of advanced technology in the field of transportation. This is achieved by automating the highway operations, the research on which was started more than three decades ago.

## **1.2 Freeway Surveillance - Modern Nomenclature**

"Surveillance" in highway terminology denotes the observations in time and space (of traffic conditions). It took a strong shape, as early as in 1960's at the Texas Transportation Institute (TTI), one of the pioneering traffic/ transportation research institutes in the world. "Intelligent Vehicle Highway Systems", popularly known as IVHS is a new name proposed for this phenomenon by the traffic researchers of this generation. It has been defined as the concept for integrating the driver, vehicle, highway, automatic control system, and hardware equipment and its software applications to achieve a coordination for multiple task performance (Mobility 2000, 1989).

The freeway surveillance with closed circuit television as the tool began in 1961 on the John C. Lodge Freeway in Detroit (Drew, 1968). It became a control project in 1962 and soon, speed sensors with relay racks, analog computers and display panels were added, followed by initiation of lane and off-ramp signals and speed signs. Thus in a short period, an entirely new concept in freeway traffic control was operational, capable

of traffic detection, measuring and transmitting the messages to matrix variable signs, lane controls and ramp controls. The Detroit project was a pioneer in motorist information services, which are now known as "Advanced Driver Information Systems". A proper lane control utilization and real-time change of traffic speed messages were supplied to the user. This project was followed by "the Chicago Area Expressway Surveillance Project", established in 1961 as a research program of Illinois DOT. The aim of this endeavor was similar in nature to that of the Detroit experiment. But the most significant advances in freeway surveillance were obtained on research facilities off freeways. In 1963, the Port of New York Authority installed a surveillance system in the Holland Tunnel with features such as vehicle detection with traffic condition display and control devices, a special computer which receives traffic information and activates controls to prevent congestion from occurring inside the tunnel, closed circuit television, two way radio communication between control centers and police in the tunnel and a monorail for speedily moving tunnel police to any point in the tunnel (Drew, 1968).

The National Proving Ground for Freeway Surveillance, control, and Electronic Traffic Aids was a major installation for testing in the history of all surveillance projects. In September, 1963, the Texas Transportation Institute started research in the area of freeway surveillance and control. This was a great contribution made to the future freeway planners and designers of the subsequent generations. The project was titled "The Gulf Freeway Surveillance and Control Project".

The scientific community overlooked the ideas put forth by the traffic researchers at that time, possibly because of lack of awareness and/ or skepticism about its potential and/ or lack of funding from federal sources. Drew forecasted the future of the transportation industry in 1965 as "there is a need for special-purpose vehicles-automobiles especially designed for commuting. Such vehicles might be designed to seat two people, to be considerably smaller than even today's compacts, and to be powered by high-efficiency batteries or chemical cells. Another special-purpose vehicle might be equipped with automatic guidance and control for high-speed (150 mph) intercity freeway driving" (Drew, 1968). Similarly, the night vision systems, which are under research as if it were a newly formed idea, have been studied earlier. Drew states that "highway illumination should also be studied to determine its compatibility with vehicle lighting in order to develop an optimum night driving environment", which is precisely the point of research of the night vision systems (Drew, 1968). Regarding the geometric design of a high-speed highway, Drew suggests "there is an intimate connection between the safety of a highway and the complex interrelations between curvature, grade, and sight distance. For low to moderate speed operation the empirical methods currently used are perhaps adequate. However, for the high speed operation now approaching, a closer look at the assumptions and criteria for geometric designs is mandatory. If past trends are to be taken seriously, the next generation of highways will be based on design speeds of 100 mph or more. This will have a far reaching effect on geometric design and even structural design of the road. Flatter curves and slopes will necessitate more and longer

spans on elevated structures. There shall be a demand for 200 ft. prestressed concrete beams and perhaps prefabricated structures. The entire right-of-way must be made free of such obstructions as trees and utility poles. Signs should be of the harmless breakaway type. Guard-rails and barriers are collision objects, themselves, so that rational warrants should developed for their installation" (Drew, 1968).

### **1.3 Research Objectives and Approach**

The objective of this research is to investigate the ramp control and geometry of the freeway and the ramps upon the introduction of the intelligent vehicle highway systems in rural scenarios, which will necessitate the use of design speeds in excess of 200 mph in order to provide larger practical roadway capacities and adequate intercity travel times. If a new IVHS interstate highway system is to be built in the next forty years, the geometric design requirements of such a system would differ substantially from those of today's interstate expressways. For example, such a highway would presumably require much flatter horizontal and vertical curves than those now in use.

A review of the various macroscopic and microscopic models is done to determine the best model for design of a traffic stream which has a very special set characteristics of fast moving cars at close headways, with automatic control over merging and weaving. Since requirements seek individual vehicle characteristics replication in fine detail as

against a more general and extensive behavior pattern, microscopic models, which do not allow any overtaking are chosen. The length and shape of the ramp is determined by imposing the maximum design speed conditions. The length of freeway acceleration lane under the maximum capacity conditions and the control algorithm to affect the lane change operations is also developed.

STELLA, an Apple Macintosh based simulation software has been used for car following model development and simulation. It is a user friendly software and applies Systems Dynamics techniques which are very well suited to transportation engineering applications. It has a number of built-in functions, which eliminate the need of a lengthy programming code and perform certain specific tasks for running simulation programs with ease.

It is followed by an analysis of the expected problems and their nature in designing the geometric design elements of the intelligent highway, such as horizontal and vertical curve radii for vehicle turning and the alignment of the highway and the superelevation criteria for horizontal curves and gradients which are proven to be dependent on the aerodynamic and tire interface laws. A basic understanding of the vehicle performance under the high-speed conditions is probed by applying the geometric design and vehicle aerodynamic principles. An effort has been made in this research to extend the AASHTO standards to the vertical curve design in an IVHS scenario.

# 2 LITERATURE REVIEW

## 2.1 Introduction

Traffic congestion has been a major problem identified by the citizens of U.S., in the recent times. Three strategies for minimizing traffic congestion are

1. Increase capacity by physical expansion either by building more roadways or widening of the freeways (up to 10 ten lanes have been reported in the past)
2. Managing transportation systems efficiently (encouraging mass transportation and other measures)
3. Improve efficiency by operational improvements (like installation of signals, enforcement of traffic regulations)

IVHS technology encompasses all the above strategies, which are not mutually exclusive. One of the most important elements of any freeway operation is the design for a merging maneuver from an entrance ramp onto the shoulder lane of a freeway. Merging, is simply the absorption of the stream of ramp traffic. Merging is also the process of the vehicle moving from the acceleration lane to the shoulder lane. In the context of an intelligent highway, the problem facing the researchers is the entrance of and exit maneuvering of vehicles, equipped with automatic controls to a high-speed highway (i.e., "Smart Highway") under the very high-speed conditions, on the order of

200-300 miles per hour at close headways. The gap acceptance theory, which is the basis for the design of all entrance ramps so far, has no particular application in the case of a high speed guideway such as this, because of the predicted automation, in coming years. The weaving maneuver also calls for as much attention as a merging maneuver, under high speed conditions, contrary to the case of the present day design.

## **2.2 Present Research - Components of an IVHS System**

Mobility 2000, a forum represented by industry, university and federal, state, and local government officials was formed to advance transportation research particularly the IVHS systems. It has identified four different categories of research for the development of the technology in future (Mobility 2000, 1989). These are

- Advanced Driver Information Systems (ADIS)
- Advanced Traffic Management Systems (ATMS)
- Advanced Vehicle Control Systems (AVCS)
- Commercial Vehicle Operations (CVO)

## **2.2.1 Advanced Traffic Management Systems**

These will form solutions for tomorrow's traffic jams. Upon complete development, ATMS seeks to permit real-time adjustments in response to the traffic conditions of the highway ahead. ATMS is an array of institutional, human, hardware, and software components designed to manage traffic. Surveillance system detects and transmits the real-time traffic patterns at different locations simultaneously to a central computer which is responsible for evolving the traffic management strategies to avoid congestion problems. It predicts the potential congestion area and prevents it by way of decision support and communication facilities. In a fully automated phase (the ultimate stage), it corresponds directly with the ADIS systems to direct the vehicle into alternative routes. Many incidents could be avoided, which was not possible before. Several field tests have taken place to validate these promises. Their application reduced the delay, travel time and accidents. Examples are DRIVE (a combined European effort), AMTICS and RACS (Japanese projects) which are preludes for future systems.

## **2.2.2 Advanced Driver Information Systems**

It is a system software which provides a chain of information flow to the highway driver about the location of the vehicle geographically as well as in a traffic stream so he can make valuable alterations to the route chosen. It acts in parallel with ATMS and

AVCS systems to permit communication between the driver and ATMS for continuous advice regarding traffic conditions, alternative routes and safety issues. Color video display of maps, locations of specific services about the area including the tourist attractions, boarding or/ and lodging or rest areas, hospitals etc. are supplied alongside with the vehicle movement in conjunction with an on-board database. Prior warning messages are issued about the road ahead which are especially beneficial in case of poor visibility or inclement weather conditions, to enable driver to be better prepared to respond to those situations. It is known that half of rear-end collisions and one-third of all head-on collisions are avoidable if the driver had known about the happening, half a second before the accident and responds promptly. The research and development in this area is proposed to occur in three stages. These are:

- (1) *Information stage* (1990-95): Ease the driver's task by a display of real-time traffic information using on-board equipment
- (2) *Advisory stage* (1995-2000): Process and filter the real-time traffic data and weather input by in-vehicle infrastructure and guide the driver through the optimum route
- (3) *Coordination stage* (2000-2010): Automation of the entire network for optimum speeds and safety by using simulation and other techniques

### **2.2.3 Advanced Vehicle Control Systems**

Initially, the Advanced Vehicle Control Systems (AVCS) are aimed at augmenting driver performance by improving technology of identification of obstacles, adjacent vehicles, and negotiating sharp turns for safe and efficient operations at the intended high speeds. AVCS could relieve most driving tasks in high demand traffic corridors or long distance high speed trips. It uses radar type technology to give additional warning time to motorists which can prevent many traffic accidents. Eventually, it will interact with fully developed ATMS to provide automatic vehicle operations. It will exercise the chauffeuring of the vehicles from their on-ramp arrival to off-ramp departure. It increases the throughput of traffic, both in urban and intercity carriage, realizing a new level of safety and mobility through high speed operation. An intensive, multi-year program of research, development, demonstration, and evaluation is required to reach the goal of improving highway safety and reducing congestion through the application of AVCS concepts. There are three levels of AVCS technologies planned in future. They are AVCS-I (individual vehicle control), AVCS-II (cooperative driver-vehicle-highway systems), and AVCS-III (automated vehicle-highway systems).

## **2.2.4 Commercial Vehicle Operations**

The ultimate goal of Mobility 2000 is to ensure that all types of motor vehicles, regardless of type or ownership are involved in future transportation, for successful implementation. Global competition is intense, forcing the U.S. Companies to improve their productivity, safety and regulation of all commercial operations. IVHS technologies are emerging as the key tools to reduce the costs and improve competitiveness for U.S.businesses in ten world markets by way of economical and rapid transfer of goods and persons, like never before. Weigh-in-motion sensors, automated vehicle identification transponders and automated vehicle classification devices reduce labor costs, save time and minimize use of red tape. Automatic vehicle location, tracking and two way communications, routing algorithms are already being used for timely pickups and deliveries. They have an impact on environmental protection, quality improvements and the overall success of industries at national and international levels. Commercial operations are likely to be the first beneficiaries of next generation IVHS technologies. The key benefits include reductions on operating costs, fewer halts over long distances, reduced paperwork burden, improved safety performances, larger volumes of transportation over less periods, satisfaction for general public and local and state governments.

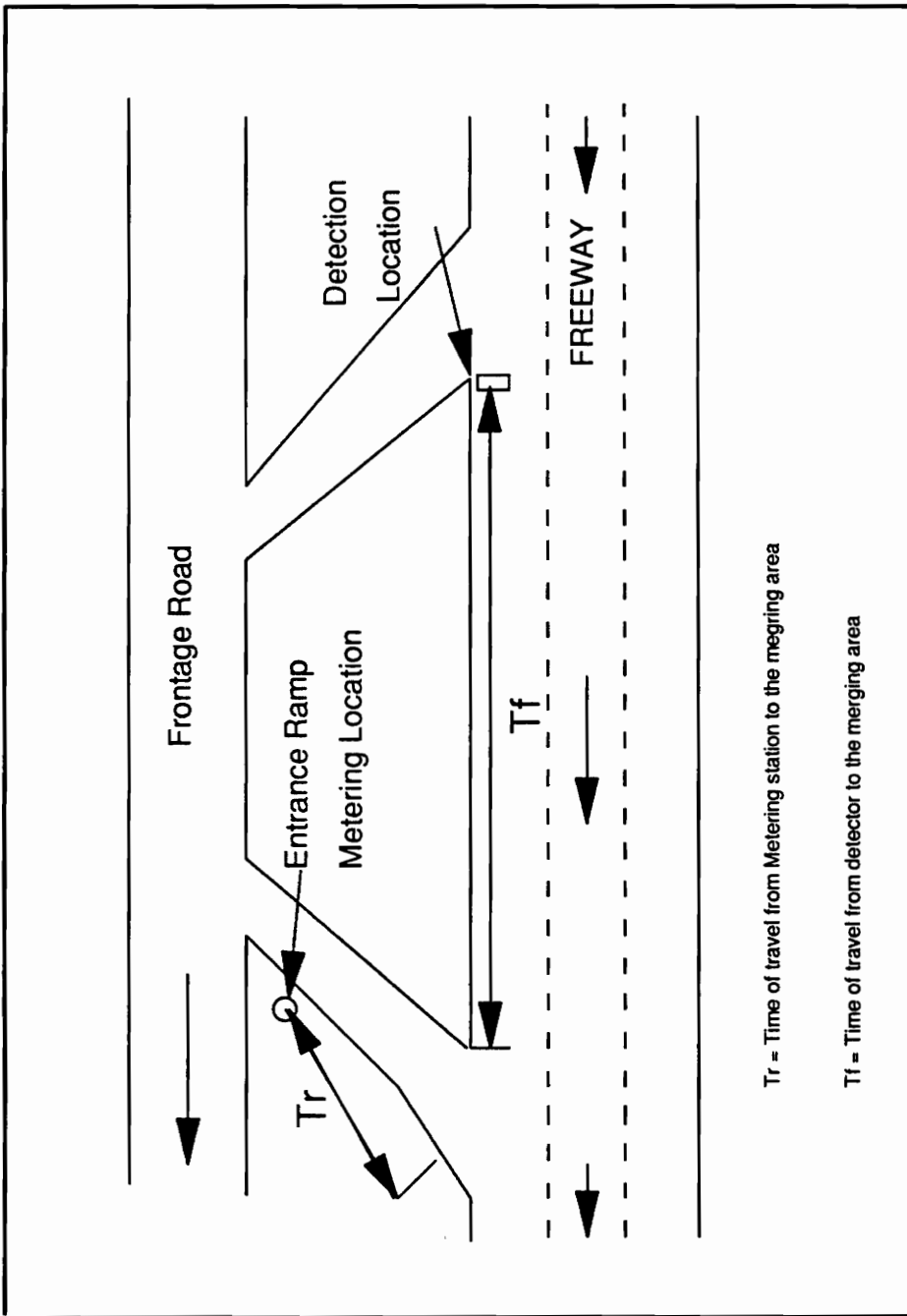
## 2.3 Past Research Projects

### 2.3.1 The Gulf Freeway Surveillance & Control Project

The control strategy for freeway- ramp model which is being discussed as a newly formed concern of traffic researchers now, was forecasted more than thirty years ago, during the research on freeway-ramp traffic control under the Gulf Freeway Surveillance & Control project, conducted in phases (Pinnell et.al, 1965). The control study was initiated on five inbound entrance ramps between Wayside Drive and Dowling street on the "Gulf freeway". A 20 pen graphic recorder operated by four men stationed near the merging area between the freeway and the frontage roads was used in the data collection process. Objectives of the project were:

- To develop basic research on the characteristics of operation on both the freeway and connecting arterial system.
- To experiment with the detection and sensing equipment to generate an automatic controllers to congestion prediction and prevention.
- To install and evaluate the final automatic surveillance and control system.

The study pointed out the need to control ramps to improve the freeway operations and allow greater use of ramp metering. *Ramp metering* is defined as the process of controlling the amount of entering traffic to prevent congestion. The approach



**Figure 2.1 Gulf Ramp-Freeway Surveillance and Control Project**

adopted was to employ classical control systems to reduce the demand fluctuations. The research surfaced the need for advances in the studies of a ramp control system which would respond to the traffic conditions on the freeway. The control of ramp should be based on what the freeway traffic conditions are at the particular instant of time. There should be a means of determination of traffic variables and the knowledge of their dynamic variations as they occur which is an important step required before an automatic control system is given a thought. It was suggested that for future highways, an automatic control system with interconnections of all control stations could be adopted so that they operate in unison. It was perceived that some form of computer or real-time control system would be required to accomplish this task. Figure 2.1 shows the "Gulf Ramp-freeway Surveillance & Control Project". The detection location is placed just after the exit ramp, to facilitate ideal traffic counting. The number of vehicles entering the freeway are controlled by the "*Entrance Ramp Metering station*", which is located at the beginning of the ramp. Major conclusions drawn from the Gulf freeway experiment were as follows (Pinnell et.al, 1965):

1. The distribution of critical gaps conform to a gamma distribution.
2. The merging delay values calculated using the gamma distribution were higher than those calculated assuming that all the drivers have a fixed critical gap.
3. Any scheme for controlling the flow on entrance ramp on to the freeway should be capable of reacting to the operation on the freeway lanes.

### **2.3.2 Chicago Area Expressway Surveillance Project**

The intent of this project which was established in 1961 was to determine the congestion causes and zones and investigate methods of alleviation of the same. The expressways in the Chicago area were sought to be controlled by means of automatic traffic control and information measures (Adolph D. May Jr., 1963). Machine counts were taken at all the entrance and exit ramps and four important mainline expressway points. Speeds were recorded at all the locations, simultaneously. The data compiled over a 24 hour duration was interpreted according to the changes in traffic flow characteristics. The roadside detectors were located to conveniently access the information of a single lane in each case. The detectors were connected to the central office housing analog computers, map display and data recording devices. Some of the initial traffic observations made, based upon the punched tape output were:

- The inter-relationships between volume, occupancy and speed
- A comparison of measured speed and the calculated speed
- A comparison of traffic characteristics just before and after congestion
- The measurement of the effect of congestion on the traffic flow and travel time

### **2.3.3 Lodge Freeway Traffic Surveillance and Control Project**

The objective of the project titled "The John C. Lodge Freeway Traffic Surveillance Control Research Project" was to apply the latest scientific developments in electronics industry to optimize and conduct research on the traffic flow (Frank DeRose, Jr., 1963). It was initiated in July 1960, as a combined effort of Michigan State Highway Department, the City of Detroit Department of Streets & Traffic, Wayne County Road Commission and U.S. Bureau of public roads. At the time of its development, it was rated as the most sophisticated assembly of equipment/ technology for traffic studies research on freeways. The instrumentation and equipment used was grouped into Television Surveillance system, Traffic information collection equipment and traffic control system. The data collected was similar to the Pilot detection system in Illinois. After its successful launch on May 7, 1962, an evaluation of the operation revealed that quite a few improvements were needed for the realization of an efficient traffic surveillance system in the "Lodge Freeway". These were:

1. Provision of additional lane signals and speed signs
2. Individual speed sign control rather than the design of signals into groups of twos or threes
3. Necessity of more information on the stream conditions at many locations, which were left uncovered

## 2.4 Traffic Stream Models

Analytical process of building a model starts from the understanding of the flow characteristics and the selection of appropriate equations, with suitable assumptions to simplify the model but forcing all the control variables at the same time which influence the traffic flow system.

Applying dimensional analysis to any two successive vehicles in traffic flow, we have the following relationship between the density of flow, vehicle speed and the volume:

$$\text{Velocity (ft/sec)} = \text{flow (sec}^{-1}\text{)} / \text{concentration (ft}^{-1}\text{)}$$

The general equation of a traffic stream is expressed in the form

$$q = k * u$$

where,

q = Mean rate of flow (vehicles per hour, vph)

u = Mean speed (m.p.h.)

k = Mean concentration (veh/mi/lane)

## 2.4.1 Macroscopic Models

A linear density relationship is given by

$$u = u_f - \left(\frac{u_f}{k_j}\right)k \quad (1)$$

where,

$u$  = Velocity at any time

$u_f$  = Free-flow speed

$k$  = Density at that instant

$k_j$  = Maximum concentration

substituting  $u$  from the general equation of a traffic stream,

$$\frac{q}{k} = u_f - \left(\frac{u_f}{k_j}\right)k \quad (2)$$

Interchanging the relationships between the variables velocity, flow and density by successive elimination one of these variables, we find that as the flow increases, density increases and the speed decreases. At the optimum density, flow becomes maximum. In other words, as the speed increases from zero, flow increases from zero, until it becomes  $q_m$  at  $u = u_f/2$  and  $k = k_j/2$  and again decreases from  $u = u_f/2$  to zero at  $u_f$ .

Hence,

$$\begin{aligned}q_m &= \frac{u_f k_j}{2} - \left(\frac{u_f}{k_j}\right)\left(\frac{k_j}{2}\right)^2 \\ &= \frac{u_f k_j}{2} - \frac{u_f k_j}{4} \\ q_m &= \frac{u_f k_j}{4}\end{aligned}\tag{3}$$

where,

$u_f$  = Free-flow speed

$q_m$  = Maximum volume

$k_j$  = Maximum concentration

Highway Capacity Manual (HCM) and all traditional computational codes use this set of equations. However, practical field data does not follow this relationship accurately. Hence a number of theoretical models have cropped up over the past six decades. Earlier models assumed a single regime which would include the gamut of flow conditions.

### ***Greenshields' Model***

According to Greenshields, speed is a linear function of density. Thus,

$$u = u_f - \left(\frac{u_f}{k_j}\right)k \quad (4)$$

$$q = u_f k - \left(\frac{u_f}{k_j}\right)k^2 \quad (5)$$

### ***Greenberg's Model***

This is a non-linear model where a hydrodynamic analogy is combined with equations of motion in Mechanics. The velocity is governed by

$$u = u_o \ln\left(\frac{k_j}{k}\right) \quad (6)$$

where,

u = Speed at any time

u<sub>o</sub> = Optimum speed

### ***Underwood's Model***

This was a new single regime model proposed to account for the problem of free-flow reaching infinity value during free flow conditions, in the above model. According to this theory,

$$u = u_f e^{-\frac{k}{k_o}} \quad (7)$$

where,

$u$  = Speed at any time

$k_o$  = Optimum density

$k$  = Density at any time

$u_f$  = Free-flow speed

### *Drew's Model*

Drew proposed a formulation which modifies Greenshields' model by introducing a parameter called 'n'.

$$u = u_f \left[ 1 - \left( \frac{k}{k_j} \right)^{n + \frac{1}{2}} \right] \quad (8)$$

where,

$n = 1 \rightarrow$  Linear model

$n = 2 \rightarrow$  Parabolic model

$n = 3 \rightarrow$  Exponential model

### ***Pipes-Munjal Model***

Pipes-Munjal proposed a generalized approach to the single regime models, by following equation:

$$u = u_f \left[ 1 - \left( \frac{k}{k_j} \right)^n \right] \quad (9)$$

All the single regime models have been found to be lacking in tracking down the field data. Due to this, research progressed into two and multi-regime models, with different equations for free-flow, congested flow and the transitional conditions. Edie was the first researcher to present a multi-regime model. Adolf May (Adolph May, 1990) tabulated the different multi-regime models. The multi-regime models explain the observed data more closely than the single regime models.

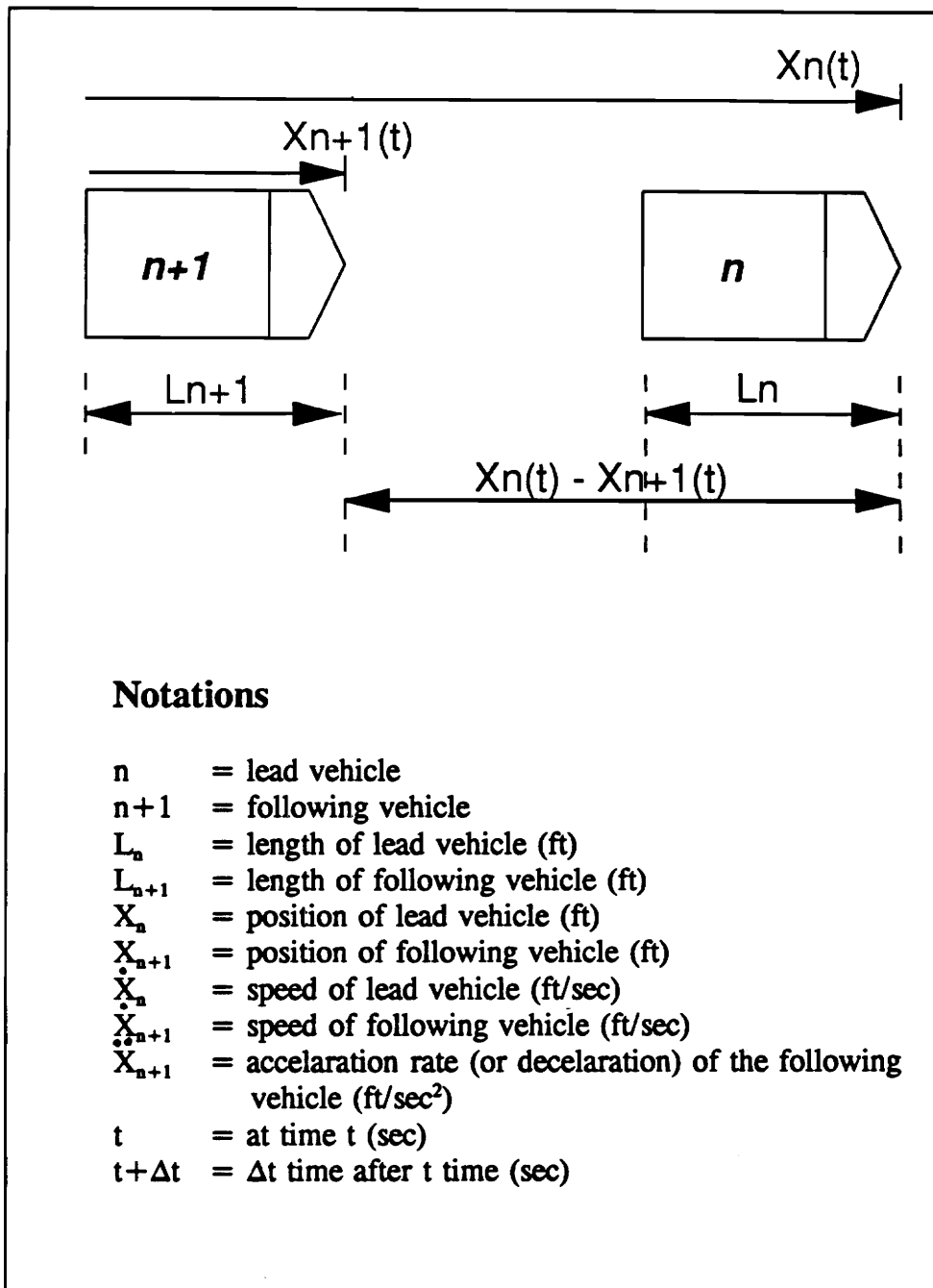
### **2.4.2 Microscopic Models**

"Microscopic modeling" is concerned with individual time and space headway between the vehicles while "macroscopic modelling is concerned with macroscopic flow characteristics, which are expressed as flow rates, where attention is given to temporal, spatial and modal patterns (Adolph May, 1990). Microscopic analysis may be selected for moderate sized systems where there is a need to study the behavior of individual units in the system. Macroscopic analysis may be selected for higher density, larger scale

systems, in which a study of the behavior of groups of units is adequate. A knowledge of traffic situations and the ability to select the more appropriate modelling technique among the above two is required for the case at hand. For an IVHS system, a microscopic approach is considered to be a better choice over macroscopic approach, as this model depicts the traffic flow patterns like acceleration/ deceleration, merging etc. for each individual vehicle with in a stream more vividly than a macroscopic model.

Consider two vehicles moving from left to right in the diagram. Let these be denoted by 'n' and 'n+1' respectively. Figure 2.2 shows two vehicles moving at the same time and the distance between them at any time 't'. All the assumptions made about the vehicle composition and behavior are valid.

California Motor Vehicle Code: A good rule for following another vehicle at a safe distance is to allow yourself at least the length of a car between your vehicle and the vehicle ahead for every ten miles per hour speed, at which you are travelling. So, as speed increases, minimum safe distance headway increases and time headway decreases. For automatically controlled vehicles-highways, the time headway are expected to be less than a second.



