# System Dynamics Model for Testing and Evaluating Automatic Headway Control Models for Trucks Operating on Rural Highways

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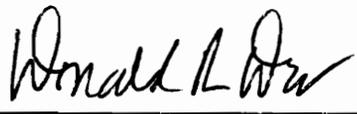
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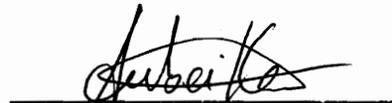
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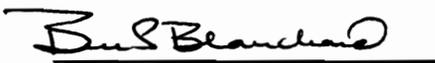Donald R. Drew, Chairman
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(ABSTRACT)

The objective of this research is to explore a methodology that can be used for testing and evaluating AVCS technologies, and, in particular, automatic headway control models for trucks operating on rural highways. The emphasis is put on the realization of vehicle headway control in the real world highway systems. System dynamics has been selected as the simulation tool for developing, testing and evaluating vehicle headway control models. The following behavior of human driver in a real world highway environment is studied and simulated. An automatic headway control model, Multiple-mode Vehicle Headway Control (MVHC) model, is developed for single lane, cars and trucks mixed flow control in a rural highway system. Using safety and motorist comfort as MOE criteria and the acceleration noise as the index of motorist comfort, some selected automatic headway control models are evaluated. This study demonstrated that simulation affords a means of modeling control processes with various certain and uncertain factors, and therefore, it plays a key role in the development of automatic headway control systems.

# Acknowledgment

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# 1. Introduction

## 1.1 Surface Transportation Systems: Yesterday and Today

America's transportation system has been a key factor in the nation's development and prosperity. Surface transportation was once a pride of Americans. The vast network of transportation facilities helped to compress the vast geographic expanse of the continent into a surprising close-knit society, whose residents feel at home wherever their wheels may take them.

Mobility became an integral part of agriculture, manufacturing, the life of a city, programs of education, access to sports and recreation, and the conduct of international trade, travel, and investment. North Americans were propelled into new ways of living through the forces generated by a transportation system accounting for 10,000 ton-miles for freight per capita per year and 10,000 miles of travel for every person inhabiting the continent.[1] Although airlines provide a great portion of transportation of people and goods, motor vehicles continue to be the principal means of transportation in the United States.

Now the surface transportation system in the United States is at a crossroad. As the traffic volume on major highway system increases year after year, the level of service of the roadway system within major cities deteriorates rapidly. The mobility Americans prized so highly is threatened by congestion, accidents, low productivity, and pollution.

Congestion continues to increase and many of the nation's roads around metropolitan areas are badly clogged. Congestion costs the nation an estimated $100 billion each year.[1] Safety continues to be a prime concern. In 1991, 41,000 people died in traffic accidents, and more than 5 million were injured. Traffic accidents drain away about $70 billion per year.[2] Inefficient movement of vehicles reduces productivity, wastes energy, and increases pollution; buses, trucks, and automobiles idled on road waste billion of gallons of fuel and needlessly emit tons of pollutants each year.

Although traffic demand keeps increasing nationwide, the conventional approach of the past, building more roads or adding more lanes, can not work in many areas of the country, for financial, land resource, and environmental reasons.

Recognition of these problems led to the passage of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). The purpose of ISTEA is " … to develop a National Intermodal Transportation System that is economically sound, provides the

foundation for the Nation to compete in the global economy, and will move people and goods in an energy efficient manner."[3, 4]

## 1.2 Intelligent Transportation Systems: Tomorrow

There is no single answer to the whole set of complex transportation problems we are facing today. A group of technologies known as Intelligent Transportation Systems (ITS) (referred as IVHS-Intelligent Vehicle Highway Systems in its early stage) thus emerged as a combination effort of governments, private sectors, and universities. ITS is composed of a number of technologies, including information processing, communications, control, and electronics. Joining these technologies to the surface transportation system can save lives, time, and money.

The goals for ITS are to improve safety, reduce congestion, enhance mobility, minimize environmental impact, save energy, and promote economic productivity. Five functional subjects have been identified as major ITS programs.[5,6] These are:

- Advanced Traveler Information Systems (ATIS)

  ATIS will provide a variety of information that assists travelers in reaching a desired destination via private vehicle, public transportation, or combination of the two.[7]

- Advanced Traffic Management Systems (ATMS)

ATMS will integrate management of various roadway functions, including freeway ramp metering and arterial signal control. Furthermore, ATMS will predict traffic congestion and provide alternative routing instructions to vehicles over wide areas.[8] Therefore, it can maximize the efficiency of the highway network.

- Advanced Vehicle Control Systems (AVCS)

AVCS will enhance the driver's control of vehicle to make travel safer and more efficient. Accidents can be avoided, as opposed to just having their consequences mitigated. AVCS includes a broad range of concepts that will become operational on different time scale.[9]

- Commercial Vehicle Operations (CVO)

CVO is an application that use the technologies of the first three subjects on the operations of fleets of trucks, buses, vans, taxis, and emergency vehicles.[10]

- Advanced Public Transportation Systems (APTS)

APTS will use constituent technologies of ATMS, ATIS, and AVCS to improve operation of high occupancy vehicles, including transit, buses, carpools and vanpools.[5]

Now the sixth area, Advanced Rural Transportation Systems (ARTS), has been defined and added to the ITS program.

ITS can help tremendously in meeting the goals of ISTEA and begin a new era in transportation in the United States. The succeed of ITS will bring tremendous benefits to the surface transportation systems of the country in the future. It is estimated that ITS can reduce traffic fatalities by eight percent by the year of 2011, and reduce traffic congestion as much as twenty percent in cities that adopt ITS technologies.[5,11,12] Improved efficiency of transportation will boost economic productivity, since nearly all economic activity uses transportation directly or indirectly.

## 2. Advanced Vehicle Control Systems

## 2.1 Introduction

Intelligent Transportation Systems (ITS) is a program aimed at solving surface transportation problems by providing drivers traffic information, vehicle control assistance, and advanced traffic management. Among all the ITS subjects, Advanced Vehicle Control Systems (AVCS) plays the key role for eventually solving the transportation problems we are facing today.

Advanced Vehicle Control Systems include individual vehicle controls, cooperative driver-vehicle-highway systems, and eventually full automation on certain roadways. AVCS combines sensors, computers, and control systems in the vehicle and in the infrastructure to warn and assist drivers in controlling the vehicles, or even assuming the control task from the drivers. The purposes of AVCS include achieving much higher vehicle safety levels, ameliorating urban freeway congestion, achieving a new standard of inter-city highway productivity, and eventually creating entirely new concepts for surface transportation services.

AVCS can enhance the control of vehicle by facilitating and augmenting driver performance. The AVCS technologies will enable drivers to operate their vehicles closer together while maintaining a higher level of safety than at present, by enhancing driver's ability to detect and avoid hazards and eventually by assuming responsibility for controlling the speed, steering, and braking of the vehicles. By compensating for the limitations of the human driver, AVCS makes it possible to achieve increases in road capacity and safety rather than just offering incremental percentage improvements.

With the development and realization of AVCS, significant benefits will be brought into surface transportation systems. These include: major increases in highway system capacity that are much less expensive and more environmentally acceptable than that achievable by adding additional lanes, easier and safer travel for even less skilled and elderly drivers, and productivity increases for commercial vehicle operators.

## 2.2 AVCS Concepts

AVCS will be built upon the technologies developed and deployed during the other facets of the overall ITS program to solve the safety and congestion problems of the transportation systems.

The technologies involved in advanced vehicle control systems include: [5,9]


- Driver warning, vision enhancement, and assistance systems

- Automatic headway control and automatic steering control

- Obstacle avoidance or automatic braking

- Automatic trip routing and scheduling

- Control merging of streams of traffic

- Transition to and from automatic control


AVCS is not a single operational concept, but a broad range of capabilities that will be translated into products and systems in an evolutionary progression. Three stages of AVCS technology are anticipated and planned. [9,13] These are:


- AVCS-I:     Autonomous Driver-Vehicle Systems

- AVCS-II:    Cooperative Driver-Vehicle-Highway Systems

- AVCS-III:   Automated Vehicle-Highway Systems


Comparing with human driving process, the three stages of AVCS will bring the progress into surface transportation as: stimulus enhancement, perception enhancement, and full automated highways.

## 2.2.1 AVCS -I: Autonomous Driver-Vehicle Systems

AVCS-I includes only those advanced vehicle control systems that are vehicle based, i.e. they are only self-contained within the vehicle and do not require the existence of any roadway or roadside equipment to perform their desired functions. The principal benefit provided by AVCS-I is safety improvement. With development and deployment of AVCS-I devices and technologies, there will be significant reduction in the yearly toll of crashes, fatalities, and injuries.

The principles of AVCS-I can be summarized as: combinations of specifically designed sensors detect imminently dangerous situations. The system provides visual or auditory warning to the driver, and, in later evolutionary stage, automatically takes control actions, such as applying the brakes to avoid collisions.

Some studies have shown that 50 percent of all rear end and intersection-related collisions and 30 percent of collisions with oncoming traffic could have been avoided had the driver recognized the danger half second earlier and reacted correctly.[14,15] The technologies included in AVCS-I have the potential to provide a fraction of seconds to expand the driver's margins for safety in high risk environment. They can help drivers sense impending danger, alert them of lapse in their judgment or skills, aid them in performing the driving task and, ultimately, compensate for some of their errors.

## 2.2.2 AVCS -II: Cooperative Driver-Vehicle-Highway Systems

AVCS-II requires both vehicle and highway based equipment and utilizes the vehicle to vehicle and roadway to vehicle communication systems developed in ATMS and ADIS. AVCS-II begins implementation of a driver-vehicle-highway system whereby vehicle lateral and longitudinal position is controlled when suitable equipped vehicles are operated on dedicated instrumented lanes.

The principal benefits of AVCS-II will include increased travel speed and enhanced safety. Adding vehicle to vehicle and roadway to vehicle communication can enhance system performance, increase potential safety improvement, and yield some increases in roadway throughput, thus beginning the evolution toward higher levels of control.

## 2.2.3 AVCS-III: Automated Vehicle-Highway Systems

AVCS-III includes complete automation of the driving function for vehicles operating on specially equipped freeway facilities. It incorporates elements in both vehicles and roadway to provide "automatic chauffeuring" of vehicles from arrival at the freeway on-ramp to departure from the freeway off-ramp.

More significant increases in both safety and capacity are achievable when AVCS-III are implemented. Faster and more precise automated control will permit vehicles to operate with closer longitudinal and lateral spacing and while traveling at higher speeds without sacrificing safety. The capacity of the existing road system will be significantly increased.

## 2.3 AVCS Technologies

AVCS technologies provide significant potential for improvement in traffic safety and roadway capacity, initially by means of warning and collision avoidance systems and eventually through various stages of automatic control. Although AVCS is generally regarded as the most long-term of the ITS functional areas, AVCS research and development has been in progress in a variety of forms for over 30 years.[9,16] Some technologies for AVCS (anti-lock brakes, traction control, active suspension, four-wheel steering) are available as either standard or optional equipment on motor vehicles today and are increasing their market penetration.

Driver warning, perception enhancement, and assistance/control systems are under active research, development, and testing in the United States, Europe, and Japan by motor vehicle manufacturers, as well as by large and small component supplier companies. The

Europe PROMETHEUS program includes various "Common European Demonstrator" projects in the areas including driver warning, perceptual enhancement, and assistance/control. The application of fully autonomous vehicle concepts to road transportation has received more attention in Japan, with the projects in the Personal Vehicle System (PVS) and Super-Smart Vehicle Systems (SSVS) programs. Work on those concepts has also been conducted in the United States industrial and academic sectors. Much work is based on military development of "Autonomous Land Vehicles", which are designed to operate in hazardous, unstructured off-road environments.

Vehicle-highway automation is currently being pursued under the California PATH Program. Research, development, and small-scale testing have already been conducted. Large-scale testing under realistic operation conditions is planned during the next several years. The work is beginning toward demonstrating the feasibility of significantly increasing the density of vehicles in a lane of traffic, thereby enabling dramatic increases in effective freeway capacity.

## 2.4 AVCS Development

The major factors affects driving safety and road capacity are: perception-reaction time of human driver, spacing between vehicles and speed of operation. AVCS will bring an

evolutionary progress into surface transportation system, from operating assistance to human driver to fully automatic control on dedicated freeway.

AVCS-I provides drivers technical aids on individual vehicle, which can keep detecting the changes of driving environment and thus decreases the perception time of human drivers.

With vehicle to vehicle and roadway to vehicle and partial automatic control, AVCS-II not only provides further decrease in perception time of human driver, but also the reaction time to impending danger, thus provides further enhancement of traffic safety. Moreover, with the technologies of AVCS II, such as platooning, the roadway capacity will be greatly increased.

AVCS-III will eventually take over the driving task on automated freeways. It can take a very quick response to any changes of operating environment. The time delay caused by human driver perception and reaction will be reduced to a fraction of original value, as sensor and information processing time. With this advantage, AVCS-III can significantly increase travel speed while decrease the spacing between vehicles, provide great improvement for both safety and capacity.

# 3. Commercial Vehicle Operation

## 3.1 Introduction

The activities of ITS America with respect to ITS technologies will ultimately involve all types of vehicles. Commercial Vehicle Operations (CVO) systems are specially concentrated on the application of these technologies to commercial vehicles. Commercial vehicles include trucks, delivery vans, inter-buses, and emergency vehicles. CVO studies aim at increasing safety, expediting deliveries, improving operational efficiency, and decreasing operational cost.[10]

CVO has unique needs because of the special operating requirements of commercial vehicles. Commercial vehicles are identified either by their physical characteristics (heavy trucks) or by the type of function that they perform (ambulance or taxi). All of these vehicles are normally operated more hours per day than a typical passenger car. Therefore, commercial vehicle may require system designs with greater safety and reliability.

The application of ITS technologies will improve the safety, productivity, and regulation of all commercial vehicle operations. Safety is enhanced both for commercial

vehicle operators and for other drivers affected by them. Productivity is enhanced because more effective fleet management tools are available to the private sector, thereby facilitating efficient fleet management and administration. Regulation cost is reduced as the result of reductions in administration labor.

The capabilities of CVO included in ITS are built upon a broad range of technologies and applications under development, many of which also address non-CVO vehicles and operators.[5] Commercial vehicles will benefit not only from the technologies above, but also from the research and operational tests, and deployment activities proposed by other ITS efforts dealing with ATMS, ATIS, and AVCS. The early application of ITS technologies to CVO offers the U.S. a unique opportunity to accelerate the development of ITS systems for non-commercial drivers.

## 3.2 CVO Concepts

Commercial Vehicle Operations systems apply various ITS technologies to improve the safety and efficiency of commercial vehicle and fleet operations. CVO builds on the functional areas of ATMS, ATIS, and AVCS. The primary technologies currently identified for special consideration in commercial vehicle operations include:

- Advanced Traveler Information Systems (ATIS)

- Automatic Vehicle Identification (AVI)

- Automatic Vehicle Classification (AVC)

- Automatic Vehicle Location (AVL)

- Weigh-in-Motion (WIM)

- On-board Computer (OBC)

- Two-way Real-time Communication (TWC)

- Automatic clearance Sensing (ACS)

Commercial vehicle operators are the leading-edge users of currently available ITS technologies (automatic vehicle location, tracking and two-way communications; etc.). Some commercial users are investing in these technologies to increase productivity, reduce costs, and increase profit. In many instances, the ITS systems that are developed for ATMS, ATIS, or AVCS are likely to be first implemented on commercial vehicles. Thus, CVO can serve as the logical testing ground for many additional ITS technologies before they are made available to other motorists.

Current developments in advanced technologies and their application to commercial vehicles have three basic goals: (1) improving productivity in private sector portion of commercial operators, (2) improving efficiency and effectiveness of traffic management and administration by transit agencies, state and local governments, and (3) improving safety for commercial vehicle operations and others affected by them.

The changes in domestic and global competition have required commercial carriers to provide faster, more reliable, and more cost effective services. ITS technologies are emerging as the key tools for carriers to reduce costs and improve productivity. Automatic vehicle location, tracking and two-way communications, routing algorithms, in-vehicle text and map displays are making possible faster dispatching, fuel-efficient routing, and more timely pick ups and deliveries. These productivity improvements have a direct impact on the quality and competitiveness of U.S. businesses and industries at the local, national, and international levels.

The safety goal of CVO is to significantly reduce fatalities, injuries, property damage, and productivity loss from crashes involving commercial vehicles. Many motor carrier safety regulations exist to reduce safety hazards, such as extreme driver fatigue and vehicle brake failure. A number of CVO initiatives will apply technology to improve driver and vehicle compliance with those safety regulations. Advanced vehicle control technologies will provide for enhanced safety. A variety of perceptual enhancement features (such as assisted night/fog vision), warning systems (such as obstacle warning), and vehicle control systems (such as automated braking) provide significant safety benefits to commercial vehicle operators.

Many of the proposed CVO applications and systems are directed at improving the timeliness, efficiency, and accuracy of commercial vehicle operations. Improvements are

achieved by automating existing manual procedures, electronically capturing and reporting data, and improving the flow of information between carriers and regulatory agencies and between operators and dispatchers. The efficiencies come from simplification or elimination of the efforts required by the motor carrier industry to comply with various regulations and from overall improvements in fleet management.

Some of the CVO benefits from the adoption of ITS technologies can be, and are already being, achieved through private actions. Thousands of heavy trucks are already equipped with automated location systems and two-way radios that link drivers with their dispatch centers. Automated Vehicle Identification systems are already automating toll collection and thus improving traffic in some states. A number of commercial and public fleet operators use Automatic Vehicle Location systems, with which dispatchers can instantly determine the location of any vehicles.

## 3.3 Trucks in the US Transportation Systems

Trucks represent a major portion of commercial vehicles. In the past decades, there has been enormous growth in the trucking industry. The industry has been seeking means to increase its productivity by increasing the load-carrying capacity of trucks. This has been achieved through increased vehicle size and weights and through the use of tractor

multiple trailer combinations. Now trucks constitute more than twenty percent of total motor vehicles operating on the nation's highways. [5,15,17]

## 3.3.1 Truck Design Characteristics

Trucks consist of single unit trucks and combination trucks, i.e. tractor trailers. According to the 1982 Surface Transportation Assistance Act and states imposed limitations, the truck design characteristics are:[18]

- **Length** The standard length is 48 feet for single trailers and 28 ft for doubles. The overall vehicle length of double trailer combination can be up to 75 feet.

- **Width** According to the 1982 STAA, the width limit of truck is 102 inches.

- **Height** The 1982 STAA did not affect State control of vehicle height restrictions. Height limits among the States range from 12 feet 6 inches to 14 feet 5 inches with the most prevalent being 13 feet 6 inches.

- **Weight** The weight provisions of the 1982 STAA apply only to the Interstate systems. The limits are 80,000 pounds maximum gross, 34,000 pounds per tandem axle, and 20,000 pounds per single axle.

## 3.3.2 Truck Operating Characteristics

Because of their configuration, large trucks have some special operating characteristics which must be considered in vehicle control system design and highway facility design. These characteristics include:[18,19]

- **Offtracking**

Offtracking occurs when successive axles on a vehicle follow different paths as a vehicle turns. The distance between the path of the tractor's front axle and the path of the rearmost trailer axle as a vehicle negotiates a particular turn is the amount of offtracking for that turn. If these two paths deviate from one another too much, the vehicle can not stay within its proper lane, either the front of the vehicle must swing into opposing lanes of traffic or the rear wheels must run off the roadway or into adjacent lanes to make the turn. All vehicles offtrack to a certain extent at low speeds, but in general, the longer the vehicle and the fewer the number of articulation points, the greater the offtracking.

- **Backing Up**

Semitrailer combinations can be backed up with relative ease and control by the driver. Double or triple combinations do not share the same backing qualities as a semitrailer combination because of the additional articulation points.

- **Braking**

Large variances in braking ability may exist among trucks because of brake condition, weather, loading and other variables. Vehicles with more articulation points are more likely to become unstable if their wheels lock. Empty or lightly loaded trucks have a greater tendency to jackknife and require greater distances for stopping than heavily loaded trucks.

- **Rearward Amplification**

Rearward amplification is a characteristic of multi-trailer trucks where the lateral acceleration of the tractor is amplified rearward to the point where the rear trailer might roll over. A double combination has an amplification ratio of about 2.0, which means the trailer experiences twice the lateral acceleration of the tractor. This can result in a driver making an evasive maneuver that feels safe, but can cause the rear trailer to roll over.

## 3.4 CVO Safety Issues

### 3.4.1 Commercial Vehicle Safety Problems

Operating safety is the primary concern of most ITS functional areas. It is of special importance for CVO due to the operating characteristics of commercial vehicles.

Commercial vehicles are involved in a relatively small share of all motor vehicle accidents, but in a higher share of fatal accidents. When differences in travel by vehicle type are taken into account, the accidents involvement rates for commercial vehicles are lower than those of passenger cars but are higher for fatal accidents.[5] That is partly due to the fact that a higher share of commercial vehicle travel is on rural highways, where speeds are high and accidents tend to be more severe, and partly due to the difference in size and weight between those vehicles and passenger cars.

Vehicles with significantly different operating and design characteristics share the nation's highway systems. In the past decades, the nation invested in smaller passenger cars for fuel efficiency and larger trucks for productivity. Now they are operated together on very congested highways, many of which were designed for fewer cars and smaller trucks. The mixed truck/car flow aggravates the traffic situation on many highways.

## 3.4.2  Accident Factors

Like motor vehicle accidents in general, commercial vehicle accidents are caused by the interaction of road, human, environmental, and vehicle factors. The following gives the major truck accident factors.

- Highway Factors: Road characteristics have important influence on traffic accidents and their consequences. Highway causes of commercial vehicle accidents include roadside objects, lane widths, pavement strengths, intersection turning radii and other physical features. Most of the existing highways accommodate passenger cars more adequately than large trucks. Many roadside restraining structures were intended to be functionally adequate for cars only, thus may contributes to heavy truck accidents.[20]

- Driver Factors: The most important human factors for safe driving are driver perception time, reaction time, visual acuity, judgment and performance. Most vehicle accidents are attributed to "driver error". Driver causes of vehicle accidents include extreme fatigue and boredom, emotional instability, and driving while intoxicated. All of these can greatly reduce driver's vigilance, increase their perception-reaction time, and impair their abilities for judgment and performance. Because of the long driving hours, commercial vehicle drivers are more likely to get fatigued or bored, and thus their chances of being involved in an accident are increased.[21,22]

- Vehicle Factors: Vehicle causes of commercial vehicle accidents include vehicle configuration and vehicle equipment conditions. Double trailer trucks and vehicles with equipment defects are overinvolved in crashes. Brake defects and steering defects tend to be the leading factors of vehicle accidents. The results a two-year period truck crashes investigation conducted in Washington State show that trucks

with brake defects had a crash risk one and one-half times than that for trucks without brake defects, and trucks with steering defects had a risk that was at least twice that of trucks without defects.[17,23]

## 3.4.3 CVO Safety Related Technologies

Most safety-related ITS systems aim at improving driver performance, and decreasing the probability that a driver will make a serious error. The major safety related ITS systems that specifically address CVO issues are:[10]

- **Driver/vehicle Real-Time Safety Monitoring**  A comprehensive safety system, for driver and vehicle, monitors and electronically records the status of critical safety-related factors and reports on them while the vehicle is traveling. Elements pertaining to the driver include records of duty logs, medical qualification data, and commercial driver's license information. Vehicle related elements include operational data and conditional information, such as status of brakes, lights, tires, and steering. Feedback on potentially dangerous vehicle conditions would be directed to the driver for correction. AVCS capabilities will provide additional warning information and will ultimately provide automated responses to those situations.

- **Hazardous Material Information Systems** Safe shipment of hazardous materials is of great concern to society, to truck operators, and to those who regulate truck movements. Electronic tracking technologies are being developed that hold promise as a means of providing enforcement and incident management response teams with timely, accurate information on cargo contents, enabling them to react properly in emergency situations. Early detection of cargo problems would allow time for the driver to respond and possibly prevent a serious accident.

- **Site-specific Highway Warning Systems for Trucks** Certain highway features cause difficult maneuvering for trucks due to their weight, stability, and acceleration and braking capability. Challenging highway features include steep downgrades, tight ramps, and intersections and railroad grade crossings with limited sight distances. Warning signs and other existing techniques often can not provide commercial vehicle drivers with adequate information to avoid serious accidents. Warning systems that provide information specific to the vehicle and its capabilities in relation to the highway features in question would significantly improve commercial vehicle safety.

- **Automated Mayday Capabilities** Technologies used for vehicle tracking and communications also provide a basis for implementing Mayday capabilities. In emergency situations, drivers would be able to communicate with their dispatchers or with local police agencies.

# 4.  Longitudinal Control Concepts

## 4.1  Introduction

Vehicle longitudinal control has been an active research topic in transportation system studies for many years. It includes manual car following control in early years and automatic vehicle headway control in recent ITS studies. Although having different objectives, both the manual car following control and automatic vehicle headway control studies concentrate on the behavior of a following vehicle with respect to the changes of position and velocity of the vehicle ahead, accelerating to reach a desired speed or braking to avoid collision.

The study of the behavior of car following started in the 1950's and continued in the 1960's.[24,25,26]  The major focus of manual car following studies is the operating strategy of one following vehicle based on the relative distance and relative velocity with respect to the vehicle directly ahead. The study of automatic headway control started in the 1970's and has been increasing rapidly in recent years,  as the congestion and safety  problems on highways nationwide are worsening year after year. Various automatic control laws are  presented  and  various  automatic  control  models  are  developed,  which

give different control strategies, from individual vehicle control to a platoon of vehicles control, from vehicle based control to infrastructure based control. [27,28]

## 4.2 Manual Car Following Concept

The objective of manual car following studies is to investigate those characteristics of both driver and vehicle that are most important in safe automobile driving. Car following theory assumes that the traffic stream is a superposition of vehicle pairs where each vehicle follows the vehicle ahead according to a specific stimulus-response equation that approximates the behavioral and mechanical aspects of the driver-vehicle-road system.[29]

Typical manual car following models are in the form of stimulus-response equations where the response (acceleration or deceleration) of a driver is determined by a stimulus function. The stimulus function involves the relative velocity between the driver's car and the car directly ahead, their relative spacing, the absolute velocity level, the driver's sensitivity, and many other factors, human, mechanical, and environmental.

- Mathematical Model

Gazis, Herman, Potts, and Edie proposed a driver stimulus-response model[30] expressed as the following equation:

$$\frac{d^2 x_{n+1}(t)}{dt^2} = \alpha v_{n+1}(t) \frac{v_n(t-T) - v_{n+1}(t-T)}{[x_n(t-T) - x_{n+1}(t-T)]^p}$$

(4.1)

where:     $x_n$ = the position of car n

$v_n$ = the velocity of car n

$\alpha$ = driver's "sensitivity" factor

$T$ = time lag in driver's response

$p$ = constant, usually 1 or 2

- Driving Mode

The driver, simulated in the model, is governed by the equation above whenever some test value of that driver exceeds a prescribed threshold. Within that threshold, the driver will not consider the relative velocity; his behavior is mainly based on the relative spacing between his car and the car ahead and the particular velocity he wishes to maintain. Outside that threshold, an individual driver will make responses roughly in accordance with the car following model above.

- Desired Spacing

Desired spacing is the major factor used to determine the threshold of mode change. The much quoted "California Driving Law" is supposed to recommend a separation of one car

length for each ten miles per hour of speed of the vehicles concerned. This can be written as the spacing equation below:

$$S=1/k+Tv \qquad (4.2)$$

where:          $S$ = spacing (front bumper to front bumper)

$k$ = jam concentration

$T$ = one car length for each 10 mph

$v$ = velocity

Assuming a car length of 15 feet, this gives for the recommended spacing in feet

$$S=15+1.02v \qquad (4.3)$$

where $v$ is velocity in feet per second.

## 4.3  Automatic Longitudinal Control Concepts

### 4.3.1  Introduction

Automatic longitudinal control is the primary concern of Advanced Vehicle Control Systems. There are two fundamentally different ways of providing automatic longitudinal

control for roadway vehicles: vehicle based control and infrastructure based control. The vehicle based control system uses the differences between the state of each vehicle and the state of its predecessor as the error signals for regulation. The infrastructure based control system uses the differences between the position and/or velocity of each vehicle and the corresponding position and/or velocity of a virtual reference point that moves along the roadway as its error signals.