**Figure 2.2 Car Following Theory Notations and Definitions**

Among the various car following theories developed, researchers at General Motors have extensively tested and improved the models, with the help of the results obtained. There were a series of car following theories proposed (Adolph May, 1990). The basic form of these was

$$\text{Response} = f \{ \text{Sensitivity, Stimuli} \}$$

where,

Response = Acceleration or deceleration of the vehicle which is dependent on the sensitivity of the automobile and the driver himself

Sensitivity = Ability of the driver to perceive and react to the stimuli

Stimuli = Visual and auditory inputs that influence the driver's decision

Initially, the sensitivity was assumed to be constant for all the vehicles in the moving together in the stream. The first General Motors model was derived using a functional value for acceleration as follows (Adolph May, 1990):

$$\ddot{X}_{n+1}(t+dt) = \alpha [\dot{X}_n(t) - \dot{X}_{n+1}(t)] \quad (10)$$

A second look at the model, on account of discrepancy from the field values indicated that the sensitivity was more whenever the headway was less. A relationship was drawn to account for this error. Thus,

$$\alpha = \frac{\alpha_o}{d} = \frac{\alpha_o}{X_n(t) - X_{n+1}(t)} \quad (11)$$

Further improvements about the sensitivity were introduced by the speed difference, i.e, relative velocity, because of the concept that as the speed difference increases, the sensitivity increases. Every system has a time lag to react to the changes occurring ahead of it. This is accounted for, by the term  $\Delta t$  which represents the reaction time on part of the following vehicle to accelerate or decelerate. Finally, the powers of the terms of headway and acceleration of the vehicle ahead were proposed and these constants were called speed component (m) and headway component (l). The resultant equation (The fifth General Motors model) can be stated as

$$\ddot{X}(t + \Delta t) = \frac{\alpha_{l,m} [\dot{x}_{n+1}(t + \Delta t)]^m}{[X_n(t) - X_{n+1}(t)]^l} [\dot{X}_n(t) - \dot{X}_{n+1}(t)] \quad (12)$$

Range of values:  $m = -2, 2$  and  $l = -1, 4$

It can be found that upon substitution of different combinations of m and l terms, the resultant microscopic General Motor's formulae take the shape of various macroscopic models, proposed by various researchers, which has been discussed already. The model is widely accepted as a generalized car following model, which can be modified and applied to a particular case.

## **2.5 Highway Geometric Design**

Highway Design deals with the proportioning of the elements of the highway. The characteristics of driver, vehicle and road serve as the basis for the geometric design. The objective of geometric design of highways is to produce access for smooth-flowing, accident-free and comfortable traffic flow. The guidelines for design are developed by AASHTO (The American Association of State Highway and Transportation Officials), which consists of officials from various State Departments of Transportation (DOT's) and the Federal Highway Administration (FHWA). All of the highway design engineers are required to adhere to the guidelines set by "A policy on Geometric Design of Highways and Streets", which has been updated last in 1990. However, the AASHTO design standards are based on a maximum design speed of 70 mph, which proves inadequate in case of a future ground transportation system with speeds exceeding 200 mph. If the dreams of this kind of expressways are realized, then again a publication will be necessary which will stipulate the conditions of satisfactory design for such highways.

### **Design Criteria**

The present day highway geometric design is governed by the AASHTO regulations and the following design criteria (AASHTO, 1990).

#### **1. Design Speed**

2. Expected volume of traffic
3. Topography of the proposed site
4. Safety and Comfort
5. Mixture of vehicles
6. Funding of the project
7. Level of service desired (A, B, C etc.)
8. Social and environmental factors

The first five of the factors cited above are particularly important for the case of a *Smart Highway*. The Design speed is defined as (Garber and Hoel, 1988) "the maximum safe speed that can be maintained over a specified section of highway when the conditions are favorable such that design features of the highway govern".

The most important geometric design feature is the alignment of the highway. The vertical and horizontal layouts make up the alignment. The design of the horizontal and vertical layouts should avoid sudden deviations, which is even more important for the case of a high speed highway. The vertical alignment consists of curve, when there is a change of elevation between the two stretches or there is a steep change of slope occurring in a short distance. Any terrain which has steep inclinations occurring too often is topographically ill-suited for any right-of-way layout.

## 2.5.1 Horizontal Curves

A horizontal curve provides a directional transition of the roadway in a horizontal plane. In the design of highway curves, it is necessary to establish proper relation between design speed, curvature, super-elevation, and side friction. The basic point mass (curve) formula for vehicle operation on a curve is the following:

$$R = \frac{V^2}{g(f_s + e)} \quad (13)$$

where,

- V = Design speed in ft/ Sec
- e = Rate of roadway super-elevation, ft/ft
- $f_s$  = Side friction factor (unit less)
- g = Acceleration due to gravity (ft/ Sec<sup>2</sup>)

Based on research and experience, AASHTO established guidelines for e and f for design speeds and minimum radii of curvature. If the speed is defined in m.p.h., the above formula could be modified as

$$\frac{e + f}{1 - ef} = \frac{V^2}{15R} \quad (14)$$

where,

- V = Vehicle speed, mph

## 2.5.2 Aerodynamics

It is that branch of science of Physics which is concerned with the study of the interaction between a body and the atmosphere through which it moves. The forces which are created by this interaction are called "Aerodynamic Forces". The magnitude of these forces depends on the relative velocity of the air, the body, and the shape of the vehicle. The objective of Vehicle Aerodynamics is to keep the aerodynamic effects as small as possible in order to improve the efficiency, safety and environmental compatibility of the road and railway operations. Understanding the vehicle's performance is a valuable foundation for highway design. The comprehension of vehicle capabilities and limitations heavily impact the advancement of highway/ vehicle technologies. Any vehicle passing through a prepared surface of right-of-way faces forces acting against the direction of its motion. These are known as "vehicle resistances".

There are three major sources of vehicle resistance. They are

- a) Aerodynamic Resistance ( $R_a$ )
- b) Rolling Resistance ( $R_r$ )
- c) Grade or Gravitational Resistance ( $R_g$ )

The force required to put the body into motion is

$$F = ma + R_a + R_r + R_g \quad (15)$$

where,

$m$  = Mass of the vehicle (lb)

$a$  = Applied acceleration (ft/ sec<sup>2</sup>)

$R_a$  = Aerodynamic resistance (lb)

$R_r$  = Rolling resistance (lb)

$R_g$  = Gravitational resistance (lb)

The applied force is the combination of the tractive effort of the forward and rear wheels. Similarly, the aerodynamic forces acting against the body's motion can act on either of the wheels. Hence,

$$(F_f + F_r) = ma + (R_f + R_r) + R_g + R_a \quad (16)$$

where,

$F_f$  = Force on the forward wheels (lb)

$F_r$  = Force on the rear wheels (lb)

## Aerodynamic Resistance

$$R_a = \frac{\rho}{2} C_D A_f V^2 \quad (17)$$

where,

$\rho$  = Air density in slugs\ ft<sup>3</sup>

$C_D$  = Coefficient of Drag (unit less)

$A_f$  = Vehicle frontal area (projected area in the direction of travel, ft<sup>2</sup>)

$V$  = Speed of vehicle (ft\ sec)

**Table 2.1 Variation of Air-Density with Altitude**

Altitude (ft)	Temperature (°F)	Pressure (psia)	Air Density (slugs/ ft <sup>3</sup> )
0	59	14.7	.002378
5000	41.2	12.2	.002045
10000	23.4	10.1	.001755

Drag Coefficient for an automobile = 0.15 to 0.55

Frontal area = 11 to 25 ft<sup>2</sup>

Aerodynamic resistance can make significant impact on vehicle performance, which is overwhelming at high speeds. About 85 percent of all aerodynamic resistance results from the turbulence of air flow and about 10 percent is due to the air friction of air and the remaining is from the air flow in radiators and other sources (Scibor-Rylski, 1984).

### **2.5.2.1 Aerodynamic Forces**

Aerodynamic forces are grouped into two major categories. They are

1. Aerodynamic Drag (opposes fluid motion)
2. Aerodynamic Lift (reduces friction and affects steering and propelling characteristics)

#### *Drag Forces*

Resistance of the air to the forward motion consists of the following components. Most of the forces assume significance for the stability/ design criteria as the speed of the vehicle increases and predominate any design process above 140 mph. There is always a frictional drag created by the turbulence of the viscous air which is affected by the sharp variation of velocity experienced at the boundary layer of air and the surface of the body. The air friction causes aerodynamic force indirectly, by introducing asymmetry in the general airflow pattern, which radically changes pressure distribution. From basic laws of Physics, the following components of aerodynamic forces have been

defined under the ideal conditions of no relative movement of air with respect to ground, initially and no air viscosity.

(i) Aerodynamic drag force

$$D_A = \frac{\rho V^2}{2} S C_D \quad (18)$$

where,

$C_D$  = Drag Coefficient

The causes for aerodynamic drag are too complex to be incorporated into the discussion. The following are some of the important types of drag resistances.

1. Form Drag: This is the resistance offered to the air, causing its deflection owing to the vehicle body's shape profile.

2. Surface Friction: The vehicle movement produces a frictional force in the boundary layer between the air and the body's outer surface, as the air passes through it. A narrow body design is the traditional approach to prevent surface friction. But if it is too drastic, it results in turbulent air flow.

3. Induced Drag: The induced drag is caused by the lift forces developed from the circulating flow pattern causing pressure distribution. A download on the body or styling the rear surface to slope gently can substantially reduce induced drag.

4. Interference Drag: Any small object can obstruct the air flow around the body and add to the other drag forces. e.g., the side and rear view mirrors. A clean body design permits minimum drag.

5. Internal Flow Resistance: Inefficient cooling and ventilation are the main causes for the drag losses of this nature. The air flow required by braking etc. loses momentum due to friction and leakages inside the internal ducts and thus offers drag resistance.

### *Lift Forces*

The high speed travel on the fast roads under development will accentuate the problem of aerodynamic lift and the need to address it. The lift force acts in the direction normal to the ground. In aeronautics, special arrangements like wing aerofoils are made to lift the aircraft into the air (what is known as positive direction of lift). The object of interest in case of automobile is to reduce this lift force as much as possible or even to change sign to maximize the stability and passenger comfort. Researchers estimate that aerodynamic force reaches 250 lbf (1112 N), about 25% of the weight of a sedan car travelling at 100 m.p.h. (Scibor-Rylski, 1984). This can be hazardous for the vehicle on a highway under cross-wind conditions, affecting the steering response and creating a positive lift. There is a circulation of air on the upper surface travelling still higher, which moves faster than on the lower surface. There is aerodynamic lift caused

because of this flow pattern, proportional to the speed of circulation. The lift is more for the ground vehicles compared to the aviation vehicles. The airflow underneath the vehicle slows down which increases circulation and lift. The total aerodynamic lift usually acts in front of C.G. The lift on the front axle is greater than rear axle. The resulting aerodynamic lift causes instability, making the steering control more difficult. Side force acting in front of C.G. swings the front of the car away from the path of its travel. Reduction of aerodynamic lift is preferable compared to aerodynamic drag, in shaping up a high speed vehicle, because of its royal share of aerodynamic force at those speeds. It is apparent that there are contradictory suggestions made by the researchers about the styling of vehicle to ensure its safety against aerodynamic lift. Some of the basic features accepted upon to curb lift forces are:

1. Decrease of angle of frontal underside panel from  $10^\circ$  to  $0^\circ$
2. A very low center of gravity
3. Allowance of airflow between the underside of the vehicle and the ground  
(negative lift force develops)
4. Free side way airflow allowance in vehicle styling

### *Negative lift*

For ground vehicles, the local airspeed between airfoil and the ground goes up creating an attraction of airfoil towards the ground. This popular phenomenon, termed as *Negative air lift*, has been exploited by the specialists to increase the stability. Designers of the new types of vehicles should take a stock of the potential of the positive lift forces at the estimated speeds. They must employ some of the lift reducing methods that are already tested on race cars of the present generation. It is however clear that some of the methods adopted for the racing cars cannot possibly be applied to saloon car design. Alternatives must be found, backed up by sound reasoning and experimental verification. There are two types of devices suggested to reduce positive lift and cause negative lift to an extent (Scibor-Rylski, 1984). They are

1. Spoilers (an elevated ridge is placed on the rear edge of the tail which lowers local pressures) and
2. Negative lift wings (wedge type devices attached to the body of the car)

#### **2.5.2.2 Aerodynamic Moments**

The above forces act at their points of action, which need not necessarily be at the center of gravity (C.G.) of the vehicle. The resultant force causes a moment on the vehicle, called the "aerodynamic moment". The aerodynamic moment can be split into three components, each of which is irrespective of the other two as listed here under:

- a) Aerodynamic pitching moment ( $M_A$ )
- b) Aerodynamic yaw moment ( $N_A$ )
- c) Aerodynamic rolling moment ( $Q_A$ )

### 2.5.2.3 Aerodynamic forces on steady vehicle turn

Under steady state conditions of vehicle motion, if the speed and the trajectory of the car are maintained constant, the equation for the stability of a turning vehicle is shown in equation 19 (Scibor-Rylski, 1984). The total mass of the car is considered as the summation of 'suspended mass'  $M_s$  and the 'unsuspended mass'  $M_o$ . The following equation expresses the steady state equilibrium, in which the applied moments equal the suspension system of the vehicle counteracting torque:

$$M_s g h \sin\phi + \frac{M_s V^2 h}{R} + Y_A d = k\phi \quad (19)$$

where,

- R = Radius of the curvature of trajectory of vehicle (ft)
- $M_s$  = Sprung mass of the car (lb)
- V = Steady state velocity w.r.t. ground (ft/ sec)
- g = Acceleration due to gravity (ft/ sec<sup>2</sup>)
- $Y_A$  = Aerodynamic side-force (lb)
- $\phi$  = Angle of roll (radians)

- d = Distance between aerodynamic pressure and roll axis (ft)
- h = Distance between C.G. and ground (ft)
- k = Stiffness of elastic suspension (lb/ ft)

The aerodynamic side-force is given by

$$Y_A = qSC_y = qSC_{y\beta} \beta \quad (20)$$

where,

- S = Reference area of car (ft<sup>2</sup>)
- $C_{y\beta}$  = Derivative of side force coefficient w.r.t to side slip angle (lb/ rad)
- $\beta$  = Side-slip (or yaw) angle of the car (radians)
- q = Dynamic pressure of air stream =  $\rho V^2/2$  (lb-ft)
- $\rho$  = Air density (lb/ ft<sup>3</sup>)

### *Affect of Wind*

The above equation does not take into account the wind forces at high-speed conditions. Consider a car travelling at a steady speed under a constant wind. The resultant aerodynamic forces depend on the relative angle between airflow and direction of car (Scibor-Rylski, 1984).

$$\frac{1}{R} = \left(\frac{1}{R}\right)_{w=0} [f(\text{Wind factor})] \quad (21)$$

where,

$(1/R)_{w=0}$  = radius of curvature when the angle of wind is zero

The wind factor is determined from a number of complex equations, the terms of which are yet to be found out. A simplification was made by plotting a graph of this factor as a function of the car heading angle relative to the initial position ( $\theta$ ), the vehicle speed, and angle of deflection of front wheels ( $\delta$ ) (Scibor-Rylski, 1984).

### 2.5.3 Vertical Curves

Most vertical transition curves are designed as parabolic, usually because of the ease of computations and construction. The main factors for design of a conventional roadway are provision of minimum stopping sight distance, pleasant appearance, adequate drainage, and comfort in operation. There are essentially two types of vertical curves in existence. They are

- (i) Crest vertical curves (concave upwards)
- (ii) Sag vertical curves (convex upwards)

### Crest Vertical Curves

For  $S > L$ ,

$$L_m = 2S - \frac{1329}{A} \quad (22)$$

For  $S < L$ ,

$$L_m = \frac{A * S^2}{1329} \quad (23)$$

where,

$S$  = Stopping Sight distance (ft)

$L_m$  = Minimum length of vertical curve (ft)

$A$  = Algebraic difference in grades (%)

### Sag Vertical Curves

For  $S > L$ ,

$$L_m = 2S - \frac{400 + 3.5S}{A} \quad (24)$$

For  $S < L$ ,

$$L_m = \frac{A S^2}{400 + 3.5S} \quad (25)$$

## 2.6 Computer Simulation

Computer simulation plays a major role in analysis and assessment of highway system. It has wide ranging applicability to transportation in general. There are several different definitions attributed to simulation process. Adolf D. May defines simulation as follows (Adolf D. May, 1990): "Simulation is a numerical technique for conducting experiments on a digital computer, which may include stochastic characteristics, be microscopic or macroscopic in nature and involve mathematical models that describe the behavior of a transportation system over extended periods of real-time".

There are a number of other definitions which also partially serve as reasons for the selection of simulation for the investigation of car following models.

1. Simulation is a dynamic representation achieved by building a model and moving it through time.
2. Process of conducting experiments on a model of a system - Mize and Cox.
3. Simulation is an imitation of a real situation by some form of a model that assumes the appearance without reality - Wohl and Martin.
4. Simulation of a system is the operation of a model that is a representation of the system, amenable to manipulations, from which properties concerning the behavior of the actual system can be inferred.

There are numerous advantages of running the traffic flow models by subjecting them to simulation process (Adolph D. May, 1990).

1. It experiments the hypothetical situations that are non-existent today.
2. It provides insight into variables that have pronounced impact on the model and certain others which do not have significant impact.
3. Different types of output like tables, graphs and equations can be generated which are easy to read and interpret.
4. It is the only way by which real-time changes can be identified and further course of action is taken.
5. It shows the potential hazards and weaknesses which should be seriously considered and designed in the actual construction.
6. It can be run, using different means and standards and ultimately, the best possible choice could be generated.
7. Unusual flow patterns can be modelled which do not follow any mathematical distribution, ideally.
8. Different flow patterns can be tried out to test for the criticality and optimize the design.
9. It is easy to build and model and relatively inexpensive.

Simulation, however has some drawbacks, which need sincere appraisal and careful consideration.

1. Some of the data is unavailable, difficult to obtain or unusable in the models.
2. It can never depict the exact picture and leads in wrong path, if the factors are not selected properly and at best, can only be a tool to get an insight of the conditions.
3. It requires verification, calibration and validation by experienced personnel.
4. The model may fail to incorporate or represent many complex influences and may result in excessive simplifications.

# 3 METHODOLOGY

Computer Simulation is a very successful and popular way of investigating the suitability of traffic models. It offers a scope of realizing the faults of the model and is very useful in detecting the operational difficulties of the real system. It is a learning process for the developers and users and builds complex interrelationships between the parameters and provides an understanding of their combination into a conflict-system. It clearly shows the degree of dependence on each variable and its influence on the output. It can also be used to test severe & extreme conditions which are impossible to construct in the field; difficult to observe; expensive or hazardous for experimentation.

## 3.1 Simulation Language Description

A Systems Dynamics software based on Apple Macintosh computer, called "STELLA", which stands for Systems Thinking, Experimental Learning Laboratory, with Animation, has been used for model building process. STELLA II is a problem oriented software rather than a computer oriented software requiring no complex programming skills. The standard level, auxiliary and rate variables are represented by stocks, flows and converters, respectively in a STELLA II model. In addition there are arrows which connect stocks with converters and also converters with other converters.

A clear understanding of the STELLA II structural elements is necessary and a rigidly defined behavior pattern is sought, before building any STELLA II model.

Stocks are represented by rectangles, which aggregate in an accumulation process. Stock is like an inventory which continuously gets accumulated or depleted by flows into or out of it. Flows represent the stream of activity associated with particular Stocks and may be conserved (as in a closed loop) or non-conserved (as in an open loop). A flow can also be defined as a rate of change of a level variable. Flows have the same units of measure as the stocks with which they are associated, but they also include a time dimension and are depicted by a pipe. Converters act as auxiliary variables when they change with time and as constants, when they do not. Converters are the variables which convert the input to output. Converters, like stocks, exist at a point in time, but do not accumulate with rates of flow. They can be connected to or connected by any rate or auxiliary variables and constants and their magnitude changes instantaneously with the parameters which influence them. A Converter can also be used as a graphical function to translate the magnitude of a Stock into an alternative unit of measure. A graph can be generated with all the ordinate points dictated by the user, against an abscissa variable of simulation time or any other variable of the model. The basic elements of STELLA II are presented in the Figure 3.2. Description of simulation algorithms is given Appendix A.

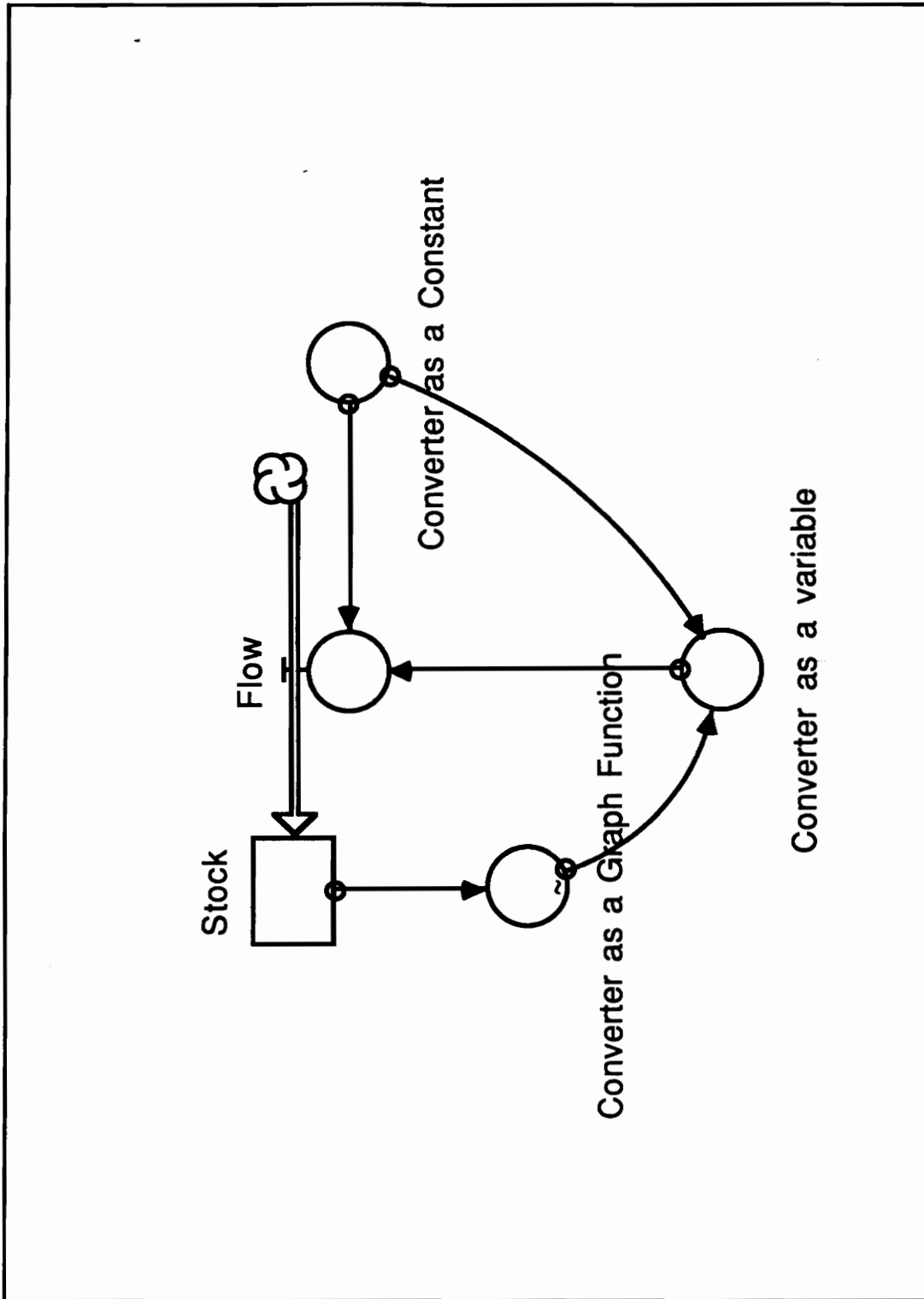


Figure 3.1 Basic Elements of STELLA II Software

## 3.2 Built-in Functions of STELLA

The built-in functions in STELLA II have been classified into logical, trigonometric, mathematical, financial, test input, and special functions. The following is the format and description of the various built-in functions utilized in the model (Richmond et al., 1987).

### Logical Functions

IF, THEN, ELSE, AND, OR, NOT are used to create expressions and output values based upon whether the conditions are true or false. When a multiple conditions exist, the expressions to be evaluated are enclosed in the parenthesis. The following is the structure of a statement involving logical functions.

```
IF (Exp 1 < Term 1 THEN (IF Term 1 < Term 2 THEN Term 1 ELSE  
Term 2) ELSE IF Exp 1 > Term 1 THEN Exp 1 ELSE 0)
```

The above argument results in the output of 'o' value for the variable when Exp 1 becomes equal to Term 1.

### Mathematical Functions

```
MAX      MAX (<expression> , <expression> , ... )
```

The MAX function gives the maximum value among the expressions contained within parenthesis.

Example:  $\text{Design\_Speed} = \text{MAX} (300, \text{TEST } 1, \text{TEST } 2)$  returns the highest value, numerically among the three inputs, making sure that 300 would be the minimum possible value of the Design Speed.

**MIN**             $\text{MIN} (<\text{expression}>, <\text{expression}>, \dots )$

The MIN function gives the minimum value among the expressions contained within the parenthesis.

Example:  $\text{Actual\_Spending} = \text{MIN} (\text{Desired\_Spending}, \text{Allowable\_Spending})$  returns the smaller value among Desired Spending and Allowable Spending.

**PI**            **PI**

The PI function gives the number 3.14159.., an approximation of the constant  $\Pi$ .

Example:  $\text{Angle} = \Pi/180 * \text{Theta}$  translates the Theta from degrees to radian units.

### **Trigonometric Functions**

**COS**             $\text{COS} (<\text{radians}>)$

The COS function gives the cosine of radians, where radians is the angle in radians. Radians can be constant or variable.



### 3.3 Geometric Elements' Computation

The formulae obtained from the analysis of vehicle aerodynamic forces and moments acting on road vehicles at high-speeds have been run on a graphics software based on IBM Personal Computer. The variables of the various equations have been allotted specific columns to generate tables for computation of the dependent variable, the radius of curvature of the horizontal curve in the last column. Graphs are drawn to show the affect of the independent variables on the radius of the curve. Further discussion on the geometric design elements can be found in Chapters 4 and 5.

# 4 DESCRIPTION OF RAMP-FREEWAY MODEL

## 4.1 Introduction

The model developed in this research uses the fifth General Motors' microscopic equation for car following (discussed in Chapter 2). The development process of the simulation model has been followed in a sequential manner. The principle aim was to merge the ramp cars at the speed of freeway stream. The gap to be accepted or generated becomes a variable which has to be fixed up by the surveillance section authority. Conventionally, Greenshields (Greenshields et al., 1947) defines the acceptable average minimum time gap as a gap accepted by half of the drivers. The gap on an automated highway is strictly a function of the safety, comfort of the passenger and the amount of throughput required at that time. A gap of double the minimum headway has been chosen for this model, to optimize the traffic density. The approach adopted of the simulation process has been shown in a chart in Figure 4.1. The various assumptions made, prior to the simulation model construction process have been given.

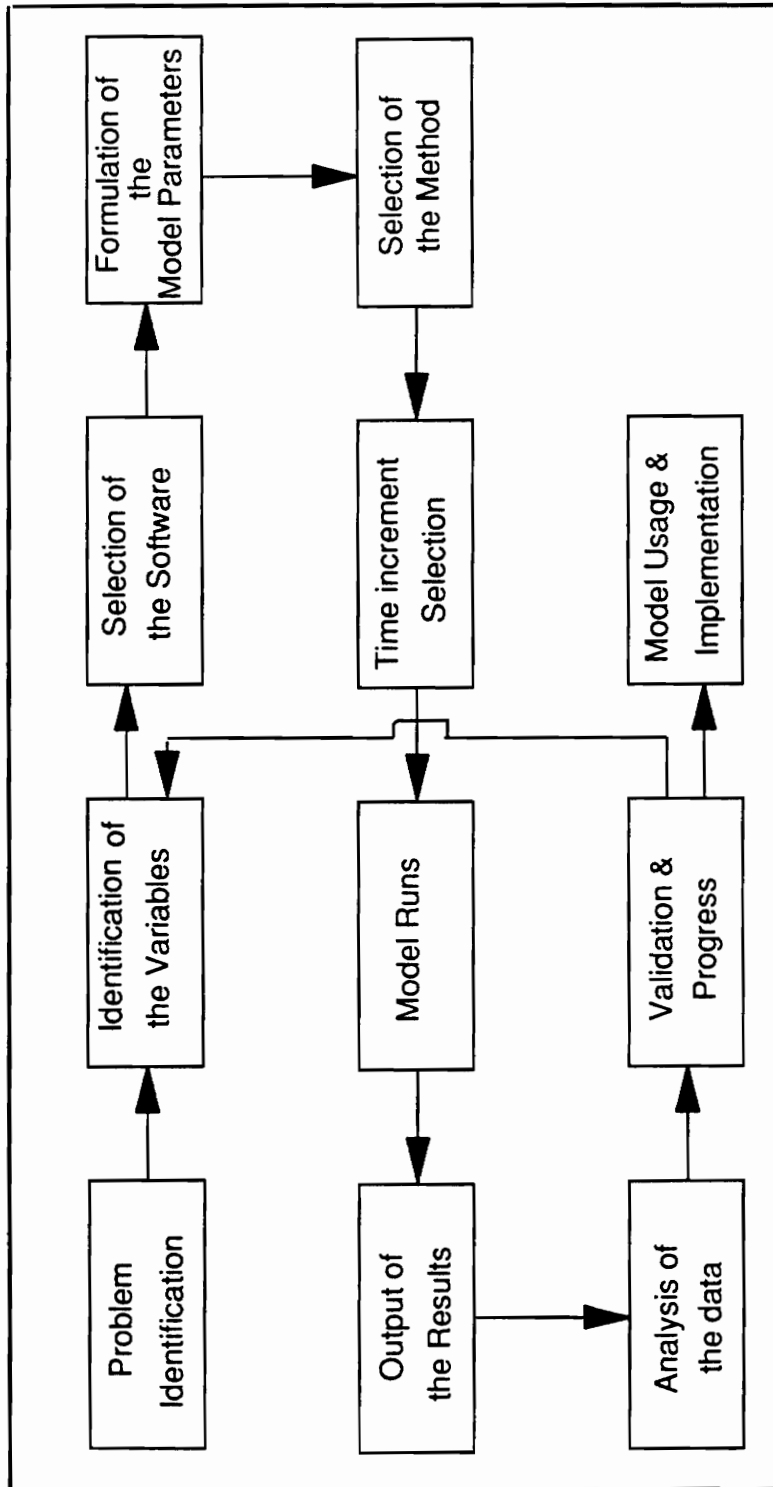


Figure 4.1 Development Process of the Simulation Model

## Assumptions

1. All the vehicles are of the same size, shape and performance.
2. A standard vehicle, aerodynamic in shape is assumed to be a model vehicle for design to be considered in the equations.
3. Each vehicle follows a particular mechanical and behavioral pattern which is quantifiable.
4. The position of a vehicle is given by the location of its front bumper and the headway between the vehicles is measured from the front bumper of the leading vehicle to the front bumper of the following vehicle.
5. Minimum spacing of ramps is sufficient to stabilize the traffic waves travelling due to the previous exit or entrance ramp.
6. Whenever there occurs a variation in change of velocity of the two cars, between which the merger is expected to take place, the merging vehicle is continuously adjusted to suit the modified time of merging.
7. There are no exit ramps on the downstream of the freeway detection to the point where the merged traffic is stabilized to create a reasonably uniform flow conditions.