All the current automatic longitudinal control technologies can be categorized as these two types. The most commonly used longitudinal control strategies are Car Following Control (Platoon Control), Autonomous Intelligent Cruise Control, and Point-Following Control. The former two are vehicle based control while the PFC is Infrastructure based control.

## 4.3.2 Car Following Control Concept

In the car following control approach, the control applied to a vehicle in a line or a platoon of vehicles is determined by its longitudinal states with respect to other vehicles within the platoon. The platoon is closely spaced, containing three or more vehicles. The control of each vehicle depends on its states with respect to all the vehicles ahead of it. In this case, considerable communication within the platoon is necessary.[31,32,33,34]

Using this type of control, a vehicle is warned to brake by a message passed back from vehicle to vehicle within the platoon. When the leading vehicle brakes, each vehicle in a platoon will start to brake at its maximum rate.

This type of control can obtain a quick response for each vehicle in the platoon in case the leading vehicle or any vehicle ahead comes to an emergency stop. By using closely spaced platoons, highway capacity can be increased considerably.[35,36]

### 4.3.3 Autonomous Intelligent Cruise Control (AICC) Concept

In AICC, autonomous control is used by each vehicle to keep a desired distance behind its predecessor, which can be taken as constant for all vehicles at any speed. AICC can operate in the presence of manually controlled vehicles, i.e., mixed-flow AICC.[37,38,39]

AICC is similar to Platoon Control in selection of error signal for the control system. The major difference is that in AICC, the input of the controller of each vehicle only comes from one vehicle ahead of it, so each vehicle needs only detect the state changes of the vehicle directly ahead of it. When it perceives that the vehicle ahead is braking, it will take the safest response to apply its brake fully, a short period after the preceding one has done so. Another difference is that the focus of AICC is safe braking, not close

following, i.e. a vehicle does not necessarily follow a vehicle beyond its desired or design speed.

Since the AICC system does not exchange information with other vehicles, it has less oscillations and slinky-effects, and thus can obtain a smoother response than the car following control. However, it may not get as quick a response to the state changes of the leading vehicle as the car following control.

## 4.3.4 Point Following Control (PFC) Concept

In PFC, a vehicle stays in a slot defined by the infrastructure, which moves along an automated lane. The control of the system comes from the infrastructure, which can advise all vehicles simultaneously of the incident, not only of its occurrence, but of its location. This makes it possible and reasonable to tailor the response to the stimulus.[16,34,40]

The PFC vehicle in the ith slot behind a failed vehicle is assumed to decelerate at either the rate which will bring it to the lengths of the rest i vehicles behind the failure, or at the maximum value of which it is capable, whichever is the smaller.

The PFC approach is easily envisioned by considering an imaginary conveyor belt, which is divided into equally spaced slots, moving at a fixed speed through a highway network. No more than one vehicle would be assigned to each slot, and that vehicle would be required to maintain itself at slot center. This is a synchronous approach as the moving slots would be controlled with respect to a master time reference. This approach would probably result in a considerable simplification in controlling a network of automated vehicles.

## 4.4 Automatic Headway Control Technologies

### 4.4.1 Deterministic Control System

Assuming the key factors in the vehicle-roadway system are deterministic, classical control theory and modern control theory have been widely used in modeling vehicle automatic headway control systems. These control models describe vehicle control process through the vehicle dynamic characteristics. Generally, they take a vehicle as a independent system, or a platoon as an independent system and each vehicle within the platoon as a subsystem. The inputs of the system (or subsystem) are usually the speed and acceleration of the leading vehicle or the vehicle ahead, and the relative distance of a vehicle from the leading vehicle. The outputs of the system could be the

speed and acceleration of the vehicle and its distance from the vehicle ahead. These usually form the feedback system, and the information used to feedback usually comes from the deviation of the desired relative distance and speed.

- **Classical Control Model**

In this type of models, transfer functions are introduced to simulate the information flow from the input to output of the headway control system and PI ( proportional and integral relation between input and output) or PID (proportional, integral, and differential relation between input and output) controllers are used to solve the signal following and stability problems. These are usually third or higher order close-loop systems and the stability of the system could be solved by selecting the parameters of the controller to set up or adjust the system pole points.[34,41]

A typical model of this type is developed by the PATH program, which is a vehicle based control system[41]. Assume a platoon consists of N vehicles. Each vehicle within the platoon gets input only from the vehicle ahead of it. The general control law of the model is described as below.

Assume $\Delta_i$ to be the deviation of the ith vehicle from its assigned position

$$\Delta_1 = x_1 - x_1 - L \tag{4.4}$$

$$\Delta_i = x_{i-1} - x_i - L \tag{4.5}$$

where, $x_i$ is the position of ith vehicle; $x_1$ is the position of leading vehicle; $L$ is the average length of vehicle. The control laws for the linearized vehicle model are

$$c_1 = c_p \Delta_1(t) + c_v \dot{\Delta}_1(t) + c_a \ddot{\Delta}_1(t) + k_v [v_l(t) - v_l(0)] + k_a a_l(t) \tag{4.6}$$

$$c_i = c_p \Delta_i(t) + c_v \dot{\Delta}_i(t) + c_a \ddot{\Delta}_i(t) + k_v [v_{i-1}(t) - v_{i-1}(0)] + k_a a_{i-1}(t) \tag{4.7}$$

Where $v_l(0)$, $v_{i-1}(0)$ denote the initial state values of the leading vehicle's velocity and the (i-1)th vehicle's velocity respectively, and $c_p$, $c_v$, $c_a$, $k_v$, and $k_a$ are design constants. From the equations above, the transfer functions of the control system are obtained as:

$$h(s) = \frac{s^2 - k_a s - k_v}{s^3 + c_a s^2 + c_v s + c_p} \tag{4.8}$$

$$g(s) = \frac{(c_a + k_a)s^2 + (c_v + k_v)s + c_p}{s^3 + c_a s^2 + c_v s + c_p} \tag{4.9}$$

Where $h(s)$ and $g(s)$ are transfer functions in the s domain used to describe the relationship between the input and output of the system. These functions are obtained

through the Laplace transform. The design of the control system is to select a set of parameters to get a stable response curve for the system.

- **Modern Control Model**

In modern control models, state equation is used to describe the vehicle or the system characteristics and real time control algorithm is used to solve the vehicle following problem.[39,42]

A typical model of this type is presented by Nasser Kehtarnavaz and Norman C. Griswold.[42] They used Kalman filter functions in the data processing procedure to diminish the observational errors. This model takes the vehicle speed and steering control according to the vehicle ahead. The input of the system is the relative position of the leading vehicle, which are denoted as the range **d** and the heading angle $\theta$. The general control algorithm of the model can be described as below.

Let $d(t)$ and $\theta(t)$ represent the trajectory of the leading vehicle at time t, and

$$u = \dot{d}, \ a = \dot{u} = \ddot{d}$$

$$w = \dot{\theta}, \ \alpha = \dot{w} = \ddot{\theta}$$

These functions are discretized with a sampling time interval T to yield $d_k$, $u_k$, $a_k$, $\theta_k$, $w_k$, $\alpha_k$. Equations of motion can then be written as follows.

$$d_k = d_{k-1} + Tu_{k-1} + \frac{1}{2}T^2 a_{k-1} + \frac{1}{6}T^3 ea_{k-1} \qquad (4.10)$$

$$u_k = u_{k-1} + Ta_{k-1} + \frac{1}{2}T^2 ea_{k-1} \qquad (4.11)$$

$$a_k = a_{k-1} + Tea_{k-1} \qquad (4.12)$$

$$\theta_k = \theta_{k-1} + Tw_{k-1} + \frac{1}{2}T^2 \alpha_{k-1} + \frac{1}{6}T^3 e\alpha_{k-1} \qquad (4.13)$$

$$w_k = w_{k-1} + T\alpha_{k-1} + \frac{1}{2}T^2 e\alpha_{k-1} \qquad (4.14)$$

Where $ea$ and $e\alpha$ are noise terms that are employed to indicate the uncertainty in the model. Define the state vectors $p_k = (d_k,\ u_k,\ a_k)$ and $q_k = (\theta_k,\ w_k,\ \alpha_k)$, then the following state equations are obtained:

$$p_k = Ap_{k-1} + Hea_{k-1} \qquad (4.15)$$

$$q_k = Bq_{k-1} + He\alpha_{k-1} \qquad (4.16)$$

where $A$, $B$, and $H$ are state transfer functions and shown as below:

$$A = \begin{bmatrix} 1 & T & \frac{1}{2}T^2 \\ 0 & 1 & T \\ 0 & 0 & 1 \end{bmatrix} \qquad (4.17)$$

$$B = \begin{bmatrix} 1 & T & \frac{1}{2}T^2 \\ 0 & 1 & T \\ 0 & 0 & 1 \end{bmatrix} \qquad (4.18)$$

$$H = \begin{bmatrix} \frac{T^3}{6} \\ \frac{T^2}{2} \\ T \end{bmatrix} \qquad (4.19)$$

The observation equations are set up by using the range and heading angle data. These equations are expressed as:

$$\lambda_k = Cp_k + e\lambda_k \qquad (4.20)$$

$$\mu_k = Cq_k + e\mu_k \qquad (4.21)$$

Where $\lambda_k = d_k$, $\mu_k = v_k$, $C = (1 \ 0 \ 0)$, and $e\lambda$ and $e\theta$ are noise terms associated with the observation.

To find an estimator $\hat{p}_k$ of $p_k$, the following Kalman filter equations are used:

$$\hat{p}_k^- = A\hat{p}_{k-1}^+ \tag{4.22}$$

$$\phi_k^- = A\phi_{k-1}^+ A' + E \tag{4.23}$$

$$\Gamma_k = \phi_k^- C'[C\phi_k^- C' + F]^{-1} \tag{4.24}$$

$$\hat{p}_k^+ = \hat{p}_k^- + \Gamma_k[\lambda_k - C\hat{p}_k^-] \tag{4.25}$$

$$\phi_k^+ = [I - \Gamma_k C]\phi_k^- \tag{4.26}$$

Where E=H var[ea}H', F=var[eλ]  are the model and the observation noise covariance matrices, and I is the identity matrix.  The symbol - indicates calculation based on the observations $\lambda_1$, $\lambda_2$,......, $\lambda_{k-1}$, but not $\lambda_k$, whereas the symbol "+" indicates calculation based on the observations $\lambda_1$, $\lambda_2$,......, $\lambda_k$. From the above equations, an estimator $\hat{p}_k^+$ is obtained from only $\hat{p}_k^-$ and $\lambda_k$ in a recursive manner. By considering the initial condition $\hat{p}_0 = (d_0 \quad 0 \quad 0)'$, and $\phi_0 = 0$, the above iterative procedure is initiated to find an estimator based on the observations $\lambda_1$, $\lambda_2$,......, $\lambda_k$.

## 4.4.2  Stochastic Control System

When considering the uncertain environmental factors existing in the vehicle-roadway systems,  stochastic control technologies have been used in headway control system modeling. Using this type of technologies, the automatic headway control is described as

a stochastic process with disturbance consisting of Gaussian random variables. Kalman Filter is often used in data processing.

Niehaus and Stengel presented a model of automated highway driving using Worst Case Decision Making (WCDM) method for automotive guidance.[43] The goal of the model is to plan trajectories that are safe while satisfying drivers' requests based on stochastic information about the vehicle states and the surrounding traffic. WCDM predicts the evolution of a controlled dynamic system's states and its dynamic environment, assuming that the environment may react in several ways to control histories. It selects the worst plausible evolution as basis for allocation of resources. The general control algorithm of the model is described as below.

The control of the discrete time dynamic system is defined by

$$x_{k+1} = f(x_k, k, u_k) + v_k \qquad (4.27)$$

where $x_k \in R^n, u_k \in R^n, v_k \in R^n$ are the state, control and disturbance vectors at time index k. This system is surrounded by an environment

$$y_{k+1} = g(y_k, k, v_k, kw_k) + \eta \qquad (4.28)$$

where $y_k \in R^n$, $\eta_k \in R^n$ are environment state and disturbance vectors. Exterior agents are assumed to control the environment through the control vectors $v_k$ and $w_k$. The former represents a set of S distinct strategies that may be chosen by A agents. The latter represents a set of r additional continuous controls. The state vectors $x_k$ and $y_k$ are assumed to be correlated Gaussian random variables prescribed by their mean value and covariances

$$\hat{x}_k = E(x_k) \tag{4.29}$$

$$P_k = E[(x_k - \hat{x}_k)(x_k - \hat{x}_k)^T] \tag{4.30}$$

$$\hat{y}_k = E(y_k) \tag{4.31}$$

$$Q_k = E[(y_k - \hat{y}_k)(y_k - \hat{y}_k)^T] \tag{4.32}$$

$$R_k = E[(x_k - \hat{x}_k)(y_k - \hat{y}_k)^T] \tag{4.33}$$

where E[.] is the expectation operator. The disturbance inputs $v_k$ and $w_k$ are two uncorrelated zero mean white Gaussian random sequences:

$$E(v_k) = 0 \tag{4.34}$$

$$E(v_k v_k^T) = \Lambda_k \tag{4.35}$$

$$E(\eta_k) = 0 \tag{4.36}$$

$$E(\eta_k \eta_k^T) = M_k \tag{4.37}$$

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The goal of WCDM is to predict how $x_k$ and $y_k$ evolve when a given control history $u_k$ is used. The mean $\hat{x}_k$ is propagated by Kalman filter.

In the first step, WCDM determines a set of plausible strategies for the external agents, taking into account the probability distributions of $x_k$ and $y_k$. The belief interval function b associates a finite interval numbers to the mean m and variance v of a random variable according to

$$b(m,v) = [m - k\sqrt{v}, m + k\sqrt{v}] \tag{4.38}$$

where $k$ is a real positive constant, bounding the distribution of the random variable to $k$ standard deviations on each side of the mean.

In the second step, WCDM identifies the strategy for each agent among a set of strategies that would be worst for the dynamic system. The hazard presented by strategy $j$ of agent $i$ is assumed to be given by the expected hazard function :

$$\hat{h}(i, j, \hat{x}_k, P_k, \hat{y}_k, Q_k, k) \in R^+ \tag{4.39}$$

Having obtained $\hat{v}_k$, the mean $\hat{y}_k$ is propagated by

$$\hat{y}_{k+1} = g(\hat{y}_k, k, \hat{v}_k, \mu(\hat{x}_k, \hat{y}_k, k, \hat{v}_k)) \tag{4.40}$$

The covariances $Q_k$ and $R_k$ are propagated using linearization of g and $\mu$ about the mean values

$$Q_{k+1} = M_k + A_k[Q_k A_k^T + R_k^T B_k^T] + B_k[R_k A_k^T + P_k B_k^T] \qquad (4.41)$$

$$R_{k+1} = \Phi_k[R_k A_k^T + P_k B_k^T] \qquad (4.42)$$

where

$$\Psi_k^y = \frac{\partial g}{\partial y}[\hat{y}_k, k, \hat{v}_k, \mu(\hat{x}_k, \hat{y}_k, k, \hat{v}_k)] \qquad (4.43)$$

$$\Psi_k^w = \frac{\partial g}{\partial w}[\hat{y}_k, k, \hat{v}_k, \mu(x_k, \hat{y}_k, k, \hat{v}_k)] \qquad (4.44)$$

$$\Gamma_k^x = \frac{\partial \mu}{\partial x}[\hat{x}_k, \hat{y}_k, k, \hat{v}_k] \qquad (4.45)$$

$$\Gamma_k^y = \frac{\partial \mu}{\partial y}[\hat{x}_k, \hat{y}_k, k, \hat{v}_k] \qquad (4.46)$$

$$A_k = \Psi_k^y + \Psi_k^w \Gamma_k^y \qquad (4.47)$$

$$B_k = \Psi_k^w \Gamma_k^x \qquad (4.48)$$

These equations enable the prediction of the worst plausible evolution of the system and environment states. At each iteration, estimates are obtained for the states, along with corresponding covariances. An important application of the method is the determination of an optimal control $u_k$ by minimization of a stochastic cost function defined on the predicted evolution.

## 4.4.3 Mechanical Control System

For the most commonly used internal combustion vehicles, acceleration and deceleration are realized through the combination of throttle/brake control. Some studies emphasized the mechanism of the vehicles and developed mechanical system models for realizing vehicle headway control.

Hedrick and McMarhon presented a control model describing a combined throttle/brake control algorithm designed to control intervehicle spacing within a fully automated platoon of vehicles.[32] The control algorithm is developed using a modified sliding control method due to the inherent nonlinearities that exist in automotive vehicles.

- Simplified Vehicle Model for Control

The flow of air into and out of the intake manifold is described by:

$$\dot{m}_a = \dot{m}_{a_i} - \dot{m}_{a_o} \tag{4.49}$$

Where $m_a$ is the mass of air in intake manifold and $\dot{m}_{a_i}$ and $\dot{m}_{a_o}$ are the mass flow rates through throttle valve and into cylinders, respectively. Empirical equations developed for these rates are:

$$\dot{m}_{a_i} = \text{max}^* \, TC(\alpha) \, PRI(P_m \, / \, P_a) \qquad (4.50)$$

$$\dot{m}_{a_o} = c_i \eta_v (P_m \omega_c) m_a \omega_c \qquad (4.51)$$

Where max is a constant dependent on the size of intake manifold, $TC(\alpha)$ is the throttle characteristic which is a nonlinear function of throttle angle, $\alpha$, and $PRI(P_m/P_a)$ is the pressure ratio influence function which is a nonlinear function of the ratio of manifold pressure, $P_m$, and atmospheric pressure, $P_a$. In order to relate $P_m$ and $m_a$, it is assumed that the ideal gas law for air is valid, i.e.

$$P_m = \frac{\overline{R}_m T_m}{V_m} m_a \qquad (4.52)$$

Where $\overline{R}_m$ is the universal gas constant for air, $T_m$ is the temperature in the intake manifold and $V_m$ is the volume of the intake manifold. The engine's rotational dynamics is described as

$$J^* \omega_e = T_{net}(\dot{m}_{a_o} \omega_c) - T_l \qquad (4.53)$$

$T_{net}$ is combined combustion and friction torque and is generally measured by steady state engine tests and supplied in tabular form as a function of the air flow rate into the cylinders($\dot{m}_{a_o}$) and engine RPM, $\omega_c$.. $J^*$ is the effective inertia attached to the engine and

$T_l$ is the effective load applied to the engine. For the controller design, it is assumed that there is a rigid link between engine and driven tires, there $T_l$ becomes

$$T_l = (hF_{tr} + T_{br}) * R^*$$ (4.54)

Where $R^*$ accounts for gear ratios between wheel and engine. This assumption provides

$$\omega_w = R^* \omega_c$$ (4.55)

In the former equation, h represents the effective radius of the driven wheel, $F_{tr}$ is the tractive force due to the slip which is defined as:

$$i = \frac{h\omega_w - V}{h\omega_w}$$ (4.56)

A simple linear brake actuator model is assumed

$$\tau_{br}\dot{T}_{br} + T_{br} = P_c(\mu Ar)$$ (4.57)

Where $\tau_{br}$ is the actuator time constant, $T_{br}$ is the brake torque applied to the driven wheel, $P_c$ is the commanded brake pressure and $\mu Ar$ are brake pad parameters. The longitudinal equation for the vehicle is

$$M\dot{V} = F_{tr} - cV^2 - F_{\pi r}$$ (4.58)

Where $V$ is vehicle velocity, $cV^2$ is aerodynamic drag and $F_{rr}=\mu Mg$ is rolling resistance.

- Nonlinear Controller Design

Assume the distance, $L_i(t)$, between the ith and (i-1)th vehicle as

$$L_i(t) = x_{i-1} - x_i - d_i - d_{i-1} \tag{4.59}$$

Where $x$ represents an initial position of the vehicle and d represents fixed vehicle geometry. $L_i(t)$ represents the spacing between the ith and (i-1)th vehicles and could be either a constant during constant speed operation or a time varying function during vehicle entry or exit. Then define the spacing error, $\varepsilon_i$, as

$$\varepsilon_i = x_i - x_{i-1} + L_{i_d}(t) + d_i + d_{i-1} \tag{4.60}$$

Where $L_{i_d}$ represents the desired spacing between the two vehicles. Following the multiple surface sliding control methodology, the first surface is defined as

$$S_1 = \dot{\varepsilon}_1 + c_1\varepsilon_i + c_2\int_0^1 \varepsilon dt \tag{4.61}$$

Which when differentiated yields

$$\dot{S}_1 = \dot{V}_i - a_{i1} + c_1\dot{\varepsilon} + c_2\varepsilon \tag{4.62}$$

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Since there is no control in the above equation, a "synthetic output" is defined as

$$\dot{S}_{1_{des}} = -K_1 S_1$$
(4.63)

Then we have

$$i_{des} = \frac{m}{K_r}(\frac{cV^2}{m} + F_{tr} + a_{i1} - c_1\varepsilon - c_2\varepsilon - K_1 S_1)$$
(4.64)

$$\dot{S}_1 = \frac{K_1}{m}(i - i_{des}) + \delta f_1 - K_1 S_1$$
(4.65)

Where $\delta f_1$ represents modeling errors associated with the longitudinal equation. $K_1$ must be chosen so that $S_1 \dot{S}_1 < 0$ outside of a region defined by $|S_1| < \phi_1$. $\phi_1$ is a tracking accuracy design parameter. A desired speed is defined as

$$\omega_{c_{des}} = \frac{V}{R^*(1 - i_{des})h}$$
(4.66)

At this point, the second surface, $S_2$ is defined as

$$S_2 = \omega_c - \omega_{c_{des}}$$
(4.67)

Using a similar procedure, one obtains

$$T_{net}(m_{a_{des}}, \omega_e) = T_1(\omega_e, V) + J^*(\dot{\omega}_{e_{des}} - K_2 S_2)$$
(4.68)

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Substituting the above equation into the $S_2$ equation yields

$$\dot{S}_2 = \frac{1}{J^*}(T_{net} - T_{net_{des}}) + \delta f_2 - K_2 S_2 \qquad (4.69)$$

Where $\delta f_2$ represents the model error in the equation of engine rotational dynamics. $K_2$ must be chosen large enough so that $S_2 \dot{S}_2 < 0$ for $|S_2| > \phi_2$.

Then a third surface is defined as

$$S_3 = m_a - m_{a_{des}} \qquad (4.70)$$

$$\dot{S}_3 = \dot{m}_a - \dot{m}_{a_{des}} = \dot{m}_{a_i} - \dot{m}_{a_o} - \dot{m}_{a_{des}} = -K_3 S_3 \qquad (4.71)$$

$$TC(\alpha) = \frac{\dot{m}_{a_o}(m_a, \omega_e) + \dot{m}_{a_{des}} - (K_3 S_3)}{MAX * PRI(P_m / P_a))} \qquad (4.72)$$

These equations can be converted to find the desired throttle angle $\alpha$. If the resulting angle is negative, braking is required.

# 5. Research Objective and Methodology

## 5.1 Background

The technologies of AVCS have received a great deal of attention as a means of solving major highway transportation problems, i.e. safety and congestion. The fundamental AVCS technologies aim at solving these problems by making vehicles keep smaller headways when operating on highways while maintaining a higher level of safety than at present. As driving involves perception reaction times, delays and human errors that affect traffic flow and safety adversely, the only way to realize such a small headway car-following system is to use an automatic control system, composed of computer controller and variety of sensors, replacing drivers when vehicles are operating on the AVCS lanes.

Through statistics we see that the probability of having fatalities in a rear end crash is much higher when the striking unit is a truck.[15,44] Because of the long driving hours, truck drivers are more likely to be involved in an accident due to fatigue and inattention. The dynamics of trucks (such as mass and dimensions) makes them more difficult to control in an emergency situation, and increases the severity of an accident when it happens. Some studies have found that accidents involving trucks operating on rural highways have higher fatality rates. A system that combines sensors with efficient

headway control models can prevent severe truck accidents. Therefore, realization of automatic headway control for trucks is of particular importance for AVCS technologies.

The first step of developing AVCS technologies for trucks is to develop automatic vehicle headway control models that can function flawlessly in automated highway environment. Then a detailed and careful evaluation is necessary before the deployment. The vehicle headway control in a real world highway is a complicated process that involves various uncertain factors. Thus, a computer simulation tool that is capable of developing headway control models as well as testing and evaluating different control models under different conditions is in need. This simulation tool should have the capability of simulating different environmental conditions, road geometric conditions, and driver behaviors, as well as sensor types and errors.

The main objective of this study is to develop a simulation tool that can be used to develop vehicle headway control models and to provide a laboratory for testing and evaluating various vehicle headway control models, specifically for trucks traveling on rural highways. Through this study, a headway control model particularly for trucks is developed to meet the need of increasing the operating safety. With the simulation tool developed, it is possible to select the most efficient headway control models that perform well under specific operating conditions and to build a system capable of selecting the

best model for the actual situations. This simulation tool will be used to accelerate the headway control model development in AVCS studies.


## 5.2 Automatic Headway Control System Design Process


When designing and developing a new system, one must know the requirements for the system: why the system is needed, what mission the system should accomplish, and what kind of characteristics the system must possess for the accomplishment of the mission.[45] This systems engineering concept is very important in the design and development of the sophisticated vehicle headway control system.


When developing an automatic headway control system, the first task should be identifying the requirements for such a system: the need for the new system, what tasks the new system should accomplish, and what characteristics the new system should possess. These requirements for the system should be qualified and quantified. This procedure can give the criterion for the design of the automatic headway control system.


Developing automatic vehicle headway control system that can partially or fully replace human drivers in certain situation is in the belief that human drivers can not perform the driving task well enough and the human limitation are the major causes of the present transportation problems. Before designing an automatic vehicle headway control system,

we must know how the human limitation affects the driving performance, and then what are the requirements for the automatic control system.

Following the systems engineering concept, this study began with the manual driving process modeling and simulation. The identification of requirements for the automatic vehicle headway control system was based on the results of simulating the human driving process. The objectives of the simulation are:

1. Determine the major problems due to human limitation, which are to be solved by automatic headway control system.

2. Qualify and quantify the characteristics the automatic vehicle headway control system should have.

The study was conducted in the following three steps.

- Manual Driving Process Analysis and Simulation

The focus of the manual driving process study is simulation, i.e. reproducing the human driving process in the real world. A car following model was developed to simulate the

human driving process under different traveling conditions. Various random factors, such as human perception reaction time, power train response time, desired spacing between vehicles and desired speed for individual drivers, and roadway geometric and environmental conditions, were considered and included in the simulation model. This model reproduced the human driving process in making longitudinal responses by drivers and found the major problems and limitations of the driving task.

- Automatic Headway Control System Design and Simulation

The focus of automatic headway control study is system design and development, i.e. developing a system that possesses desired characteristics and can accomplish the required mission. Based on the analysis for the manual driving process simulation, the requirements for the automatic headway control system was identified, and then an automatic headway control system model was developed according to the quantified requirement parameters and realized through simulation.

- Testing and Evaluating Automatic Headway Control Models

The simulation tool developed in the previous step was modified and improved to be capable of duplicating and testing various automatic headway control models, analyzing the results, and presenting evaluation of their efficiency.