## 4.2 Components of the Automated Freeway Control System

The main components of the ramp-freeway control system are as follows:

1. Specially manufactured automobiles, conducive to travel up to 300 mph at any instant of time.
2. On-board computer equipment with digital display and sound capabilities, which is in two way communication with the main computer installation by wireless contact, capable of interacting with the sensors of the pavement and receive and transmit the information about the details of the vehicle and user, destination, mileage and other information.
3. Sensors installed in the pavement which serve as reference points for the vehicle's position at any point of time, which also guide the vehicle's movement on the automated guideway, depending upon the electronic signals received about this and other vehicles in the stream.
4. A dependable computer network which connects all the infrastructure is fail-safe and redundant and is capable of working, even under extreme weather & traffic conditions.

There is a continuous two way communication link between the sensors installed in the pavement and the smart cars. Each car is specially equipped with an identifiable tag, which is perceived by the sensors and the main control computer network. All the vehicles, waiting to be merged are required to queue at the starting of the ramp, just before the ramp metering station.

### 4.3 Ramp Control

As soon as the ramp control system directs the Ramp metering station to release the next vehicle in the queue, the vehicle starts the forward motion from rest to accelerate at fixed rate to reach a velocity equal to the average traffic stream speed. From a passenger's point of view, a maximum acceleration of 5-10 ft/ sec<sup>2</sup> might be a desirable range. The equation for the vehicle acceleration on the ramp is given by

$$V_t = U + at$$

where,

$V_t$  = Velocity at any time instant 't', (ft/ Sec)

$U$  = Initial velocity (assumed to be zero ft/ Sec)

$a$  = Uniform rate of acceleration (ft/ Sec<sup>2</sup>)

$t$  = Simulation time (Sec)

The causal diagram of the entire simulation model developed, has been presented in Figure 4.2. The following discussion refers, directly to the causal diagram.

The time expended in the process is represented by an auxiliary variable, "Time\_for\_acc\_to\_Design\_speed", given by  $\text{Design\_Speed} / \text{Acc\_Rate}$ , where  $\text{Acc\_Rate}$  represents a constant rate of acceleration from the ramp and  $\text{Design\_Speed}$  is the speed of the traffic stream or the destination speed of the merging vehicle (refer to Figure 4.2).  $\text{Acclimit5}$  is a dummy rate variable which is governed by several different conditions at different stages and feeds in the value to the actual rate variable called "acc\_5". During its steady acceleration,  $\text{Acclimit5}$  equals  $\text{Acc\_Rate}$ , which is checked by  $\text{acc\_5}$ , the acceleration of the fifth vehicle. The rate variable  $\text{acc\_5}$  ensures that at no stage of the vehicle motion does the freeway user experiences acceleration rates greater than  $10 \text{ ft/sec}^2$  or deceleration rates of the same magnitude. The velocity thus is a level variable at this juncture. It also serves as a rate variable for another level variable, namely the "Position" of the vehicle. This was accomplished by adding another dummy variable titled "Dummy5" whose numerical value theoretically equals the value of "Velocity\_5" which is an auxiliary variable accepting the value of the level variable of velocity of the fifth vehicle,  $\text{Vel}_5$  (refer to Figure 4.2). The simulated value of the level variable "Vel\_5" is thus updated as the input rate variable once for every small simulation time increment "dt". The initial values for the level variables, "Position\_5" and "Vel\_5" are fixed to begin the simulation process. Also, the auxiliary variable "Acc\_Rate" was given by  $10 / \text{Cos}(\text{Theta})$  where "Theta" is the angle in radians, subtended by the ramp with the freeway and  $10 \text{ ft/sec}^2$  is the constant acceleration rate of the ramp vehicle in the direction parallel to the freeway, which was changed to be a velocity dependent, smooth

curve (Figure 4.2). In order to bring the coordinates of the Position\_5 in terms of freeway, the rate variable Dummy\_5 takes a value of Velocity\_5/ Cos (Theta) when the vehicle is still on the ramp such that the resultant level variable values obtained are in the direction parallel to the freeway. As soon as the vehicle reaches the ramp nose Dummy\_5 exactly equals the value of Velocity\_5. At this point, the vehicle control is assumed by car following algorithm. Taking into account, the practicality of the acceleration capabilities of automobiles of this generation, a modification of the acceleration on the ramp was made. Instead of a uniform, constant acceleration, a gradual decrease in acceleration was permitted with an increase in speed of the ramp vehicle. A table function was used to define a non-linear relationship of acceleration with the velocity, starting from 10 ft/ Sec<sup>2</sup> at rest to 4 ft/ Sec<sup>2</sup> at 300 ft/ Sec. In this case, Time\_for\_acc\_to\_Design\_speed becomes the simulation time elapsed until the emergence of merging vehicle at ramp nose.

Before the automatic merger occurs, the vehicle should be allowed time to straighten its trajectory of motion, parallel to the freeway lanes. The gradual lateral motion was supposed to occur on the ramp itself to optimize the time and space on the freeway. A spiral or a circular curve with large radius of curvature could be the most appropriate design for a curve at the end of the ramp, leading the vehicle into the acceleration lane. The lateral vehicle movement in the direction parallel to the freeway occurs along this curve begins at some point of curvature on the ramp. The design of

the ramp depends upon the rate of acceleration and the final speed to be achieved at the ramp nose.

The total length of the ramp required = Ramp length (straight line portion) +  
 Ramp length (curved portion) = Safety factor ( $> 1$ ) \*  $U t_s + 0.5 * a t_s^2 + \Sigma R t dt$   
 ( $t = t_s$  to  $t_e$ ).

where,

$t_s$  = Starting time

$t_e$  = Ending time

## 4.4 Freeway Control

The smart highway has a series of vehicles travelling at full speeds provided there are no natural disturbances or technical snags. Each vehicle follows the vehicle ahead and obeys the standard car following law that the response of a vehicle (n+1) at any time (t+Δt) is given by General Motor's generalized car following model (May, 1990) as

$$a_{n+1}(t + \Delta t) = \frac{\alpha [V_{n+1}(t + \Delta t)]^m}{[X_n(t) - X_{n+1}(t)]^l} [V_n(t) - V_{n+1}(t)] \quad (26)$$

where

$a_{n+1}(t + \Delta t)$  = acceleration of the (n+1)th vehicle at the time instant (t+Δt)

$V_{n+1}(t + \Delta t)$  = Velocity of the (n+1)th vehicle at the time instant (t+Δt)

$\Delta t$  = Delay or reaction time of the system

$V_n(t)$  = Velocity of the nth vehicle at time t

$V_{n+1}(t)$  = Velocity of the (n+1)th vehicle at time t

$X_n(t)$  = Position of the nth vehicle at time t

$X_{n+1}(t)$  = Position of the (n+1)th vehicle at time t

The acceleration is the only control variable in this algorithm, which depends on the relative velocity, headway and its speed at that instant for a given set of values of sensitivity " $\alpha$ ", speed exponent " $m$ ", and headway exponent " $l$ ". Sensitivity is a gain in the system which transforms the given input to an optimized output. For a small time increment, it is imperative to study the sensitivity interval within which, the system is stable. It was found that for a dt of 0.1 seconds, sensitivity values between 1.2 and 2.0 were perceived to be ideal. A value higher than 2.0 caused instability while a value less than 1.2 was too low to impart any significant inclination for the dependent variable to follow the path dictated by the vehicle ahead. The values of headway and speed exponents must be positive since the negative values would mean a transposition of the headway and relative velocity variables. A linear connection has been chosen for a generalized relationship between the dependent and independent variables. The headway and relative velocity nomenclature has been started from the second vehicle of the stream. This meant that consistently "relvel n" and "Headway\_n" would be the differences between the velocities and positions of the nth vehicle with the vehicle, it lags.

For the first vehicle of the stream, initially a non-uniform acceleration equation was assumed, to generate a smooth profile to test the car following. The expression for the acceleration of the vehicle is given by (Drew, 1968)

$$\frac{dv}{dt} = (\alpha - \beta v_0) e^{-\beta t} \quad (27)$$

where,  $\alpha$  and  $\beta$  represent maximum acceleration and inverse of time respectively. It was felt that it is not practical to assume such a smooth profile for a guided vehicle and slight fluctuations in profiles need to be accommodated into the model by waves travelling backwards. STELLA II offers the provision of dictating any profile desired, by way of a table function which pre-specifies the location of the vehicle which is independent of all the other factors. This function has been utilized to generate a series of tables with position of the first vehicle varying as a function of the time of travel and after the testing of three vehicles took place, the resultant stream performance was studied in detail, to modify the constants in the model. The profile is given in Appendix C. A number of discrete velocity points along the simulation time for every second, which is obvious from the various figures containing Velocity\_1 (Chapter 5) and tables shown in Appendix D.

All the vehicles in the stream follow successively their preceding vehicles. The initial values of the level variables for all the vehicles were chosen and entered. The minimum headway allowed in the model was represented by "MinHdwy" (refer to figure

4.2). A value of 50 ft has been chosen arbitrarily for the purposes of simulation. The spacing between the vehicles, changes as the simulation progresses. Similarly, all the vehicles have been arbitrarily started at around 280 ft/sec<sup>2</sup> which can also be changed, if required. The Acclimit2 computes the value of the acceleration of the second vehicle in response to the changes in relative velocity (relvel2) and headway (Headway\_2). This is fed into the rate variable "acc\_2", which accepts any value between -10 and 10 ft/sec<sup>2</sup> provided the headway is greater than "MinHdwy" and restricts the value if it falls outside this range for human comfort. The level variable Velocity\_2, which is the variable signifying the velocity of the second vehicle is computed and transferred to Dummy2 which is a dummy rate variable for the level, "Position\_2" (figure 4.2). The value of Position\_2 is then used for the next iteration of the simulation process for a particular time increment. The simulation time interval chosen for this model was 0.1 seconds. The other vehicles were designed to follow the same principle. The model was thus subjected to dynamic changes in the profile of the first vehicle to note the response of the entire stream. The traffic stream progresses, adapting itself to the real-time changes in the traffic conditions. "Min\_Accn" (where n stands for the number of the vehicle within the stream) was a term used to modify the car following model to suit the high-speed conditions. It is a constant which assumes a finite value or zero depending upon the relative velocity and headway. The inherent disadvantage of the General Motors formula was tackled by introducing this parameter. Upon the usage of fifth General Motors model, it was found that even when the headway > minimum headway, if the

velocity of the following vehicle is equal to or greater than the preceding vehicle, the acceleration and bridging of the gap is made impossible by the presence of the term  $relvel$ , which is rendered negative or zero. This was counteracted by introducing  $Min\_Accn$  which produces a finite amount of acceleration even when the headway exceeds the minimum headway, provided the relative velocity does not fall below a fixed negative value of relative velocity. In other words, the acceleration is allowed until the speed of the lagging vehicle exceeds that of its leader by  $5 \text{ ft/ Sec}^2$ . The tolerable limit above the  $Min\_Hdwy$  is given by " $Hdwy\_Margin$ ", which is also a previously defined constant (figure 4.2). This relationship between the first and second vehicles holds for any pair of successive freeway vehicles. The only difference between the first pair of vehicles and any other pair exists in the representation and computation of the positions by stocks (the level variables). The stream flow proceeds unabated until the next weaving or merging ramp is approached. At the ramp nose connecting the freeway with the exit or entrance ramp, the presence of a vehicle which leaves or enters the stream causes alterations in the vehicle configuration.



## 4.5 Merging Scenario

At the end of the initial acceleration phase, the ramp vehicle is considered to be on the freeway for the purposes of merging and automatic vehicular control. The ramp control system spots the two mainstream vehicles which enclose the ramp vehicle and decelerates the ramp vehicle just enough to create a minimum desired headway. Meanwhile, the vehicle destined to follow, decelerates and is entirely governed by the merging vehicle right from the point of its emergence, past the ramp nose. In this model, the sole vehicle on entrance ramp (Vehicle 5) was merged between the third and fourth vehicles of the mainstream. RCF represents "ramp control factor", which takes a value of 1 or 0 depending on the system decision of the merger. It assumes a value of 1 such that the  $Headway_4$  becomes  $(Position_5 - Position_4)$  as soon as the simulation time (TIME) exceeds "Time\_for\_acc\_to\_Design\_Speed". The vehicles affected by the merger are subjected to a fixed deceleration rate, until the headways exceed "MinHdwy" or  $relvel4$  and  $relvel5$  reach a value of -5 ft/sec. The deceleration waves travel backward as the freeway vehicle dispenses a fraction of its velocity in the process of merging. As soon as the headways are established above the minimum headway desired, the car falls into the routine stream following mode. The merging scenario has been clearly illustrated in Figure 4.3.

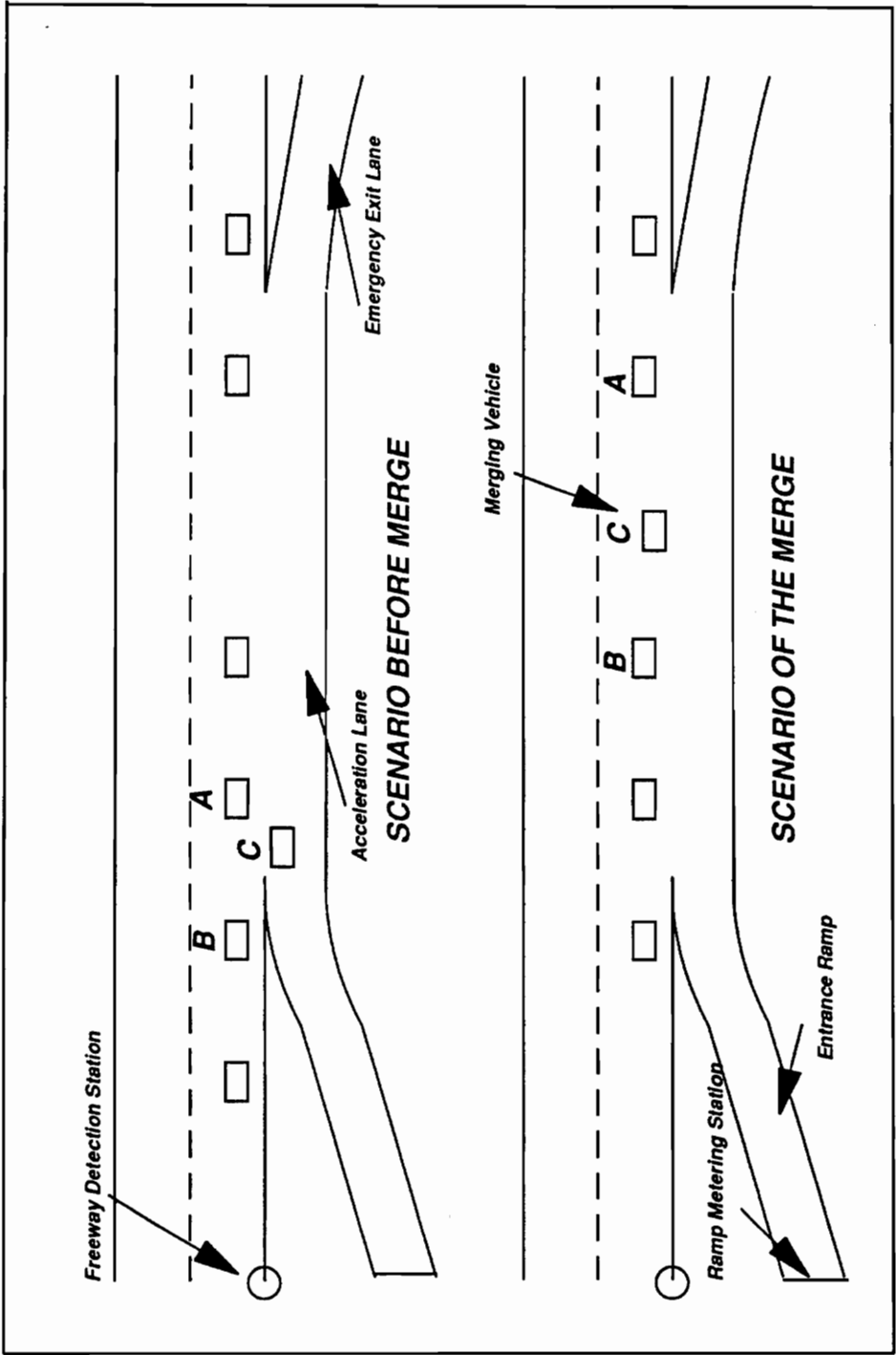


Figure 4.3 Entrance Ramp-Freeway Merging Scenario

It was evident that an instantaneous lane change would be practically impossible. This prompted an extension of the model, considering the merging process in two directions. A reverse curve was designed for the vehicle in lateral motion, which is dictated by its own velocity at every instant in X-direction (forward speed). An important step in this extension procedure was to take the numerical value of the speed obtained through the car following equation for the vehicle speed in the X-direction, and compute the angle of turn at every point, accordingly. The degree of deviation for every simulation interval is obtained by substituting the forward speed in the equation of the reverse curve. The rate of deviation becomes zero as soon as the total displacement in the Y-direction equals the lane width or any other value specified by the user.

The total acceleration lane length required = (Safety factor 1 \* Distance required to build the headways) + (Safety factor 2 + Straight-line length during the lane change)

where,

Safety factor 1 and Safety factor 2 represent the factors of safety adopted for each of the above phases. A value of 1.5 - 2.0 may be appropriate for these.

## 4.6 Model for Vehicle Lane Change

The motion of the entering vehicle into the fast lane consists of two curves, mutually opposite in their directions of curvature. The first half of this reverse curve will be governed by the same set of merging rules as the second half. The merging vehicle is admitted to enter the freeway stream as soon as the headway and velocity conditions are satisfied. Required\_Shift, the variable representing the amount of lateral shift to be achieved by the vehicle, becomes a constant, finite positive value which is a summation of the lateral displacements of the vehicle in both the lanes (refer to figure 4.4). This is obtained from the coordinates of the location of the vehicle with respect to each half of the total distance to be covered. Initially, the curve length (Path\_Length), lateral vehicle movement (Lateral\_Shift) and the total angle to be covered (Angle\_of\_Turn) are defined to be zero, whereas the radius of the curve is chosen to be a large value, of the order of 30,000 ft. Initially, when the Lateral\_Shift < Required\_Shift\_1, which is the lateral distance to be covered in the first phase, the rate variable "Rate\_of\_Shift" takes the value of "Rate\_of\_Shift1" and when Required\_Shift1 ≤ Lateral\_Shift < Required\_Shift, the rate variable takes the value of "Rate\_of\_Shift2", where Rate\_of\_Shift\_1 and Rate\_of\_Shift\_2 become products of linear velocity of the vehicle and Sin (Rate\_of\_Turn) (figure 4.4). Rate\_of\_Turn denotes the angle of turn of the vehicle per time interval. This is fed into the stock, which accumulates continuously as the simulation progresses.



The length of curve at any time has been derived from the formula for the sector length from geometry. It is the summation of its previous value and its change over that dt. The rate variable, Rate\_of\_Curvature depends on the angle of turn permitted and the radius at that instant.

$$\text{Rate\_of\_Curvature} = \text{Rate\_of\_turn} * \text{Radius}$$

The above value is then fed into the stock, Angle\_of\_turn, which is thus updated for every simulation iteration. The rate of change of angle is governed by the constraints of passenger comfort and was introduced in terms of maximum acceleration and jerk limits. Hence the angle of turn at any point of time is given by (Anderson, 1978)

$$\theta = \frac{a_n^2}{2 * \text{Jerk} * \text{Velocity}} \quad (28)$$

The direction of curvature changes, as soon as Lateral\_Shift exceeds Required\_shift1. For purposes of simulation, the jerk and normal acceleration values have been chosen to be 0.05 g/ Sec and 0.1 g respectively. Required\_Shift2 is defined at the point of change of curvature and another curve is traced, in the second phase of the vehicle motion. The extent of the replication of the first half and the time taken to achieve this depends entirely upon the linear velocity profile of the vehicle with varying time.

## 4.7 Ramp Weaving Model

The vehicles were assumed to be at steady state obeying the car following equation (12) until they reach exit ramp, when one or more vehicles are making an exit from the freeway (refer to figure 4.5). A series of five vehicles were simulated, just as in ramp-merging model. All the notations used remain same as those entrance-ramp freeway model. The third vehicle in the stream is made to leave the stream, when it passes a previously defined mark, called `Exit_Ramp_Point` (taken as 3,000 feet). A new stock, `Exiting_Time` is constructed, which represents the total time elapsed, from the time the vehicle crosses the `Exit_Ramp_Point` to its exit into the deceleration lane (figure 4.5). The flow becomes time variable whenever the  $RCF=1$ . `RCF`, which signifies 'Ramp control factor' is 1 at any entrance or exit ramp boundary limits and 0 at all the other points. The `Velocity_3` is an auxiliary variable which gets the input from the stock `vel_3` and represents the velocity of the third vehicle on the freeway at any time. `Vel_3` is a stock variable which follows the car following rule, until the time of its weaving away from its stream and slowly decelerates along the deceleration lane and on its way towards the 'exit ramp metering station' along the exit ramp. As soon as `Exiting_Time` exceeds the time taken for the vehicle to reach the outer most lane, which is given by the input from the reverse curve algorithm, the `velocity_3` becomes 0, which would mean that for purposes of freeway, the third vehicle has zero velocity or it is no longer existent on the fast lane.

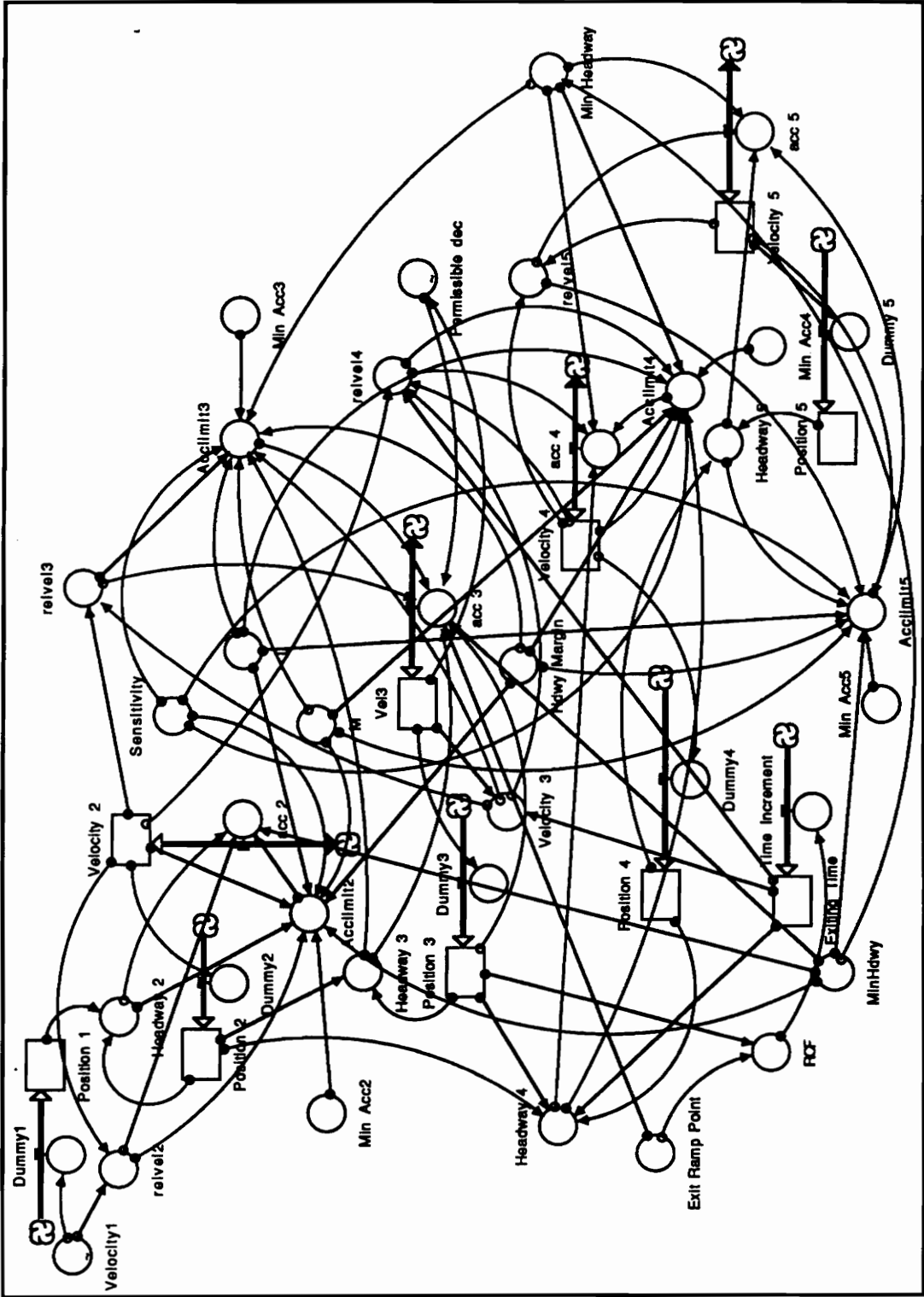


Figure 4.5 Causal Diagram for Vehicle Exit from Freeway (Ramp Weaving Model)

At this time, Headway\_4 which was originally the space headway of vehicle 2 and vehicle 3 becomes (Position\_2 - Position\_4). Similarly, the relative velocity of the vehicle 4 with the vehicle ahead of it, relvel\_4 becomes (Velocity\_2 - Velocity\_4). The following rule causes the propagation of an acceleration wave in the traffic stream on the upstream side of the vehicle 4 and bridge the gap created by the exited vehicle.

$$\text{acc}_4 = \text{IF Headway}_n > (\text{MinHdwy}+5) \text{ THEN } (\text{IF relvel}_4 > -5 \text{ THEN } \text{Min\_Accn} \text{ ELSE } 0) \text{ ELSE } (\text{sensitivity} * \text{velocity}_n^m * (\text{relvel}_n/\text{Headway}_n^l))$$

The MinHdwy, Min\_Accn values have been chosen to be exactly the same as in ramp merging model. Once again, the velocity of the first vehicle follows choicest pattern, as detected by the user. All other constants and variables, remain the same.

## 4.8 Horizontal Curve Design

A compact system of intelligent highways would require maintenance of high speeds with substantial traffic intensities which create special problems. The interaction between road, atmosphere and car introduces aerodynamic forces which exceed all other forces acting on a vehicle, threatening its stability. The aerodynamic equations have been used to design the roadway curvature in horizontal direction. The equation 19 gives the simplified relation between the radius of curvature with no wind affect and a finite wind blowing across the vehicle path. For a racing car according to Scibor-Rylski, for maximum wind speeds of 40 ft/ sec, the ratio of  $R/ R_{w=0}$  is 1.5. Combining equations 19 and 20 and substituting the terms for 'q', we arrive at the following equation of radius of horizontal curve for the case of no wind:

$$M_s g h \sin \phi + \frac{M_s V^2 h}{R} + \frac{\rho V^2}{2} S C_{y\beta} \beta d = k \phi \quad (29)$$

The following computations illustrate the usage of the above formulation for geometric design of highways:

*Handwritten notes:*  
 $H_g h_{susp} + \frac{W}{k}$   
 $\frac{1}{3} \frac{W}{k}$   
 $\frac{1}{3} \frac{W}{k} = \frac{1}{3} \frac{2350}{k}$

**EXAMPLE**

**Vehicle Characteristics of Passenger Sedan (Pershing, 1973)**

Weight, W = 2350 lb

Wheel base, L = 7.84 ft

Track width, C = 4.58 ft

Aerodynamic Reference Area, S = 25 ft<sup>2</sup>

Maximum Velocity, V = 150 ft/sec

(It is assumed that a velocity range of 320 - 340 ft/ Sec is attainable by way of improvements to the vehicle design to attain)

Unsprung weight (gross), W = 2350 lb

Acceleration due to gravity, g = 32 ft/sec<sup>2</sup>

Total height of the car, H = 5.4166

(interpolation for sedan car corresponding to a weight of 2350 lb)

Derivative of side-force coefficient w.r.t. side-slip angle  $C_{y\beta} = 2.2$

Angle of side-slip or yaw,  $\beta = 10^\circ$  (-ve or +ve)

Height of C.G. above the ground, h = 1.8055 ft

( $\frac{1}{3}$  of total height,  $H/3 = 5.4166/3$ )

Stiffness of elastic suspension, k = -(F/x)

where,

F = Force created by the load on the springs due to car weight  
 (for a gross weight of 2350 lb) = 1700 lb

$x$  = Maximum possible deflection of the springs for saloon car

$$(3 \text{ inches or } 3") = 0.25 \text{ ft}$$

$$\Rightarrow \text{stiffness, } k = 1700 / 0.25 = 6800 \text{ lb/ft}$$

$$\text{Number of springs} = 4$$

$$\text{Dynamic pressure of airstream, } q = \rho V_A^2 / 2$$

where,

$$\text{Design speed, } V = V_A = 300 \text{ ft/sec}^2$$

(airstream velocity relative to the car, assuming no wind)

$$\text{Air mass density, } \rho = 0.002378 \text{ lb/ft}^3$$

$$\text{Dynamic pressure, } q = 0.002378 * 300 = 0.7134 \text{ lb-ft}$$

$$\text{Atmospheric wind speed, } w = 40 \text{ ft/ Sec}^2$$

$$\text{Angle of roll, } \phi (5^\circ) = 0.0873 \text{ radians}$$

$$\text{Maximum distance between C.P. and roll axis, } d = 0.9028 \text{ ft}$$

(assuming height of roll axis of  $\frac{1}{3}H$ ,  $5.4166 * \{\frac{1}{2} - \frac{1}{3}\}$ )

Procedure: The above values are substituting into equation 29 and the resulting radii are as follows:

$$\text{Radius of turning without wind, } R_{w=0} = 7,323 \text{ ft}$$

$$\text{Radius of curvature with the side wind, } R = 1.2 * 7323 = 8,734 \text{ ft}$$

Different values for the terms in equation 29, such as height of center of gravity, design speed, spring deflection, aerodynamic reference, weight of the vehicle give a range of radii values for the curve design. These have been plotted to produce a graphical output for the analysis of relative importance of the above parameters. These will be discussed in the next chapter.

## 4.9 Vertical Curve Design

AASHTO gives the design criteria for sag and crest vertical curves through graphical charts for design speeds of 70 mph, both for  $S < L$  and  $S > L$ . The minimum length required of the curve is computed as the x coordinate corresponding to the point of intersection of grade (y coordinate) with the line of Design speed. Since S is inevitably more than L, the maximum grade difference allowed cannot be more than 4% longitudinally. If we assume that it takes about 30 seconds for the vehicle to come to a complete stop (design speed of 300 ft/ Sec with a maximum deceleration rate of 10 ft/ Sec),

$$\text{Stopping sight distance required} = 300 * 30 = 9,000 \text{ ft.}$$

It is impractical to assume that a vehicle comes to a complete stop on a freeway, instantaneously. Hence, taking 3,000 ft to be SSD, with a maximum longitudinal gradient of 4 percent, using equations (22) and (24), we have the following minimum length of curve values ( $L_m$ ):

In case of a crest vertical curve,

$$L_m = 2 (3,000) - 1329/ 2 = 5,335.5 \text{ ft}$$

In case of a sag vertical curve,

$$L_m = 2 (3,000) - \{(400 + 3.5*3,000)/4\} = 3275 \text{ ft}$$

The above values are obtained strictly by the application of the AASHTO formulae. It is essential to realize that these are developed for a maximum design speed of 70 miles per hour only. There are no available guidelines for design at higher speeds, at this point of time. The objective in applying these formulae is to give a preliminary treatment about the possible curve lengths to be expected in future. But, subsequently, the design must be checked for passenger comfort limitations from normal acceleration standpoint during the vertical curvature. As of now, it does not appear practical to design for curves exceeding a gradient of more than 4 percent.

# 5 RESULTS AND DISCUSSION

## 5.1 Simulation Models

The simulation model has been developed as a sequential process. In the previous chapter, a complete description of the simulation model for traffic control and the pertaining geometric design specifications has been given. This chapter discusses some of the results obtained from the modeling process as well as the geometric design alternatives attempted.

For an automatically controlled vehicle, the reaction time ( $\Delta t$ ) is expected to be a minor fraction of that of a normal highway. This is very essential to realize a traffic stream with headways in the range of 50-55 ft, which are extremely low considering the speeds achieved. The model has been tested for different time increments and a  $\Delta t$  value of 0.1 seconds was found to be an appropriate choice, which sacrifices very little accuracy of a continuous simulation process, but keeps the time required for each run, sufficiently low. A series of tables and graphs have been generated to present the results, varying a number of important terms in the process. The car following and the stability was found to be reasonable for a limited variation of 4 ft/ Sec in velocity profile of the first vehicle.

### 5.1.1 Simulation Results

A number of tables and graphs have been generated to present the output, conveniently. Figures 5.1 - 5.3 represent the time histories for velocity, position, and headway. The figures are based on the following data:

Simulation time	= 60 Sec
Time interval, dt	= 0.1 Sec
Print interval	= 1 Sec
Minimum headway	= 50 ft
Time delay, $\Delta t$	= 0.3 Sec

The value of simulation time interval 'dt' in the modeling process was selected from the 'run menu' of the STELLA II software. To get a clear picture and reduce the output from the simulation runs, the print interval was chosen to be 1 second for all the models. The time delay  $\Delta t$ , which was artificially introduced for the acceleration variable was widely varied and the output was exported to a graphics software based on Apple Macintosh to analyze the results, graphically.

Figure 5.1 shows velocities of all the four following vehicles in response to the profile introduced for the leader. Figure 5.2 plots the positions versus time. It can be seen that the gap between the Vehicle 3 and 5 increases from a near zero value at 27 Sec

to about minimum headway at 35 Sec. The bullets indicate the trajectory of the merging vehicle. The headway variation over the entire simulation time span is plotted in Figure 5.3. The stream stability is affected by a jump in Headway\_4, which is now the space headway of the last vehicle with the merging vehicle in the stream, owing to the steep velocity changes occurring ahead. The time delay gets accumulated with the addition of each vehicle and so, the stream response is delayed.

The velocities are plotted on a macro level in Figure 5.4, with a reduced time delay of 0.2 Sec. Figure 5.5 plots the vehicle movement and is concentrated on the merging section. Considerably increased stability is observed upon the reduction in reaction time. This is evident in the plot of the headways against simulation time in Figure 5.6, where the extent of wave undulations was far lesser compared to the similar plot, with a delay of 0.3 Sec (Figure 5.3). Further improvement in stream response is indicated, when the reaction time was chosen to be 0.1 Sec for Figures 5.7 - 5.9. For clarity, only the last three vehicles have been represented in Figure 5.7 (velocities vs simulation time) and Figure 5.8 (positions vs simulation time). The sharp variations in headways disappear to some extent in Figure 5.9. Another interesting aspect noticed was the profile of Headway\_2, which remains steady state (50-55 ft). With reduction in simulation time interval, the number of discrete points of the curve increase, producing increasingly smoother plots. All the figures display the adaptability in the design and flexibility in the working of the model.

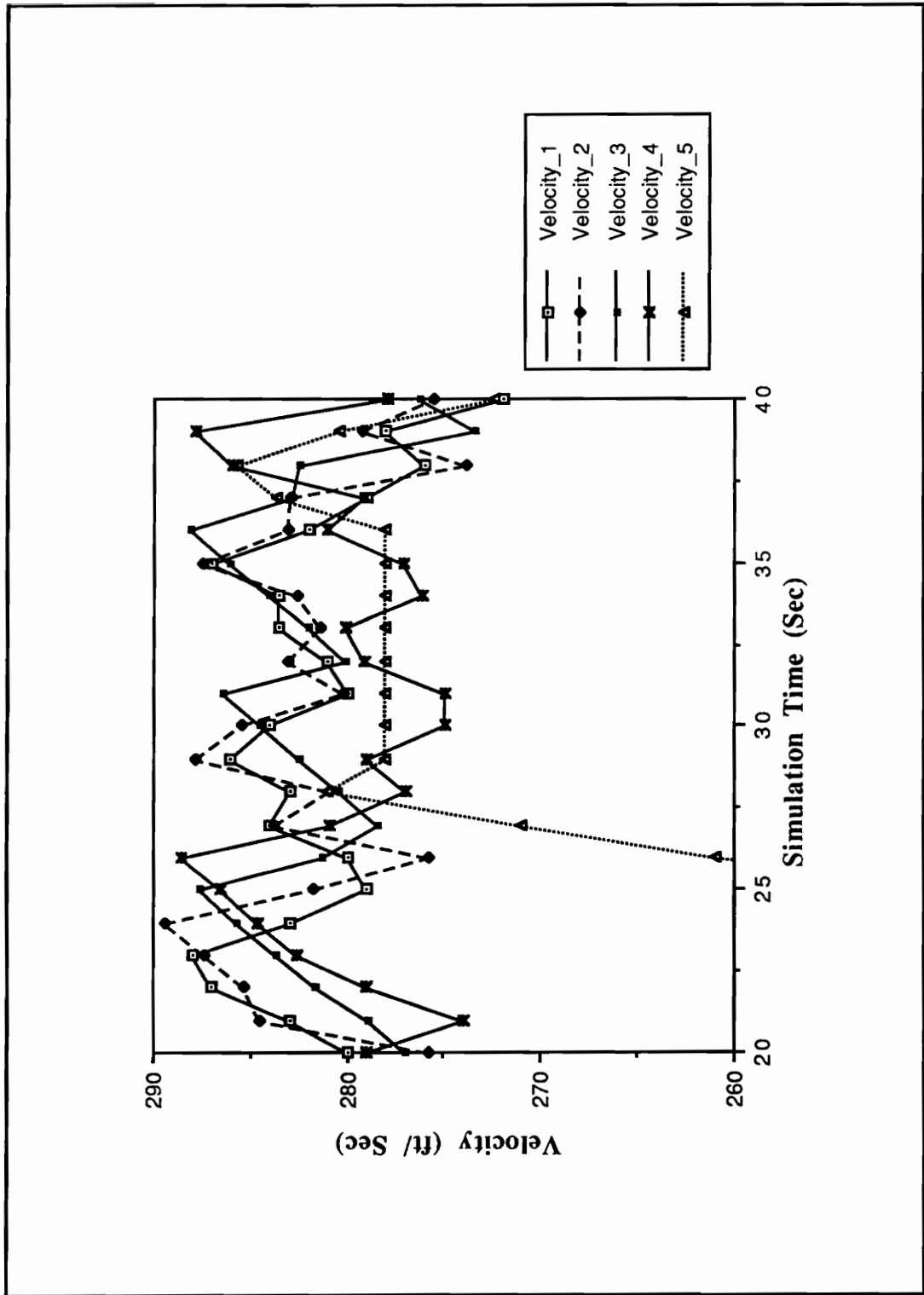


Figure 5.1 Plot Between Velocities & Simulation Time at Merging Section (Delay - 0.3 Sec)

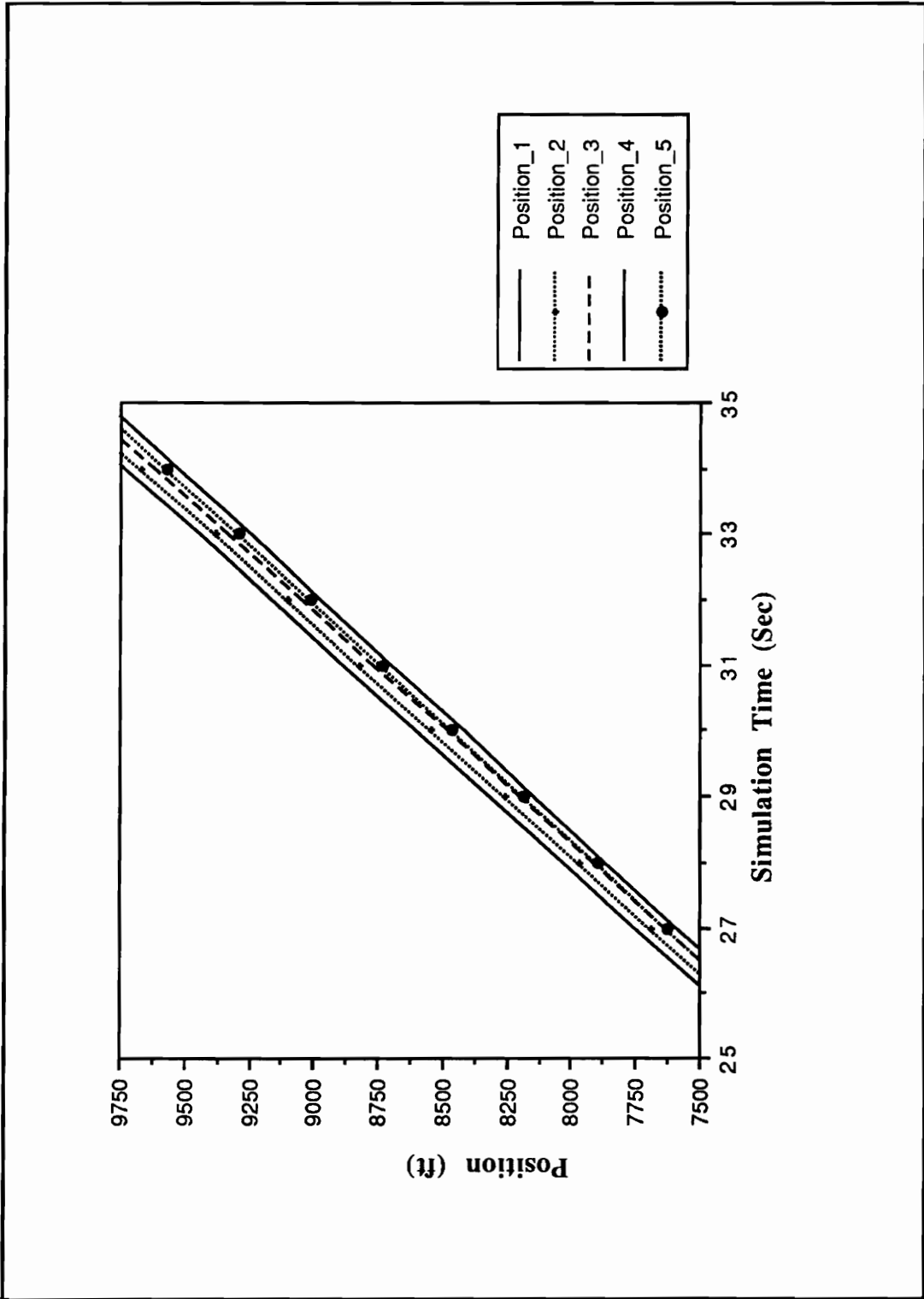


Figure 5.2 Plot Between Positions & Simulation Time at Merging Section (Delay - 0.3 Sec)

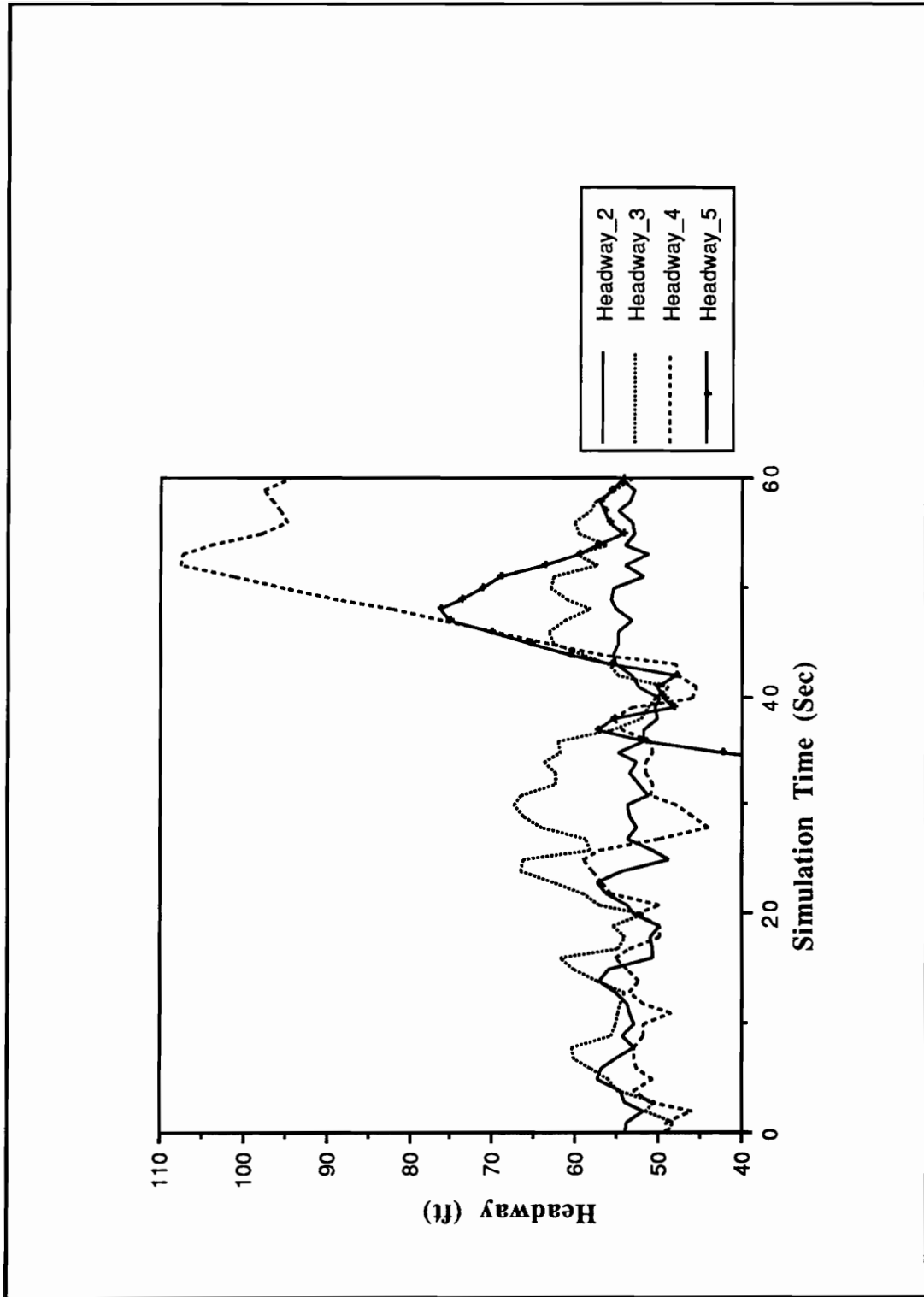


Figure 5.3 Plot Between Headways & Simulation Time at Merging Section (Delay - 0.3 Sec)

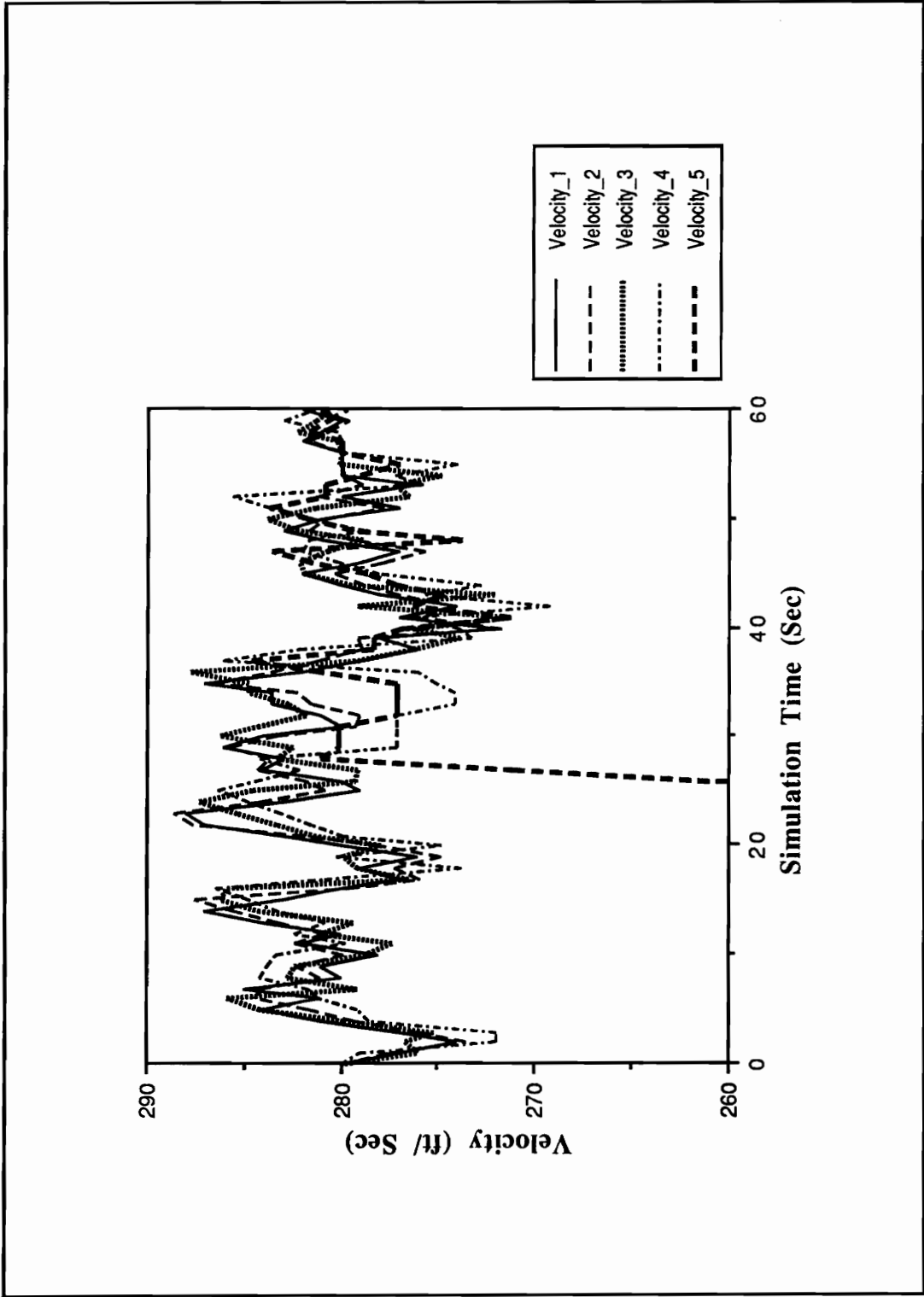


Figure 5.4 Plot Between Velocities & Simulation Time (Delay - 0.2 Sec)

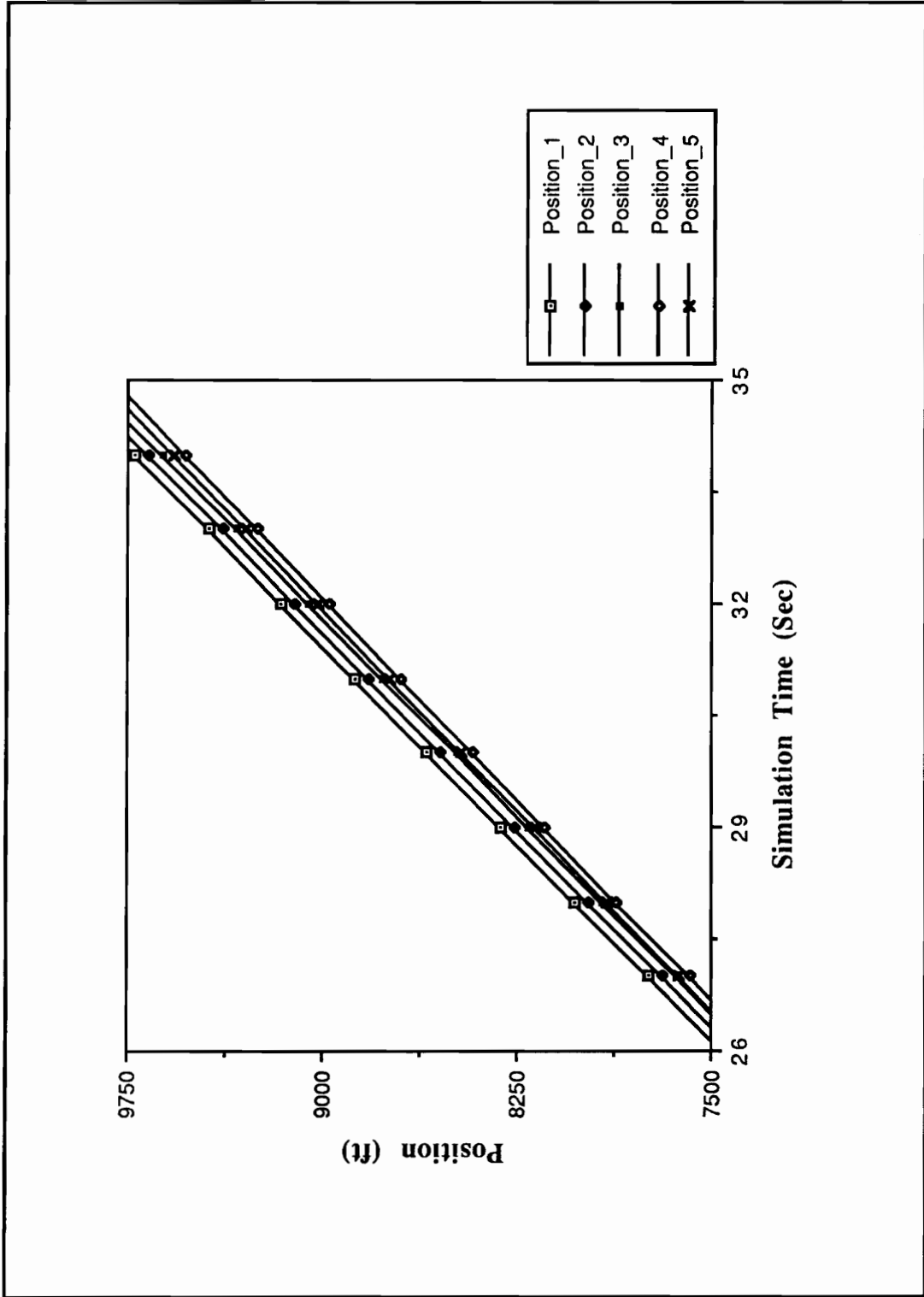


Figure 5.5 Plot Between Positions & Simulation Time at Merging Section (Delay - 0.2 Sec)

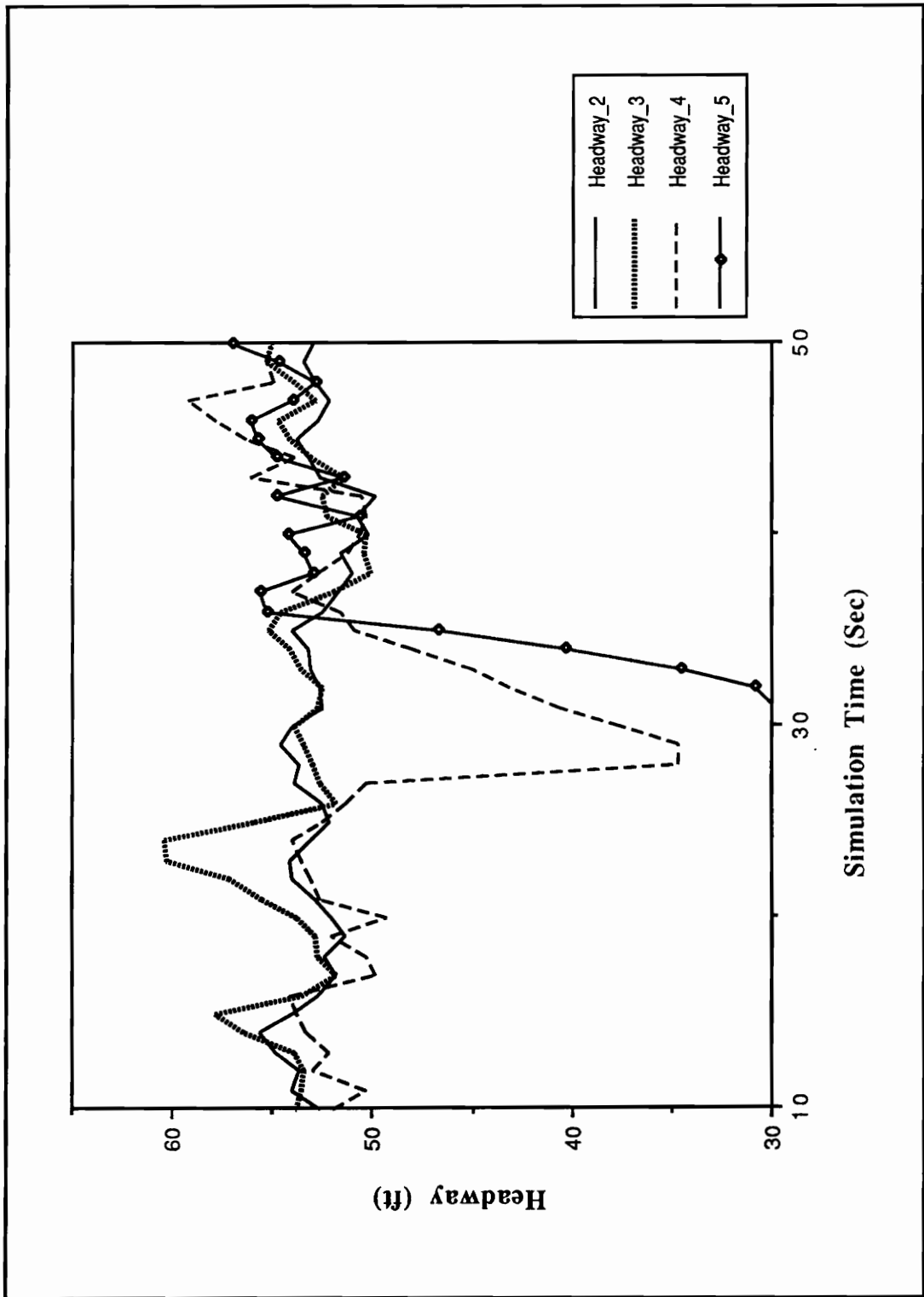


Figure 5.6 Plot Between Headways & Simulation Time (Delay - 0.2 Sec)

The above graphs have been drawn, with an initial assumption of a constant acceleration rate of  $10 \text{ ft/ Sec}^2$  for the ramp vehicle to reach the design speed from rest. A suitable modification resulted in definition of a smooth curve for vehicle acceleration. Figures 5.10 - 5.13 record the ramp merging process at macro level. Figure 5.10 illustrates the headways maintained by all the four vehicles following the leading vehicle. The Figure 5.11 clearly portrays excellently, the entire merging process. A gradual attainment of the freeway speed results in a smooth transition from the ramp into the acceleration lane/ freeway. The merging zone was shown as a part of the entire plot of velocities in Figure 5.12. The disturbances subside quickly to afford stability in the velocity waves. An enlargement of these waves appears in Figure 5.13, where the margins for the Y- Coordinate were defined from 270 - 290 ft/ Sec.