The study procedure was implemented as the flow chart shown in Figure 5.1.

```
        ┌─────────────────────────────────────────┐
        │     Identification of Requirements       │
        │    (System Analysis and Simulation)      │
        │                                          │
  ──────┤   1. manual driving process analysis,    │
        │      modeling, and simulation            │
        │                                          │
        │   2. identify requirement parameters     │
        └─────────────────────────────────────────┘
                            │
                            ▼
        ┌─────────────────────────────────────────┐
        │     System Design and Development        │
  ──────┤                                          │
        │   automatic headway control system       │
        │       modeling and simulation            │
        └─────────────────────────────────────────┘
                            │
                            ▼
        ┌─────────────────────────────────────────┐
        │     System Testing and Evaluation        │
  ──────┤                                          │
        │   testing and evaluating various         │
        │   automatic headway control systems      │
        └─────────────────────────────────────────┘
```
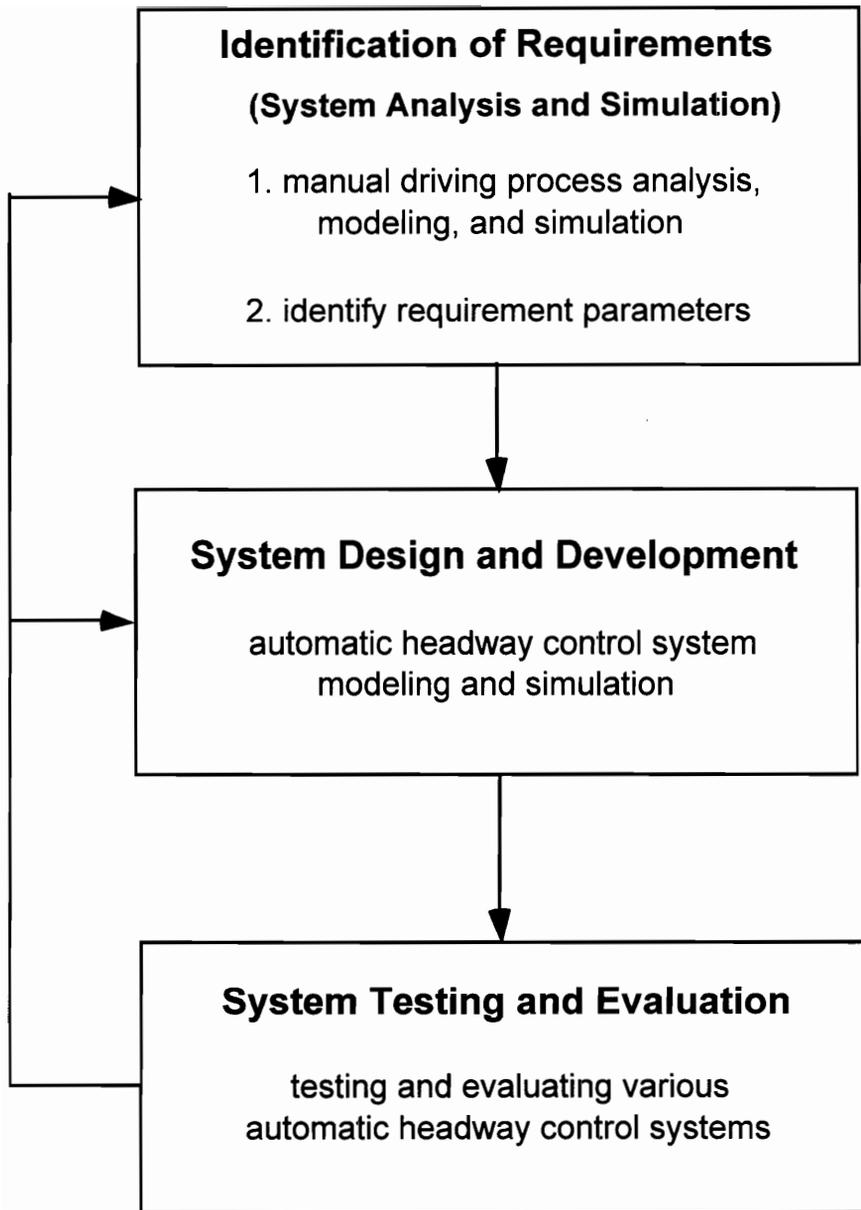
Figure 5.1  Research Procedure Flow Chart

## 5.3 Simulation Tool in the Study

Simulation is an extremely important means in the automatic vehicle headway control technologies development, especially for the testing and evaluating automatic headway control models to be used as the real world vehicle automatic control systems. AVCS studies have been conducted for years and various automatic headway control models have been presented. The highly sophisticated nature of these models and the variety of the factors involved in vehicle operating procedure necessitate a thorough evaluation prior to implementation of automatic headway control systems in the real world transportation systems. This need requires extensive computer simulations that capture the coupling of control system logic with the movements of vehicles and a prototype test facility. Therefore, a computer simulation tool capable of testing and evaluating different headway control models under different operating conditions is an ideal and necessary tool for AVCS development.

The realization of automatic headway control in future transportation systems is a complicated process. Various certain and uncertain factors, mechanical, human, and environmental, affect the control process greatly. The simulation tool used for developing, testing and evaluating the automatic control system must be capable of incorporating major related factors and simulating the behavior of the system as a whole,

not just individual control strategies. In order to meet this requirement, system dynamics is selected as the simulation tool in the research.

System dynamics is a powerful simulation approach for modeling real world higher order feedback control processes. It integrates knowledge about how feedback structures cause change through time with the art of computer simulation for dealing with systems that are too complex for mathematical analysis.[46,47] System dynamics focuses on policy and how policy determines behavior. The policy here is the criteria for decision-making. It determines how a stream of decisions will be modulated in response to changing inputs of information.[48] System dynamics starts with important problems, comes to understand the structures that produce undesirable symptoms, and moves on to finding changes in structure and policy that will make a system better behaved.

Feedback loop structure is the most important feature of vehicle headway control system. In this system, the policy is the output for the decision-making process of vehicle controller (driver or automatic controller), i.e. the amount of acceleration or deceleration, which determines the behavior of the vehicle in a study. Thus system dynamics is an appropriate tool for the simulation of the vehicle headway control system.

Moreover, system dynamics is capable of simulating the effect of random variables in feedback control systems. It can afford a means of modeling human perception reaction

times and power train responses as random variables for multiple lanes, mixed traffic situations. It can easily incorporate various roadway geometric and environmental conditions into the control algorithms and reproduce the human driving and automatic driving control process in the real world highway systems. These have little been done in the previous work for vehicle automatic headway control models. With system dynamics, various automatic control analytical models can be duplicated, since they are all developed based on the feedback control theory with different orders.

In addition to the traffic volume, roadway geometric and environmental conditions, there are a lot of uncertain factors in vehicle highway systems. All of these make the automatic headway control a complicated process for which it is very difficult to find an analytical model to describe and to get an optimal control algorithm. That is why all the previous work in this field, such as the California PATH and the Ohio State AHS studies, had a lot of simplification of assumptions in the modeling procedures. Most of the existing automatic headway control models focus on a single lane, even grade roadway, and uniform passenger car headway control, with no geometric conditions or weather conditions being considered. Even so, it is very difficult to reach an ideal analytical solution for the problems.

All of these reasons made system dynamics an ideal tool for simulating the vehicle headway control process in searching for the simulation solution for the system.

## 5. 4   The Scope and Procedure of the Study

This study is conducted based on the technologies of Advanced Vehicle Control Systems and Commercial Vehicle Operation. Various vehicle headway control theory and strategies and truck operating characteristics have been thoroughly studied, and some of them have been incorporated in simulation tool development.

The research was conducted in three major steps: developing a manual driving simulation model that can reproduce the manual driving process in a real world highway system; developing an automatic vehicle headway control system that functions flawlessly for different types of vehicles operating in a real world highway environment; and developing a simulation tool capable of testing and evaluating various headway control models under different operating conditions. Each of steps contains the following tasks.

- Manual Driving Process Simulation

    1. Single lane general car following behavior modeling and simulation

    2. Vehicle dynamics study and simulation

    3. Mixed traffic ( car and truck) following behavior modeling and simulation

    4. Incorporating traffic environment parameters

    5. System analysis and evaluation

- Automatic Vehicle Headway Control Model Development

    1. Automatic headway control system parameters selection and design

    2. Single lane, mixed traffic flow vehicle longitudinal control system design

    3. Incorporating traffic environment parameters

    4. Automatic vehicle headway control system simulation

    5. Model evaluation and modification

- System Testing and Evaluation

    1. Duplicating selected automatic vehicle headway control models

    2. Testing the duplicated models under different operating conditions

    3. Selecting MOE analysis criteria

    4. Automatic vehicle headway control models evaluation

A systematic procedure was complied in the accomplishment of the above tasks. The research started from human driving process analysis and simulation to determine the requirements for automatic headway control system design. Based on the manual driving process simulation, an automatic vehicle headway model is developed, which can realize mixed traffic (passenger cars and heavy trucks) vehicle longitudinal control.

The simulation tool developed in this study has the capability of simulating different environmental conditions, such as roadway geometry and weather conditions, and driver behavior as well as various delays involved in vehicle operating process. It is also capable of simulating continuous traffic flow on a highway, which includes different numbers of vehicles traveling at different states (position and velocity) within a section of highway. With this simulation tool, an analytical vehicle headway control model developed by PATH program has been realized and tested under different operating conditions.

# 6. Manual Driving Process Simulation

## 6.1 Manual Driving Process Analysis

Operating a vehicle on real world highway systems is a complicated process, which consists of three major factors, driver, vehicle, and environment, all interacting in a complicated manner in both time and space. The driver continuously makes decisions for operating the vehicle in accordance with the driving situation.

Once in the traffic stream, the driver is motivated by the desire for time-distance economy on the one hand and for safety, comfort, and convenience on the other. Fear of an accident motivates many driver decisions, such as in jamming the brakes when confronted with any danger.

The establishment of a manual driving simulation model is based on the analysis of the decision-making procedure of drivers and related factors of the operation of vehicles. When traveling on a highway, the behavior of a driver-vehicle system is influenced by several factors.

(1) An individual driver has a desired speed, at which he/she likes to travel, and a desired spacing with respect to the vehicle ahead that makes him/her comfortable. The desired speed and desired spacing vary from person to person, depending on different personality.

(2) A driver must observe the states of the vehicles nearby to adjust the vehicle's speed for safety and for comfort. The driver keeps detecting the changes in headway and relative velocity if there is some danger of collision, but only checks these states periodically if the driving situation seems normal.

(3) When adjusting speed, a driver accelerates or decelerates the vehicle according to relative velocity and spacing with respect to the vehicle ahead, absolute velocity, and acceleration of the vehicle ahead.

(4) There are limits to acceleration and deceleration of each vehicle, which depend on the speed of the vehicle, vehicle type, and roadway conditions.

(5) When the states (speed and space) of nearby vehicles change, there is a time lag for a driver to perceive that change and take corresponding action.

(6) When a driver initiates an action (acceleration or deceleration), there is a time lag for the power train response.

In most previous car-following studies, only two stimuli were considered in establishing the following laws: the relative velocity between a vehicle and the one ahead, and the spacing between the two vehicles.[30,49] In fact, a driver considers more. Most drivers are continually evaluating several gaps ahead and are extremely conscious of the proximity to the car behind. In particular, if a car is following a big truck, the driver would keep a much greater spacing from the truck than following a regular car. Based on this analysis, considerable realism can be achieved in the manual driving process simulation by including several vehicles ahead of and the vehicle immediately behind the driver as stimuli.

## 6.2 Feedback Control Concept in Driving Process

### 6.2.1 Feedback Control Concept

Feedback control is the most important concept in control theory. Feedback control mechanisms widely exist in nature and man-made systems and have become essential elements in modern control technology.

In a feedback control system, the output of the system is continuously compared with the input to the system. Such a system is self correcting in the sense that any deviations from the desired performance are used to produce corrective action.[50]

Figure 6.1 shows the block diagram of a simple feedback control system expressed in frequency domain, i.e. **s** domain. In this system, the control gain $G$ is used to magnify the error signal to adjust the system output. The output is fed back through feedback path $H$ to the functional standing point, where the error signal is created by comparing the feedback signal with the input. Although feedback control systems can be of various types and orders in reality, the system in Figure 6.1 consists the primary elements of feedback control systems.
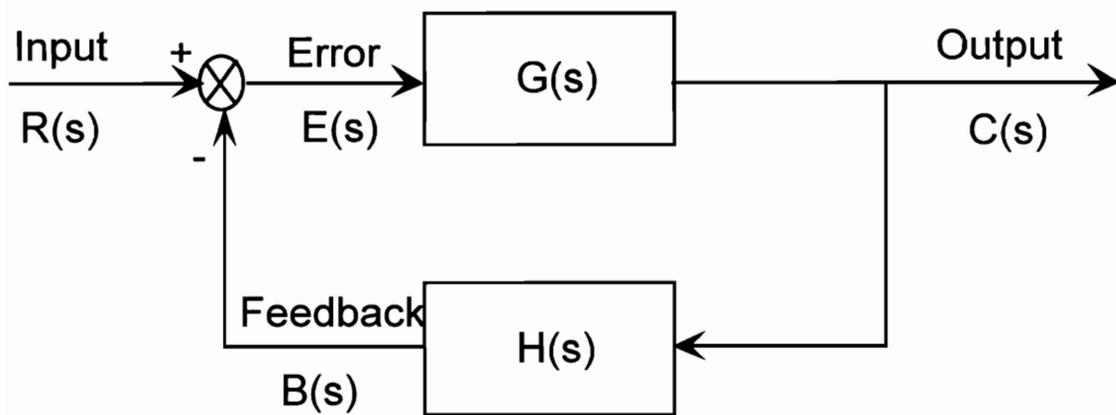
Figure 6.1 Block Diagram of Simple Feedback Control System

## 6.2.2 Feedback Concept in Vehicle Headway Control

Driving a vehicle on a highway is actually a man-machine feedback control system. A driver observes the state changes of surrounding traffic and compares the information with the input, the desired driving status, and thus makes decision as to control action. The control of the system includes steering, accelerating, and braking.

Figure 6.2 illustrates the basic feedback control mechanism of a vehicle headway control system using system dynamics. This is a second order negative feedback control system, i.e. two negative feedback loops are involved. In this system, when acceleration increases, the velocity of the vehicle increases, thus the position of the vehicle, or the distance the vehicle traveled, increases. In the first feedback loop, the velocity is compared with the velocity of the vehicle ahead to create the first error signal, relative velocity. While the velocity increases, the relative velocity decreases, then acceleration decreases. In the second feedback control loop, the position is compared with the position of the vehicle ahead to create the second error signal, relative distance. While the position increases, the relative distance decreases, then acceleration decreases.

ACCELERATION          VELOCITY                    SPEED                  POSITION

**A** $\xrightarrow{\hspace{2cm}}$ + **V** $-\ -\ -\ \dashrightarrow$ + **XX** $\xrightarrow{\hspace{2cm}}$ + **X**

RELATIVE
VELOCITY
**RV**

RELATIVE
DISTANCE
**RD**
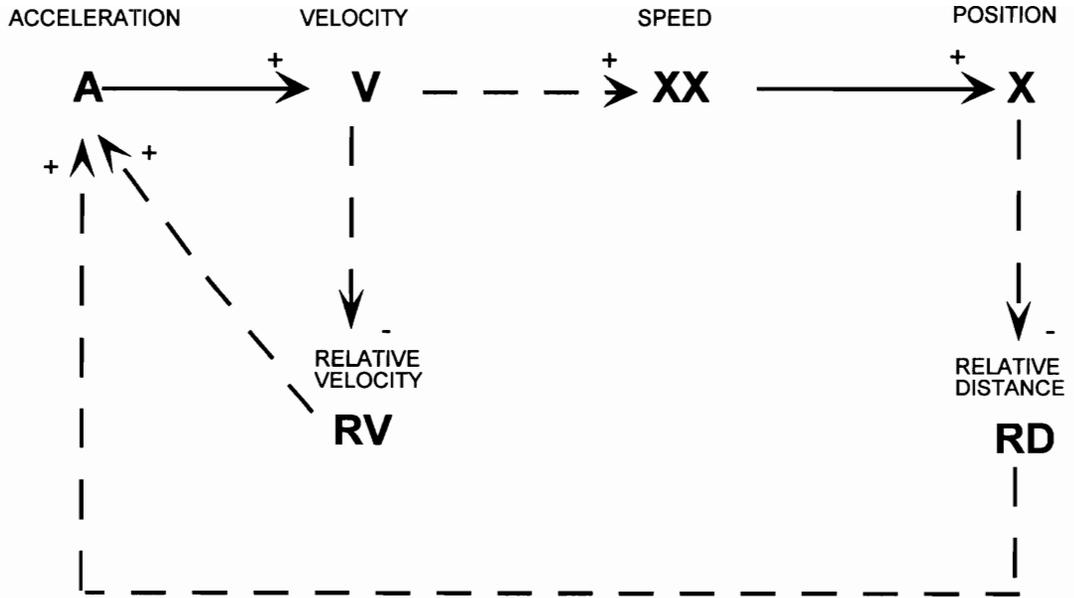
Figure 6.2  Vehicle Headway Feedback Control Diagram

## 6.3 Control Modes Identification

Driving on a highway, a driver must observe the state changes of the surrounding vehicles and change his vehicle control modes from time to time according to the operating situations. A vehicle may follow the vehicles ahead, cruise at the driver's desired speed, gradually slow down, or brake rapidly. Considering a single lane highway system, where no passing is possible, a vehicle can be operated in the following five control modes.

- Cruise

  If the relative distance with respect to the vehicle ahead is greater than a certain safety threshold, defining it as the first threshold, $SD_1$, a driver tends to operate his vehicle at his desired speed, i.e. cruise control mode. Under this control mode, a vehicle cruises at the desired speed of the driver or accelerates/decelerates to that speed.

- Following

  If the relative distance with respect to the vehicle ahead is less than the first threshold and the vehicle ahead is operating normally, a vehicle will follow the operating status of the vehicle ahead, i.e. under the following control mode. It will accelerate,

decelerate, or cruise according to the relative velocity and relative distance with respect to the vehicle ahead.

- Rapid Deceleration

If the relative distance with respect to the vehicle ahead is less than the first threshold while the vehicle ahead is braking and the headway between them is decreasing quickly, a driver must decelerate his vehicle as soon as possible, i.e. make rapid deceleration. The deceleration at that time is proportional to the relative velocity with respect to the vehicle ahead. No spacing stimulus would be considered for this situation.

- Slow Deceleration

If the vehicle ahead is decelerating rapidly or stops, while the relative distance with respect to that vehicle is greater than safe stopping distance, a vehicle will gradually decelerate and slowly approach that vehicle, then stop behind that vehicle if necessary.

- Emergency Braking

If the relative distance with respect to the vehicle ahead is less than a second threshold and the relative velocity with respect to vehicle ahead is less than a critical

value, a vehicle will brake quickly, i.e. emergency braking. The extent of emergency braking only depends on its own velocity and deceleration capacity.

The decision making procedure for control mode switches of a driver can be expressed as a control flow chart shown in Figure 6.3. Assuming that there are N vehicles ( noted as 1, 2, ..., i, ..., N ) on a single lane highway system, the notions are:

$RX_{i-1,i}$ = spacing between (i-1)th and ith vehicles

$RV_{i-1,i}$ = relative velocity between (i-1)th and ith vehicles

$A_{i-1}$ = acceleration of (i-1)th vehicle

$V_{i-1}$ = velocity of (i-1)th vehicle

$SD_1$ = first spacing threshold

$SD_2$ = second spacing threshold

CRV = critical relative velocity

CD = critical deceleration
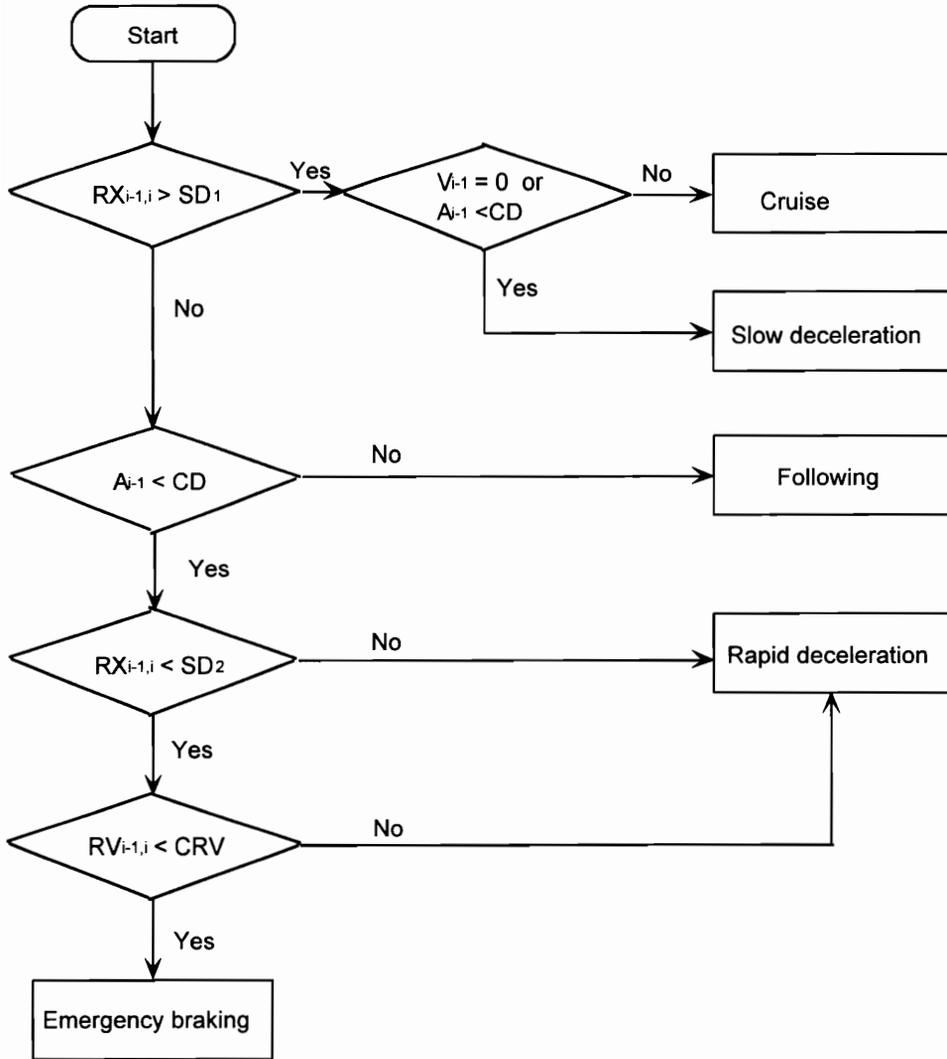
Figure 6.3  Control Mode Switching Flow Chart

## 6.4  Time Lags in Driving Process

### 6.4.1  Perception Reaction Time

Perception-reaction time in a man-machine systems is the time interval elapsing from the beginning of the stimulus signal to the completion of the operator's response. In driving situations, perception-reaction time includes the times required by the driver to perceive, to interpret, to make a decision, and to respond.[51] The dangers of collision have to be perceived, and motion must be continuously evaluated and adjusted. The driver's response at the next moment is controlled by the position of his vehicle with respect to the traffic environment at the present moment.

Perception reaction time is the most important factor in many traffic accidents. AVCS studies are conducted in the belief that if the perception reaction time is reduced to a certain value, most accidents on present highways can be avoided. Many papers give comments that if the perception reaction time could be reduced by 0.5 second, a certain percent of traffic accidents would not have happened.[51] Although a great deal of research has been done on this topic, nobody can give exact values of perception reaction time.

In fact, perception reaction time is a random variable. Its value changes from one person to another, and from one situation to another. To determine the range of perception

reaction time under different situations is a study for human factors. What is needed in the vehicle headway control study is to determine how perception reaction time effects the driving process, and what might be an appropriate or desirable perception reaction time under different situations. This is the most important parameter for automatic headway control system design.

In a single lane highway situation, each driver needs a time lag, perception-reaction time (PRT), to perceive and respond to the changes of the surrounding situation. If the relative velocity and relative spacing with respect to other vehicles change, the driver needs that time lag to perceive and take some response. PRT is a random variable varying from person to person and time to time.

## 6.4.2 Sample Time

There is a great difference in the human driving process from the automatic control process. Under automatic control, the sensor of the control system will keep measuring the system state variables (such as headway, velocity), and can report changes in system states immediately. While under human control, the drivers only keep detecting the state changes if they feel some danger of collision. Under normal driving situation, they would

only check these states periodically, i.e. there is a time interval between each state-checking, based on concentration and distractions.[14,15]

A variable, sample time, can be used to simulate this situation. Suppose human drivers check system states periodically with the same time interval under normal driving situation. Whenever they get the information about the system states, they will keep this as input for a time interval (sampling interval) to make their control decision, until they check the system states again to get new information.

Perception reaction time and sample time are two types of time lag for a driver to make a longitudinal response to the state changes of other vehicles. If the driving situation seems normal, a driver might be inattentive in detecting state changes on the roadway. The worst case is that the driver will make a response to a sudden hazard after the longest time lag, perception reaction time plus sample time.

### 6.4.3 Power Train Response Time

The third type of time lag involved in the driving process is the power train response time (PTRT). Whenever a driver initiates an execution, e.g. stepping on the brake, the vehicle needs this time lag to respond.[52]

Power train response time depends on the mechanical structure of vehicles. It varies from one type of vehicle to another. In general, the PTRT value of passenger cars is less than that of heavy trucks. The exact value of PTRT for a particular vehicle is provided by the manufacturer.

## 6.5 Vehicle Operating Characteristics

### 6.5.1 Vehicle Types and Dimensions

A variety of motor vehicle types operate on American highways. These include passenger cars, light trucks and vans, single-unit trucks, combination trucks and buses. Each type of these vehicles has unique size, weight, and operational characteristics. The mixed vehicle types are expected to be present on a highway facility.

To focus the study on cars and trucks mixed traffic flow, the simulation will include the following types of vehicles.[15,53]

**Passenger cars and light trucks** Passenger cars are two-axle, four-tire automobiles, typically weighing between 1,500 and 4,000 lb. Light trucks include pickup trucks and vans. Light trucks generally have a gross vehicle weight under 10,000 lb.

**Single-unit trucks** Single-unit trucks are trucks in which the cargo area and the power unit are mounted on a common frame and can not be separated. They include two-axle trucks, three-axle trucks, and some four-axle trucks. The general weight of single-unit trucks are between 10,000 and 40,000 lb.

**Combination trucks** Combination trucks consist of a power unit or tractor and one or more trailers, i.e. tractor-trailer. The tractors and trailers that make up a combination are joined at hitch points where the units can rotate relative to one another. Combination trucks are used extensively in local and long-haul commercial goods transportation. Generally they have gross weights up to 80,000 lb. Combination trucks are classified by the number and length of trailers used. Types of combination trucks include:

**Single-trailer trucks** -- tractor plus one semitrailer. The length of trailers is between 48 and 53 ft.

**Double-trailer trucks** -- tractor plus semitrailer plus full trailer. Three types of double combinations in common use are:

- Twin-trailer truck: a tractor plus a 27 or 28 ft semitrailer plus a 27 or 28 ft full trailer.

- Rocky Mountain double: a tractor plus a 45 ft semitrailer plus a 28 ft full trailer.

- Turnpike double: a tractor plus a 45 ft semitrailer plus a 45 ft full trailer.

## 6.5.2 Resistance to Motion

Resistance of vehicles to movement is a very complex set of forces caused by many factors. Therefore, its analysis is performed by decomposing total resistance into individual elements. The following types of resistance are considered in this research.[15,54]

**Rolling Resistance**

Rolling resistance is created at the contact of the wheel with the riding surface. Three factors contribute to the rolling resistance: (1) deformation of the wheel and surface of the traveled way; (2) a sucking effect caused by the underpressure at the separation of the wheel from the surface; (3) slippage of the wheel. The magnitude of this resistance is mostly a function of the smoothness and hardness of the wheel and support surfaces and the load on the wheel.