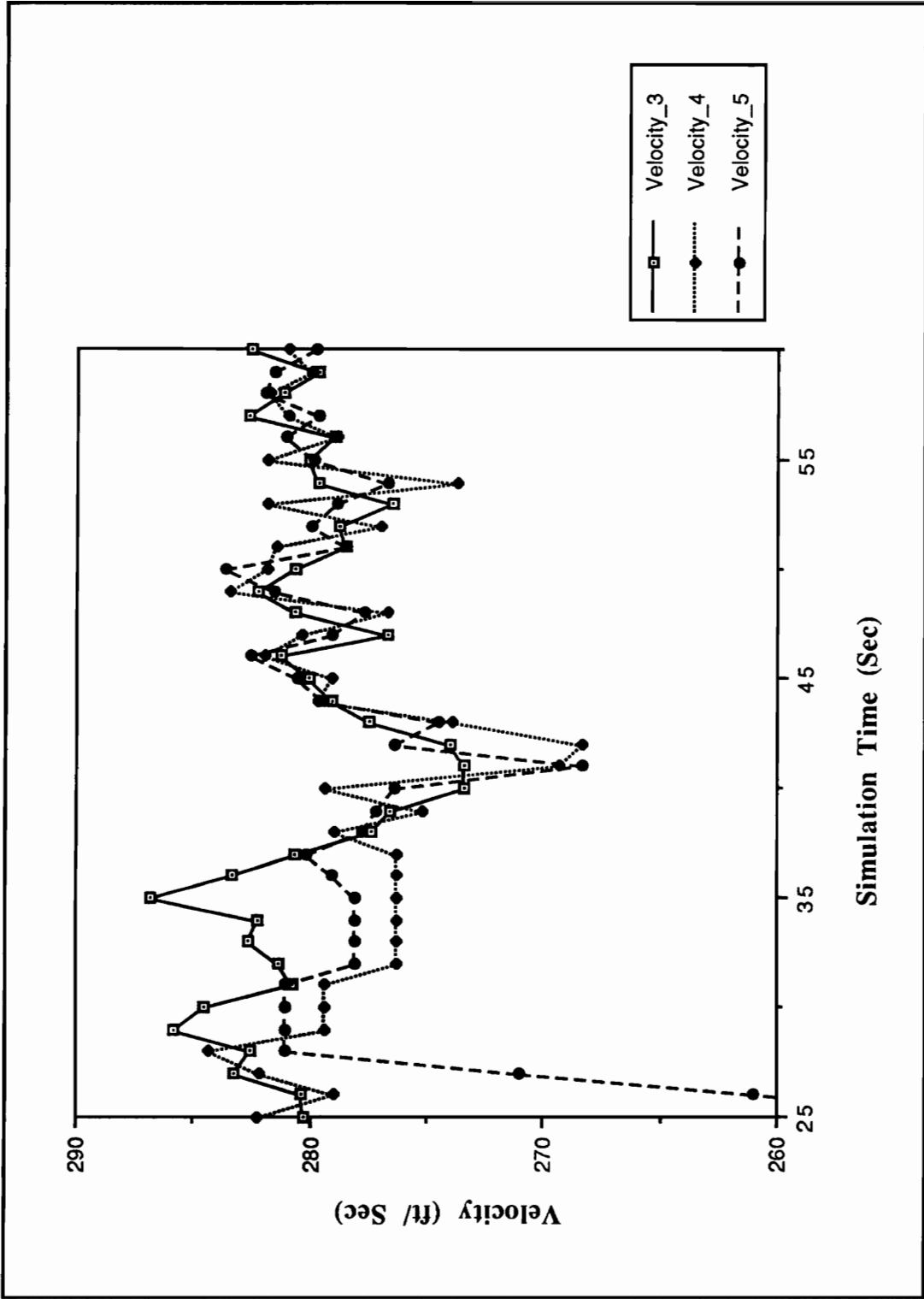


Figure 5.7 Plot Between the Velocities of the Vehicles Affected by the Merger (Delay - 0.1 Sec)

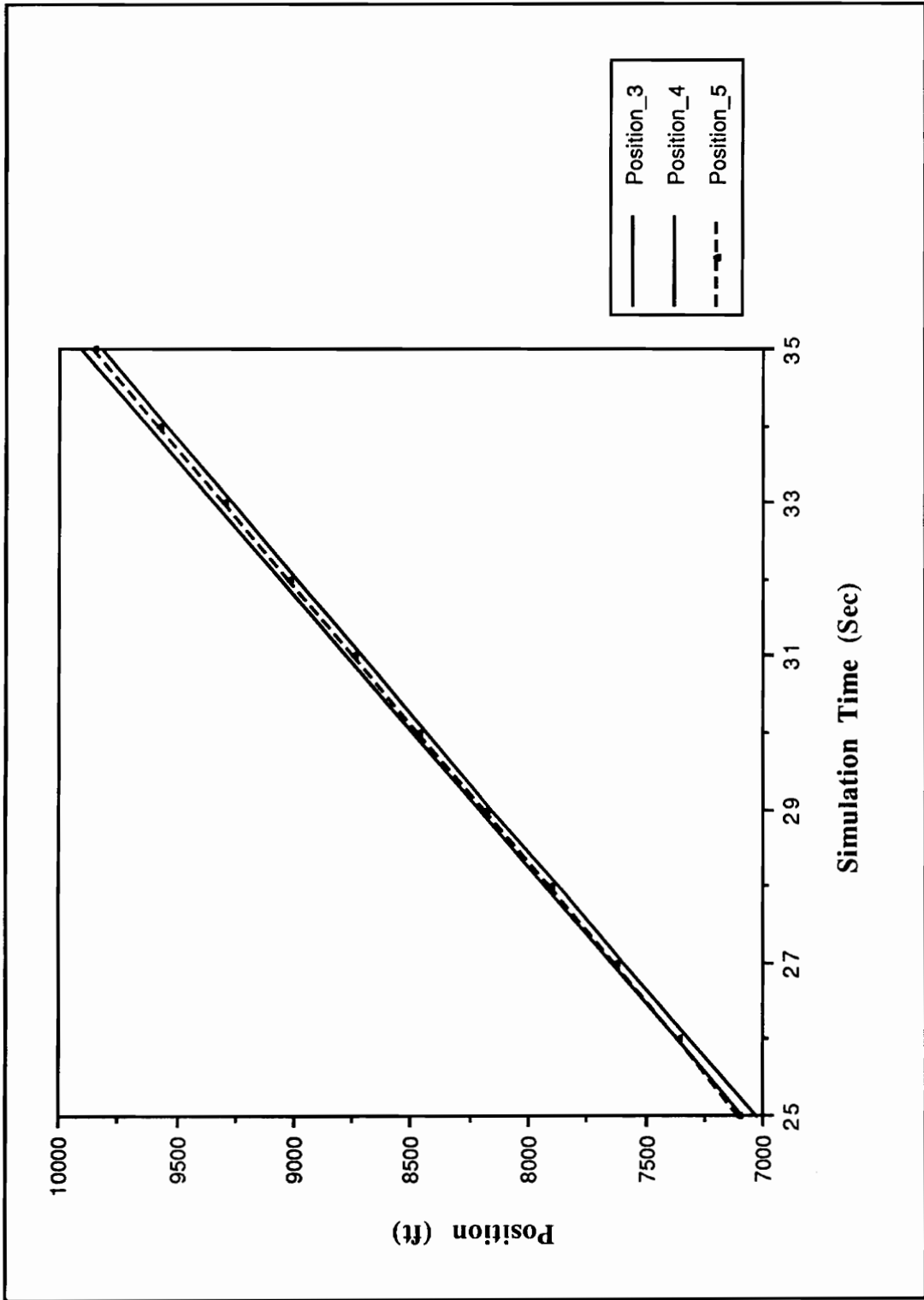


Figure 5.8 Plot Between the Positions of the Vehicles Affected by the Merger (Delay - 0.1 Sec)

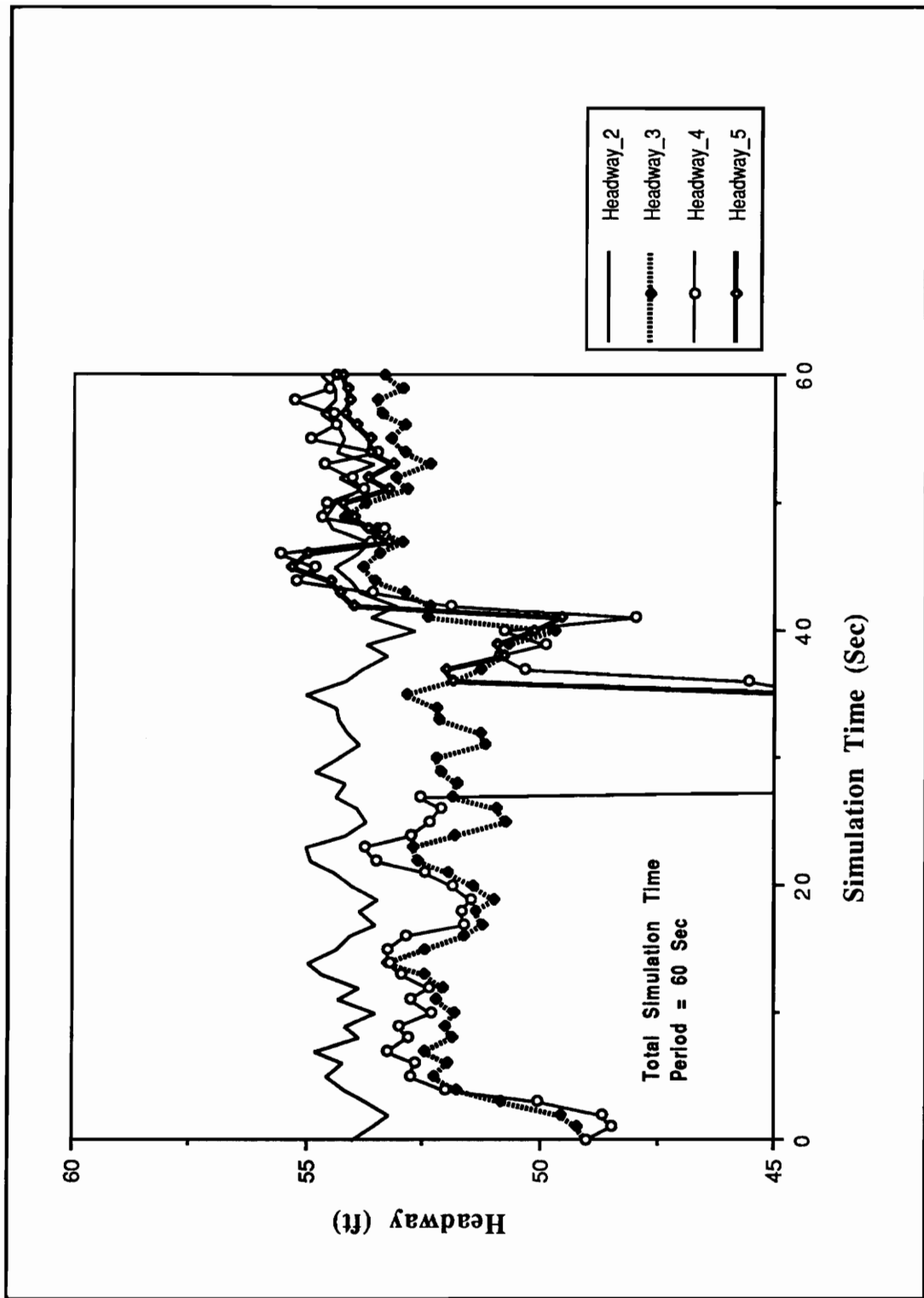


Figure 5.9 Plot Between Headways & Simulation Time (Delay - 0.1 Sec)

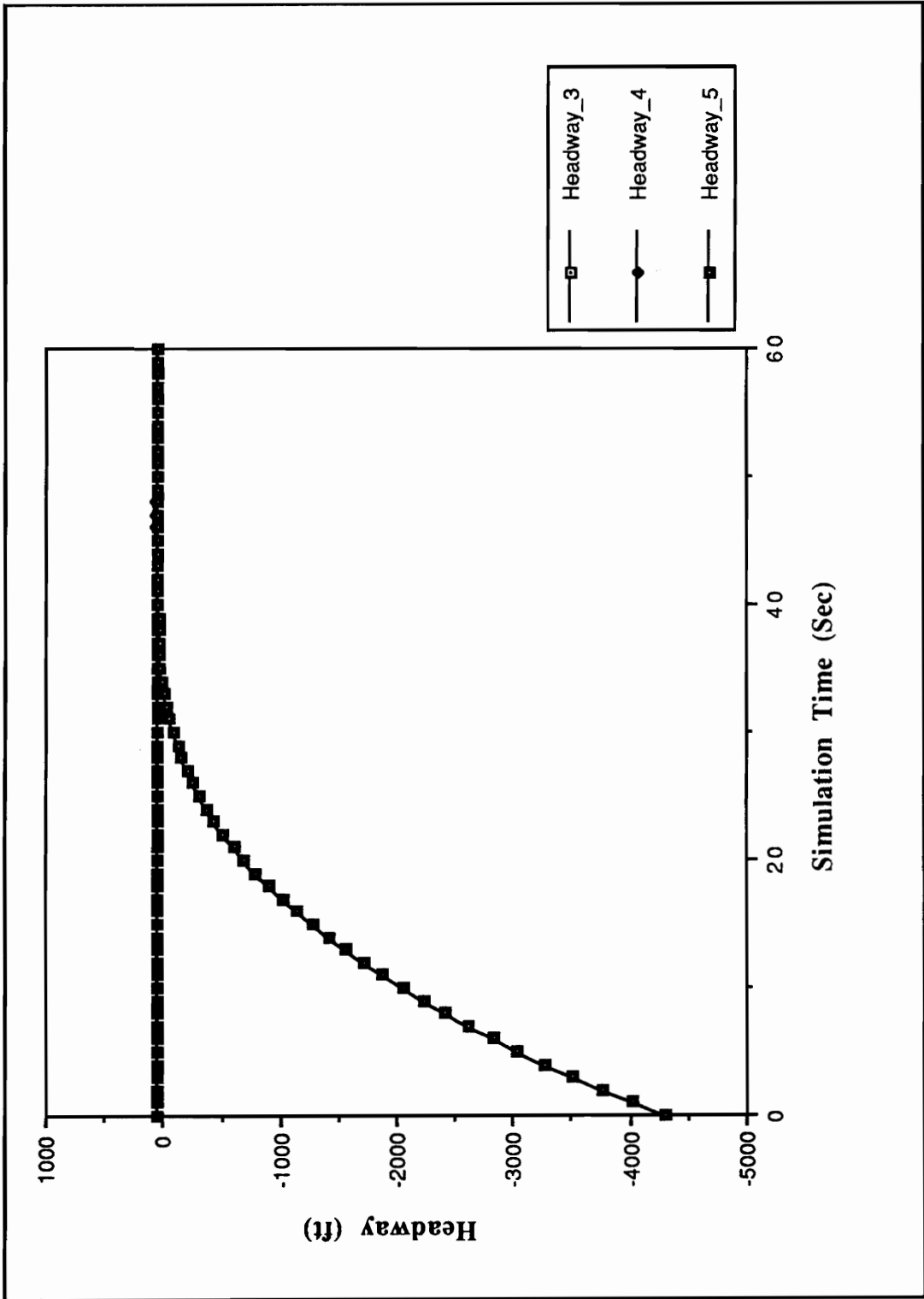


Figure 5.10 Plot Between Headways of the Third, Fourth and Fifth Vehicles (Delay - 0.2 Sec)

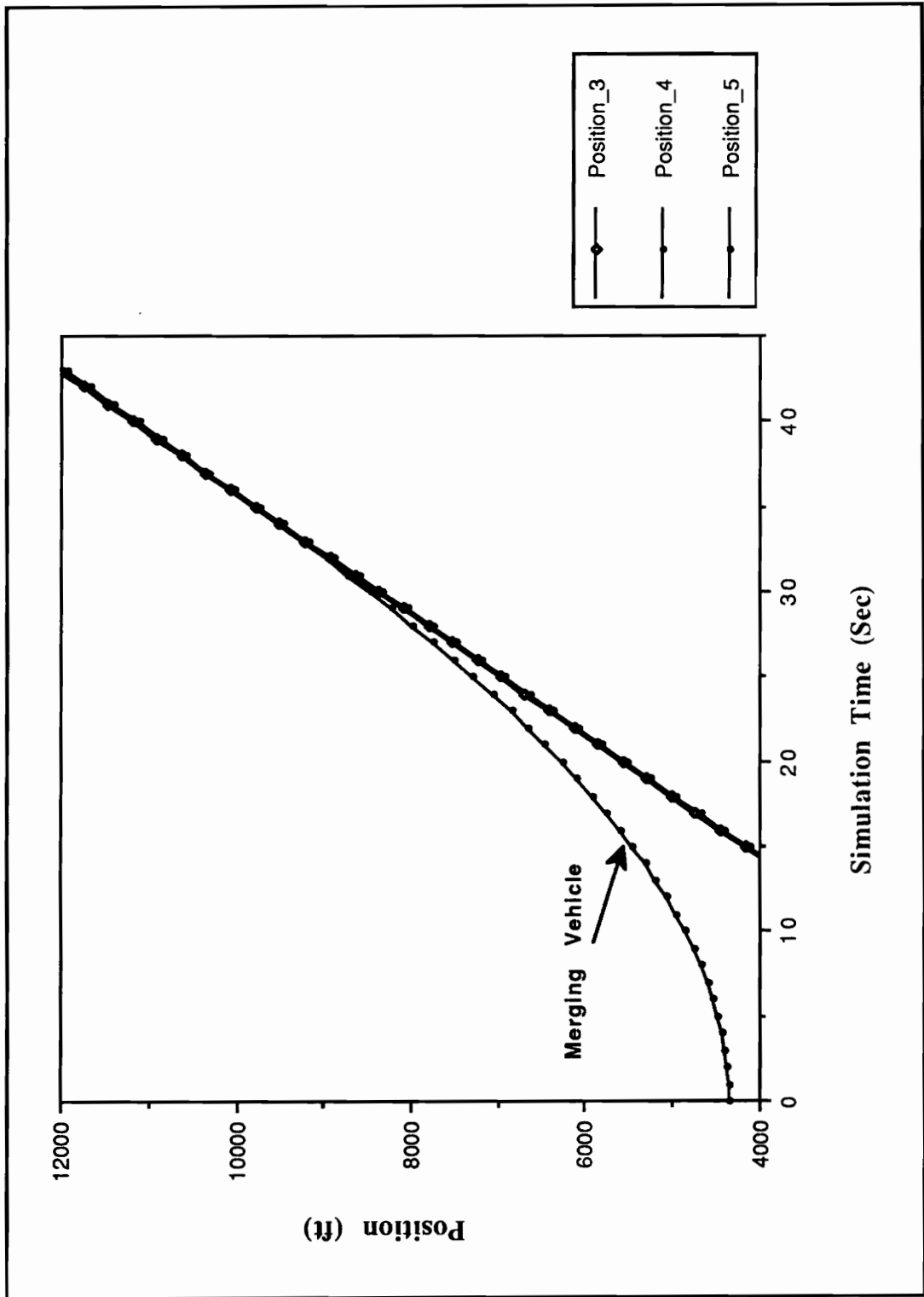


Figure 5.11 Plot of Positions Varying with the Simulation Time (Delay - 0.2 Sec)

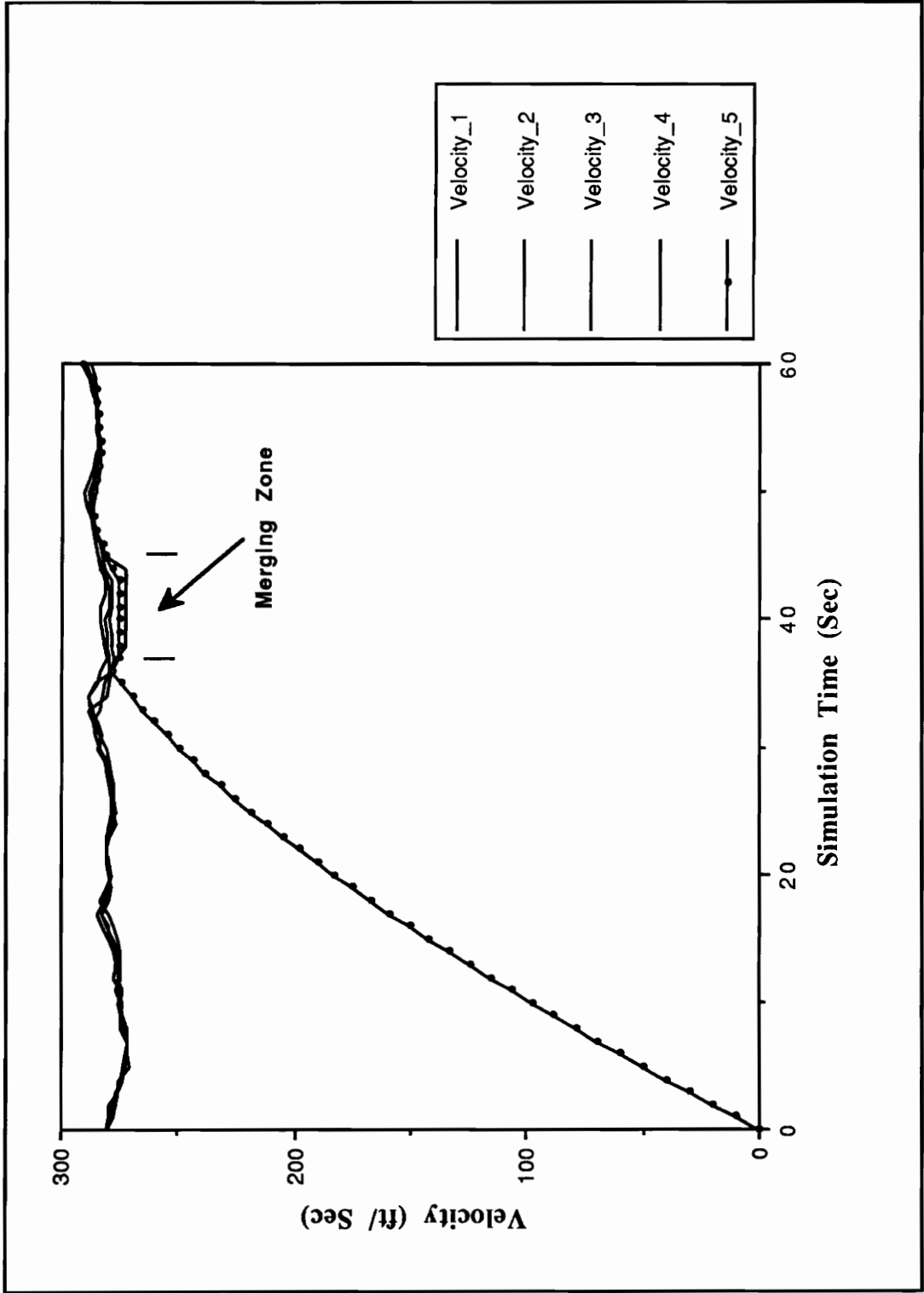


Figure 5.12 Plot of Velocities with Simulation Time (Delay - 0.2 Sec)

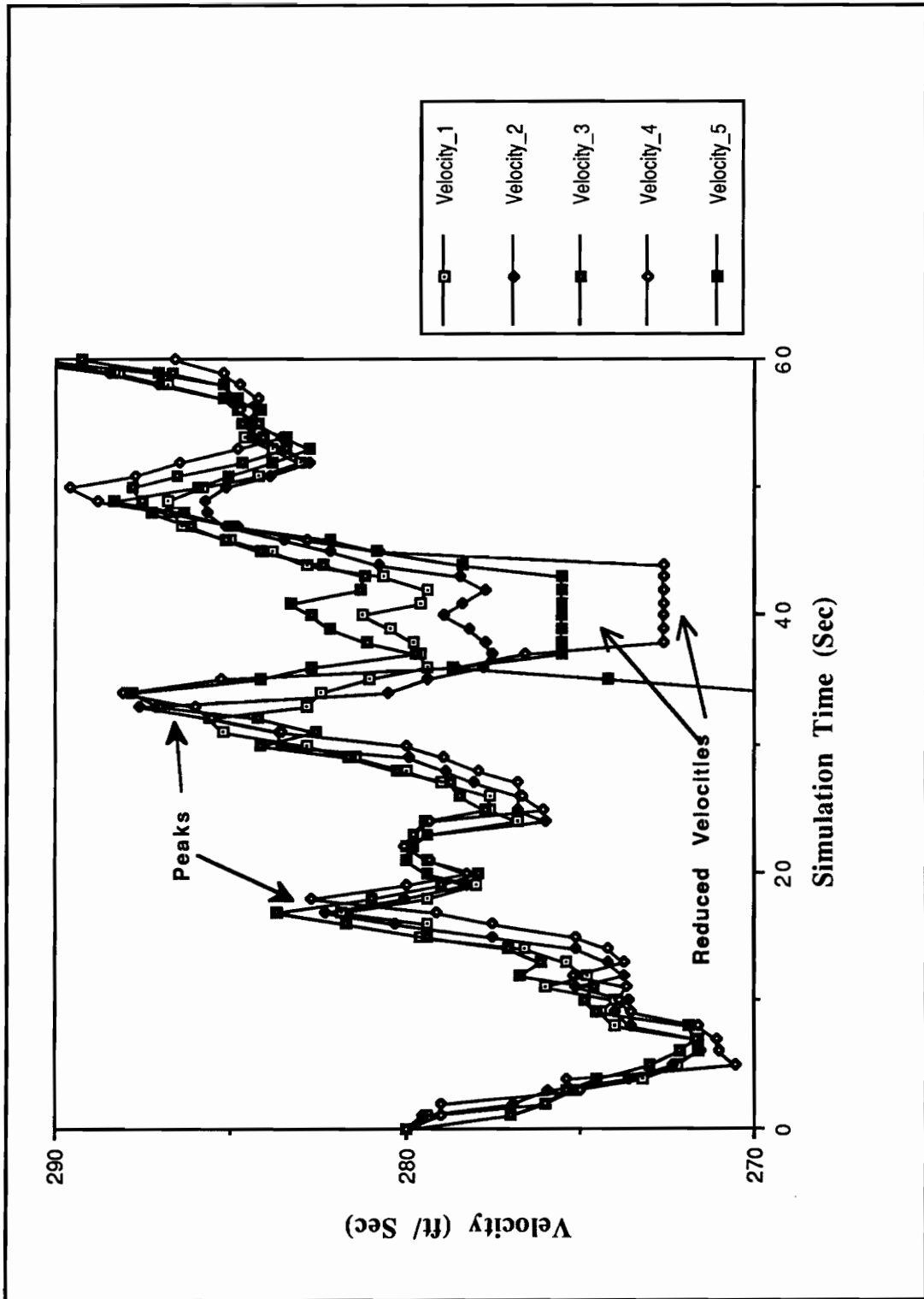


Figure 5.13 Plot of Velocities Varying with Simulation Time (Delay - 0.2 Sec)

Ramp Weaving Model: In this model, a vehicle in the stream is exited from the stream and the resultant stream conditions have been analyzed and depicted in the form of graphs and tables. First among these is Figure 5.14 which plots Simulation Time on X-axis and Position on the Y-axis. At an arbitrary point on the freeway, the vehicle 3 was moved into the deceleration lane on the automated freeway and from this point onwards, the fourth vehicle is seen to be following the second vehicle of the stream. Position\_4 traces a straight line from this instant, meaning that its subsequent movement in freeway coordinates is zero. It is patent from the figure that the vehicles bridge the gap gradually, in about 17 seconds. This is made more clear in Figure 5.15 where Headway\_4 shoots up from about 50 ft to about 105 ft and it falls to an optimum value as the simulation time progresses. This duration is marked by higher speeds of vehicles 4 and 5, as can be seen in Figure 5.16. In this set of figures, a delay of 0.2 seconds has been allowed for the reaction time in the system.