The rolling resistance force for a passenger car on a smooth pavement can be estimated as:

$$R_r = (C_{rs} + 2.15 C_{rv} V^2) W \qquad (6.1)$$

The rolling resistance for trucks can be estimated as:

$$R_r = (C_a + 1.47\, C_b V)W \tag{6.2}$$

where:    $R_r$ = rolling resistance force (lb)

        $C_{rs}$, $C_{rv}$, $C_a$, $C_b$ = constants

        $V$ = vehicle speed (mph)

        $W$ = gross vehicle weight (lb)

**Air Resistance**

Air resistance is composed of the direct effect of air in the pathway of vehicles, the fractional force of air passing over the surfaces of vehicles and the partial vacuum behind the vehicle. The air resistance force for a motor vehicle can be estimated as [54]:

$$R_a = 0.5\frac{(2.15\, \rho C_D\, AV^2)}{g} \tag{6.3}$$

where:    $R_a$ = air resistance force (lb)

        $\rho$ = density of air

        $C_D$ = aerodynamic drag coefficient

        $A$ = frontal cross-sectional area

V = vehicle speed

g = acceleration of gravity

**Grade Resistance**

Grade resistance is the force acting on a vehicle because it is on an incline. It equals the component of the vehicle's weight acting down the grade. Grade resistance force is determined as [54]:

$$R_g = \frac{W\,G}{100} \tag{6.4}$$

where:    $R_g$ = grade resistance force (lb)

W = gross vehicle weight (lb)

G = gradient (%)

**Inertial Resistance**

Inertial resistance is the force that must be overcome to change speed. It is a function of vehicle weight and the rate of acceleration of deceleration. It may be estimated from the following equation:

$$R_i = \frac{W\,a}{g}$$ (6.5)

where:     $R_i$ = inertial resistance force (lb)

W = gross vehicle weight

a = acceleration rate

g = acceleration of gravity

### 6.5.3  Acceleration and Deceleration Performance

• **Acceleration**

Vehicle acceleration capability depends on the tractive effort of the vehicle engine and the resistance of vehicle to movement. The tractive effort of a vehicle is a function of the power of the engine and the speed of the vehicle. It is determined by the following formula:[54]

$$TE = 2650\,\eta\,\frac{P}{V}$$ (6.6)

where:     TE = tractive effort

P = power output of engine

$\eta$ = coefficient of losses between the motor and the wheels

The force available for vehicle acceleration is the tractive effort overcomes the resistance to motion. Then the maximum acceleration of a vehicle can be determined by the following formula:

$$a = \frac{1}{m}(TE - R) \tag{6.7}$$

where:     a = acceleration

m = mass of vehicle

TE = tractive effort

R = total resistance force

Equation 6.6 is a simplified formula describing the relation between tractive effort and velocity. The engine power output varies with rotation speed of the engine. At the normal operation conditions, the vehicle is considered of operating close to its peak value of the engine power output. Therefore, the engine power of a vehicle could be taken as a constant without introducing significant errors to the simulation results.

- **Deceleration**

Retardation forces developed in braking determine the deceleration rates of vehicles as long as slippage does not occur between the pavement and tire surface. When the applied braking force can not be carried to the pavement without skidding, the wheels of a vehicle become locked and deceleration rates are determined by the effective coefficient of friction at the tire-pavement contact surface.[15,55,56] This coefficient of friction is a function of pavement type, tire condition, and the pavement surface is wet or dry. Because braking systems in good order can usually provide more braking force than can be carried to the pavement, maximum deceleration rates depend primarily on this coefficient of friction between tire and pavement surfaces.

## 6.6 Manual Driving Process Simulation Model

### 6.6.1 System Dynamics Model

System dynamics is used as a simulation tool in modeling manual driving behavior. Based on the analysis of the manual driving process, the five control modes in the vehicle operation are implemented to simulate different driving behaviors in the model. The control mode switches from one to another based on the thresholds of relative distance

with the vehicle ahead, relative with the vehicle ahead, and the operating mode of the vehicle ahead.

The system dynamics simulation model of manual driving process on a single lane highway is established based on the following description.

A platoon consisting of n vehicles traveling on highway. Each driver of the vehicles has a desired speed, $DS_i$, and a desired safety distance with the vehicle ahead, $SD_i$, which is proportional to its velocity. The vehicle will travel at the desired speed if the spacing with the vehicle ahead is greater than its desired safety distance.

For the sake of safety, a driver must adjust the speed of his vehicle according to the relative velocity and relative space with respect to two vehicles ahead and one vehicle behind. If there is enough space between his vehicle and the vehicle directly ahead and the vehicle behind not following too close, he will travel at his desired speed. If the space with the vehicle ahead is close to his desired safety distance, and one of the two vehicle ahead decelerates, or the velocity of that vehicle is less than his, he will use the following control strategy, accelerate or decelerate based on the velocity scenario of the vehicles ahead to keep the best possible speed and avoid crash. If the velocity of the vehicle behind is greater than his and become too close to him, he will accelerate to increase the

spacing with the vehicle behind if the relative distance with respect to the vehicle ahead is big enough.

There are time lags involved in vehicle operating process. These include the perception reaction time and sampling time of individual driver, and power train response time of the vehicle. The system dynamics casual diagram of manual driving process simulation model is shown in Figure 6.4.
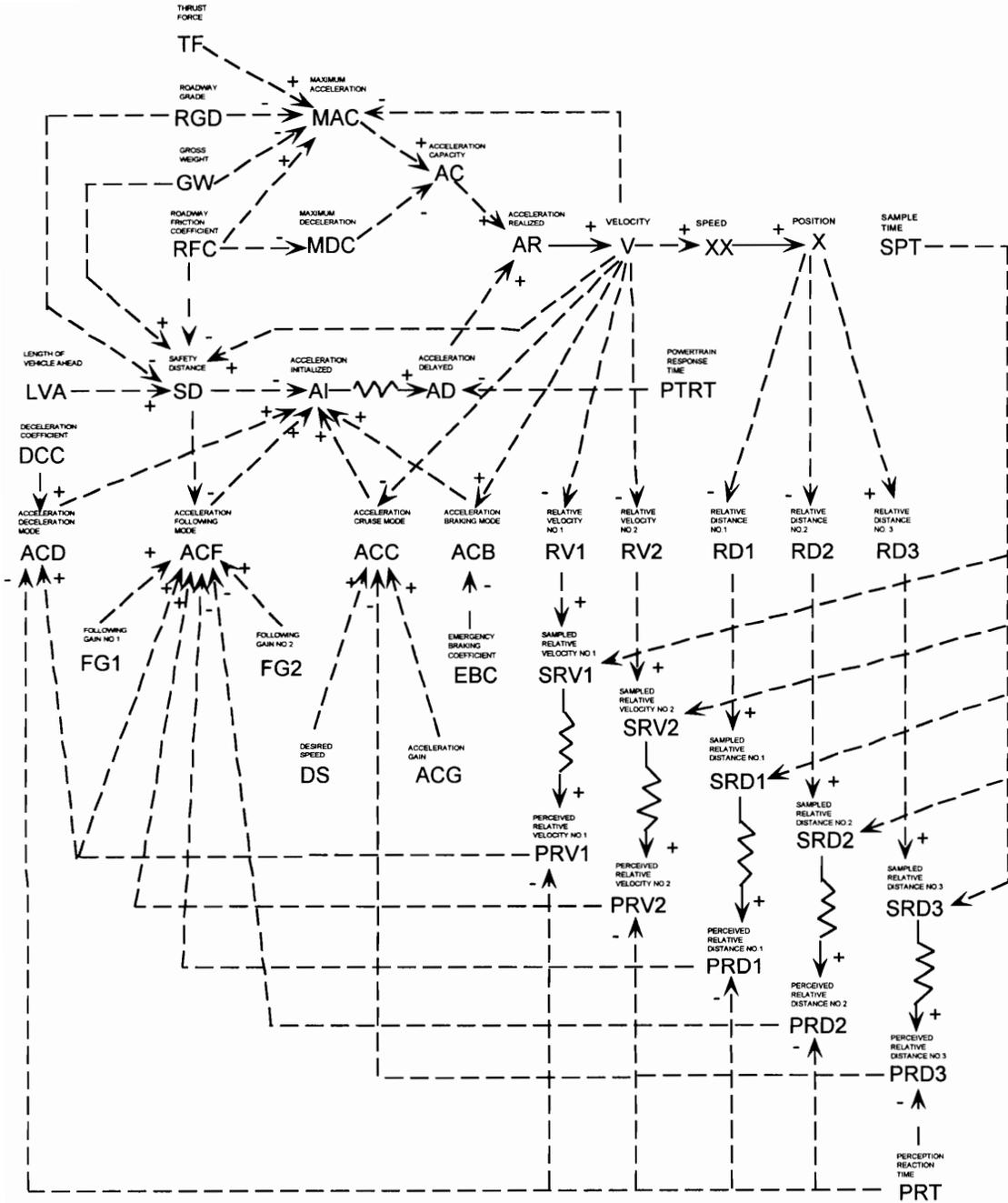
Figure 6.4  Manual Driving Simulation Model Casual Diagram

## 6.6.2 Control Mode Switch Thresholds

A driver switches the control mode of his vehicle according the operating states of surrounding vehicles and that of his own vehicle. He continually compares these states with his own safety thresholds and makes decisions about the control strategies. The major thresholds used for control mode switches include: desired safety distance, critical relative velocity, and critical deceleration of the vehicle ahead. These thresholds may vary from driver to driver, related to personalities, while the control mode switches follow the same laws.

The five control modes applying regimes are defined as:

- Cruise

$$RX_{i-1,i} > \alpha_1 \ SD_i \qquad\qquad (6.8)$$

$$V_{i-1} > 0 \qquad\qquad (6.9)$$

$$A_{i-1} > CD \qquad\qquad (6.10)$$

- Following

$$RX_{i-1,i} \leq \alpha_1 \ SD_i \qquad\qquad (6.11)$$

$$V_{i-1} > 0 \tag{6.9}$$

$$A_{i-1} > CD \tag{6.10}$$

- Rapid deceleration

$$\alpha_2 \, SD_i < RX_{i-1,i} \leq \alpha_1 \, SD_i \tag{6.12}$$

$$A_{i-1} \leq CD \tag{6.13}$$

- Slow deceleration

$$RX_{i-1,i} > \alpha_1 \, SD_i \tag{6.8}$$

$$V_{i-1} = 0 \tag{6.14}$$

$$\text{or} \quad A_{i-1} \leq CD \tag{6.15}$$

- Emergency braking

$$RX_{i-1,i} \leq \alpha_2 \, SD_i \tag{6.16}$$

$$RV_{i-1,i} < CRV \tag{6.17}$$

### 6.6.3 Control Algorithm

Assuming a platoon consisting of N vehicles operating on an automated lane. The five-mode simulation model includes the following equations.

- Cruise

$$Ac_i = \begin{cases} Max\{AMAX_i, Kc_i(DS_i - V_i)\} & RX_{i,i+1} \geq SD_b \\ K_h(\dfrac{SD_b}{RX_{i,i+1}} - 1) & RX_{i,i+1} < SD_b \end{cases} \qquad (6.18)$$

- Following

$$Af_i = Kfv_i\{\alpha(\dfrac{V_{i-1} - V_i}{RX_{i-1,i}}) + (1-\alpha)(\dfrac{V_{i-2} - V_i}{RX_{i-2,i}})\} + Kfs_i(1 - \dfrac{SD_i}{RX_{i-1,i}}) \qquad (6.19)$$

- Rapid deceleration

$$Ard_i = Krd_v\, Krd_h \dfrac{V_{i-1} - V_i}{PRT} \qquad (6.20)$$

- Slow deceleration

$$Asd_i = Ksd_i \left( \frac{V_i}{c_1 RX_{i-1,i} + c_2} \right)$$

(6.21)

- Emergency braking

$$Ab_i = Min\left\{ DMAX_i, \; Kb\left( \frac{V_{i-1}^2 - V_i^2}{c_3 RX_{i-1,i} + c_4} \right) \right\}$$

(6.22)

where:

$Ac_i$= acceleration of ith vehicle in cruise control mode

$AMAX_i$= maximum acceleration of ith vehicle

$DS_i$= desired speed of ith vehicle

$V_i$= velocity of ith vehicle

$Kc_i$ = cruise control mode control gain of ith vehicle

$Af_i$ = acceleration of ith vehicle in following control mode

$Ard_i$ = acceleration of ith vehicle in rapid deceleration mode

$Asd_i$ = acceleration of ith vehicle in slow deceleration mode

$Ab_i$ = acceleration of ith vehicle in emergency braking mode

$Kfv_i$ = velocity related following mode control gain of ith vehicle

$Kfs_i$ = spacing related following mode control gain of ith vehicle

$RX_{j,i}$ = spacing between the rear bumper of jth vehicle to front bumper of ith vehicle

$SD_i$ = desired safety distance of ith vehicle

$\alpha$ = constant between 0 to 1

$Krd_v$ = velocity related gain in rapid deceleration mode of ith vehicle

$Krd_h$ = headway related gain in rapid deceleration mode of ith vehicle

$Ksd_i$= slow deceleration mode control gain of ith vehicle

$DMAX_i$= maximum deceleration of ith vehicle

$Kb$, $Kh$, $c_1$, $c_2$, $c_3$, $c_4$= constants


The control grains of the above model were determined based on pole point method according to linear and nonlinear control theory. The parameters were selected to minimize the overshooting during the speed changing transient period and get smooth control mode switching effect.

## 6.7 Manual Driving Process Simulation

### 6.7.1 Random Number Generator

Manual driving process involves some uncertain factors in decision making for selecting control strategies. These factors vary from person to person, and from situation to situation. In order to reflect the uncertainty of driver's behavior in real world highway system, three random number generators[57] are created in the program to simulate the perception reaction time, desired speed, and desired spacing of an individual driver.

- Perception reaction time generator: A Beta distributed random number generator is used to generate PRT for each driver, i.e.

$$PRT_i = Beta(\alpha_1, \alpha_2) \qquad (6.23)$$

- Desired speed generator: A Normal distributed random number generator is used to generate desired speed for each driver, i.e.

$$DS_i = N(\mu_1, \sigma_1^2) \qquad (6.24)$$

The mean value of the desired speed is determined by the speed limit of the highway.

- Desired spacing generator: A Normal distributed random number generator is used to generate desired spacing for each driver, i.e.

$$SD = N(\mu_2, \sigma_2^2) \qquad\qquad\qquad (6.25)$$

The mean value of the desired spacing is determined through a commonly used rule of thumb that a driver should follow another vehicle no closer than one car length for each 10 mph of speed.

## 6.7.2  Adaptive Control Gains

Under following and rapid deceleration operating modes, a vehicle may accelerate or decelerate according to the states of the vehicles ahead. The control algorithms for these modes take the headway and/or relative velocity with respect to the vehicles ahead as inputs. In fact, the human driving process is a kind of adaptive control, the relative velocity and headway are not the only variables to determine the value of acceleration or deceleration, the gains of the system also vary according to the different situation.

Based on the consideration above, the simulation model uses varying parameters, instead of constants, in the acceleration algorithm for the following and rapid deceleration operating modes. These parameters vary with the changes in relative velocity or headway with respect to the vehicle ahead, through which, the over-shoot during the response procedure is greatly dampened. Thus a  stable and realistic response process is realized.

### 6.7.3 Simulation Scenario

The driving process of a platoon consisting of four vehicles on a single lane highway has been simulated using the system dynamics software, DYNAMO.[58]

At initial state, the vehicles are at standing position or operate at a relatively low speed (20 mph to 30 mph ) and the leading vehicle of the platoon begins to accelerate. The leading vehicle accelerates to its desired speed and then cruises at that speed, until an incident forces it to brake. The other vehicles in the platoon take different operation modes depending on the surrounding traffic and its desired speed and desired spacing with respect to the vehicle ahead. At steady state, all vehicles come to a stop at the point of incident.

Three major types of vehicles are selected to simulate a mixed traffic flow, i.e. passenger cars and light trucks; single unit trucks; and combination trucks. The average length of the vehicle in the mixed traffic flow  ranges from 15 ft to 75 ft, and gross weight ranges from 3,500 lb to 60,000 lb.

The mean value of Desired Speed Generator is selected as 65 mph, based on the speed limit of major highways today. With different random seeds, the generators give individual vehicles different desired speed and desired spacing.

The objective of the simulation is to reproduce the human driving process and determine the effect of different system parameters on the driving process, such as perception-reaction time, power train response time, and safe spacing under different velocities, especially in the situation that the leading vehicle takes emergency braking. In the simulation runs, the same value of PTRT is used for trucks and cars to simplify the simulation procedure since the influence of the differences in PTRT values of the same platoon is not the objective in this simulation.

## 6.7.4 Simulation Results

The simulation for the manual driving process has been conducted for different types of vehicles with various perception-reaction times, power train response times, desired speeds and desired spacings for individual vehicles, and deceleration scenario of the leading vehicle. Through simulation for different cases, the desired spacing of individual vehicle and perception reaction time show the greatest effect on the driving process.

Some of the simulation results of a platoon consisting of different types of vehicles under different operating scenarios are shown in the following graphs.

**Case 1.** A platoon of vehicles consists of only passenger cars and light trucks. The parameters of the vehicles are:

Vehicle Length:   vl1 = 15 ft;   vl2 = 21 ft;   vl3 = 18 ft;   vl4 = 25 ft

Vehicle Weight:   wt1 = 3500 lb;   wt2 = 6000 lb;   wt3 = 4500 lb;   wt4 = 8000 lb

The leading vehicle starts to accelerate from the initial speed of 30 mph to its desired speed and then cruises at that speed. With the advent of an incident, it decelerates at the rate of 0.25g to stop before the spot. The following vehicles follow the leading vehicle, accelerate, decelerate and brake, try to keep their own desired speed and spacing respectively. At the steady state, all vehicles stop before  the incident spot, closely spaced, and no crash occurs. The simulation procedure is shown in Figure 6.5.

**Case 2.** A platoon of vehicles consists of passenger cars and trucks. The parameters of the vehicles are:

Vehicle Length:   vl1 = 15 ft;   vl2 = 45 ft;   vl3 = 75 ft;   vl4 = 25 ft

Vehicle Weight: wt1 = 3500 lb; wt2 = 15,000 lb; wt3 = 60,000 lb;

wt4 = 8000 lb

The simulation scenario is the same as case 1. At the steady state, no crash occurs. The simulation procedure is shown in Figure 6.6.

**Case 3.** A platoon of vehicles consists of passenger cars and trucks. The parameters of the vehicles are:

Vehicle Length: vl1 = 15 ft; vl2 = 75 ft; vl3 = 45 ft; vl4 = 25 ft

Vehicle Weight: wt1 = 3500 lb; wt2 = 60,000 lb; wt3 = 15,000 lb;

wt4 = 8000 lb

The simulation scenario is same as case 1. At the steady state, no crash occurs. The simulation procedure is shown in Figure 6.7.

**Case 4.** A platoon of vehicles consists of passenger cars and trucks. The parameters of the vehicles are:

Vehicle Length: vl1 = 15 ft; vl2 = 75 ft; vl3 = 45 ft; vl4 = 25 ft

Vehicle Weight: wt1 = 3500 lb; wt2 = 60,000 lb; wt3 = 15,000 lb;

wt4 = 8000 lb

The simulation scenario is same as case 1, except that the leading vehicle decelerates at the rate of 0.4g. At the steady state, the third vehicle and fourth vehicle bump into the vehicle ahead of them. The simulation procedure is shown in Figure 6.8.

Figure 6.5 (a)  Time-Acceleration Graph



Figure 6.5 (b)  Time-Speed Graph

Figure 6.5 (c)  Time-Spacing Graph



Figure 6.5 (d)  Time-Jerk Graph

Figure 6.5  Manual Driving Process Simulation Case 1

Figure 6.6 (a)  Time-Acceleration Graph



Figure 6.6 (b)  Time-Speed Graph

Figure 6.6 (c)  Time-Spacing Graph
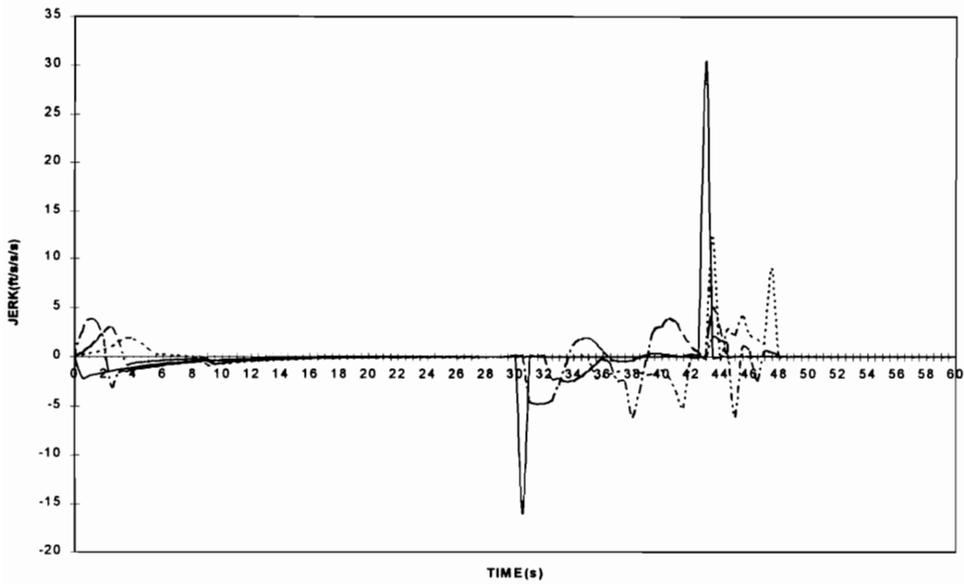


Figure 6.6 (d)  Time-Jerk Graph

Figure 6.6  Manual Driving Process Simulation Case 2
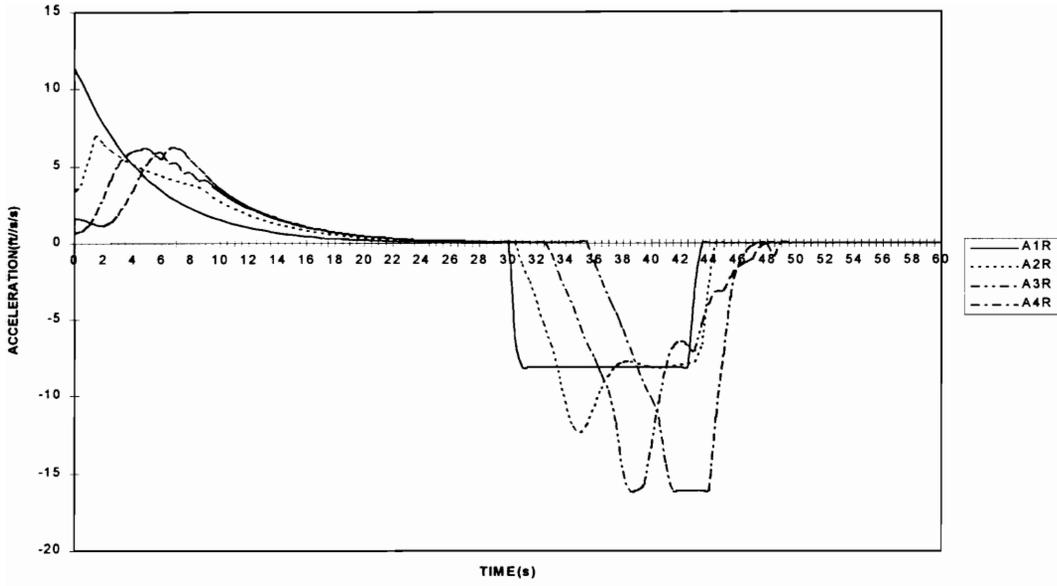
Figure 6.7 (a)  Time-Acceleration Graph
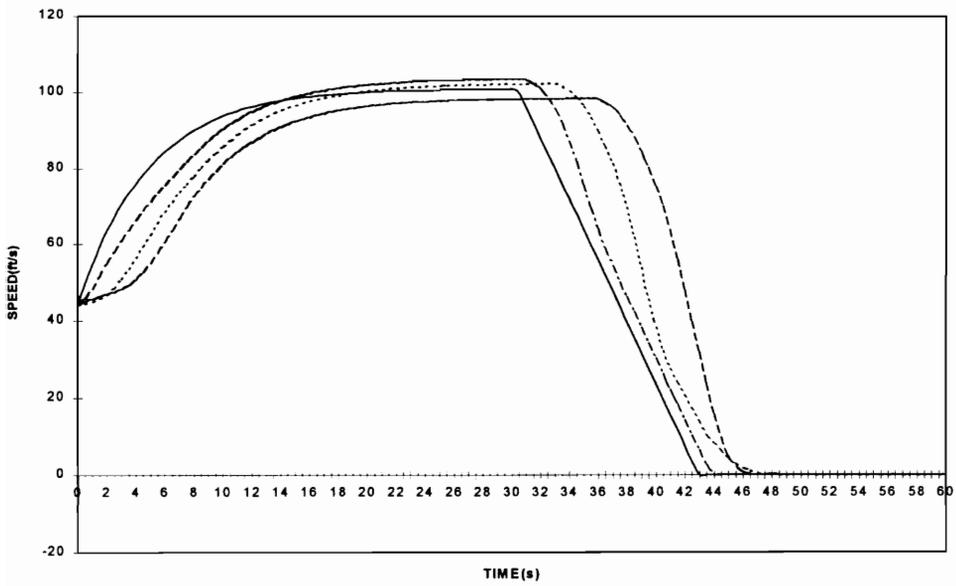


Figure 6.7 (b)  Time-Speed Graph

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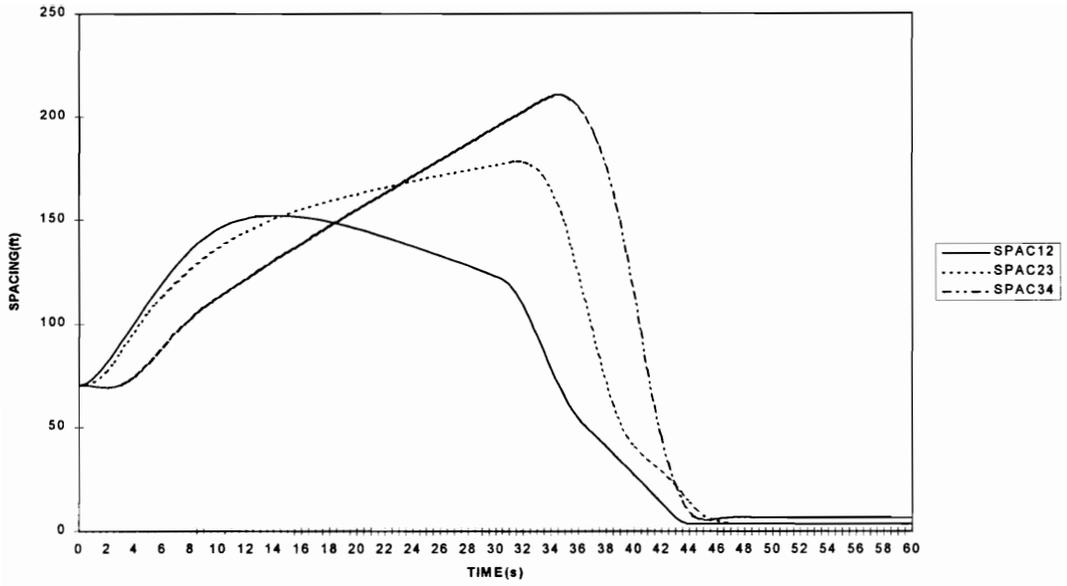
Figure 6.7 (c)  Time-Spacing Graph
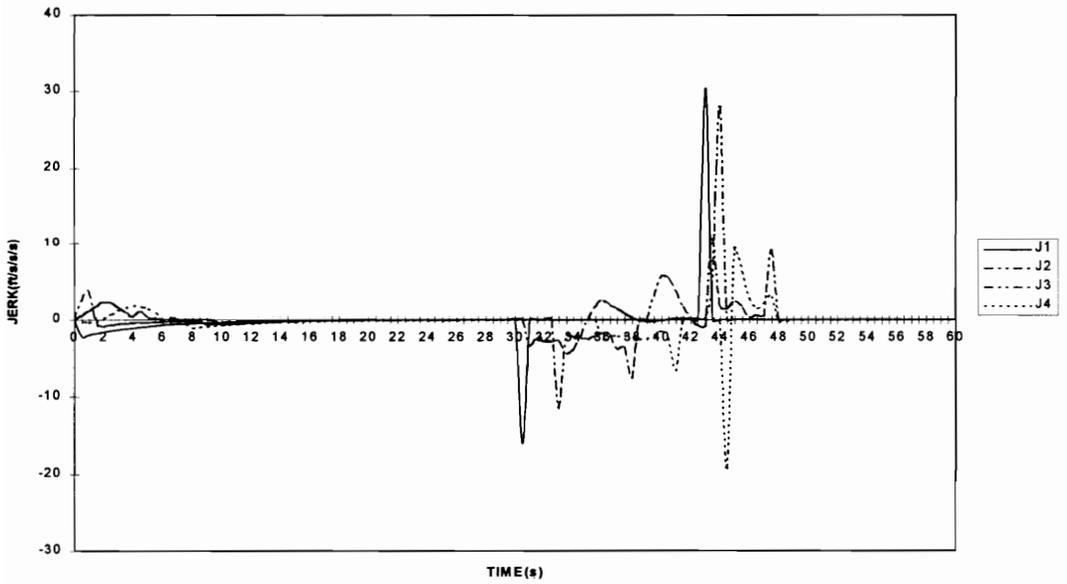


Figure 6.7 (d)  Time-Jerk Graph

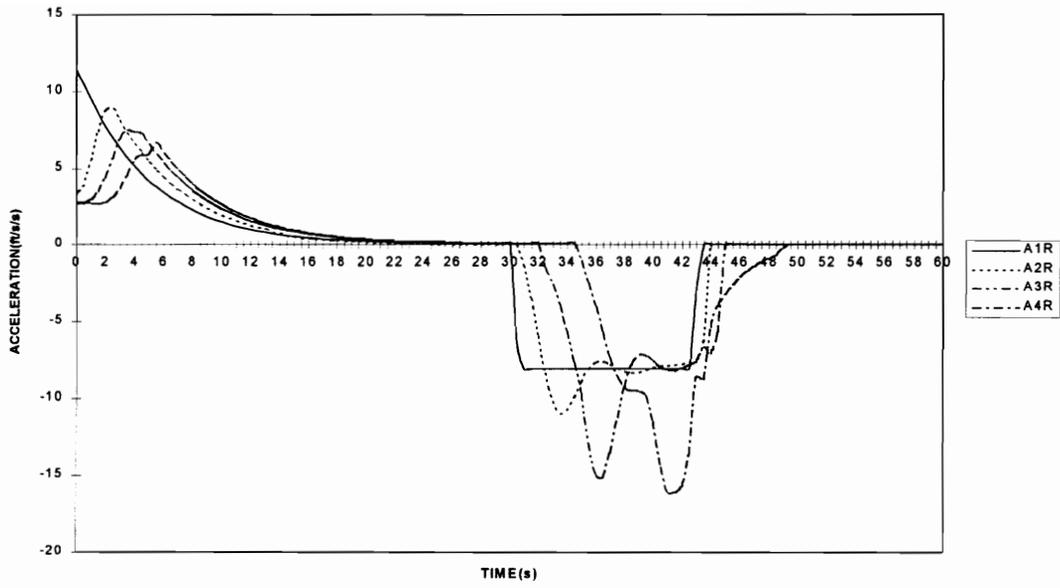Figure 6.7  Manual Driving Process Simulation Case 3
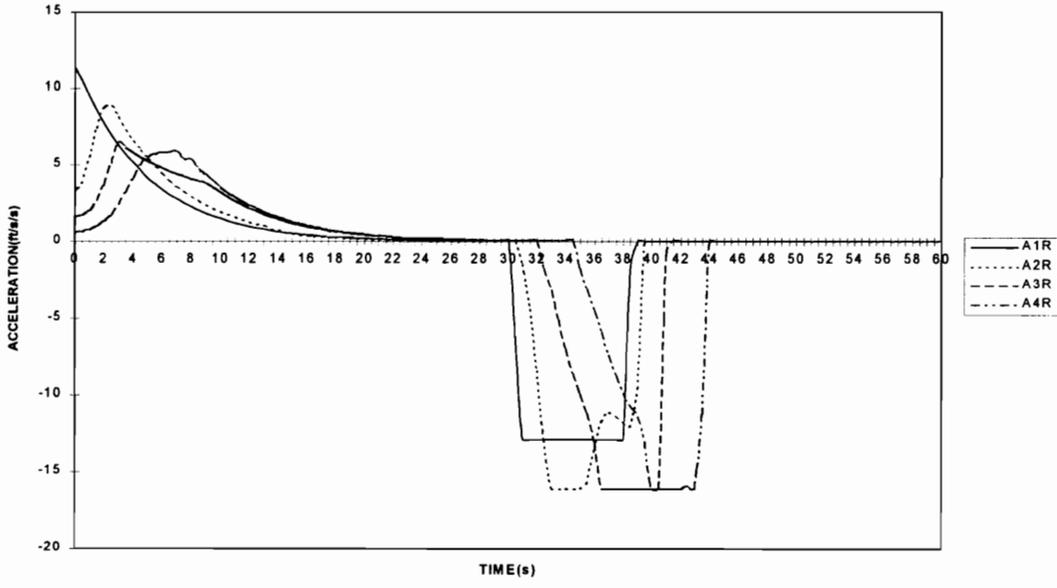
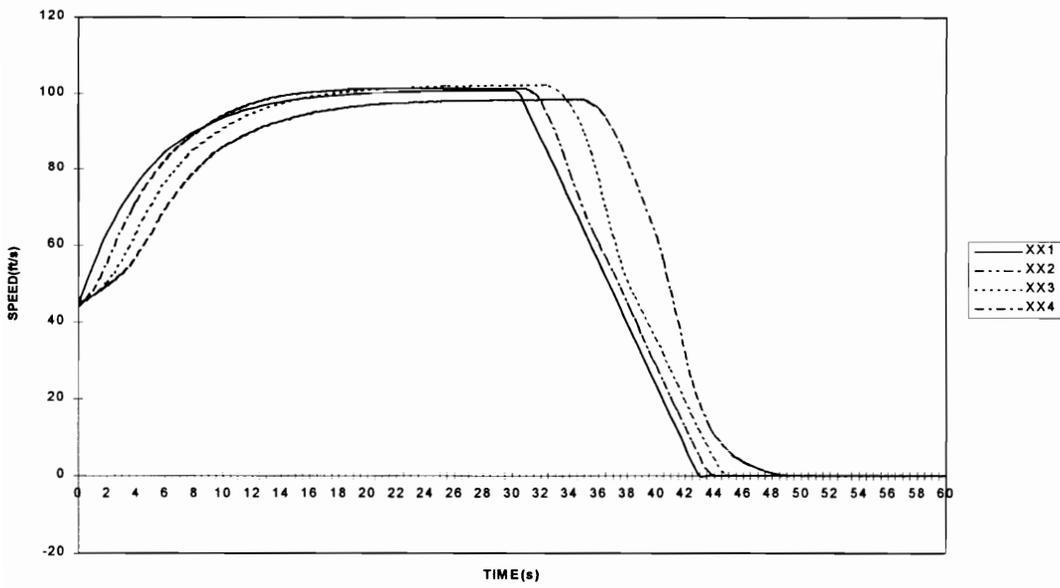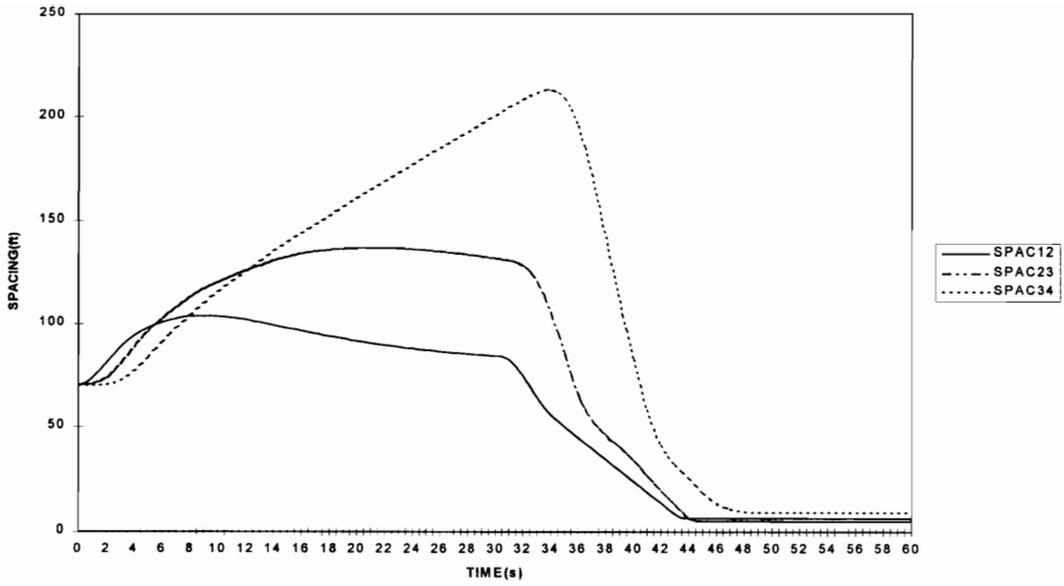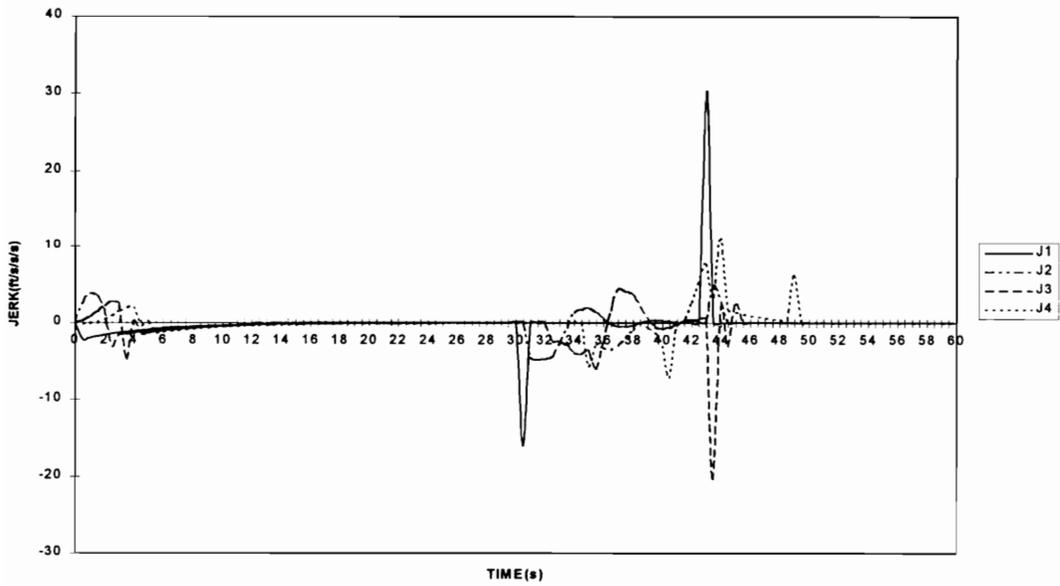Figure 6.8 (a)  Time-Acceleration Graph
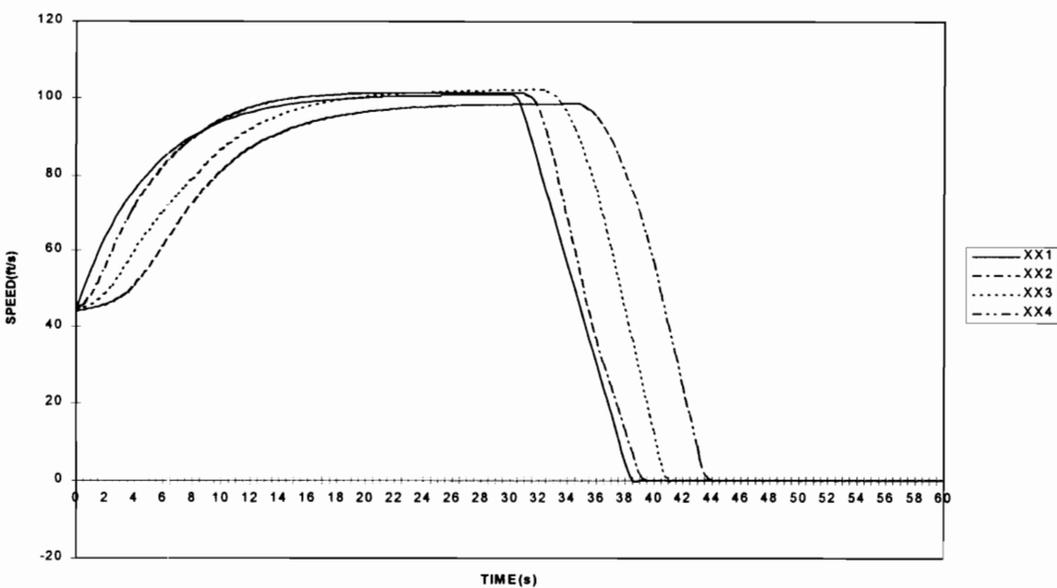


Figure 6.8 (b)  Time-Speed Graph

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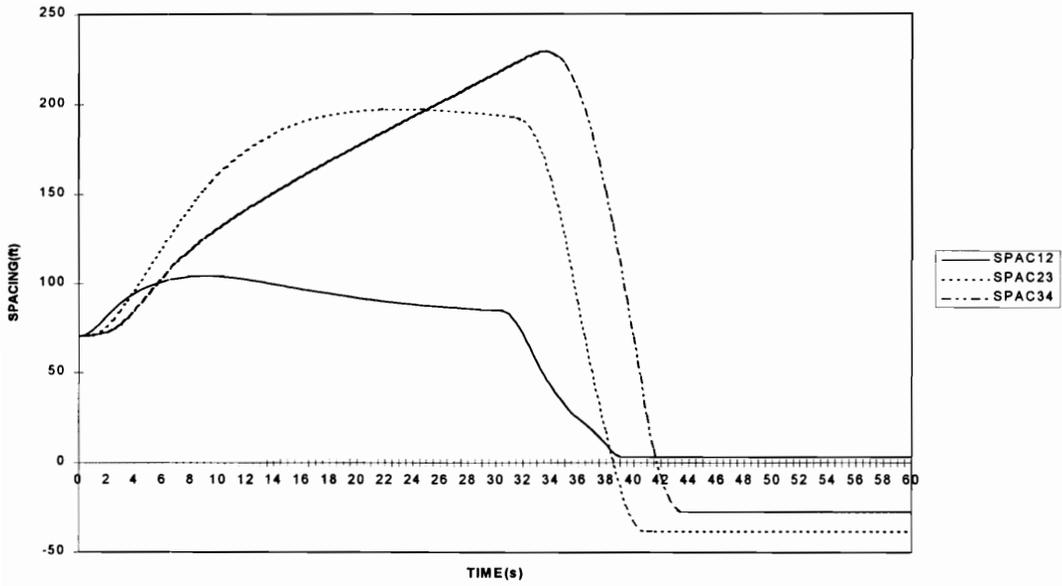
Figure 6.8 (c)  Time-Spacing Graph
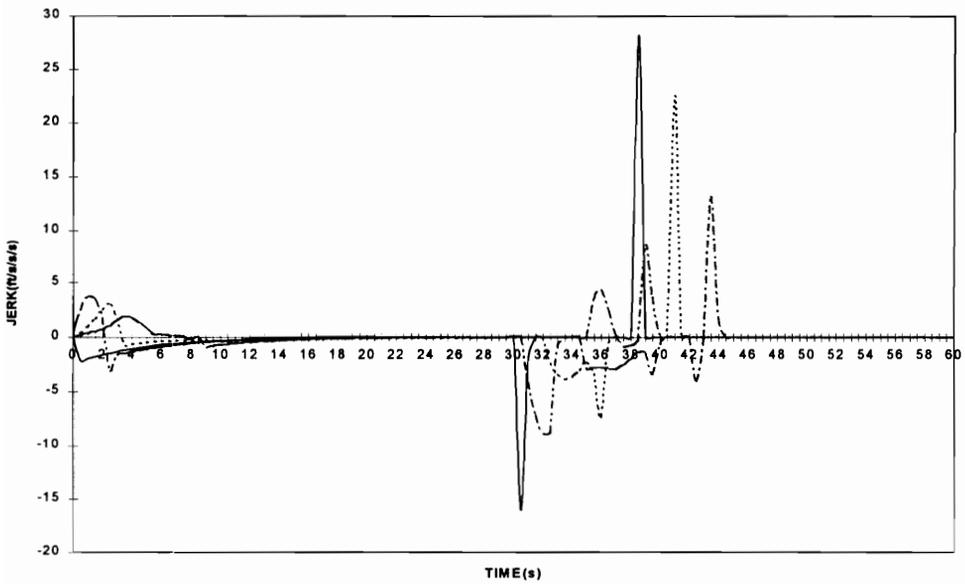


Figure 6.8 (d)  Time-Jerk Graph

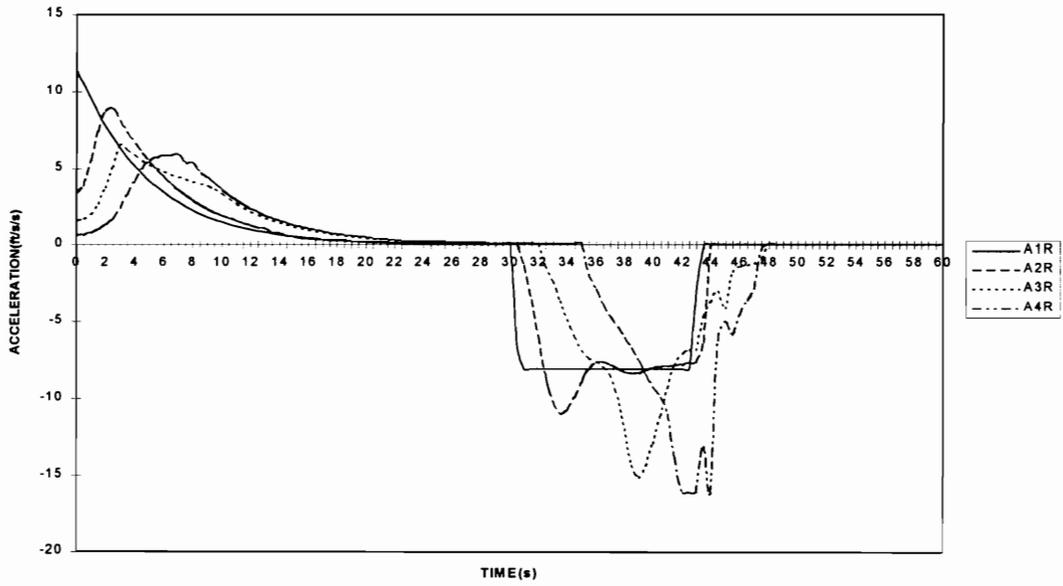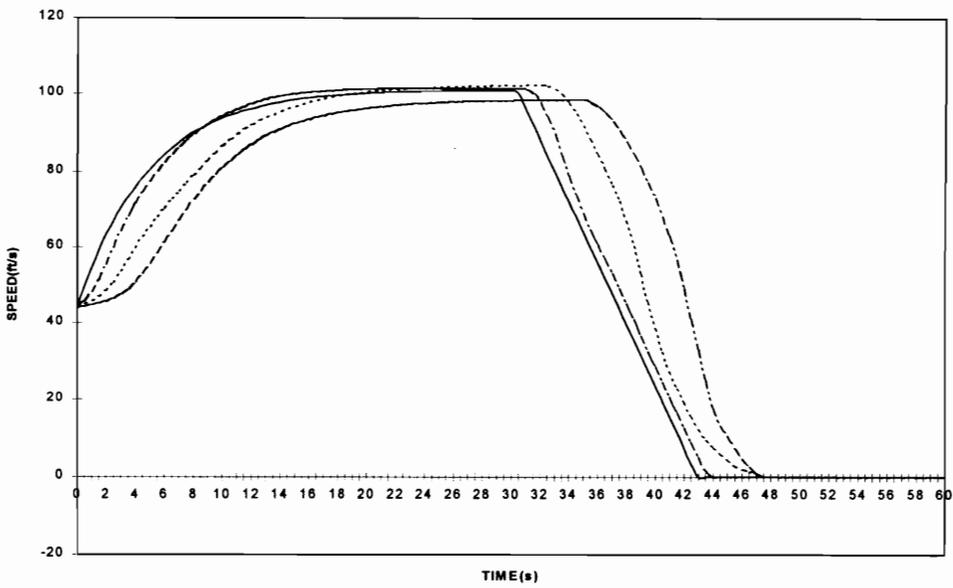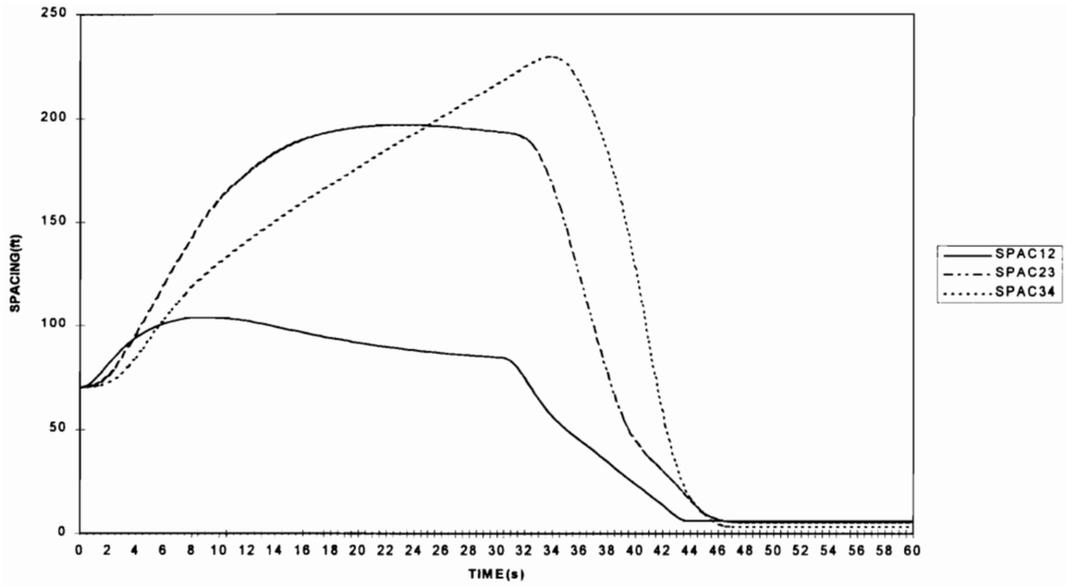Figure 6.8  Manual Driving Process Simulation Case 4

# 7. Automatic Headway Control System Design and Simulation

## 7.1 AHS Studies

The automated highway system (AHS) concept is receiving renewed consideration as a means of alleviating some serious highway problems. The vision for the AHS program is to create a fully automated system that evolves from today's roads, beginning in selected routes or corridors, eventually providing fully automated, "hands off" vehicle operation at better levels of performance than today in terms of safety, efficiency and comfort, while retaining the advantages of personal mobility, and allows equipped vehicles to operate both on instrumented roads under automatic control and on conventional roads under manual control.[59]

Early research in the area of the automatic control of individual vehicles was conducted on both theoretical and experimental bases, and prototype experimental equipment was developed and operationally tested by General Motors Corporation,[60,61] the Ohio State University,[62] Ford Motor company,[63] the Japan Governmental Mechanical Laboratory,[64] the Japan Automobile Research Institute,[65] and the UK Road Research Laboratory.[66] Most of the studies on AHS were conducted using computer simulations of theoretical network configurations; however, some of the network analyses were site specific.

Howson developed a simulation model of an automated roadway network for the metropolitan Detroit area.[67] The simulation studies were conducted to determine the performance of systems as a function of the various design parameters, to develop operation software, and to evaluate the computer hardware needs of a real world system.

Two fundamental AHS technologies are automatic longitudinal control and automatic lateral control. Longitudinal control (automatic headway control) serves to substantially enhance capacity, safety and motorist comfort.[68] Lateral control (automatic steering) serves to let vehicles follow the center of a lane with better accuracy and reliability than when vehicles are steered by human drivers.[69,70]

The principal reasons for considering an AHS are the prospects of substantial increases in traffic flow capacities and improved safety. The envisioned capacity increases range up to 800% and would result in improvements in traffic throughput and decreases in congestion.[16] The safety aspect would be a result of the virtual elimination of the human factor in vehicle control, and its replacement by faster reacting, more consistent, and highly reliable automatic control systems. It is envisioned that certain types of accidents would be virtually eliminated, while others would tend to be much less severe than at present. Although the complete deployment of AHS is a long term goal, pursuit of this goal is very important since a new level of benefits would be realized with full automation of certain facilities.

## 7.2 Requirements for Automatic Headway Control System

Automatic headway control is one of the major topics of AHS. It is implemented by automatic acceleration and braking. This kind of system is characterized by dramatically enhanced human driver's perception reaction time and control accuracy, enabling vehicles to be operated safely with high cruise speed and small headways. With automatic headway control systems, vehicles would be constrained generally to move at fixed speeds, thereby avoiding both unneceaasry fuel consumption and excessive noxious exhaust products, the negative environmental impact.

Through the manual driving simulation we see that some human factors have adverse effects in the manual headway control process. These are: (1) sample time; (2) perception reaction time; (3) uncertain desired speed of individual drivers; and (4) uncertain desired spacing of individual drivers. These factors may affect the control process greatly and result in unstable traffic flow and collisions in some situations.

Sample time and perception reaction time increase the delay of a vehicle's response to a sudden state change of surrounding traffic. They are the major causes of many accidents. When operating at high speed, the longer the delay is, the greater the chance of a vehicle will have an accident.

The randomly distributed desired speed and desired spacing of individual drivers depend on their personalities. Reckless drivers generally attempt to drive faster than the stream of traffic and, therefore, will accelerate and decelerate violently and frequently. While conservative drivers may drive at a relatively low speed and keep bigger spacing with other vehicles. These factors may have two possible effects on the headway control process quality. High desired speed and small desired spacing increase a vehicle's chance of bumping into the vehicle ahead in case of emergency, and thus affect the operating safety. While low desired speed and big desired spacing slow down the traffic flow, and thus affect the operating efficiency.

An automatic headway control system is designed to solve the problems due to human limitation and improve operating safety and vehicle control quality. It should have advantages in the following aspects.

- Time Lag: A sensor keeps detecting the state changes of surrounding traffic. The sample and perception reaction time is replaced by a much smaller and deterministic sensor time.

- Operating Speed: All the vehicles operate at an identical design speed for individual sections of highway. This speed is designated according to the roadway conditions.

- Safe Spacing: A controller keeps calculating safe spacing for individual vehicles. The spacing is a function of speed, deceleration capacity, and roadway conditions.

In addition, the automatic headway control system should possess the property of quick and stable response in the control process. Oscillations must be controlled under certain limit since they are undesirable factor that affects motorist comfort greatly.

## 7.3  Automatic Headway Control System Design

## 7.3.1  Control Strategy in System Design

This research focuses on the automatic headway control system for individual vehicles. There are two control strategies that can be used for vehicle automatic headway control: speed based control and spacing based control. The objective of speed based control is to realize a designated speed. With this control strategy, a vehicle operates at, or adjusts to, the designated speed whenever that is possible. The objective of spacing based control is to realize an even spacing of a platoon of vehicles. With this control strategy, a vehicle will keep a designated spacing with respect to the vehicle ahead and follow the state changes of its predecessor.

The first objective of automatic headway control is to improve highway safety. Both speed based control and spacing based control must determine a safety criterion first. Using the safety criterion, speed based control can realize a relative stable response and therefore contribute more to motorist comfort, while spacing based control can increase highway throughput and therefore contribute more to solving congestion.

Most previous research on automatic headway control concerned about solving congestion in urban area, therefore, increasing lane capacity is essential. In this kind of work, a minimum safe headway policy is used in vehicle control system design. Vehicles would be formed into platoons with small distances (e.g., 1 meter) between vehicles within the platoon, and much larger distances (e.g., 100 meters) between platoons.[71,72] With this control strategy the highway throughput can be significantly increased. Improved safety is achievable in that if a failure that produces an abrupt but finite deceleration of a vehicle, the vehicle behind it would collide with it at modest relative speed.

The principal objective of the research is the operating safety of trucks on the rural highway systems, where congestion is not the major concern. Platooning is not an appropriate strategy for the vehicle headway control system design here. First, there is no need to form different types of vehicles into closely spaced platoon on highways with relatively light traffic. Second, the momentum of heavy truck is much greater than that of

small car, therefore, it may cause serve damage of a car even with modest relative speed. In this research, the automatic headway control system is designed for mixed flow with different types of vehicles, from passenger cars to tractor trailers, and the speed based control strategy is selected in the automatic system design.

## 7.3.2 Control Modes Identification

On a highway system with less congestion problems, vehicles can be operated under either the car following control mode or autonomous control mode, i.e., following the behavior of the vehicle ahead or cruising at a designated speed. In this research a multiple mode vehicle control system is designed as following descriptions.

Assuming that there is an identical design speed for each section of highway, the automated vehicles can be operated in the following five control modes.

- Cruise Control

This is a normal operating mode. When the spacing with vehicle ahead is greater than a safety threshold, a vehicle will operate under this control mode, cruise at the design speed or accelerate/decelerate to the design speed.