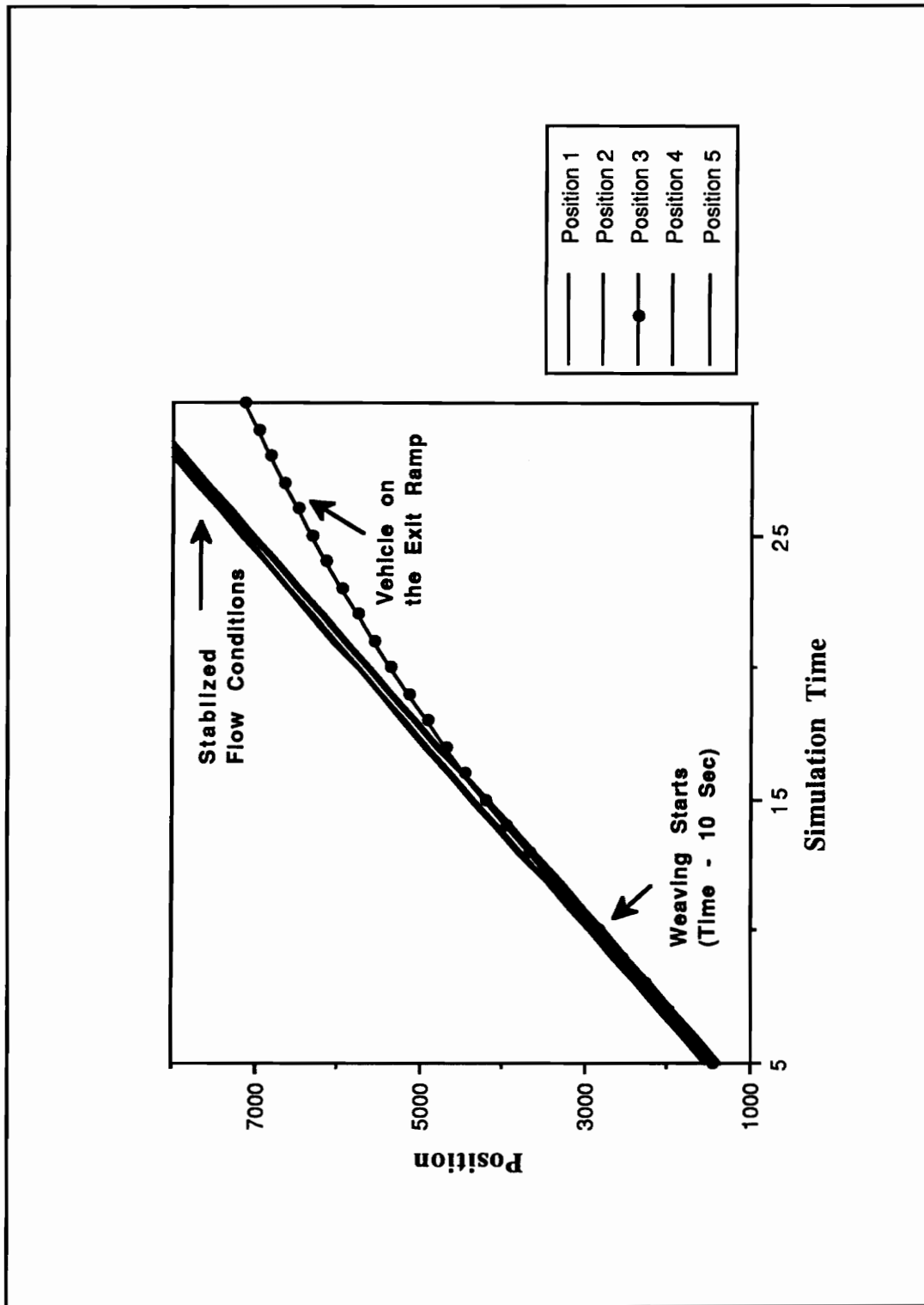


Figure 5.14 Plot Between Positions and Simulation Time (Ramp Weaving Model)

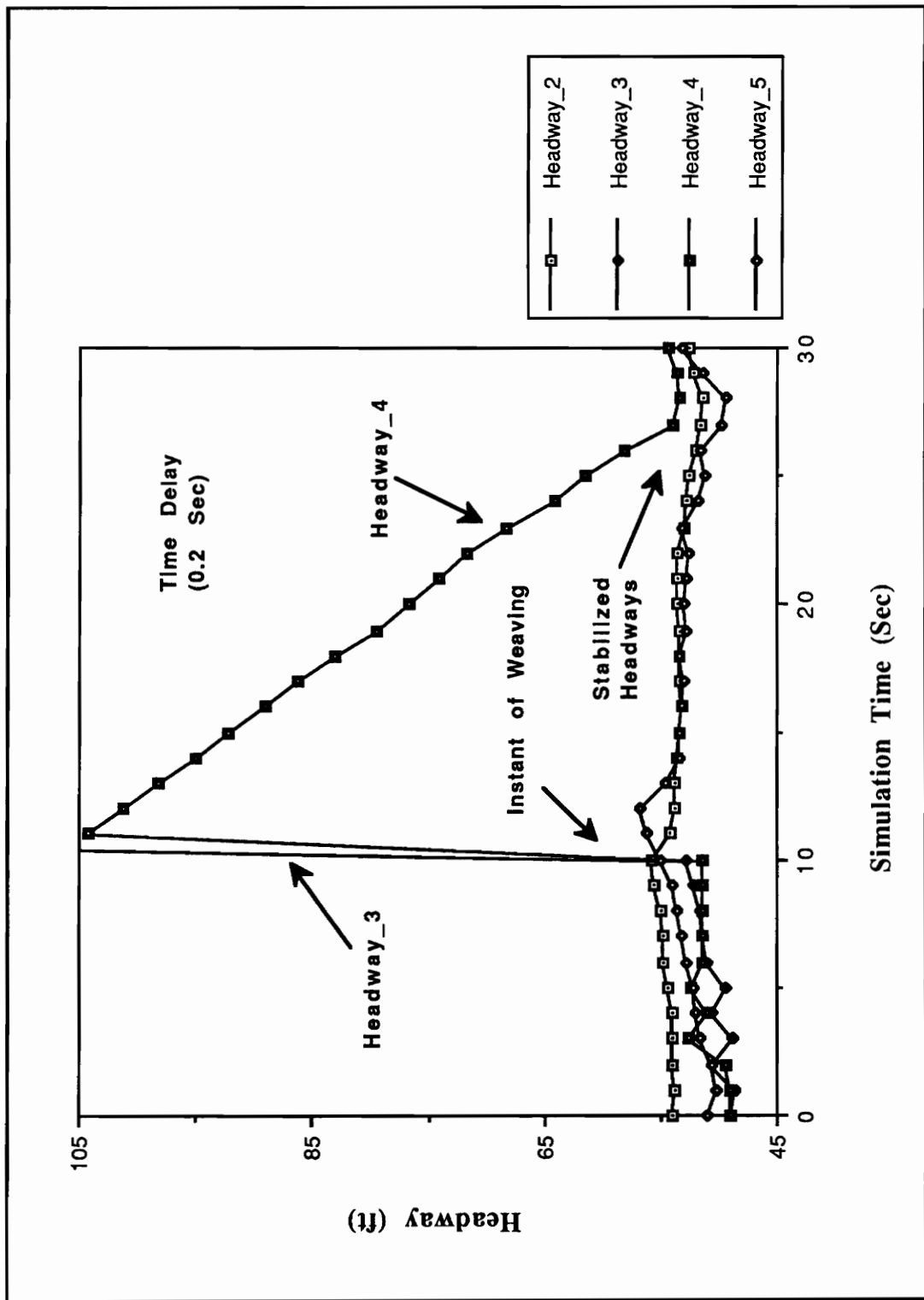


Figure 5.15 Plot Between Headways and Simulation Time (Ramp Weaving Model)

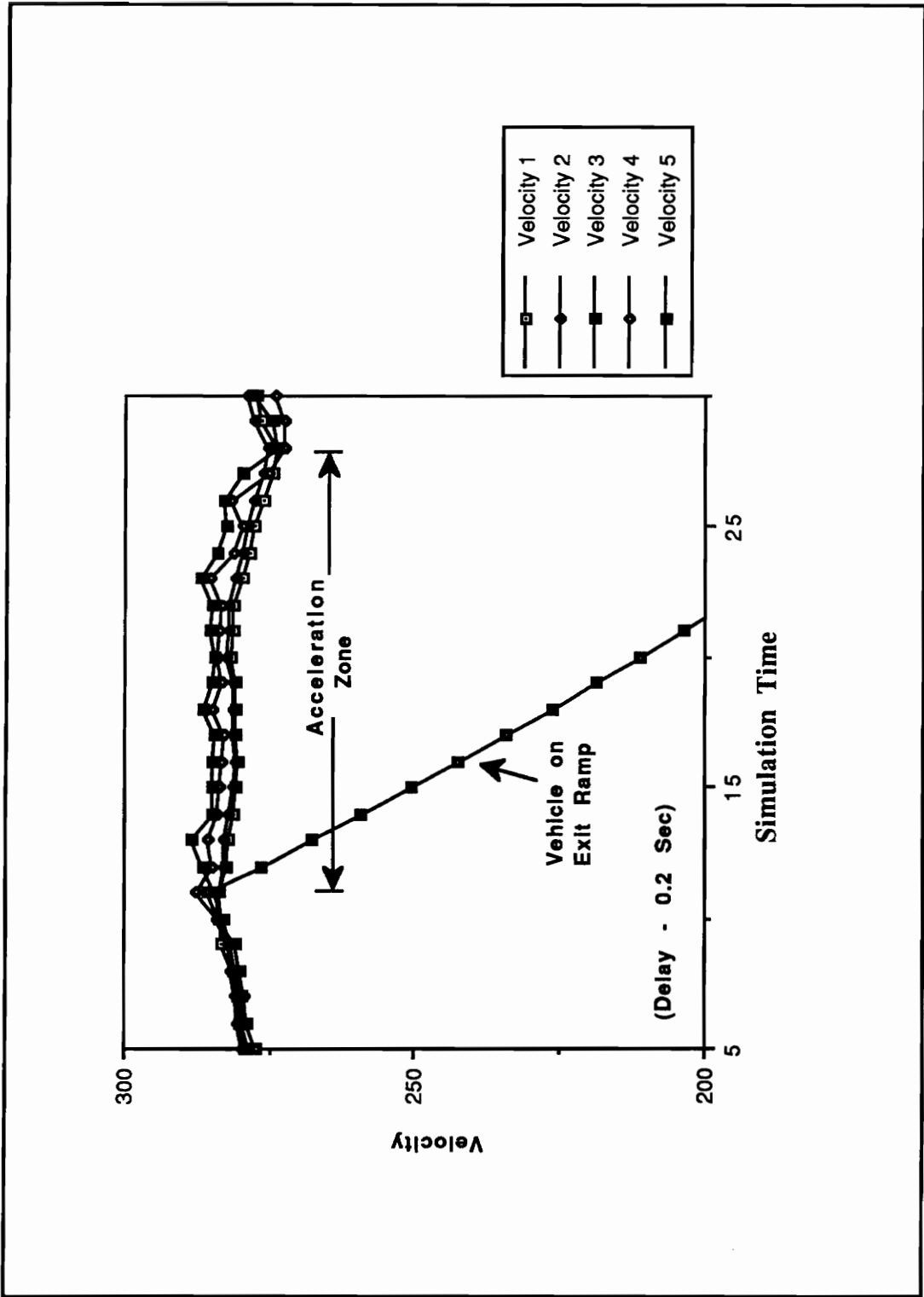


Figure 5.16 Plot Between Velocities and Simulation Time (Ramp Weaving Model)

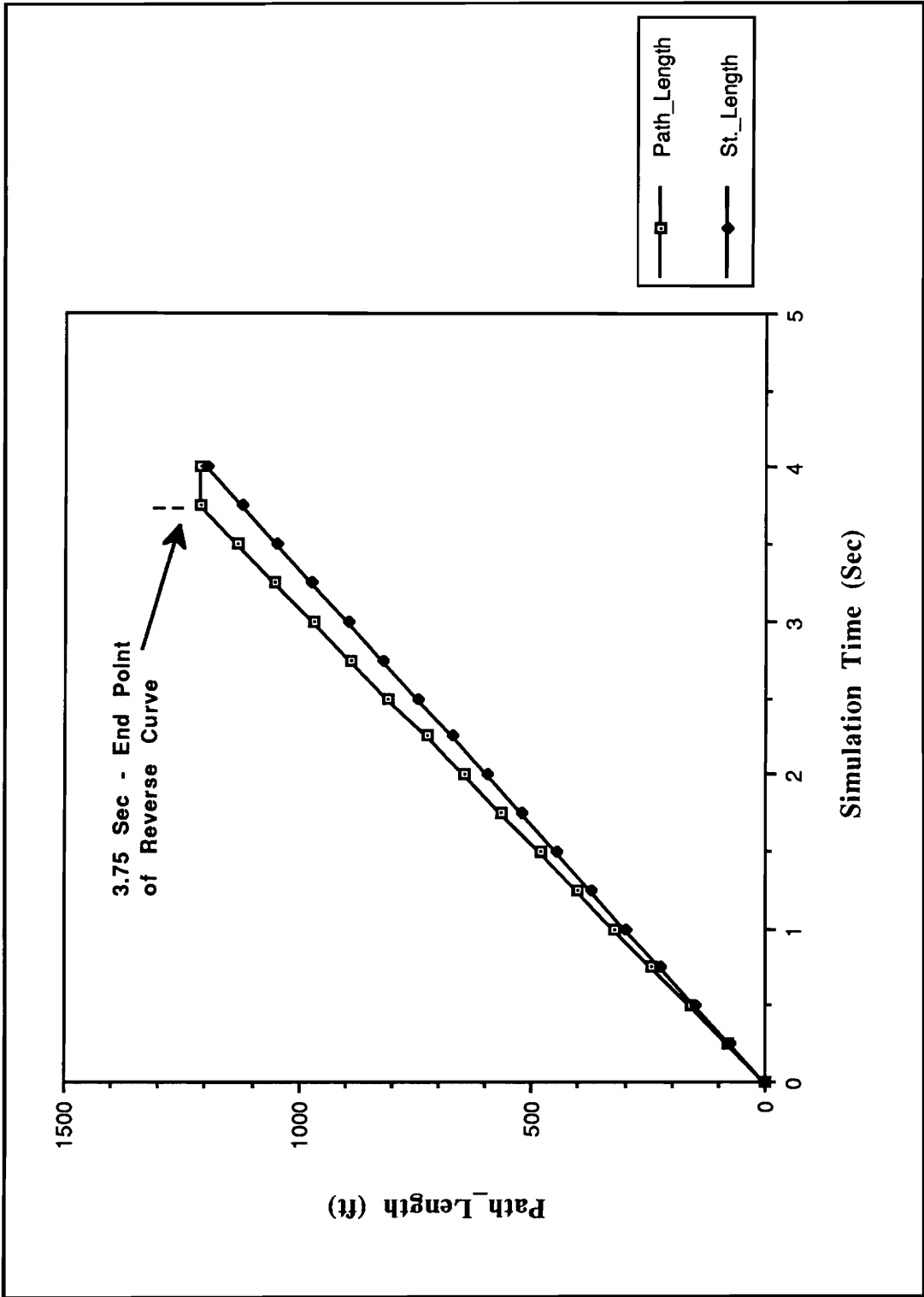


Figure 5.17 Plot Between the Path Length and the Linear Length Covered during Merging Time

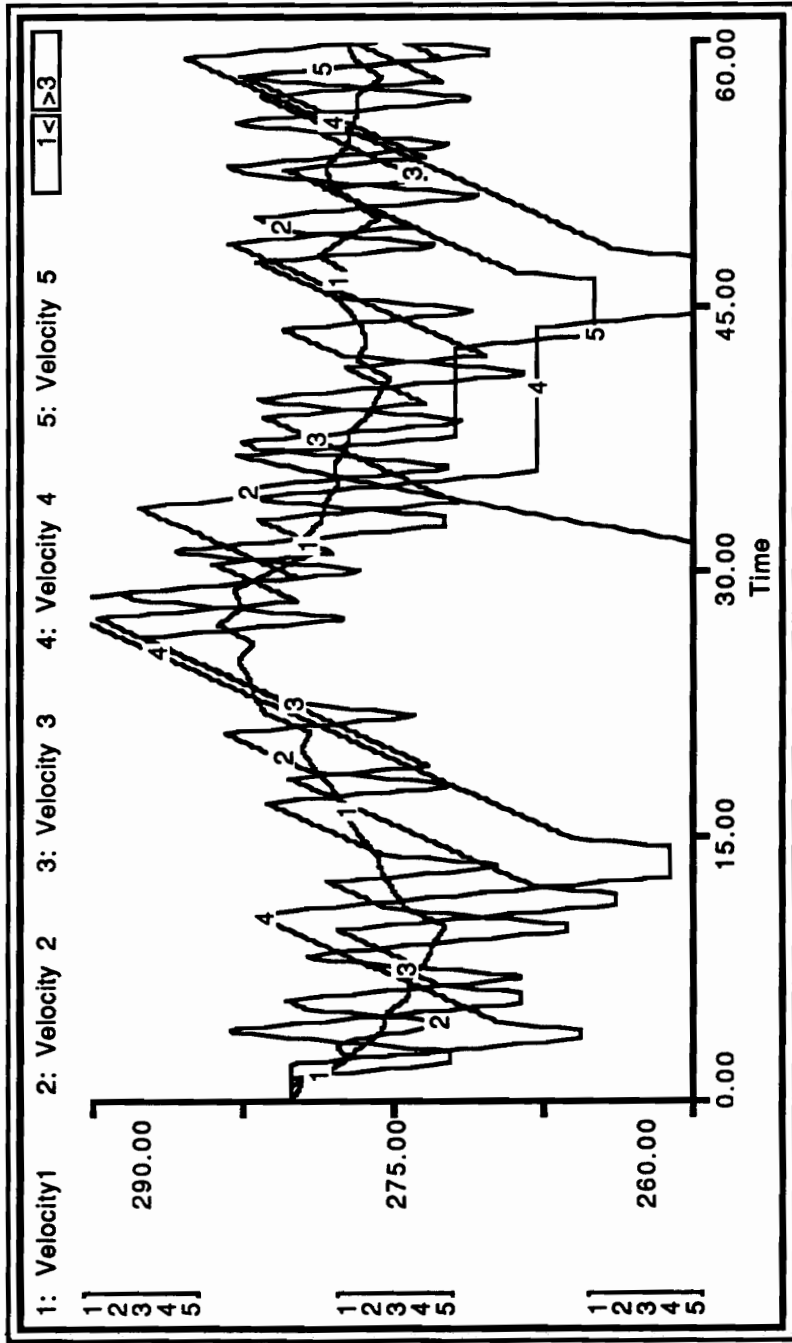


Figure 5.18 STELLA II Comparison of Velocities Under 100 ft Headway Conditions (Delay - 0.6 Sec)

Reverse Curve for Vehicle Lane Change: Figure 5.17 shows the comparison of the path length of the trajectory followed by the vehicle undergoing a lateral displacement towards the freeway lane and its length in the direction parallel to the traffic stream movement until it completes its journey into the freeway lane. Minimum radius required is given by the following equation (Anderson, 1978):

$$a_n = \frac{V^2}{R} \quad (30)$$

where,

R = Radius of curvature (ft)

$a_n$  = Maximum normal acceleration (ft/ Sec<sup>2</sup>)

V = Design speed of the highway (ft/ Sec)

Using a normal acceleration value of 0.05 g/ Sec,

$$\text{Required radius} = 300^2 / (0.1 * 32) = 28125 \text{ ft.}$$

A radius of 30,000 ft has been used resulting in vehicle merger in about 4 seconds as shown in Figure 5.17. A difference of about 90 ft was observed between Path\_Length and straight-line length. The tables generated during the simulation runs for all the three models have been included in Appendix D.

### 5.1.2 Discussion on the Simulation Results

The output of the varied experimentation on the three simulation models developed in this research highlighted several important factors involved in stability of a high-speed traffic stream. Definition of the stability, by itself is a relative term which can vary from a highly oscillatory traffic variation to collision of vehicles. The stability of the model was found to be a function of a number of independent traffic variables.

$$\text{Stability} = f \{N, \pm a, \text{relative velocity}, \Delta t, \text{minimum headway}, dt\}$$

where,

N = Number of vehicles in the stream

a = Allowable acceleration/ deceleration per unit time

$\Delta t$  = Delay or the reaction time of the system

dt = Simulation time interval

The following conditions should be noted:

1. A maximum acceleration/ deceleration of  $10 \text{ ft/sec}^2$  was adopted, which makes it mandatory for the variable acc to curtail values of Acclimit values to this limit.
2. It is a discrete simulation process, whose accuracy is questionable at large simulation intervals.
3. Total number of vehicles allowed by the simulation software was five.

Average vehicle speeds upto 300 ft/ sec have been considered with a time delay of 0.3 seconds was tolerated for a minimum headway of 50 ft for the profile used. The velocity at each point of the first vehicle has been listed in Appendix C. The distance that a lag vehicle covers during the delay amounts to 90 ft, which  $\geq$  50 ft. The results of the simulation have been tabulated in Table 5.1. The range of satisfactory controlled stream performance have been briefly outlined. Further increases in design speed, time delay, and/ or a drastic variation in the profile of the leading vehicle cause instability in the system. Instability raised two options for the developer, increase the minimum headway permitted in the system or reduce the time increment. Both these steps have been tested, producing positive results. The results of the sensitivity analysis have been presented in Table 5.1 for a case of average vehicle speeds in the order of 280 ft/ Sec.

**Table 5.1 Acceptable Range of Delay for Stream Stability**

	Simulation Time Interval	Maximum Reaction Time allowed with Stability
Minimum Headway = 50 ft	0.1 Sec	0.3 Sec
Minimum Headway = 50 ft	0.05 Sec	0.4 Sec
Minimum Headway = 100 ft	0.1 Sec	0.6
Minimum Headway = 100 ft	0.05 Sec	0.7

### **5.1.3 Summary of Modelling Process**

A number of modifications have been made to the original concept of ramp-merging model. To start with, a case of a single vehicle merging compulsorily at the ramp-nose was envisioned. A modification of this idea was a continuous merging of vehicles from the entrance ramp into a gap created between any two vehicles of the freeway stream which lag and lead the merging vehicle. This has been illustrated in figure 4.1. Later, a weaving model was developed using the same set of car following principles. The vehicles which leave the stream start a lateral displacement towards the deceleration lane from a previously defined freeway point. The limitations of normal

acceleration and jerk are strictly adhered to, at every point of simulation. Another addition to the merging section was an "emergency exit lane" which forms as an extension for acceleration lane to accept those vehicles which are found unsuitable for merger due to mechanical failures or other technical snags. The car following theory used in the simulation model was found to possess certain drawbacks as applied to an automated traffic stream. Corrective measures have been taken suitably to account for each of them. These are the following:

1. Deceleration of the vehicles if the headways drop below minimum headway permitted, if the speed of the following vehicle is greater than the leading vehicle.
2. Optimization of traffic throughput by maintaining the acceleration of the vehicle following vehicle at a finite pace, when the headway exceeds the permitted range, until either the headway falls below the maximum headway permitted or the speed of the vehicle exceeds that of the leading vehicle by a specified margin.
3. The model was constrained to maximum acceleration/ deceleration rates, to introduce the element of practicality of the vehicle mechanics.

## 5.2 Design of Geometric Elements of Ramp and Freeway

The design of the geometric elements of the ramp and freeway design involved exploring the length of ramp, length of acceleration lane, radius of the reverse curve for vehicle merging, and the rate of curvature of freeway to aid the vehicle turn with safety and comfort for a given set of design speed, super-elevation, and wind speed conditions and the allowable vertical curvature.

Time taken for vehicle merger from the ramp-nose: A large, constant radius of reverse curve was assumed for the vehicle motion into the express lane. According to the simulation runs, for a design speed of 300 ft/sec, the maximum expected amount of time required for the headway creation was 15 secs. Time required for actual vehicle lane change was about 4 Sec.

The design merging time = 20 sec

Linear distance covered during this period =  $20 * 300 = 6,000$  ft

Hence, an acceleration lane length of 6,000 ft is suggested. It is expected that the angle of turn necessary to be made by the vehicle at the end of the entrance ramp would be quite narrow and the time required to do so would be minute. For a  $2^\circ$  rotation, a ramp with a curve at the end would be sufficient. It should be noted that the actual values obtained from the simulation process were far lesser compared to the value suggested here.

Entrance Ramp Length: According to simulation runs, the time required for the vehicle body to accelerate smoothly to 300 ft/ Sec was about 40 seconds. The distance required for the acceleration process was found to be 6,000 ft, for a given table function for vehicle acceleration. Hence, about 1.5 mile long entrance and exit ramps would be required for the above design speed.

In order to extend the applicability of the investigation of ramp-freeway geometry, a range of entrance & exit ramp lengths and acceleration lane lengths required for a completely automated freeway at different design speeds has been presented in Table 5.2. It should however be noted that the figures quoted herein strictly apply to the acceleration profile used for the ramp vehicle and the average freeway speeds assumed.

**Table 5.2 Ramp and Acceleration Lane Lengths for Various Speeds**

Design Speed	Entrance & Exit Ramp Length	Acceleration Lane Length
100 ft/ Sec	700 ft	1000 ft
200 ft/ Sec	3000 ft	2200 ft
300 ft/ Sec	6000 ft	2500 ft

Horizontal Radius of Curvature: The radius of curvature has been plotted as a function of suspended weight of the vehicle body in figure 5.19. Obviously, the required minimum radius increases with the increase in suspended weight. It was seen that as the height of center of gravity from the ground is raised, the stresses increase linearly. Figure 5.20 shows the variation of radius with increase in stiffness constant,  $k$ . As the vehicle's springs take more and more aerodynamic forces per unit compression of springs, the required radius of curvature reduces. But again, vehicles with greater height of center of gravity prompt an increase in minimum radius of horizontal curve. Figure 5.21 plots design speed on X-axis which exhibits a non-linear relationship with the radius of curvature, the dependent variable on the Y-axis. Four curves were drawn with a difference in 'h' of 0.5 feet between them. The gap between the curves increases with an increase in design speed from 100 ft/ sec<sup>2</sup> to 300 ft/ sec<sup>2</sup>. It was proved that height of C.G. is an important factor of consideration in high-speed vehicle design. The stiffness constant,  $k$  and angle of roll,  $\phi$  should be as high as possible where as the suspended weight should controlled to an extent to optimize the vehicle/ highway design.