- Following Control

When the spacing with respect to the vehicle ahead is within a designated threshold, a vehicle will enter this control mode, follow the operating status of the vehicle ahead. It will adjust its speed according to the relative velocity and relative distance with respect to the vehicle ahead.

- Rapid Deceleration

If the relative distance with respect to the vehicle ahead is less than a third designated threshold while the vehicle ahead is decelerating quickly, the vehicle will make rapid deceleration. Under this control mode, the deceleration is proportional to the relative velocity with respect to the vehicle ahead.

- Slowly Deceleration

When approaching a distant stopping or quickly decelerating vehicle, the controlled vehicle will be under this control mode and decelerate slowly. This control mode is designed analogy to human driving process and allows a vehicle slow down gradually to avoid abrupt deceleration that makes motorist discomfort.

- Emergency Braking

In case of emergency, such very high relative velocity and/or very small relative distance, a vehicle will brake quickly, and the value of braking only depends on its own velocity and deceleration capacity.

## 7.4 Multiple-Mode Vehicle Headway Control Model

### 7.4.1 System Dynamics Model

System dynamics is used in automatic headway control system design. A nonlinear, automatic headway control system model, multiple-mode vehicle headway control model (MVHC model), is set up based on the work of manual driving process simulation. The model incorporates vehicle dynamics and roadway conditions in the control algorithms, and is suitable for mixed traffic flow on a rural highway.

There is an assumption that there is an identical design speed for all the vehicles operating on each section of the automated highway. The design speed is set up based on the roadway geometric conditions. The MVHC model is established based on the following description.

A platoon consisting of n vehicles is traveling on an automated highway, which has a design speed, DS. A safety distance with respect to the vehicle ahead is assigned to each vehicle at any moment of its traveling, which is a function of the speed and deceleration capacity of the vehicle.

For the sake of safety, a vehicle must keep sensoring the state changes of the vehicle ahead and comparing its control mode thresholds with the relative speed and relative distance with respect to the vehicle ahead. A vehicle will travel at the design speed if the spacing with respect to the vehicle ahead is equal to or greater than a first safe spacing threshold. If the spacing is less than the first safe spacing threshold, the controller will check with second threshold, relative speed, and operating status of the vehicle ahead, and switch the control mode to the following, decelerating, or braking correspondingly. There are two time lags in the model, sensor time and power train response time.

The system dynamics casual diagram of automatic headway control simulation model is shown in Figure 7.1.
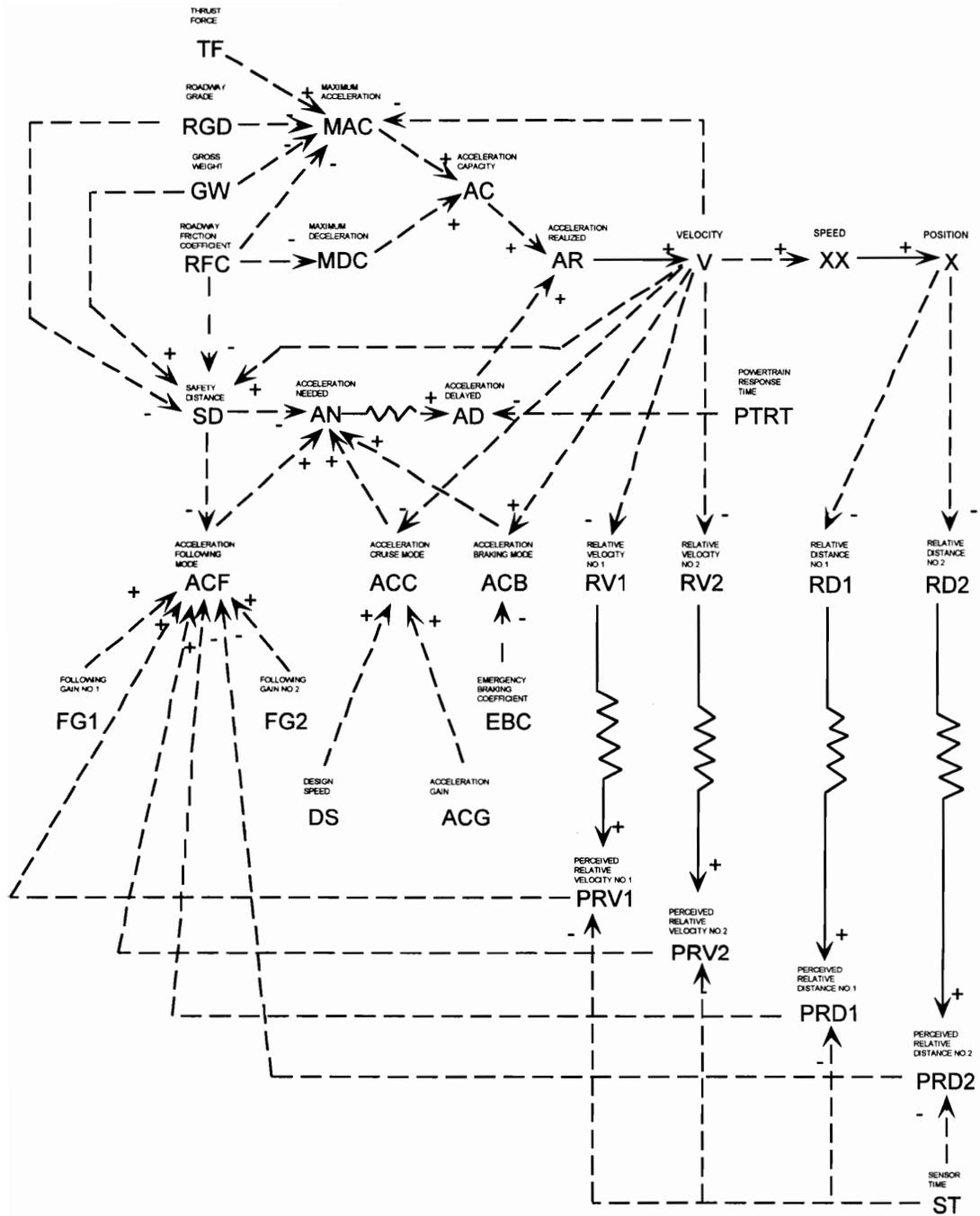
Figure 7.1  MVHC Model Casual Diagram

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## 7.4.2 Control Mode Switch Thresholds

There are five control modes in the MVHC system. Using this system, the control mode of a vehicle on a single automated lane switches from one to another based on the thresholds of relative velocity, relative distance, and the operating mode of the vehicle ahead.

The thresholds for the control mode switches are related to a fundamental safety distance function, $SD_i$, which is

$$
SD_i = \begin{cases} b_1 \dfrac{V_i^2}{DMAX_i} - b_2 \dfrac{V_{i-1}^2}{Be} & V_i \geq V_{i-1} \\ b_3 V_i & V_i < V_{i-1} \end{cases} \tag{7.1}
$$

The five control modes applying regimes are defined as:

- Cruise Control Mode

$$
\Delta_{i-1,i} > a_1 \, SD_i \tag{7.2}
$$

- Following Control Mode

$$
\begin{cases}
a_2 SD < \Delta_{i-1,i} < a_1 SD_i \\[2mm]
\dfrac{\Delta_{i-1,i}}{V_i} \leq \beta \dfrac{V_i}{DMAX_i}
\end{cases}
\tag{7.3}
$$

or

$$
\begin{cases}
\Delta_{i-1,i} < a_2 SD_i \\[2mm]
\Delta V_{i-1,i} > CRV
\end{cases}
\tag{7.4}
$$

- Rapid deceleration

$$
a_2 SD_i < \Delta_{i-1,i} \leq a_1 SD_i
\tag{7.5}
$$

$$
A_{i-1} \leq CD
\tag{7.6}
$$

- Slowly Decelerating Mode

$$
\begin{cases}
a_2 SD_i < \Delta_{i-1,i} \leq a_1 SD_i \\[2mm]
\dfrac{\Delta_{i-1,i}}{V_i} \geq \beta \dfrac{V_i}{DMAX_i}
\end{cases}
\tag{7.7}
$$

- Emergency Braking

$$\begin{cases} \Delta_{i-l,i} < a_2 SD_i \\ \\ \Delta V_{i-l,i} < CRV \end{cases} \tag{7.8}$$

where

$\Delta_{j,i}$ = spacing between (i-1)th vehicle and ith vehicle

$V_i$ = velocity of ith vehicle

$DMAX_i$ = maximum deceleration of ith vehicle

$\Delta V_{j,i}$ = relative velocity of (i-1)th and ith vehicle

$B_e$ = emergency braking rate

$CRV$ = critical relative velocity

$CD$ = critical deceleration

$\beta, a_1, a_2, b_1, b_2, b_3$ = constants

## 7.4.3  Control Model Design

Assuming a line of vehicles is operating on an automated lane. The MVHC control model includes the following equations.

- Cruise Control

$$Ac_i = Max\{AMAX_i, Kc_i(DS - V_i)\} \tag{7.9}$$

- Following Control

$$Af_i = Kfv_i\{\alpha(\frac{V_{i-1} - V_i}{\Delta_{i-1,i}}) + (1-\alpha)(\frac{V_{i-2} - V_{i-1}}{\Delta_{i-2,i}})\} + Kfs_i(1 - \frac{SD_i}{\Delta_{i-1,i}}) \tag{7.10}$$

- Rapid deceleration

$$Ard_i = Krd_v\, Krd_h\, \frac{V_{i-1} - V_i}{ST + PTRT} \tag{7.11}$$

- Slowly Decelerating

$$Asd_i = Ksd_i(\frac{V_i}{c_1\Delta_{i-1,i} + c_2}) + KSD \tag{7.12}$$

- Emergency Braking

$$Ab_i = Min\{DMAX_i, Kb(\frac{V_{i-1}^2 - V_i^2}{c_3\Delta_{i-1,i} + c_4})\} \tag{7.13}$$

where  $Ac_i$ = acceleration of ith vehicle in cruise control mode

$AMAX_i$ = maximum acceleration of ith vehicle

$DS$ = design speed

$V_i$ = velocity of ith vehicle

$Kc_i$ = cruise control mode control gain of ith vehicle

$Af_i$ = acceleration of ith vehicle in following control mode

$Ard_i$ = acceleration of ith vehicle in rapid deceleration mode

$Asd_i$ = acceleration of ith vehicle in slowly decelerating mode

$Ab_i$ = acceleration of ith vehicle in emergency braking mode

$Kfv_i$ = velocity related following mode control gain of ith vehicle

$Kfs_i$ = spacing related following mode control gain of ith vehicle

$Krd_v$ = velocity related gain in rapid deceleration mode of ith vehicle

$Krd_h$ = headway related gain in rapid deceleration mode of ith vehicle

$\Delta_{j,i}$ = spacing between rear bumper of jth vehicle to front bumper of ith vehicle

$SD_i$ = safety distance for ith vehicle

$\alpha$ = constant between 0 to 1

$Ksd_i$ = slowly decelerating mode control gain of ith vehicle

$DMAX_i$ = maximum deceleration of ith vehicle

$ST$ = sensor time

$PTRT$ = power train response time

$Kb$, $KSD$, $c_1$, $c_2$, $c_3$, $c_4$ = constants

Same as the manual driving simulation model, the control gains were selected to minimize the overshooting during the speed changing period and get smooth control mode switching.

## 7.5 Automatic Headway Control System Simulation

### 7.5.1 Simulation Scenario

The MVHC control system simulation was performed using the system dynamics software DYNAMO. It was used to simulate the control process of a line of five vehicles. At the initial state, the vehicles are evenly spaced, operating at a speed of 50 mph. The leading vehicle begins to accelerate to the design speed and then cruises at that speed. When an incident happened on the highway, the leading vehicle is forced to decelerate and finally stops at the point. The other vehicles take different control modes depending on the surrounding traffic during the whole period. At steady state, all vehicles come to a stop at the point of incident.

Three major types of vehicles are selected to simulate a mixed traffic flow, i.e. passenger cars and light trucks; single unit trucks; and combination trucks. The average length of the vehicle in the mixed traffic flow ranges from 15 ft to 75 ft, and gross weight ranges

from 3,500 lb to 60,000 lb. The design speed is selected as 70 mph. Two types of time lag were used in the system simulation: power train response time and sensor time. It is assumed that each type of time lag is identical for all the vehicles.

## 7.5.2 Simulation Results

The simulation for the automatic headway control process has been conducted for different types of vehicles with various sensor times, power train response times, design speeds, roadway conditions, and deceleration scenarios of the leading vehicle. The simulation results show that the control model can realize a quick and stable response to the system state, thus achieves the principal control objectives, safety and comfort.

Some of the simulation results of a platoon consisting of different types of vehicles under different operating scenarios are shown in the following graphs. The following are the parameters used in the simulation runs.

$Kfs_i = 1.8$

$Ksd_i = -60$

$KSD = 1$

$Kb = 2.5$

$C_1 = 2$

$C_2 = 200$

$C_3 = 1$

$C_4 = 10$

Some table functions were used in the control model, they are determined as following:

$Kc_i$:  KC.K=TABHL(ACG1TAB,V.K,0,120,20)

KCTAB=.12/.18/.25/.41/.6/.85/1


$Kfv_i$:  KFV.K=\$ACG2.K*\$ACG3.K*(RV.K/(\$ASPACE.K+ABSC))

ACG2.K=TABHL(ACG2TAB,SPACE.K,5,145,20)

ACG2TAB=4/5/7/8.5/9/9.5/9.8/10.2

ACG3.K=TABHL(ACG3TAB,RV.K,-21,18,3)

ACG3TAB=14/13/12.2/11.5/10.5/9.6/8.8/10/10.8/11.5/12.3/13.2/13.8/14.5


$Krd_h$:  KRDH.K=TABHL(FVTAB,V.K,0,100,25)

KRDHTAB=1.0/1.1/1.2/1.4/1.6


$Krd_v$:  KRDV.K=TABHL(FSTAB,SPACE.K,0,140,20)

KRDVTAB=1.8/1.4/1/.7/.5/.3/.22/.2


**Case 1.** A platoon of vehicles consists of only passenger cars and light trucks. The parameters of the vehicles are:

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Vehicle Length:  vl1 = 15 ft;  vl2 = 35ft ft;  vl3 = 20ft;  vl4 = 20ft;  vl5 = 15ft

Vehicle Weight:  wt1 = 3500lb; wt2 = 10,000lb; wt3 = 4500lb; wt4 = 6000lb;

wt5 = 5000lb

A platoon consisting of five vehicles travels on an even graded automated highway, with initial speed of 50 mph. The leading vehicle starts to accelerate from the initial speed to the design speed and then cruises at that speed. With the advent of an incident, it decelerates at the rate of 0.25g. The following vehicles follow the leading vehicle, accelerate, decelerate and brake, try to keep their own desired speed and spacing respectively. At the steady state, all vehicles stop before the incident spot, closely spaced, and no crash occurs. The simulation procedure is shown in Figure 7.2.

**Case 2.**  A platoon of vehicles consists of passenger cars and trucks. The parameters of the vehicles are:

Vehicle Length:  vl1 = 15 ft;  vl2 = 45 ft;  vl3 = 25 ft;  vl4 = 75 ft;  vl5 = 15ft

Vehicle Weight:  wt1 = 3500 lb;  wt2 = 9,000 lb;  wt3 = 4500 lb;

wt4 = 60,000 lb; wt5=5000 lb

The simulation scenario is the same as case 1. At the steady state, no crash occurs. The simulation procedure is shown in Figure 7.3.

**Case 3.** A platoon of vehicles consists of passenger cars and trucks. The parameters of

the vehicles are:

Vehicle Length: vl1 = 15 ft; vl2 = 45 ft; vl3 = 25 ft; vl4 = 75ft; vl5 = 15ft

Vehicle Weight: wt1 = 3500 lb; wt2 = 9,000 lb; wt3 = 4500 lb;

wt4 = 60,000 lb; wt5=5000 lb

The simulation scenario is the same as case 1. The roadway grade is -3% at this

section. At the steady state, no crash occurs. The simulation procedure is

shown in Figure 7.4.

**Case 4.** A platoon of vehicles consists of passenger cars and trucks. The parameters of

the vehicles are:

Vehicle Length: vl1 = 15 ft; vl2 = 45 ft; vl3 = 25 ft; vl4 = 75 ft; vl5 = 15ft

Vehicle Weight: wt1 = 3500 lb; wt2 = 9,000 lb; wt3 = 4500 lb;

wt4 = 60,000 lb; wt5=5000 lb

The simulation scenario is same as case 1, except that the leading vehicle

decelerates at the rate of 0.4g. At the steady state, no crash occurs. The simulation

procedure is shown in Figure 7.5.
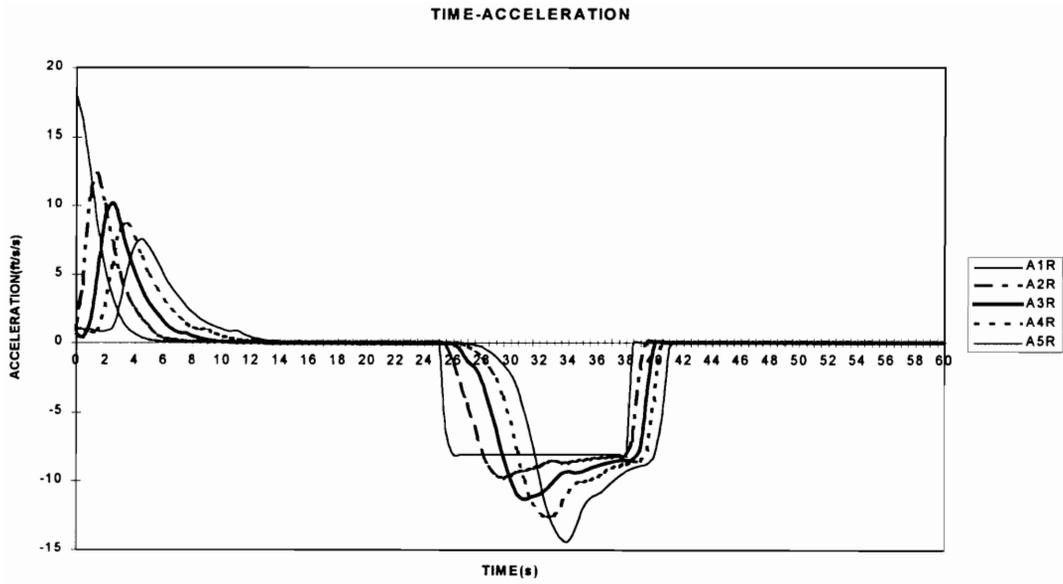
**TIME-ACCELERATION**



Figure 7.2 (a) Time-Acceleration Graph
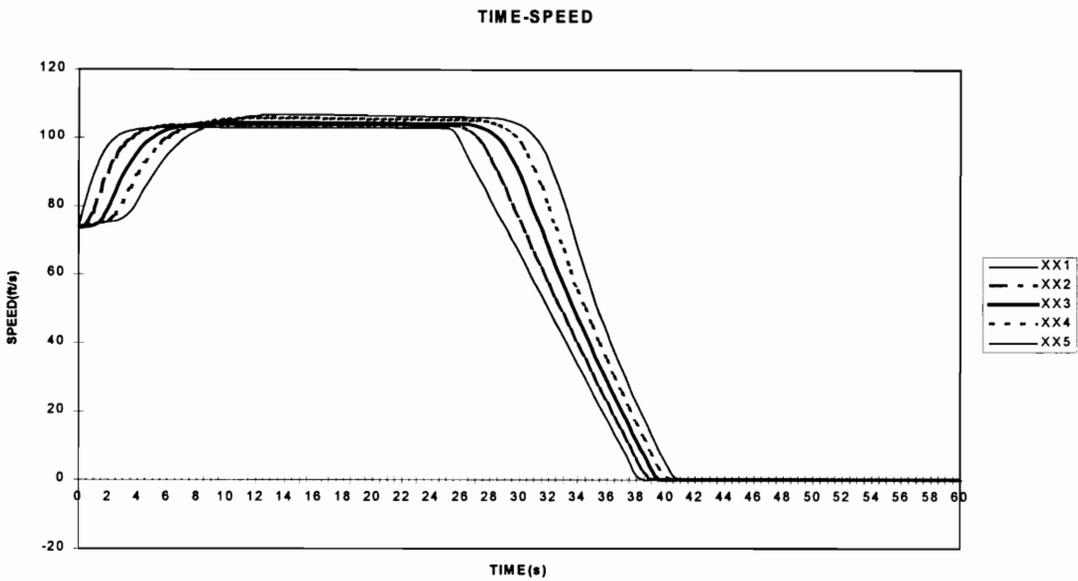
**TIME-SPEED**



Figure 7.2 (b) Time-Speed Graph
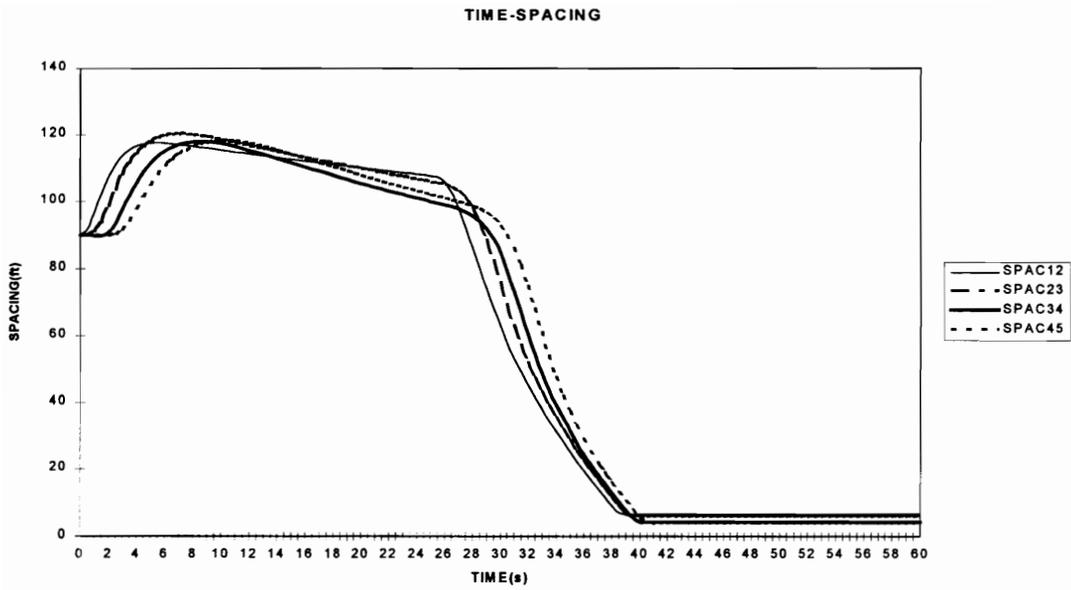
**TIME-SPACING**



Figure 7.2 (c)  Time-Spacing Graph
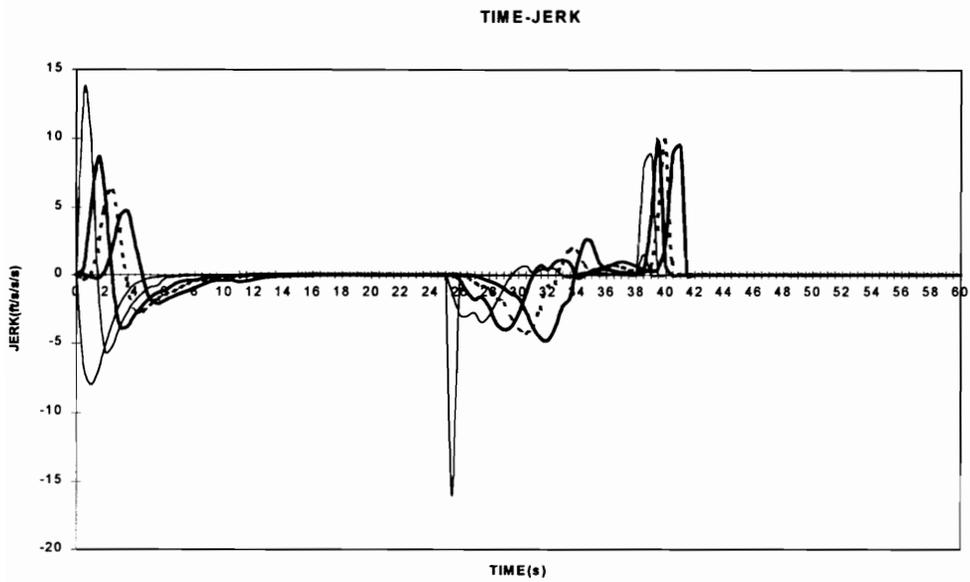
**TIME-JERK**



Figure 7.2 (d)  Time-Jerk Graph

Figure 7.2  MVHC Model Simulation Case 1
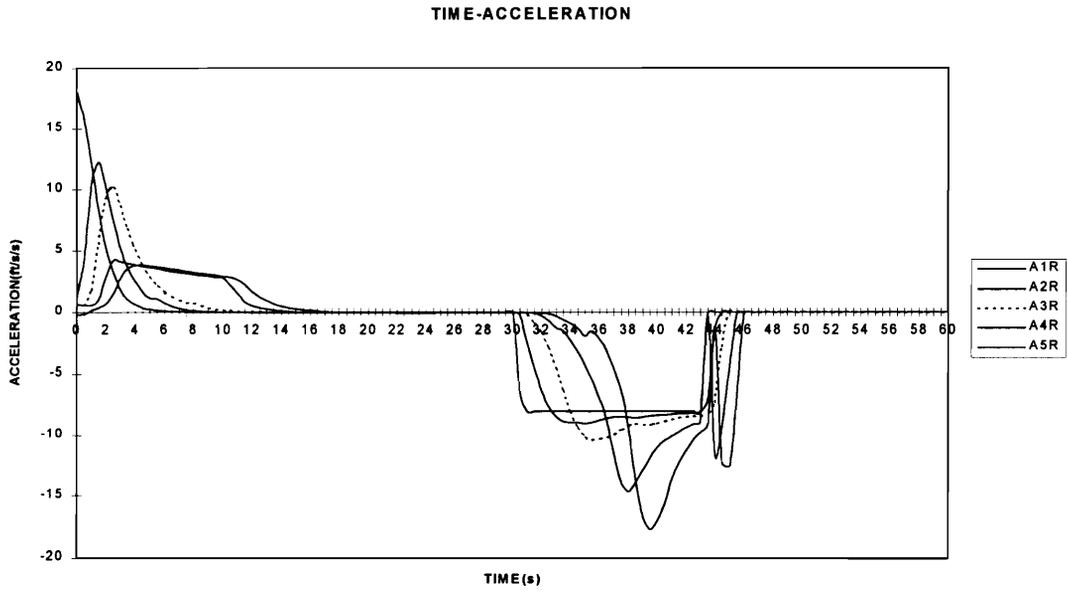
**TIME-ACCELERATION**



Figure 7.3 (a)  Time-Acceleration Graph
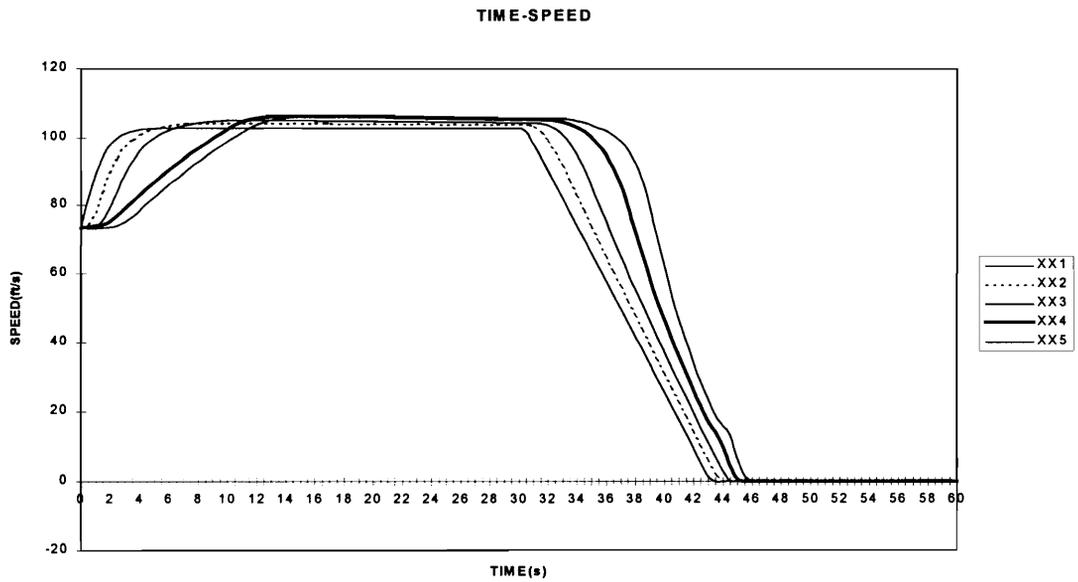
**TIME-SPEED**