# Relationship Between $W_s$ and $R$ (Aerodynamic Considerations)

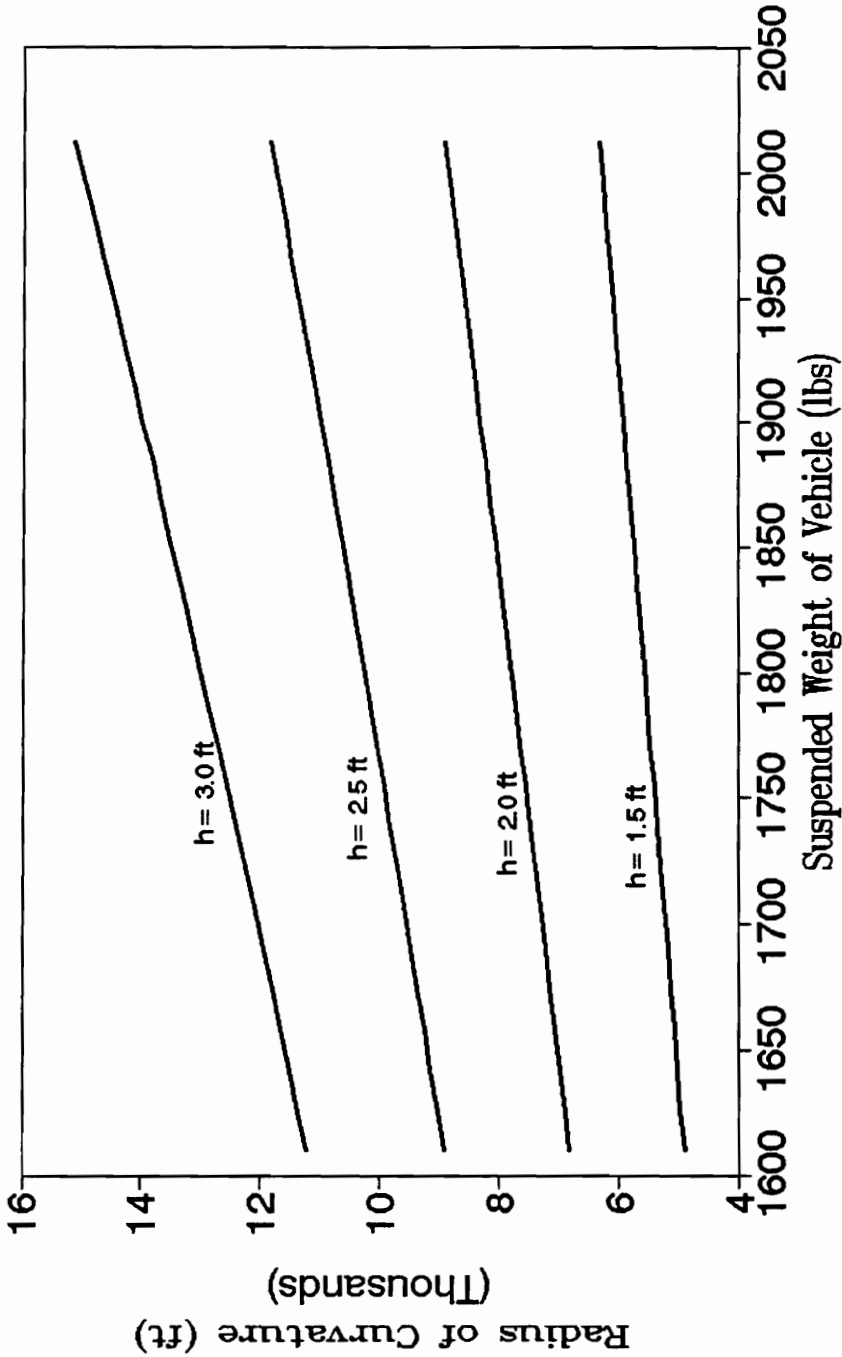


Figure 5.19 Relationship Between Suspended Weight and Radius of Curvature

# Relationship Between K and R (Aerodynamic Considerations)

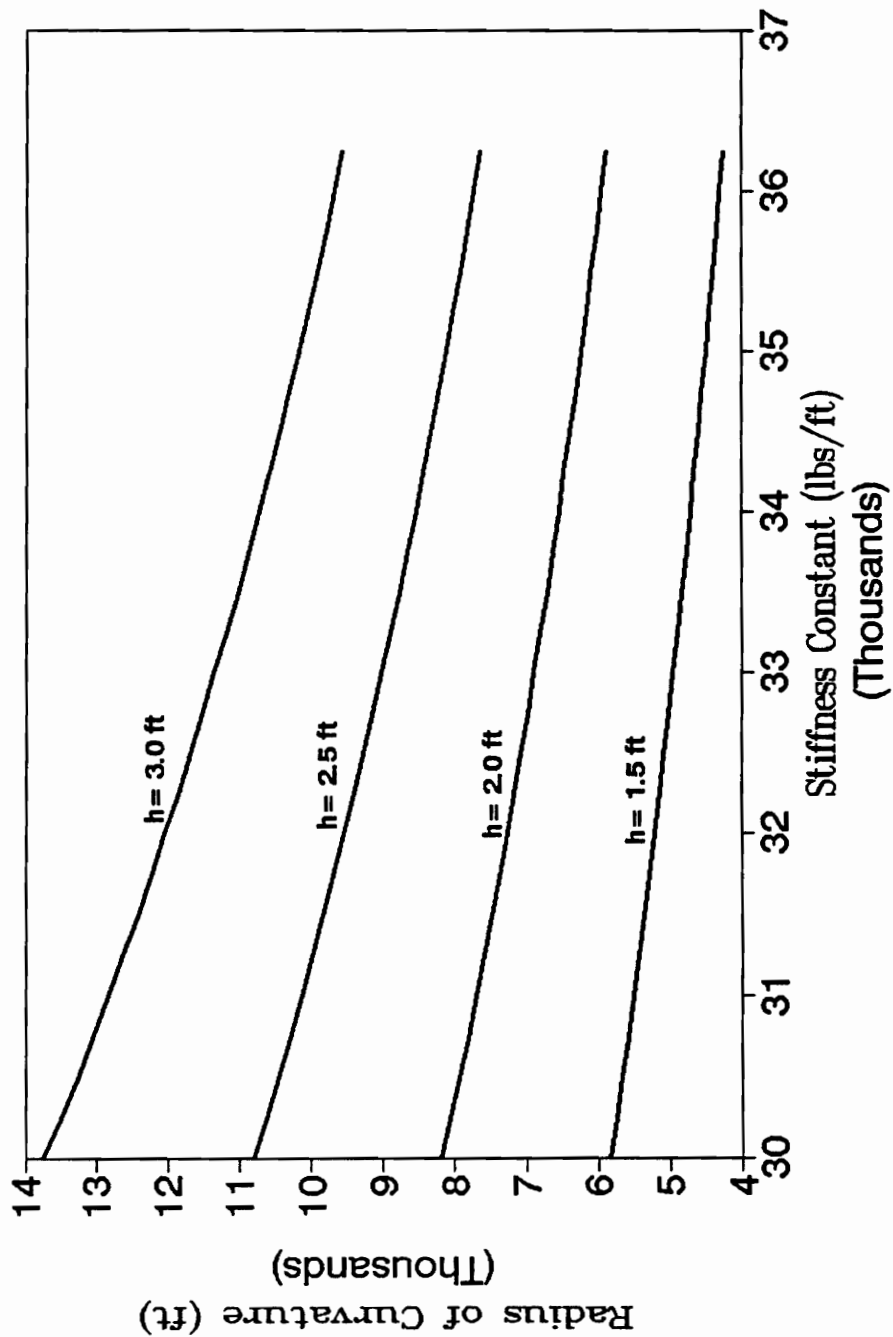


Figure 5.20 Relationship Between Stiffness Constant and Radius of Curvature

# Relationship Between V and R (Aerodynamic Considerations)

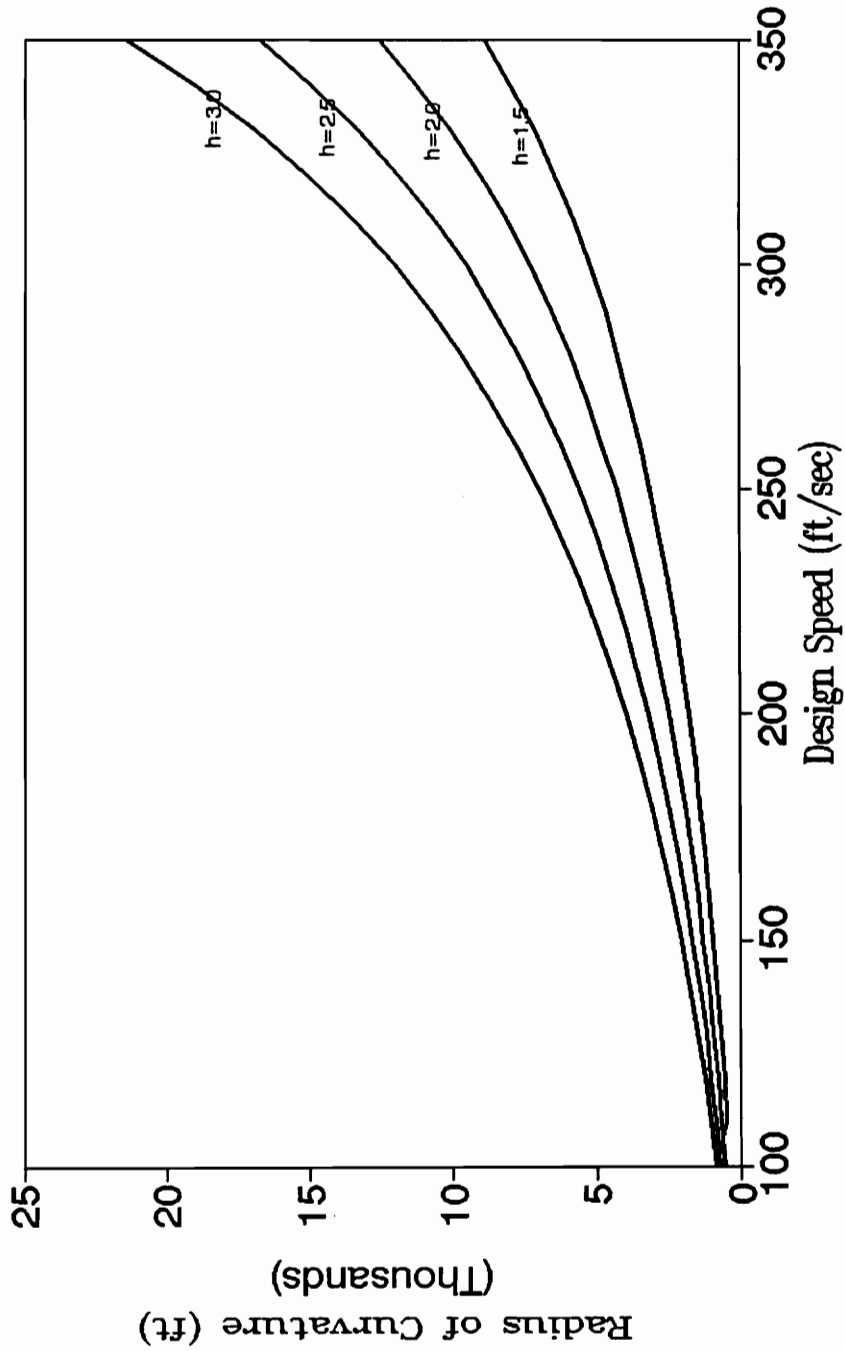


Figure 5.21 Relationship Between Design Speed and Radius of Curvature

The geometric design of horizontal curve has been built from the basic assumptions of steady state motion of the vehicle with the addition of wind affects and guideway curvature. Actually, this analysis is of preliminary nature as the direction of the external wind is extremely important in undertaking a horizontal curve, because the wind force may be directed in one particular direction which might mean a sudden decrease or increase in this component. Each time a car is faced with a side-ward wind component, it passes through two velocity steps (one negative and another, positive). Sedan cars are known to resist the side-ward forces fairly well at the ordinary speeds. Their performance is hampered at high-speeds and remains a matter of research. The studies include the affects of wind gust, overtaking a slower moving or stationary vehicle.

All the theoretical models face the problem of unknown variables and their relative importance with increasing degrees of freedom. There is also the added fear of over-simplification of the model by reducing degrees of freedom which leads to inaccurate results. So, there is a definite tendency to rely on experimental testing. The results obtained from the past experiments were higher compared to those obtained from theoretical methods, which again point out the need for further research, theoretically. The following conclusions are drawn about the vehicle experimentation for aerodynamic affects' determination (Scibor-Rylski, 1984).

1. Experimental testing should be preferred against the standard theoretical models because of the omission of key factors whose degree of cannot be determined by the theoretical means.
2. The test tracks should have the same track properties and camber levels as the actual pavement to be built in future for accuracy in simulation.

Vertical Curve Design: No guidelines are available for vertical curve design for high speed highways. The application of sight distance formulae yielded a length of curve of 3,275 ft for a sag vertical curve. If the maximum normal acceleration allowed is 0.1 g,

$$\text{Time required to travel 3275 ft} = 3275 / 300 = 10.9 \text{ Sec}$$

$$\text{Vertical distance covered in this duration} = 4\% \text{ of } 3275 = 131 \text{ ft}$$

$$\text{Normal acceleration} = (131 / 10.9 - 0) / 10.9 = 12.01 / 10.9 = 1.1 \text{ ft/ Sec}^2 < 3.2 \text{ ft/ Sec}^2$$

Hence the design is satisfactory.

For a crest vertical curve,

$$\text{The minimum length of the vertical curve obtained} = 5,335 \text{ ft}$$

Normal acceleration borne by the passenger against this inclination =

$$\{(5334 * 0.04) / (5335 / 300) - 0\} / (5335 / 300) = 0.67 \text{ ft/ Sec}^2$$

The design is satisfactory.

# 6 CONCLUSIONS

This research approach demonstrated the feasibility of microscopic car following models in the traffic operations of high-speed, high density, automated highway traffic of the future. The conclusions could be divided into two parts. a) those dealing with the STELLA II simulation models and b) those dealing with geometric design process.

## 6.1 Simulation Models

The simulation results support the argument that microscopic traffic flow theories are well suited for development and operation of high-speed vehicles on automated freeways. The factors affecting the performance of model are the headway, vehicle speed, sensitivity, the maximum acceleration/ deceleration limitations, and most importantly, the delay in response of the vehicle control system. Although STELLA II is an easy and comprehensive tool of developing a simulation model, it has the following disadvantages:

1. It is not possible to show a series of vehicles waiting to be merged into a huge stream of freeway vehicles at each ramp, in a series of ramps.
2. It fails to plot the characteristics of the stream of more than 5 vehicles.

3. It takes long simulation time when the simulation time interval ( $dt$ ) is kept low. It however is very sensitive requiring the  $dt$  value to be only a fraction of a second. The velocity and position variables shoot off the time-space diagram for large values of  $dt$ . This however, is not the problem concerning only this model. Under no overtaking scenario and high sensitivity, any model would behave in the same fashion. This could be obviated by small values of  $dt$ .

## 6.2 Geometric Design - Vehicle Aerodynamic Theory

There is an urgent need for development of vehicle technologies to determine the various factors involved in the stability of the vehicle/ track under IVHS conditions, including aerodynamic derivatives and their impact on automated highway/ vehicle design. This should be done by both theoretical and experimental methods with the aid of efficient testing infrastructure/ techniques.

The horizontal curve radii required at high-speed intercity transportation would be far higher compared to the existing interstate highways. The vertical curve limitations support the statement too. Therefore, the existing highways would have to be limited to the applications of advanced technologies to real-time driver information systems and to some extent, the advanced vehicle control systems only. It is felt that to reap the benefits and realize the dreams of advanced stage IVHS systems where the automobiles travel at

speeds in excess of 200 mph, a whole new network of smart highways would have to be built, incurring heavy expenditures and seeking availability of land.

## 6.3 Recommendations

1. The delay of the vehicle response to the real-time changes in traffic conditions should be cut down as much as possible.
2. It is essential to design for excessive length than required, both in case of entrance ramp and the acceleration lane.
3. Redundancy of all the error-prone equipment and automatic detection of breakdowns in one or more parts is mandatory, in addition to the routine manual check-up and replacement of defective infrastructure.
4. Guide the ramp vehicle(s) out of the entrance ramp/ acceleration lane, in case of problem detection, e.g, lack of gap, lack of control over the coordination caused by speed discrepancy.
5. An entirely different strategy of accommodating ramp vehicles should be employed in case of an entrance ramp, bringing traffic from a large metropolis or where the volume of traffic carried is of high order due to another automated freeway passing across this stretch. The suggested strategy is to merge a group of waiting vehicles at the ramp together at a time, by means of regional surveillance management.

# BIBLIOGRAPHY

1. The American Association of State Highway and Transportation Officials, *A Policy on Geometric Design of Highways and Streets*, 1984.
2. Anderson, Edward J., *Transit Systems Theory*, Lexington Books, Lexington, MA 1978, pp 23-46.
3. Barry Richmond, Peter Vescuso and Steve Peterson, *An Academic User's Guide to STELLA*, High Performance Systems, Inc., Lyme, NH, 1987, 392 pages.
4. Drew, D.R., *Traffic Flow Theory and Control*, McGraw-Hill Book Company, New York, 1968.
5. Drew, Donald R., *Freeway Surveillance and Control*, Research Report Number 24-12, Texas Transportation Institute.
6. Frank DeRose, J.R., Lodge Freeway Traffic Surveillance and Control Project, Development and Evaluation, *Highway Research Record 21*, Highway Research Board 1963, pp-69-89.
7. Fred L. Mannering, Walter P. Kilareski, *Principles of Highway Engineering and Traffic Analysis*, John Wiley & Sons, 1990.
8. Garber, Nicholas J. and Hoel, Lester A., *Traffic and Highway Engineering*, West Publishing Company, St.Paul 1988.

9. Greenshields, B.D., Shapiro, D. and Ericuson, E.L., *Traffic Performance at Urban Street Intersections*, Technical Report No. 1, Bureau of highway traffic, Yale University 1947.
10. Institute of Transportation Engineers, *Highway Facts*, 1990-92.
11. International Road Federation, *World Road Statistics* 1983-87.
12. May, Adolf D., *Traffic Flow Fundamentals*, Prentice Hall, New Jersey 1990.
13. May, Adolf D. Jr., Patrick Athol, William Parker and James B. Ruddens, Highway Research Record Number 21, Highway Research Board 1963, pp 48-5
14. Mobility 2000, *Intelligent Vehicle Highway Systems*, Texas Transportation Institute, Texas A&M University, College Station, Texas, 1989.
15. Pershing, B., The Influence of External Aerodynamics on Automotive System Design Requirements, *Advances in Road Vehicle Aerodynamics 1973*, BHRA Fluid Engineering, Bedford, England, 1973.
16. Pinnell, Charles, Donald R. Drew, William R. McCasland and Joseph A. Wattleworth, *Inbound Gulf Freeway Ramp Control Study II*, Research Report Number 24-13, Texas Transportation Institute, July 1965.
17. Scibor-Rylski, *Road Vehicle Aerodynamics*, John Wiley & Sons, New York 1984, 244 pages.

# APPENDIX A - DESCRIPTION OF SIMULATION ALGORITHMS

The Simulation language STELLA II uses certain standard numerical methods to solve the system of equations in a simulation model. There are three simulation algorithms used by STELLA II. They are Euler's method, 2nd order Runge-Kutta and 4th order Runge-Kutta. According to authors, STELLA II follows a two step initialization phase and a three step iterative evaluation phase.

## *Initialization Phase*

Step 1: It creates a list of all equations in required order of evaluation.

Step 2: It calculates initial values for all stocks, flows and converters (in order of evaluation).

## *Iteration Phase*

Step 1: It estimates the changes in stocks over the interval  $DT$ ; and calculates new values for all stocks based on this estimate.

Step 2: It then uses the new values of stocks to calculate new values for flows and converters.

Step 3. It then updates simulation time by an increment of DT; and finally stops when time is greater than simulation stop time.

The most important step is the step 1, where STELLA II calculates the change in level variables over small time increment DT. There are three methods of the estimation of these values namely, Euler's method, 2nd order Runge-Kutta method and 4th order Runge-Kutta method, which are explained briefly below.

## **EULER'S METHOD**

It is the simplest algorithm in STELLA II. The computed values for flows provide the estimate for the change in corresponding stocks over the interval DT. The steps mentioned below are followed.

### *Initialization Phase*

It creates a list of variables and then calculates the initial values for all the terms.

Time = Start Time -----> Time = 0

Stock<sub>t=0</sub> = f(initial values, stocks, converters, flows)---->

INIT (STOCK) = initial value stock variable.

Converters = f(stocks, converters, flows)----> Constant = 'DT' Value

Flows = f(stocks, converters, flows) ----> Equation for flow

### *Iteration Phase*

In this phase it estimates changes in stocks over the interval DT.

$$\Delta = DT * Flow$$

It calculates the new value for stocks based on this estimate.

$$Stock_t = Stock_{t-DT} + \Delta Stock$$

In the second step of this phase, it calculates the values for flows and converters.

Converters = f(stocks, converters, flows)

Flows = f(stocks, converters, flows)

It then updates the simulation time and finally stops when time is greater than simulation stop time.

The above procedure can be best described an approximate solution for a list of equations. The accuracy involved in Euler's simulation algorithm is not so good as compared to the analytical solution, because of integration errors. Although, the error could be reduced by taking smaller time increments, it will also result in increase in number of calculations required.

## **RUNGE-KUTTA METHODS**

The problem mentioned above could be solved to an extent by adapting more sophisticated procedure for estimating the changes in stocks over a given DT. 2nd order Runge-Kutta and 4th order Runge-Kutta methods provide a higher degree of precision.

### **2nd ORDER RUNGE-KUTTA METHOD**

2nd order Runge-Kutta method is the simplest among the two Runge-Kutta methods. This algorithm uses the flow calculations for every iteration to create an estimate for change in a stock over the DT.

#### *Initialization Phase*

This phase is similar to that of Euler's method.

#### *Iteration Phase*

In this phase, if 'x' represents any stock and  $f(t,x)$  represents the functional notation for flows that depend on time 't' and stock 'x', then

Step 1:

$$(1) F1 = DT * f(t,x)$$

$$(2) F2 = DT * f(t+DT,x+F1)$$

$$(3) \Delta Stock = \frac{1}{2} * (F1+F2)$$

where, F1 and F2 are the two components which are averaged to give the change

in stock variables. New values for stocks are based on the estimate,  $Stock_t = Stock_{t-DT} + \Delta Stock$ .

Step 2: The new values for flows and converters are calculated as in Euler's method.

Step 3: The simulation time is updated as before.

The intermediate calculations in step 1, enable the 2nd order Runge-Kutta method to create a more accurate estimate for change in stocks during time interval DT. This estimate is based on an average of flow values computed at the beginning, and at the end of the time interval DT.

#### **4th ORDER RUNGE-KUTTA METHOD**

This algorithm works similar to the 2nd order Runge-Kutta method, but uses four flow calculations in step 1 of the iteration phase, instead of just two. They are mentioned below:

$$F1 = DT * f(t,x)$$

$$F2 = DT * f(t+DT/2, x + 1/2F1)$$

$$F3 = DT * f(t+DT/2, x + 1/2F2)$$

$$F4 = DT * f(t+DT, x + F3)$$

$$\Delta Stock = 1/6 * (F1 + 2F2 + 2F3 + F4)$$

A weighted average of the four calculations is used to create this estimate. F1 represents the rate of change of the stock, i.e, the flow, at the time 't'. F2 is a new calculation of the flow at 1/2 an interval into the future, t+DT/2. F1 is used to update

the stocks, which are then used to re-calculate the flows at the  $t+DT/2$ . One-half of  $F1$  is used in estimating  $F2$  since the calculation of the flow at  $t+DT/2$  interval.  $F3$  is a new calculation of the flow at  $t+DT/2$ .  $F2$  is then used to update stocks, which are then used to re-calculate the flows at  $t+DT/2$ . Again only  $\frac{1}{2}$  of  $F2$  is used to update the stocks since the calculation is made over  $\frac{1}{2}$  interval.  $F4$  is a calculation of the flow at one full interval in the future,  $t+DT$ . To calculate  $F$ ,  $F3$  is used as the flow over the full interval. The stocks are then updated using  $F3$ , then  $F4$  is estimated. The average flow is computed and used to update stock before the next iteration begins.

# **APPENDIX B -**

## **DESCRIPTION OF VARIABLES IN SIMULATION MODELS**

### **RAMP-MERGING AND RAMP-WEAVING MODELS**

Position\_1 = Position of the first vehicle at a particular instant of time

Position\_2 = Position of the second vehicle at a particular instant of time

Position\_3 = Position of the third vehicle at a particular instant of time

Position\_4 = Position of the fourth vehicle at a particular instant of time

Position\_5 = Position of the fifth vehicle at a particular instant of time

Velocity\_1 = Velocity of the first vehicle at any time, as dictated by the user

Velocity\_2 = Velocity of the second vehicle at any time in the direction parallel to the  
guideway

Velocity\_3 = Velocity of the second vehicle at any time in the direction parallel to the  
guideway

Velocity\_4 = Velocity of the second vehicle at any time in the direction parallel to the  
guideway

Velocity\_5 = Velocity of the second vehicle at any time in the direction parallel to the  
guideway

acc\_2 = Controlled acceleration of the second vehicle at any time, in the direction parallel to the guideway

acc\_3 = Controlled acceleration of the third vehicle at any time, in the direction parallel to the guideway

acc\_4 = Controlled acceleration of the fourth vehicle at any time, in the direction parallel to the guideway

acc\_5 = Controlled acceleration of the fifth vehicle at any time, in the direction parallel to the guideway

Dummy\_1 = A rate variable (flow) which feeds in the value of velocity into the stock, Position\_1

Dummy\_2 = A rate variable (flow) which feeds in the value of velocity into the stock, Position\_2

Dummy\_3 = A rate variable (flow) which feeds in the value of velocity into the stock, Position\_3

Dummy\_4 = A rate variable (flow) which feeds in the value of velocity into the stock, Position\_4

Dummy\_5 = A rate variable (flow) which feeds in the value of velocity into the stock, Position\_5

Acclimit2 = An auxiliary variable which feeds the uncontrolled acceleration magnitude obtained from the car following algorithm into the flow, acc\_2

Acclimit3 = An auxiliary variable which feeds the uncontrolled acceleration magnitude

obtained from the car following algorithm into the flow,  $acc\_3$

Acclimit4 = An auxiliary variable which feeds the uncontrolled acceleration magnitude obtained from the car following algorithm into the flow,  $acc\_4$

Acclimit5 = An auxiliary variable which feeds the uncontrolled acceleration magnitude obtained from the car following algorithm into the flow,  $acc\_5$

Design\_Speed = The speed at which the traffic stream is assumed to move

Hdwy\_Margin = Margin of the headway allowed for a lagging vehicle beyond the minimum headway

Headway\_2 = Space headway between the second vehicle with the vehicle it follows

Headway\_3 = Space headway between the third vehicle with the vehicle it follows

Headway\_4 = Space headway between the fourth vehicle with the vehicle it follows

Headway\_5 = Space headway between the fifth vehicle with the vehicle it follows

l = Headway exponent in the car following model

m = Speed exponent in the car following model

MinHdwy = Minimum, safe headway between any two vehicles in the stream under consideration

Min\_Headway = Same value as MinHdwy

RCF = Ramp control factor which assumes a value of 1 in the ramp boundaries (exit ramp and entrance ramp) and 0 elsewhere

relvel2 = Relative velocity (difference in velocities) between the second vehicle of the stream with the vehicle immediately preceding it

relvel3 = Relative velocity (difference in velocities) between the third vehicle of the stream with the vehicle immediately preceding it

relvel4 = Relative velocity (difference in velocities) between the fourth vehicle of the stream with the vehicle immediately preceding it

relvel5 = Relative velocity (difference in velocities) between the fifth vehicle of the stream with the vehicle immediately preceding it

Sensitivity = Degree of sensitivity imposed in the car following system

### **Additional Terms in Ramp-Merging Model**

Vel\_5 = A stock which describes the speed of the fifth vehicle, irrespective of its existence on freeway or ramp

Acc\_Rate = Rate of acceleration of the vehicle on ramp at any instant

Theta = Angle that the straight-line portion of the ramp makes with the freeway

### **Additional Terms in Ramp-Weaving Model**

Exiting\_Time = Time elapsed after the weaving vehicle crosses the Exit\_Ramp\_Point

Vel\_3 = A stock which describes the speed of the third vehicle, irrespective of its existence on freeway or ramp

Exit\_Ramp\_Point = Any defined reference point on the freeway, which is the earliest point at which the weaving operations can start before an exit ramp

Permissible\_dec = Rate of deceleration for the vehicle on the ramp

## REVERSE CURVE MODEL FOR VEHICLE LATERAL DISPLACEMENT

Curve\_Length = The curved length of the trajectory traced by the merging or weaving vehicle from the initial position

Lateral\_Shift = The total amount of lateral displacement of the vehicle from its initial position

Radius = Radius of the circular arc traced by the moving vehicle

Angle\_of\_turn = Total angle of deviation away from the initial X-direction (parallel to the guideway)

Rate\_of\_turn = Angle of deviation over the previous time increment

Rate\_of\_Curvature = Curved length of the guideway over the previous time interval

Rate\_of\_Shift1 = Auxiliary variable, feeding in the value for flow into the stock, Lateral\_Shift, in the first phase

Rate\_of\_Shift2 = Auxiliary variable, feeding in the value for flow into the stock, Lateral\_Shift, in the second phase

Required\_Shift = Total lateral displacement to be achieved by the merging vehicle

Required\_Shift1 = Lateral distance to be covered in the first phase

Required\_Shift2 = Lateral distance to be covered in the second phase

Acc\_due\_to\_gravity = Acceleration of gravity ( $32 \text{ ft/sec}^2$  - a constant)

Direc\_Change = Variable which indicates a change in the direction of curvature of the vehicle moving from acceleration lane to freeway lane

Jerk = Maximum permissible normal jerk for passenger comfort and safety ( $0.05 \text{ g/ Sec}$ )

Normal\_Acceleration = Maximum permissible normal acceleration for passenger comfort and safety (0.1 g)

Required\_Shift = Amount of lateral displacement to be achieved in each phase of merging or weaving

Straightline\_Length = Distance covered by the merging vehicle in the X- direction

Velocity = Velocity of the vehicle taking the curved path

# APPENDIX C - EQUATIONS IN THE STELLA II SIMULATION MODELS

## Ramp Merging Model

Position\_1(t) = Position\_1(t - dt) + (Dummy1) \* dt  
INIT Position\_1 = 156

INFLOWS:

Dummy1 = Velocity1

Position\_2(t) = Position\_2(t - dt) + (Dummy2) \* dt  
INIT Position\_2 = 101

INFLOWS:

Dummy2 = Velocity\_2

Position\_3(t) = Position\_3(t - dt) + (Dummy3) \* dt  
INIT Position\_3 = 53

INFLOWS:

Dummy3 = Velocity\_3

Position\_4(t) = Position\_4(t - dt) + (Dummy4) \* dt  
INIT Position\_4 = 0

INFLOWS:

Dummy4 = Velocity\_4

Position\_5(t) = Position\_5(t - dt) + (Dummy5) \* dt  
INIT Position\_5 = 4350

INFLOWS:

Dummy5 = IF TIME < Time\_for\_acc\_to\_Design\_Speed  
THEN (Velocity\_5 / COS(Theta)) ELSE Velocity\_5

Velocity\_2(t) = Velocity\_2(t - dt) + (acc\_2) \* dt  
INIT Velocity\_2 = 280

INFLOWS:

⚡  $acc\_2 = \text{DELAY}(\text{IF} (\text{Headway\_2} < \text{MinHdwy}) \text{ THEN}$   
 $(\text{IF relvel2} < 0 \text{ THEN } -10 \text{ ELSE } 0)$   
 $\text{ELSE} (\text{IF Acclimit2} < -10 \text{ THEN } -10$   
 $\text{ELSE IF Acclimit2} > 10 \text{ THEN } 10$   
 $\text{ELSE Acclimit2}), 0.2)$

▣  $\text{Velocity\_3}(t) = \text{Velocity\_3}(t - dt) + (acc\_3) * dt$   
INIT Velocity\_3 = 280  
INFLOWS:


⚡  $acc\_3 = \text{DELAY} (\text{IF Headway\_3} < \text{MinHdwy} \text{ THEN}$   
 $(\text{IF relvel3} < 0 \text{ THEN } -10 \text{ ELSE } 0)$   
 $\text{ELSE} (\text{IF Acclimit3} < -10 \text{ THEN } -10$   
 $\text{ELSE IF Acclimit3} > 10 \text{ THEN } 10$   
 $\text{ELSE Acclimit3}), 0.2)$

▣  $\text{Velocity\_4}(t) = \text{Velocity\_4}(t - dt) + (acc\_4) * dt$   
INIT Velocity\_4 = 280

INFLOWS:

⚡  $acc\_4 = \text{DELAY}(\text{IF Headway\_4} < \text{Min\_Headway}$   
 $\text{THEN} (\text{IF relvel4} < 0 \text{ THEN } -10 \text{ ELSE } 0)$   
 $\text{ELSE} (\text{IF Acclimit4} < -10 \text{ THEN } -10$   
 $\text{ELSE IF Acclimit4} > 10 \text{ THEN } 10$   
 $\text{ELSE Acclimit4}),0.2)$

▣  $\text{Vel\_5}(t) = \text{Vel\_5}(t - dt) + (acc\_5) * dt$   
INIT Vel\_5 = 0  
INFLOWS:


`acc_5 = DELAY(IF TIME < Time_for_acc_to_Design_Speed  
THEN Acclimit5  
ELSE (IF Headway_5 < MinHdwy THEN  
(IF relvel5 < 0 THEN -10 ELSE 0)  
ELSE (IF Acclimit5 < -10 THEN -10  
ELSE IF Acclimit5 > 10 THEN 10  
ELSE Acclimit5)), 0.2)`

- `Acclimit2 = IF (Headway_2 > (MinHdwy + Hdwy_Margin) AND  
relvel2 > -5)  
THEN Min_Acc2  
ELSE (sensitivity * Velocity_2^M * relvel2 / Headway_2^L)`
- `Acclimit3 = IF (Headway_3 > (Min_Headway + Hdwy_Margin) AND  
relvel3 > -5)  
THEN Min_Acc3  
ELSE sensitivity * (Velocity_3^M) * relvel3 / (Headway_3^L)`
- `Acclimit4 = IF (Headway_4 > (Min_Headway + Hdwy_Margin) AND  
relvel4 > -5)  
THEN Min_Acc4  
ELSE (sensitivity * (Velocity_4^M) * relvel4 / (Headway_4^L))`
- `Acclimit5 = IF (TIME < Time_for_acc_to_Design_Speed AND  
Vel_5 < Design_Speed) THEN Acc_Rate  
ELSE (IF (Headway_5 > (Min_Headway + Hdwy_Margin) AND  
relvel5 > -5) THEN Min_Acc5  
ELSE sensitivity * (Vel_5^M) * relvel5 / (Headway_5^L))`
- `Acc_Rate = Acc_table / COS(Theta)`
- `Design_Speed = 280`
- `Hdwy_Margin = 5`
- `Headway_2 = Position_1-Position_2`
- `Headway_3 = Position_2-Position_3`

- Headway\_4 = IF (TIME  $\geq$  Time\_for\_acc\_to\_Design\_Speed AND RCF = 1)  
THEN (Position\_5 - Position\_4)  
ELSE (Position\_3-Position\_4)
- Headway\_5 = Position\_3 - Position\_5
- L = 1
- M = 1
- MinHdwy = 50
- Min\_Acc2 = 2
- Min\_Acc3 = 2
- Min\_Acc4 = 2
- Min\_Acc5 = 2
- Min\_Headway = MinHdwy
- RCF = 1
- relvel2 = Velocity1 - Velocity\_2
- relvel3 = Velocity\_2 - Velocity\_3
- relvel4 = IF TIME  $\geq$  Time\_for\_acc\_to\_Design\_Speed  
THEN (Velocity\_5 - Velocity\_4)  
ELSE (Velocity\_3 - Velocity\_4)
- relvel5 = (Velocity\_3 - Velocity\_5)
- sensitivity = 2
- Theta = (PI/180)\*5
- Time\_for\_acc\_to\_Design\_Speed = 36
- Velocity\_5 = Vel\_5
- Acc\_table = GRAPH(Velocity\_5)  
(0.00, 10.0), (20.0, 9.95), (40.0, 9.75), (60.0, 9.70), (80.0, 9.40),  
(100, 9.15), (120, 8.85), (140, 8.50), (160, 8.10), (180, 7.70),  
(200, 7.25), (220, 6.65), (240, 5.80), (260, 4.95), (280, 4.25),  
(300, 3.00), (320, 2.05), (340, 1.10), (360, 0.05), (380, 0.4), (400,  
0.05)

⊗ Velocity1 = GRAPH(TIME)

(0.00, 280), (1.00, 279), (2.00, 276), (3.00, 275), (4.00, 273),  
(5.00, 272), (6.00, 272), (7.00, 272), (8.00, 274), (9.00, 274),  
(10.0, 274), (11.0, 276), (12.0, 275), (13.0, 275), (14.0, 277),  
(15.0, 280), (16.0, 279), (17.0, 282), (18.0, 279), (19.0, 278),  
(20.0, 279), (21.0, 280), (22.0, 280), (23.0, 279), (24.0, 277),  
(25.0, 278), (26.0, 278), (27.0, 279), (28.0, 280), (29.0, 281),  
(30.0, 283), (31.0, 285), (32.0, 286), (33.0, 283), (34.0, 282),  
(35.0, 281), (36.0, 279), (37.0, 280), (38.0, 280), (39.0, 280),  
(40.0, 281), (41.0, 280), (42.0, 279), (43.0, 281), (44.0, 283),  
(45.0, 284), (46.0, 285), (47.0, 286), (48.0, 287), (49.0, 287),  
(50.0, 286), (51.0, 284), (52.0, 283) ...

## Ramp Weaving Model

Exiting\_Time(t) = Exiting\_Time(t - dt) + (Time\_Increment) \* dt  
INIT Exiting\_Time = 0

INFLOWS:

Time\_Increment = IF RCF = 1 THEN (1/DT) \* DT ELSE 0

Position\_1(t) = Position\_1(t - dt) + (Dummy1) \* dt  
INIT Position\_1 = 153

INFLOWS:

Dummy1 = Velocity1

Position\_2(t) = Position\_2(t - dt) + (Dummy2) \* dt  
INIT Position\_2 = 99

INFLOWS:

Dummy2 = Velocity\_2

Position\_3(t) = Position\_3(t - dt) + (Dummy3) \* dt  
INIT Position\_3 = 50

INFLOWS:

Dummy3 = Vel3

Position\_4(t) = Position\_4(t - dt) + (Dummy4) \* dt  
INIT Position\_4 = 1

INFLOWS:

Dummy4 = Velocity\_4

Position\_5(t) = Position\_5(t - dt) + (Dummy\_5) \* dt  
INIT Position\_5 = -50

INFLOWS:

Dummy\_5 = Velocity\_5

Vel3(t) = Vel3(t - dt) + (acc\_3) \* dt  
INIT Vel3 = 280

INFLOWS:

⚙️  $acc\_3 = DELAY (IF (Position\_3 \geq Exit\_Ramp\_Point) THEN$   
-Permissible\_dec  
ELSE (IF Headway\_3 < MinHdwy THEN  
(IF relvel3 < 0 THEN -10 ELSE 0)  
ELSE (IF Acclimit3 < -10 THEN -10  
ELSE IF Acclimit3 > 10 THEN 10  
ELSE Acclimit3)), 0.2)

▣  $Velocity\_2(t) = Velocity\_2(t - dt) + (acc\_2) * dt$   
INIT Velocity\_2 = 280  
INFLOWS:

⚙️  $acc\_2 = DELAY (IF Headway\_2 < MinHdwy THEN$   
(IF relvel2 < 0 THEN -10 ELSE 0)  
ELSE (IF Acclimit2 < -10 THEN -10  
ELSE IF Acclimit2 > 10 THEN 10  
ELSE Acclimit2), 0.2)

▣  $Velocity\_4(t) = Velocity\_4(t - dt) + (acc\_4) * dt$   
INIT Velocity\_4 = 280  
INFLOWS:

⚙️  $acc\_4 = DELAY (IF Headway\_4 < Min\_Headway THEN$   
(IF relvel4 < 0 THEN -10 ELSE 0)  
ELSE (IF Acclimit4 < -10 THEN -10  
ELSE IF Acclimit4 > 10 THEN 10  
ELSE Acclimit4), 0.2)

▣  $Velocity\_5(t) = Velocity\_5(t - dt) + (acc\_5) * dt$   
INIT Velocity\_5 = 280  
INFLOWS:

- $acc\_5 = \text{DELAY} (\text{IF Headway\_5} < \text{Min\_Headway} \text{ THEN} \\ (\text{IF relvel5} < 0 \text{ THEN } -10 \text{ ELSE } 0) \\ \text{ELSE} (\text{IF Acclimit5} < -10 \text{ THEN } -10 \\ \text{ELSE IF Acclimit5} > 10 \text{ THEN } 10 \\ \text{ELSE Acclimit5}), 0.2)$
- $Acclimit2 = \text{IF} (\text{Headway\_2} > (\text{MinHdwy} + \text{Hdwy\_Margin}) \text{ AND} \\ \text{relvel2} > -5) \\ \text{THEN Min\_Acc2} \\ \text{ELSE} (\text{Sensitivity} * \text{Velocity\_2}^M * \text{relvel2} / \text{Headway\_2}^L)$
- $Acclimit3 = \text{IF} (\text{Headway\_3} > (\text{Min\_Headway} + \text{Hdwy\_Margin}) \text{ AND} \\ \text{relvel3} > -5) \\ \text{THEN Min\_Acc3} \\ \text{ELSE Sensitivity} * (\text{Velocity\_3}^M) * \text{relvel3} / (\text{Headway\_3}^L)$
- $Acclimit4 = \text{IF} (\text{Headway\_4} > (\text{Min\_Headway} + \text{Hdwy\_Margin}) \text{ AND} \\ \text{relvel4} > -5) \\ \text{THEN Min\_Acc4} \\ \text{ELSE Sensitivity} * (\text{Velocity\_4}^M) * \text{relvel4} / (\text{Headway\_4}^L)$
- $Acclimit5 = \text{IF} (\text{Headway\_5} > (\text{MinHdwy} + \text{Hdwy\_Margin}) \text{ AND} \\ \text{relvel5} > -5) \\ \text{THEN Min\_Acc5} \\ \text{ELSE Sensitivity} * (\text{Velocity\_5}^M) * \text{relvel5} / (\text{Headway\_5}^L)$
- $\text{Exit\_Ramp\_Point} = 3000$
- $\text{Hdwy\_Margin} = 5$
- $\text{Headway\_2} = \text{Position\_1} - \text{Position\_2}$
- $\text{Headway\_3} = \text{Position\_2} - \text{Position\_3}$
- $\text{Headway\_4} = \text{IF Exiting\_Time} > 0 \text{ THEN} (\text{Position\_2} - \text{Position\_4}) \\ \text{ELSE} (\text{Position\_3} - \text{Position\_4})$
- $\text{Headway\_5} = \text{Position\_4} - \text{Position\_5}$

- L = 1
- M = 1
- MinHdwy = 50
- Min\_Acc2 = 2
- Min\_Acc3 = 2
- Min\_Acc4 = 2
- Min\_Acc5 = 2
- Min\_Headway = MinHdwy
- RCF = IF (Position\_3 ≥ Exit\_Ramp\_Point) THEN 1 ELSE 0
- relvel2 = Velocity1 - Velocity\_2
- relvel3 = Velocity\_2 - Velocity\_3
- relvel4 = IF Exiting\_Time ≥ 0 THEN (Velocity\_2 - Velocity\_4)  
ELSE (Velocity\_3 - Velocity\_4)
- relvel5 = Velocity\_4 - Velocity\_5
- Sensitivity = 2
- Velocity\_3 = IF Exiting\_Time > 0 THEN 0 ELSE Vel3
  
- Permissible\_dec = GRAPH(Vel3)  
(0.00, 0.00), (20.0, 0.25), (40.0, 0.65), (60.0, 1.10), (80.0, 2.05),  
(100, 3.00), (120, 4.25), (140, 4.95), (160, 5.80), (180, 6.65),  
(200, 7.25), (220, 7.70), (240, 8.10), (260, 8.50), (280, 8.85),  
(300, 9.15), (320, 9.40), (340, 9.70), (360, 9.75), (380, 9.95),  
(400, 10.0)
- Velocity1 = GRAPH(TIME)  
(0.00, 280), (1.00, 277), (2.00, 278), (3.00, 277), (4.00, 278),  
(5.00, 279), (6.00, 280), (7.00, 281), (8.00, 281), (9.00, 283),  
(10.0, 283), (11.0, 284), (12.0, 282), (13.0, 282), (14.0, 281),  
(15.0, 281), (16.0, 280), (17.0, 281), (18.0, 281), (19.0, 281),  
(20.0, 282), (21.0, 281), (22.0, 281), (23.0, 280), (24.0, 279),  
(25.0, 278), (26.0, 276), (27.0, 274), (28.0, 274), (29.0, 276),  
(30.0, 277)

## Vehicle Lane Change Merging Model

▣ Angle\_of\_turn(t) = Angle\_of\_turn(t - dt) + (Rate\_of\_turn) \* dt  
 INIT Angle\_of\_turn = 0

INFLOWS:

⊗ Rate\_of\_turn = IF Lateral\_Shift < Required\_Shift  
                   THEN (Normal\_Acceleration^2) /  
                           (2 \* Jerk \* Velocity)  
                   ELSE 0

▣ Lateral\_Shift(t) = Lateral\_Shift(t - dt) + (Rate\_of\_Shift) \* dt  
 INIT Lateral\_Shift = 0

INFLOWS:

⊗ Rate\_of\_Shift = IF Lateral\_Shift < Required\_Shift1  
                   THEN Rate\_of\_Shift1  
                   ELSE Rate\_of\_Shift2

▣ Path\_Length(t) = Path\_Length(t - dt) + (Rate\_of\_Curvature) \* dt  
 INIT Path\_Length = 0

INFLOWS:

⊗ Rate\_of\_Curvature = Rate\_of\_turn \* Radius

○ Acc\_due\_to\_gravity = 32.2

○ Direc\_Change = IF Rate\_of\_Shift1 ≥ Required\_Shift1  
                   THEN 1 ELSE 0

○ Jerk = 0.5 \* Acc\_due\_to\_gravity

○ Normal\_Acceleration = 0.2 \* Acc\_due\_to\_gravity

○ Radius = 3e4

○ Rate\_of\_Shift1 = IF Lateral\_Shift < Required\_Shift1  
                   THEN (Velocity \* SIN (Rate\_of\_turn))  
                   ELSE 0

- Rate\_of\_Shift2 = IF  $0 \leq (\text{Lateral\_Shift} - \text{Required\_Shift1}) < \text{Required\_Shift2}$   
THEN Velocity \* SIN(Rate\_of\_turn)  
ELSE 0
- Required\_Shift = Required\_Shift1 + Required\_Shift2
- Required\_Shift1 = 6
- Required\_Shift2 = 6
- Velocity = GRAPH(TIME)  
(0.00, 300), (2.50, 298), (5.00, 299), (7.50, 300), (10.0, 299),  
(12.5, 302), (15.0, 300), (17.5, 301), (20.0, 301), (22.5, 299),  
(25.0, 300), (27.5, 300), (30.0, 296)

# **APPENDIX D - TABLES IN THE SIMULATION MODELS**

Numerous tables have been generated in the process of simulation model development and validation. Sample tables for position, velocity, and headway variables, have been given in this Appendix, from the output of the simulation model "Ramp Merging Model" which was run with a delay of 0.2 Secs.

**Table of Positions and Simulation Time (Ramp Merging - Delay 0.2 Secs)**

	TIME	Position_1	Position_2	Position_3	Position_4	Position_5
1	0.000	153.000	99.000	50.000	1.000	3950.000
2	1.000	431.400	377.610	329.200	280.950	3955.038
3	2.000	706.800	653.886	603.833	555.400	3970.153
4	3.000	982.400	928.616	878.028	827.400	3995.344
5	4.000	1261.533	1206.820	1154.580	1102.452	4030.612
6	5.000	1544.133	1488.673	1434.560	1381.733	4075.957
7	6.000	1826.533	1772.056	1717.390	1663.491	4131.378
8	7.000	2109.667	2054.469	1999.195	1947.398	4196.875
9	8.000	2392.000	2338.908	2280.795	2227.953	4272.449
10	9.000	2672.533	2619.076	2563.594	2511.021	4358.100
11	10.000	2951.933	2899.285	2845.476	2793.604	4453.827
12	11.000	3232.067	3178.062	3124.565	3074.276	4559.631
13	12.000	3513.000	3459.328	3405.922	3352.986	4675.511
14	13.000	3795.133	3740.314	3686.399	3634.313	4801.468
15	14.000	4080.733	4025.067	3968.642	3915.316	4937.501
16	15.000	4365.600	4311.584	4253.825	4200.029	5083.611
17	16.000	4647.000	4594.270	4540.769	4486.687	5239.797
18	17.000	4925.400	4873.619	4821.790	4771.946	5406.060
19	18.000	5203.467	5151.141	5098.403	5048.144	5582.400
20	19.000	5480.867	5429.517	5376.696	5324.708	5768.816
21	20.000	5759.000	5706.952	5653.228	5604.016	5965.309
22	21.000	6040.600	5987.825	5932.304	5879.739	6171.878
23	22.000	6325.733	6271.711	6214.583	6161.496	6388.523
24	23.000	6613.267	6559.147	6498.862	6445.347	6615.246
25	24.000	6898.600	6845.538	6785.142	6731.140	6852.044
26	25.000	7179.467	7127.349	7071.501	7018.994	7098.920
27	26.000	7459.000	7406.556	7354.820	7303.520	7355.871
28	27.000	7741.133	7687.295	7634.730	7584.438	7622.900
29	28.000	8024.600	7970.916	7918.023	7865.148	7899.809
30	29.000	8309.200	8254.682	8201.297	8146.209	8180.832
31	30.000	8594.133	8540.191	8486.320	8423.319	8460.905

	TIME	Position_1	Position_2	Position_3	Position_4	Position_5
32	31.000	8876.000	8823.548	8770.779	8700.430	8740.978
33	32.000	9156.533	9103.979	9051.464	8977.541	9020.602
34	33.000	9438.867	9385.750	9332.229	9252.701	9297.675
35	34.000	9722.367	9669.173	9615.067	9526.812	9574.749
36	35.000	10007.733	9953.709	9898.549	9800.972	9851.822
37	36.000	10292.067	10239.569	10184.997	10078.111	10129.695
38	37.000	10572.467	10520.742	10468.839	10359.181	10413.209
39	38.000	10849.867	10798.843	10748.760	10643.120	10695.822
40	39.000	11126.933	11075.385	11025.019	10920.342	10971.587
41	40.000	11401.733	11351.534	11301.291	11196.365	11247.021
42	41.000	11676.400	11625.619	11573.405	11472.499	11522.777
43	42.000	11951.800	11902.011	11849.546	11744.167	11794.689
44	43.000	12227.933	12175.338	12123.896	12016.424	12072.494
45	44.000	12507.000	12453.879	12400.781	12292.081	12345.999
46	45.000	12788.067	12734.362	12680.242	12568.161	12624.526
47	46.000	13068.467	13015.714	12961.011	12847.201	12904.978
48	47.000	13346.400	13294.284	13241.430	13128.241	13187.470
49	48.000	13625.533	13572.682	13518.808	13411.042	13465.978
50	49.000	13907.600	13854.201	13798.923	13688.991	13744.266
51	50.000	14189.533	14136.593	14081.618	13969.558	14024.645
52	51.000	14468.400	14416.609	14363.235	14252.166	14307.264
53	52.000	14747.000	14694.100	14641.327	14536.773	14590.924
54	53.000	15024.867	14972.716	14920.659	14817.388	14869.243
55	54.000	15303.000	15249.616	15197.663	15096.308	15147.797
56	55.000	15583.000	15529.543	15476.856	15373.319	15423.444
57	56.000	15863.000	15809.543	15756.862	15649.476	15702.467
58	57.000	16144.067	16090.085	16036.903	15929.474	15982.467
59	58.000	16425.533	16371.832	16318.367	16209.518	16262.998
60	59.000	16706.000	16652.578	16599.629	16491.019	16545.005
61	60.000	16987.067	16933.039	16879.976	16772.533	16825.774

**Table of Velocities and Simulation Time (Ramp Merging - Delay 0.2 Secs)**

	TIME	Velocity_1	Velocity_2	Velocity_3	Velocity_4	Velocity_5
1	0.000	280.000	280.000	280.000	280.000	0.000
2	1.000	277.000	277.408	276.000	279.000	10.038
3	2.000	274.000	273.477	276.667	272.000	20.076
4	3.000	277.000	275.862	275.225	272.000	30.115
5	4.000	281.000	279.215	279.801	278.581	40.153
6	5.000	284.000	281.623	284.174	279.120	50.191
7	6.000	281.000	284.423	285.844	281.206	60.229
8	7.000	285.000	284.179	279.160	281.653	70.267
9	8.000	280.000	280.979	282.760	284.117	80.306
10	9.000	281.000	282.195	282.360	283.734	90.344
11	10.000	278.000	279.808	278.808	283.348	100.382
12	11.000	282.000	282.375	277.346	279.756	110.420
13	12.000	280.000	280.833	281.092	282.300	120.458
14	13.000	284.000	283.192	279.362	280.788	130.497
15	14.000	287.000	285.517	284.184	283.163	140.535
16	15.000	283.000	287.517	286.184	284.787	150.573
17	16.000	280.000	279.586	285.784	286.397	160.611
18	17.000	277.000	275.934	276.510	280.747	170.649
19	18.000	279.000	277.201	279.165	273.747	180.688
20	19.000	276.000	274.877	279.898	280.215	190.726
21	20.000	280.000	278.022	277.973	274.873	200.764
22	21.000	283.000	281.903	281.279	279.873	210.802
23	22.000	287.000	287.559	283.279	281.492	220.840
24	23.000	288.000	288.555	285.279	283.126	230.879
25	24.000	283.000	284.116	287.279	284.696	240.917
26	25.000	279.000	280.802	284.479	286.235	250.955
27	26.000	280.000	281.714	279.279	284.328	260.993
28	27.000	284.000	284.214	279.137	282.111	271.031
29	28.000	283.000	283.659	283.358	284.111	281.070
30	29.000	286.000	285.686	282.464	277.111	280.073
31	30.000	284.000	283.330	286.231	277.111	280.073

	TIME	Velocity_1	Velocity_2	Velocity_3	Velocity_4	Velocity_5
32	31.000	280.000	279.264	284.274	277.111	280.073
33	32.000	281.000	279.021	281.733	277.111	277.073
34	33.000	283.500	281.513	282.702	274.111	277.073
35	34.000	283.500	282.276	284.691	274.111	277.073
36	35.000	287.000	286.413	284.713	275.111	277.073
37	36.000	282.000	283.502	287.691	276.070	281.073
38	37.000	279.000	281.202	279.099	286.070	284.673
39	38.000	276.000	278.903	276.210	282.168	278.273
40	39.000	278.000	279.112	273.875	273.262	278.254
41	40.000	272.000	271.771	276.264	273.840	276.865
42	41.000	277.000	275.721	271.264	276.217	271.252
43	42.000	274.000	274.077	279.105	269.217	276.265
44	43.000	278.000	277.077	272.075	275.617	274.665
45	44.000	280.000	278.755	279.474	272.817	277.034
46	45.000	282.000	280.318	281.829	278.040	278.692
47	46.000	279.000	277.845	282.136	280.040	281.492
48	47.000	277.000	275.710	280.728	282.040	283.492
49	48.000	281.000	279.323	278.841	281.640	273.801
50	49.000	283.000	281.667	282.195	278.808	279.350
51	50.000	281.000	280.789	283.795	281.608	281.619
52	51.000	277.000	277.788	281.246	283.608	283.619
53	52.000	280.000	281.131	276.544	285.608	280.819
54	53.000	276.000	278.923	277.185	275.750	280.819
55	54.000	280.000	279.792	274.780	277.239	278.947
56	55.000	280.000	279.999	280.032	273.955	276.947
57	56.000	280.000	280.000	280.000	279.997	279.997
58	57.000	282.000	281.667	280.165	280.000	280.000
59	58.000	281.000	280.657	282.227	280.175	281.612
60	59.000	280.000	279.645	281.239	282.982	280.646
61	60.000	282.000	281.232	280.583	281.273	279.692

**Table of Headways and Simulation Time (Ramp Merging - Delay 0.2 Secs)**

	TIME	Headway_2	Headway_3	Headway_4	Headway_5
1	0.000	54.000	49.000	49.000	-3900.000
2	1.000	53.790	48.410	48.250	-3625.838
3	2.000	52.914	50.053	48.433	-3366.320
4	3.000	53.784	50.588	50.628	-3117.316
5	4.000	54.713	52.241	52.128	-2876.033
6	5.000	55.460	54.113	52.827	-2641.397
7	6.000	54.477	54.666	53.898	-2413.988
8	7.000	55.198	55.274	51.797	-2197.680
9	8.000	53.092	58.113	52.842	-1991.654
10	9.000	53.458	55.481	52.573	-1794.506
11	10.000	52.648	53.809	51.873	-1608.351
12	11.000	54.005	53.497	50.289	-1435.066
13	12.000	53.672	53.406	52.936	-1269.589
14	13.000	54.819	53.915	52.086	-1115.069
15	14.000	55.667	56.425	53.326	-968.859
16	15.000	54.016	57.758	53.797	-829.786
17	16.000	52.730	53.501	54.082	-699.029
18	17.000	51.781	51.829	49.844	-584.270
19	18.000	52.326	52.738	50.259	-483.997
20	19.000	51.350	52.820	51.989	-392.120
21	20.000	52.048	53.724	49.212	-312.081
22	21.000	52.775	55.521	52.565	-239.574
23	22.000	54.022	57.128	53.087	-173.940
24	23.000	54.119	60.285	53.515	-116.383
25	24.000	53.062	60.397	54.002	-66.903
26	25.000	52.118	55.848	52.507	-27.419
27	26.000	52.444	51.736	51.300	-1.051
28	27.000	53.839	52.564	50.293	11.831
29	28.000	53.684	52.893	34.660	18.214
30	29.000	54.518	53.385	34.623	20.465
31	30.000	53.942	53.871	37.586	25.415

	TIME	Headway_2	Headway_3	Headway_4	Headway_5
32	31.000	52.452	52.769	40.548	29.800
33	32.000	52.554	52.515	43.061	30.862
34	33.000	53.117	53.521	44.974	34.554
35	34.000	53.194	54.105	47.937	40.319
36	35.000	54.024	55.160	50.849	46.727
37	36.000	52.497	54.572	51.584	55.302
38	37.000	51.725	51.903	54.028	55.630
39	38.000	51.024	50.083	52.702	52.938
40	39.000	51.548	50.366	51.244	53.432
41	40.000	50.200	50.243	50.657	54.269
42	41.000	50.781	52.214	50.278	50.628
43	42.000	49.789	52.465	50.522	54.857
44	43.000	52.595	51.442	56.070	51.402
45	44.000	53.121	53.098	53.918	54.781
46	45.000	53.705	54.120	56.366	55.716
47	46.000	52.753	54.703	57.777	56.033
48	47.000	52.116	52.854	59.229	53.959
49	48.000	52.851	53.874	54.936	52.831
50	49.000	53.399	55.278	55.275	54.657
51	50.000	52.940	54.976	55.087	56.973
52	51.000	51.791	53.374	55.099	55.971
53	52.000	52.900	52.773	54.151	50.403
54	53.000	52.151	52.056	51.856	51.416
55	54.000	53.384	51.953	51.489	49.866
56	55.000	53.457	52.687	50.124	53.412
57	56.000	53.457	52.680	52.991	54.395
58	57.000	53.982	53.181	52.993	54.437
59	58.000	53.702	53.464	53.481	55.369
60	59.000	53.422	52.950	53.987	54.623
61	60.000	54.027	53.064	53.241	54.202

# VITA

Venkata Giri Nanduru was born on August 16, 1969, in Hyderabad, a south Indian city. His brothers (who are presently employed as engineers in India) greatly influenced him to pursue engineering as a profession while his father was instrumental in his visit to the United States for graduate studies. Soon after his graduation from Osmania University, Hyderabad with a bachelor's degree in Civil Engineering in June 1990, he joined the master's program in Civil Engineering at Virginia Tech (August 1990). After graduating in October 1992, the author plans to work in the field of highway and transportation engineering.

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