Figure 7.3 (b)  Time-Speed Graph
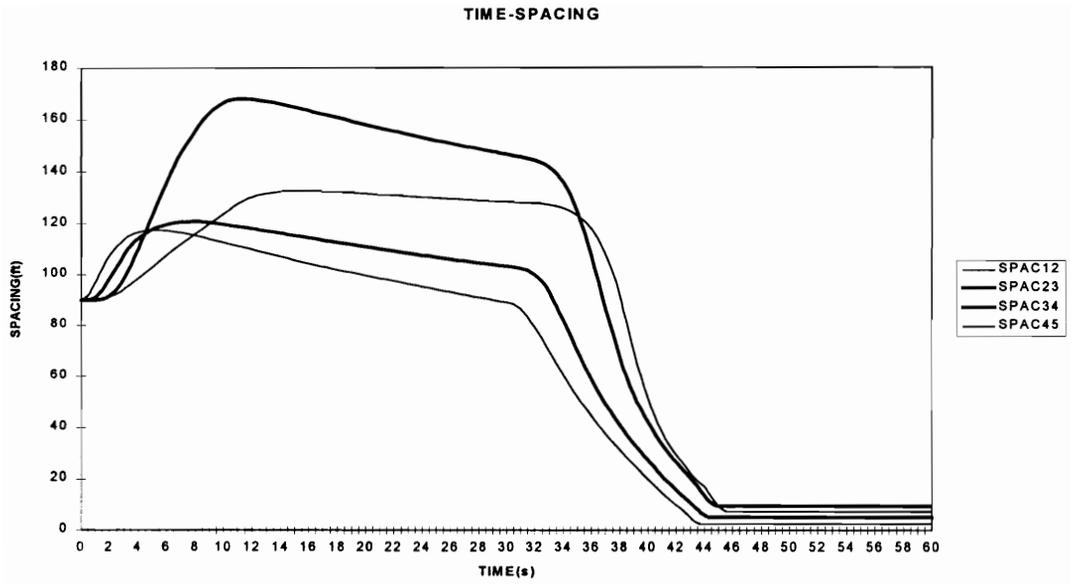
**TIME-SPACING**



Figure 7.3 (c) Time-Spacing Graph
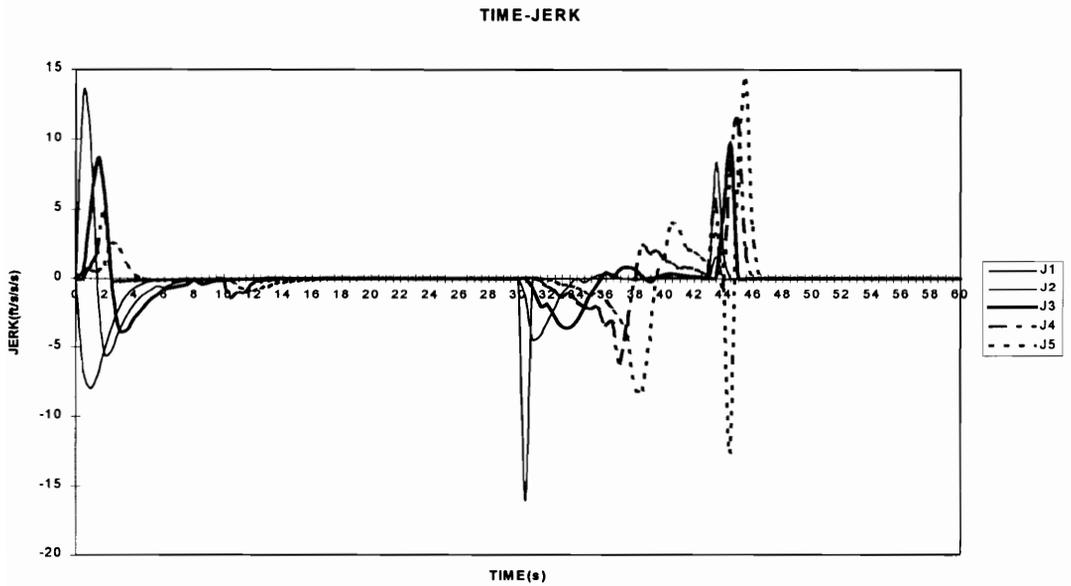
**TIME-JERK**



Figure 7.3 (d) Time-Jerk Graph

Figure 7.3 MVHC Model Simulation Case 2
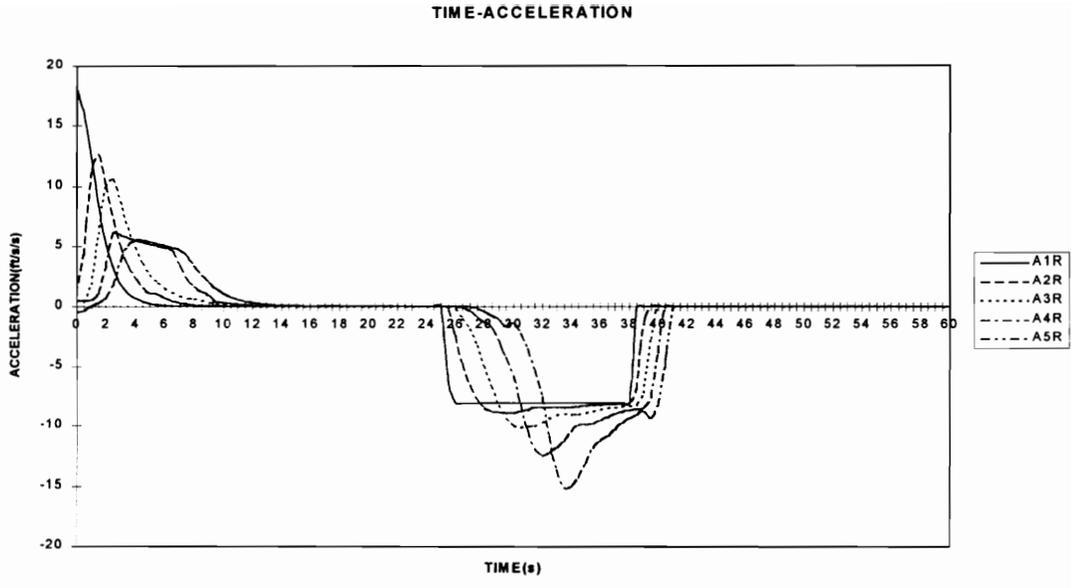
**TIME-ACCELERATION**



Figure 7.4 (a)  Time-Acceleration Graph
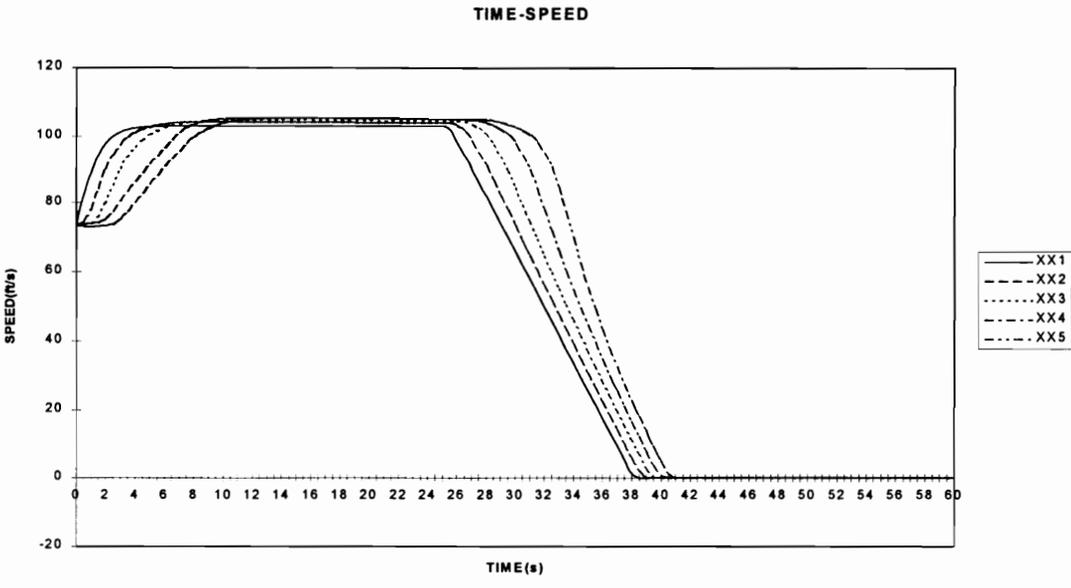
**TIME-SPEED**



Figure 7.4 (b)  Time-Speed Graph
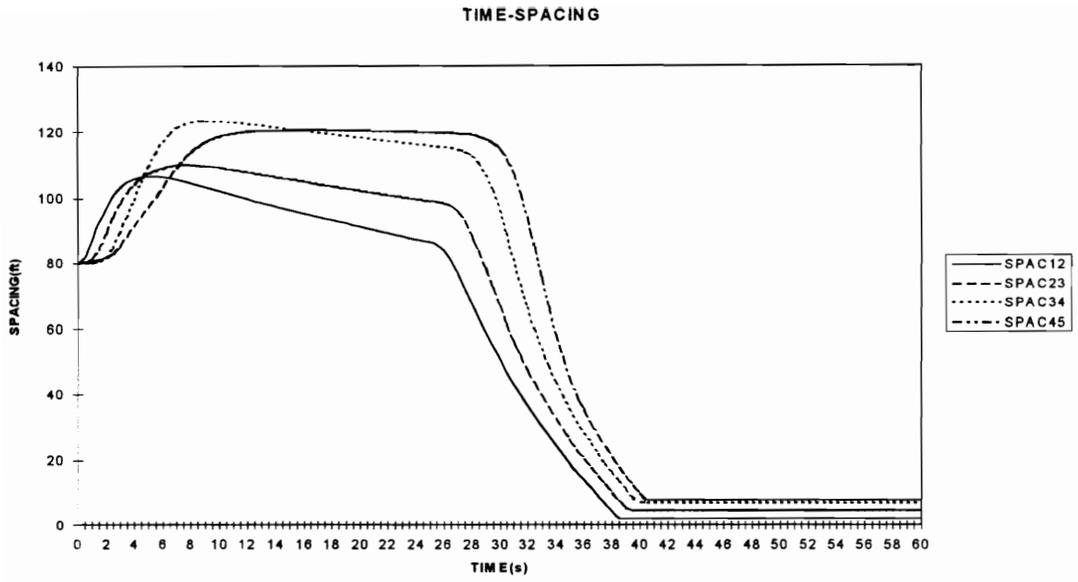
**TIME-SPACING**



Figure 7.4 (c)  Time-Spacing Graph
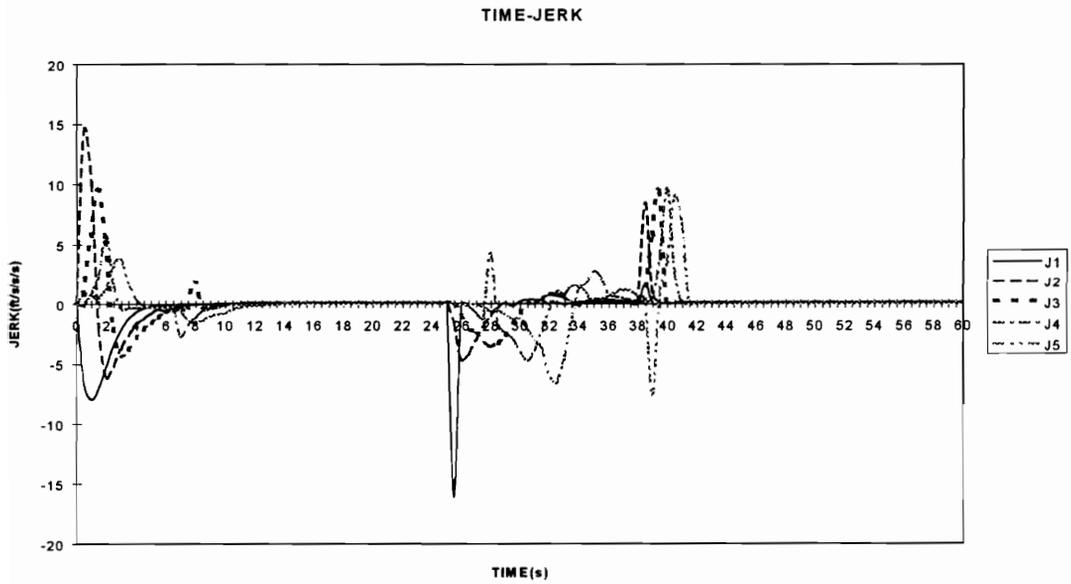
**TIME-JERK**



Figure 7.4 (d)  Time-Jerk Graph

Figure 7.4 MVHC Model Simulation Case 3

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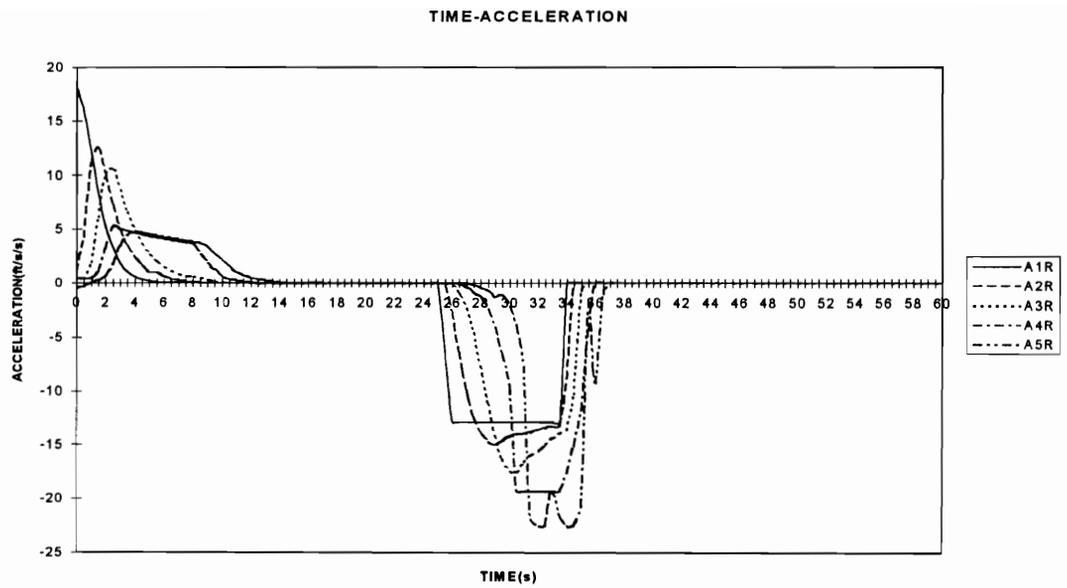
**TIME-ACCELERATION**



Figure 7.5 (a)  Time-Acceleration Graph
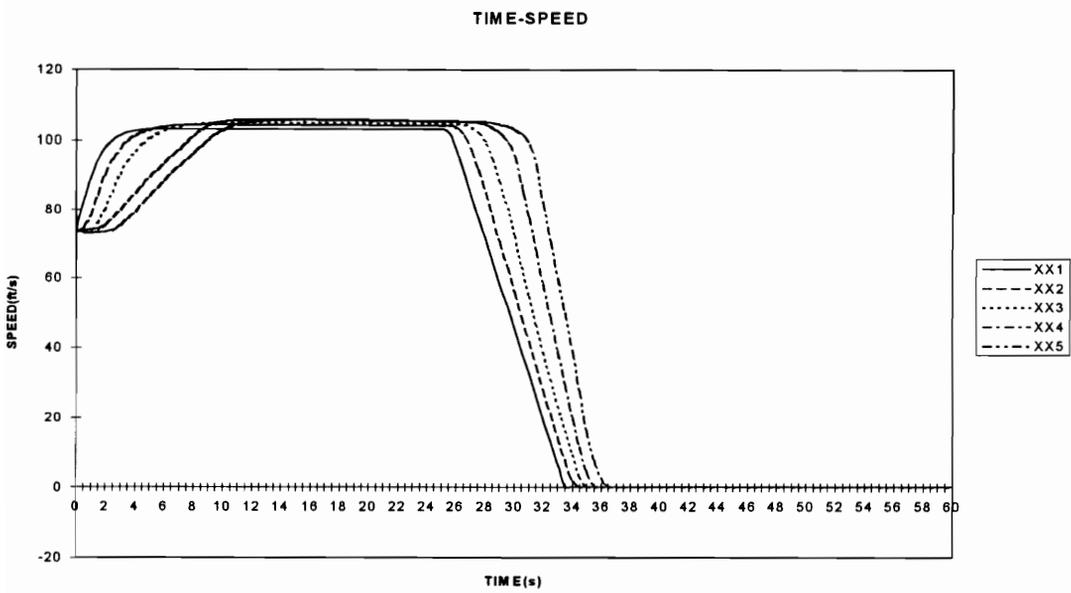
**TIME-SPEED**



Figure 7.5 (b)  Time-Speed Graph
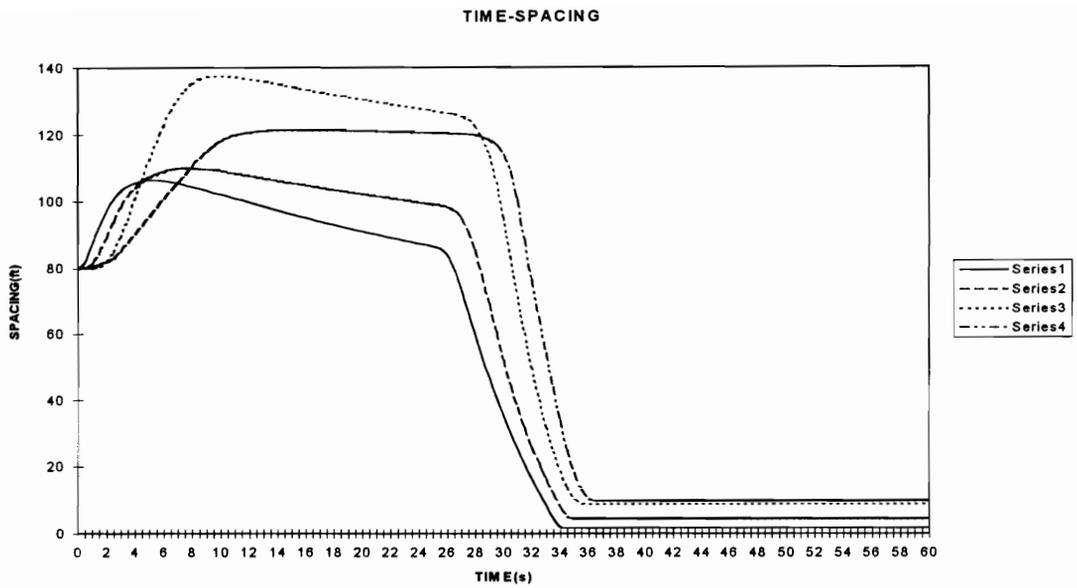
**TIME-SPACING**



Figure 7.5 (c)  Time-Spacing Graph
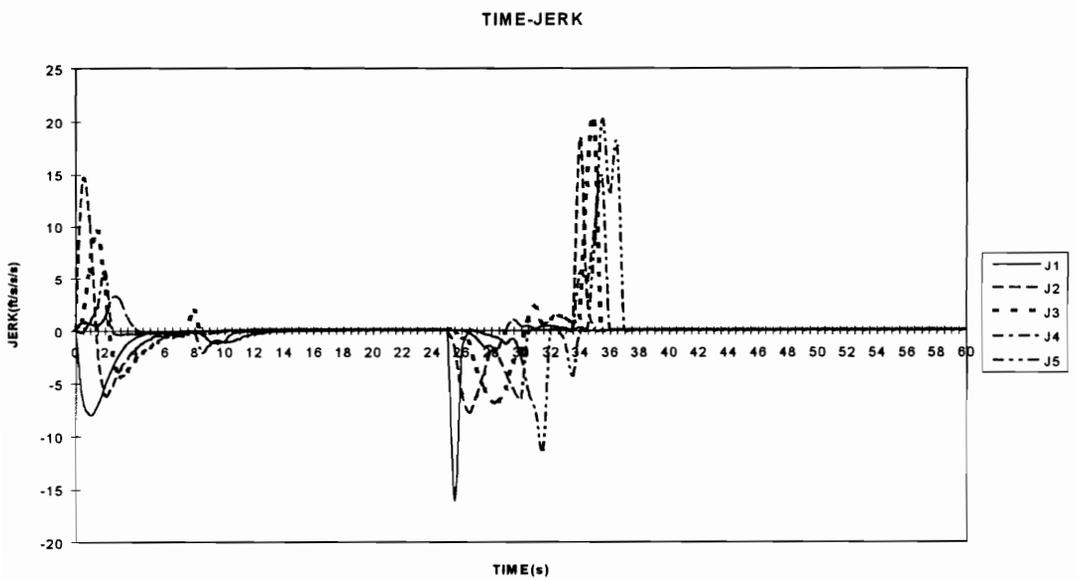
**TIME-JERK**



Figure 7.5 (d)  Time-Jerk Graph

Figure 7.5 MVHC Model Simulation Case 4

# 8. Simulation Tool in Testing and Evaluating AVCS Technologies

## 8.1 Introduction

The development of AVCS technologies can be divided into the following stages: analytical modeling, simulation, field test, and deployment. Research on the technologies associated with automated highway operation has been conducted for many years. Various automatic headway control models have been proposed based on a variety of control strategies. The complex nature of these models and the effects caused by different external factors result in a thorough model testing and evaluation prior to the automatic control systems deployment.

The objective of this research is to explore a methodology that can be used for testing and evaluating AVCS technologies, in general, and automatic headway control models for trucks operating on rural highways, in particular. The simulation tool used for this goal must be capable of: (1) duplicating various existing automatic vehicle headway control models; (2) simulating these models under different operating conditions to test their control effects; and (3) evaluating the models under certain criteria. As system dynamics has the capability of accomplishing these requirements and therefore is selected as the simulation tool for performing automatic headway control models testing and evaluation.

## 8.2 Testing Automatic Headway Control Models with System Dynamics

### 8.2.1 Duplication of Analytical Longitudinal Control Model

Most existing automatic headway control models were established based on feedback control principles. These models generally possess the properties of higher order feedback control systems, therefore, system dynamics is an appropriate simulation tool for their testing and evaluation. For the purpose of testing and evaluating AVCS technologies, the automatic headway control models under study should first be duplicated with system dynamics, implemented with the simulation tool, and then tested under certain selected simulation scenarios. In this research, some existing analytical automatic headway control models were duplicated with DYNAMO, the simulation software of the research, and tested with various parameter combinations.

With system dynamics, a longitudinal control model developed by PATH[41] (Eq. 4.4 - 4.9) has been duplicated with system dynamics and simulated under different operating conditions. This model is a third order feedback control system. It can be converted into the differential equation below:

$$\dddot{\Delta}_i(t) = \dddot{\Delta}_{i-1}(t) - k_a \ddot{\Delta}_{i-1}(t) - k_v \dot{\Delta}_{i-1}(t) - c_a \ddot{\Delta}_i(t) - c_v \dot{\Delta}_i(t) - c_p \Delta_i(t) \qquad (8.1)$$

where $\Delta_i$ is the deviation of the $i$th vehicle from its assigned position. Then the model can be easily implemented with system dynamics. First convert the model into the following differential equations.

$$\frac{d\Delta_i(t)}{dt} = \dot{\Delta}_i(t) \tag{8.2}$$

$$\frac{d\dot{\Delta}_i(t)}{dt} = \ddot{\Delta}_i(t) \tag{8.3}$$

$$\frac{d\ddot{\Delta}_i(t)}{dt} = \dddot{\Delta}_i(t) \tag{8.4}$$

$$\dddot{\Delta}_i(t) = \dddot{\Delta}_{i-1}(t) - k_a\ddot{\Delta}_{i-1}(t) - k_v\dot{\Delta}_{i-1}(t) - c_a\ddot{\Delta}_i(t) - c_v\dot{\Delta}_i(t) - c_p\Delta_i(t) \tag{8.1}$$

Based on these equations, the system dynamics casual diagram of the model is developed as Figure 8.1. Then it can be implemented with DYNAMO to make simulation run.
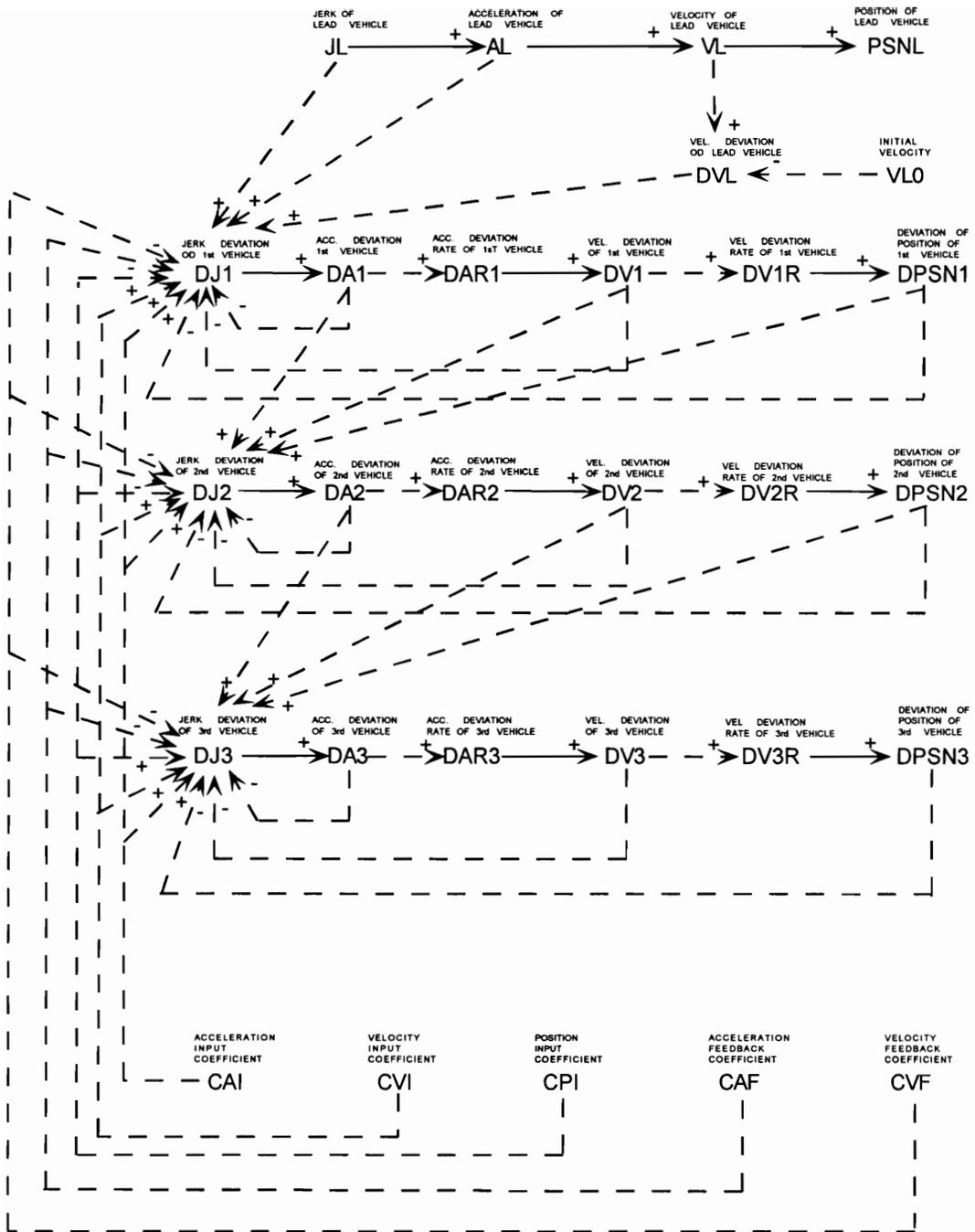
Figure 8.1 Casual Diagram of PATH Longitudinal Control Model

## 8.2.2 PATH Longitudinal Control Model Testing

The simulation for the duplicated longitudinal control model was first conducted with the same scenario used in the PATH experiment, in which the control was applied to a platoon of passenger cars with identical length. Then applying to a platoon consisting of passenger cars and trucks, while varying some parameters, the model was tested for a different scenario.

- **Scenario 1**

A platoon consisting of seven vehicles (a leading vehicle and six following vehicles) is operating on a highway, with initial speed of 40 mph. The leading vehicle starts to accelerate at time t=0, with an acceleration rate of 0.2g. When the speed reaches 60 mph, it stops acceleration and cruises at that speed. The following vehicles follow the leading vehicle to accelerate to 60 mph and then cruise at that speed. No crash occurs during the speed transition procedure.

The vehicles have identical length, 18 feet. At initial state, the vehicles are evenly and closely spaced, three feet apart, with a position deviation of zero. The control variables of the model are the position deviations of the vehicles. No time lag is considered in the control process. The simulation results are shown in Figure 8.2.

- **Scenario 2**

This scenario is based on the first scenario with some changes. The leading vehicle accelerates from 40 mph to 60 mph, with acceleration rate of 0.2g, cruises at 60 mph for a while, and then decelerates to 40 mph again, with deceleration rate of -0.2g. The following vehicles follow the behavior of the leading vehicle, accelerate, cruise, and decelerate respectively. No crash occurs during the speed transition procedures.

Two time lags are included in the control process, sensor time and power train response time. The platoon consists of seven vehicles of different types, passenger cars and trucks. The lengths of the vehicles are 20ft, 18ft, 25ft, 70ft, 15ft, 48ft, and 20ft, from the leading vehicle to the sixth following vehicle respectively. The mass effects of vehicles is not considered because of the limitation of the original model. The objective of the second scenario is to test the control effect of the model under different conditions, especially the effect of time lags. The simulation results are shown in Figure 8.3.

Through the simulation results, we can see that the PATH model has the property of quick response. With the first simulation scenario, the whole platoon completed speed transition and entered steady state in nine seconds, oscillations and overshoots were insignificant. With the second simulation scenario, in which time lags were considered, the model could still reach steady state in ten seconds, but much more oscillations and overshoots occurred during the control process. This situation aggravates as the number of vehicles increases.
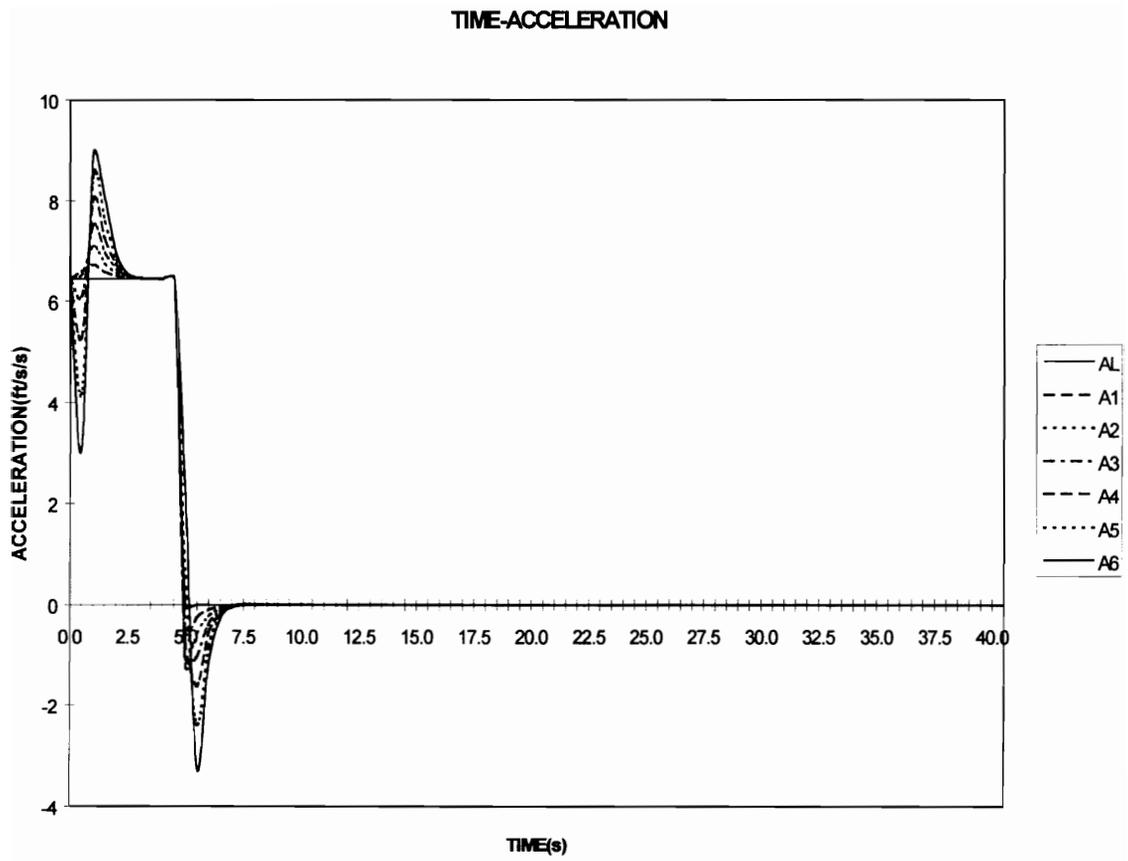
8.2 (a) Time-Acceleration Graph
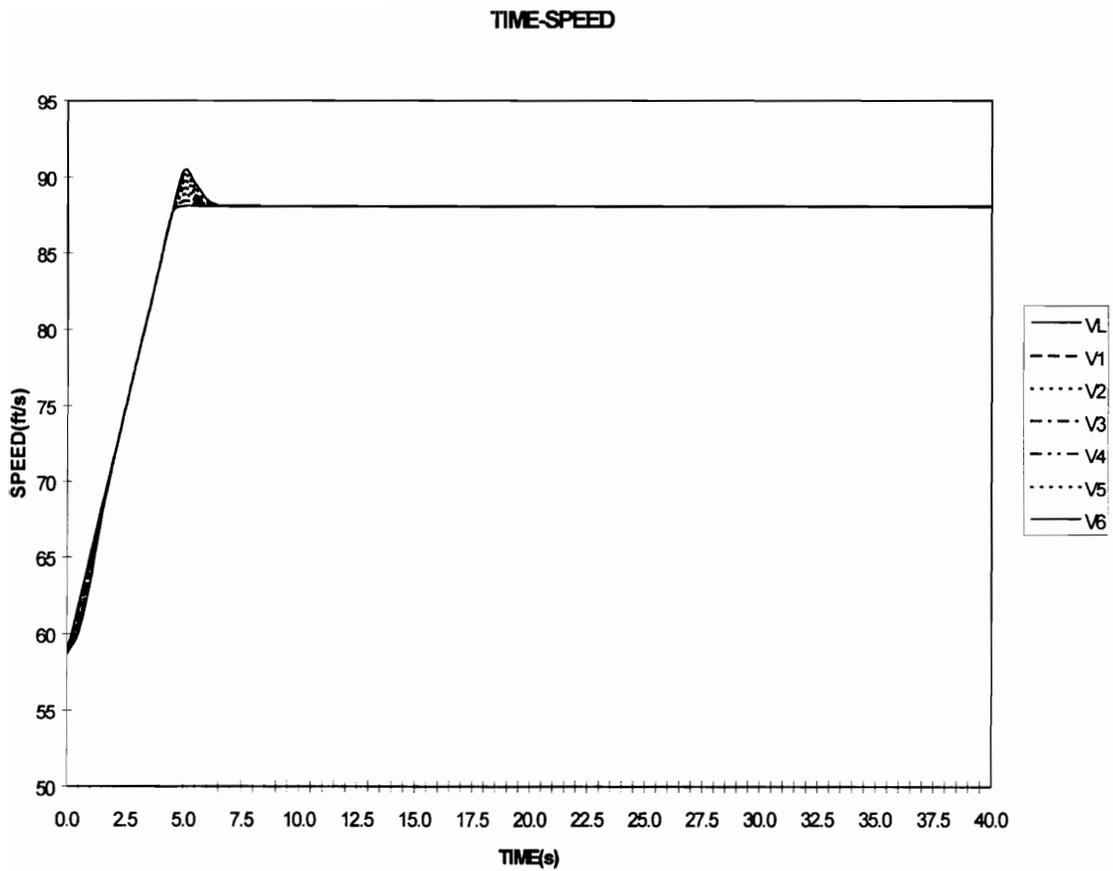
Figure 8.2 (b)  Time-Speed Graph
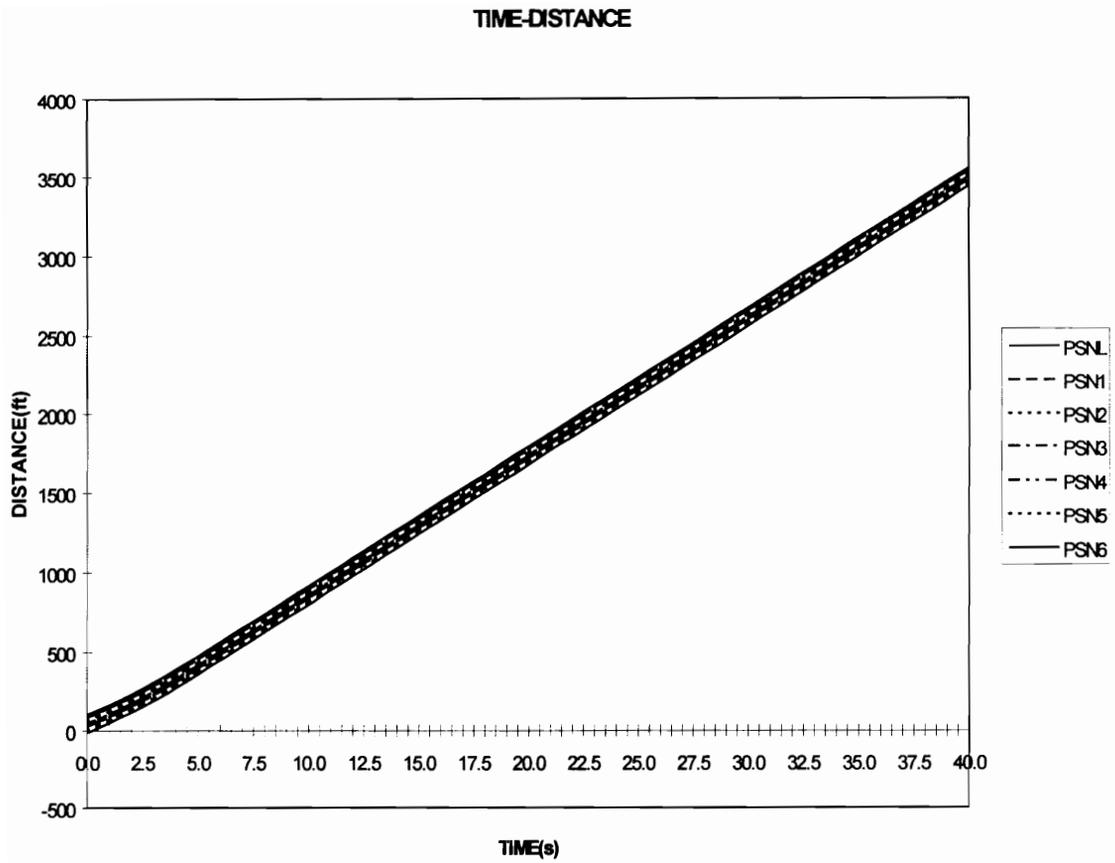
Figure 8.2 (c)  Time-Distance Graph

**TIME-POSITION DEVIATION**
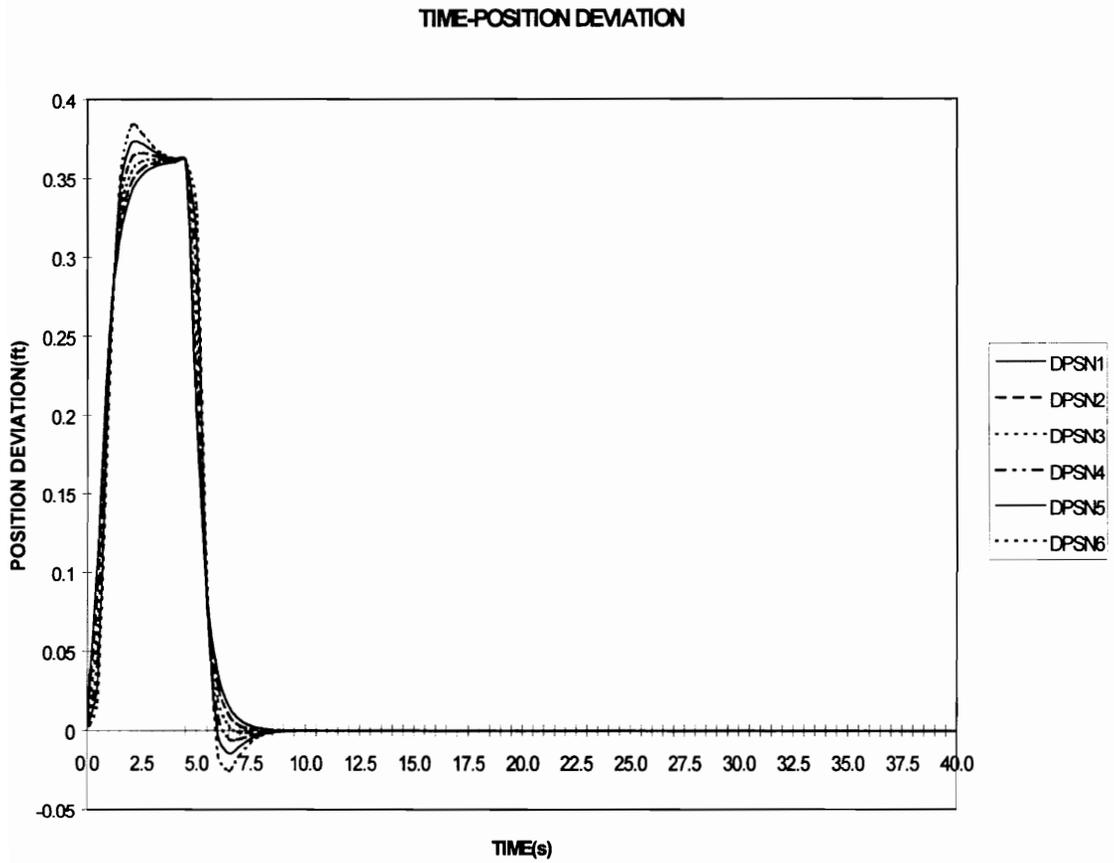


Figure 8.2 (d)  Time-Position Deviation Graph

Figure 8.2  Simulation Results of Original PATH Model
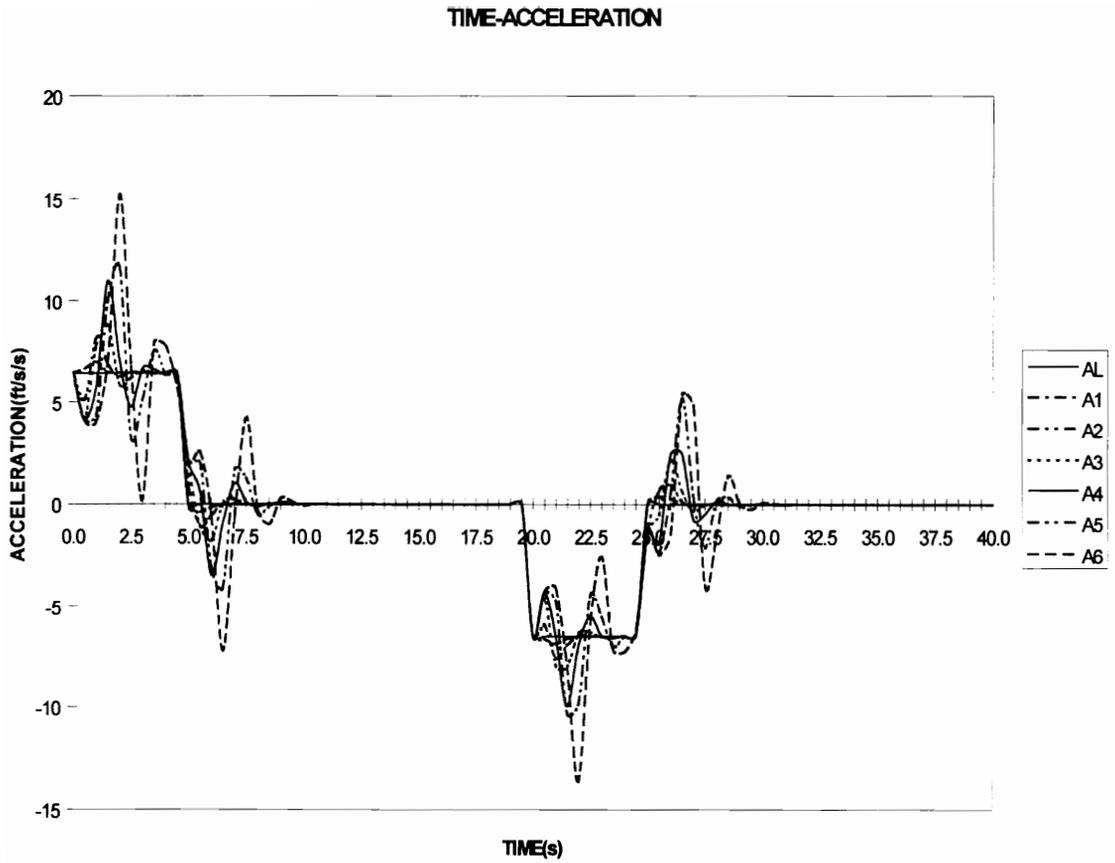
8.3 (a) Time-Acceleration Graph
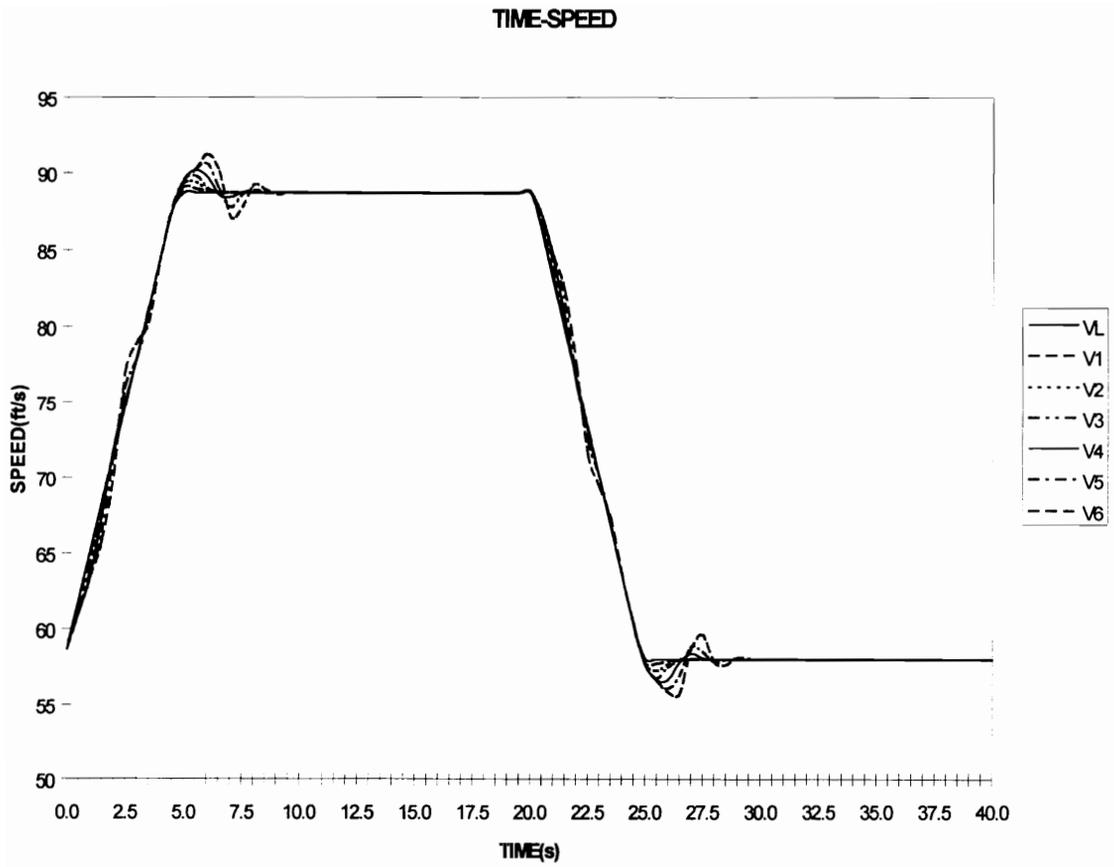
**TIME-SPEED**

Figure 8.3 (b)  Time-Speed Graph
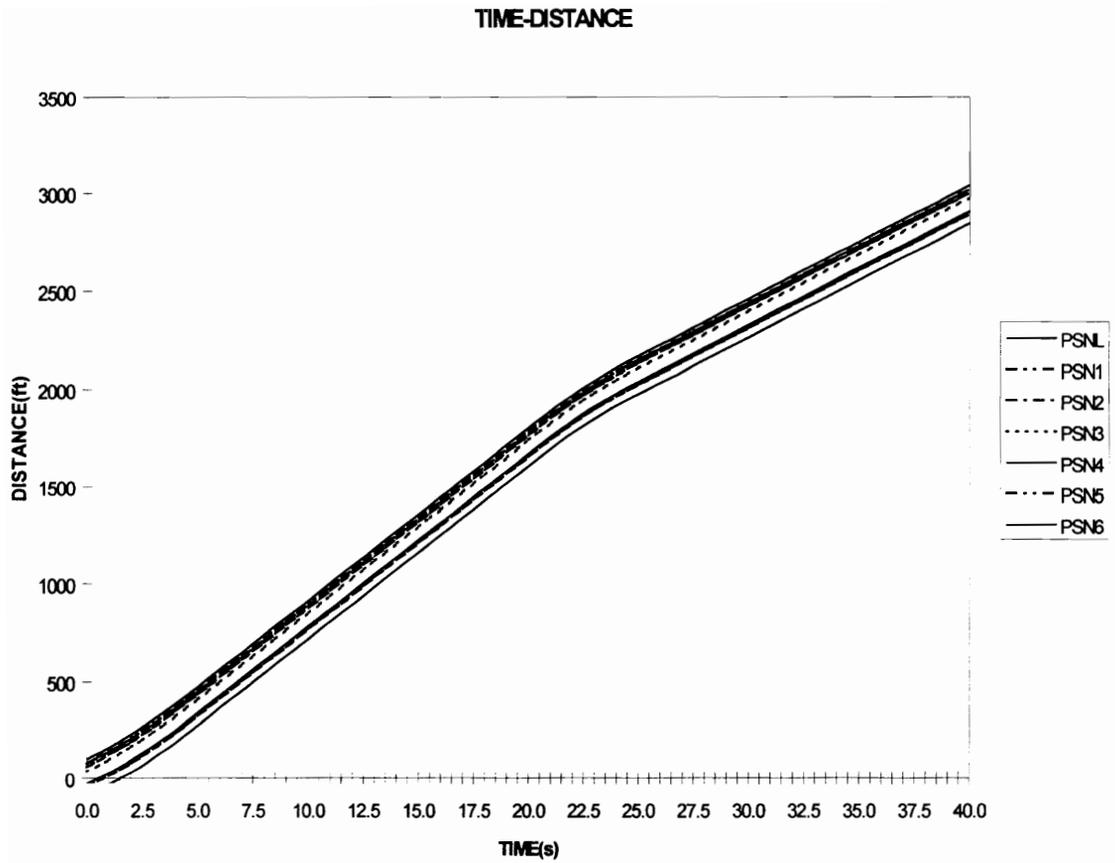
Figure 8.3 (c)  Time-Distance Graph

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**TIME-POSITION DEVIATION**
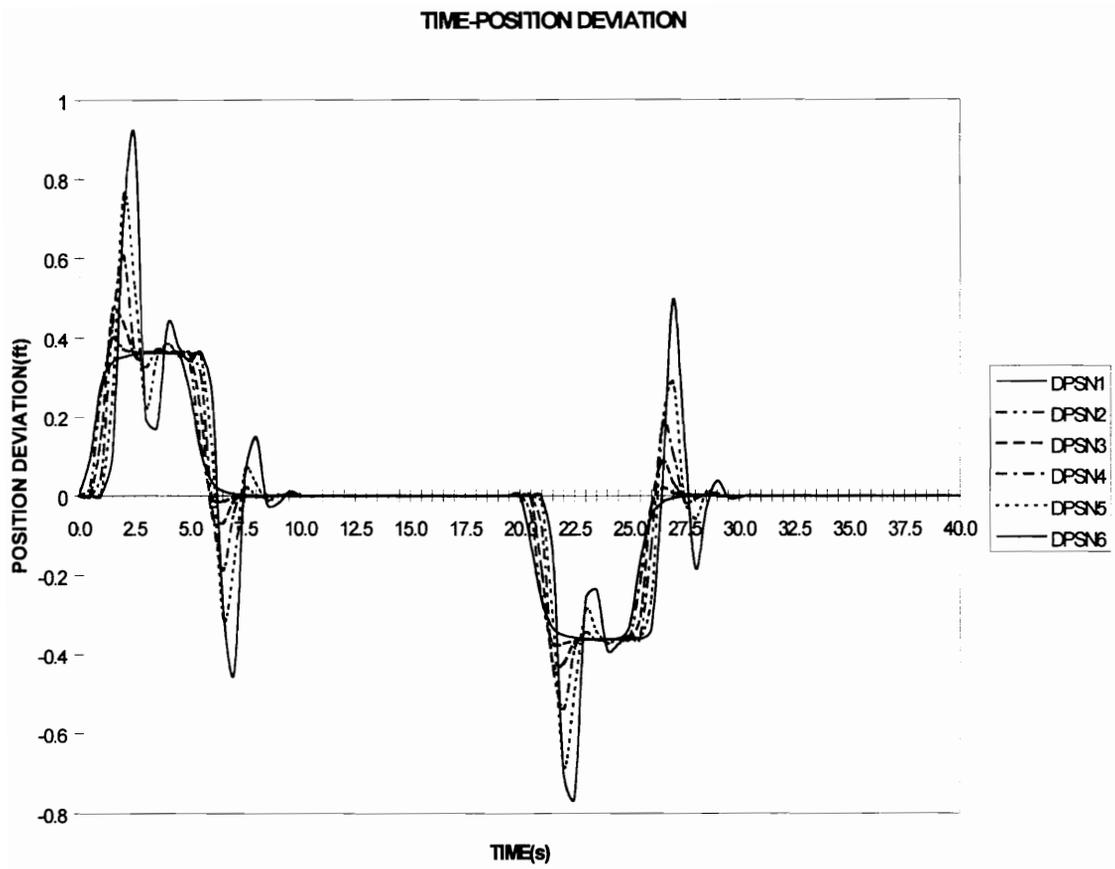
Figure 8.3 (d)  Time-Position Deviation Graph

Figure 8.3  Simulation Results of Modified PATH Model

## 8.3 AVCS Evaluation Criteria

Evaluation is a very important stage in system development. It refers to the judgment of a system in terms of worth, quality of performance, degree of effectiveness, and condition. The purpose of evaluation is to determine the true characteristics of the system and to ensure that it can fulfill its intended mission.[45] Considering the highly sophisticated nature and variety of factors, it is specifically important in the implementation of AVCS technologies. Any automatic control systems must be thoroughly evaluated before deployment. For the purpose of selecting best models to build an automatic headway control system, various headway control models should be tested under different operating conditions and evaluated with the same criterion.

MOE analysis for AVCS can be conducted under different criteria. The most popular evaluation criteria include safety, roadway capacity, and traffic stream stability. In German PRO-GEN Group, Intelligent Cruise Control systems were evaluated in terms of traffic safety, transport efficiency and environmental pollution, based on microscope traffic simulations.[73] In PATH program, a simulator, SmartPath, has been used to examine transient behavior of the traffic stream under various conditions and measure the maximum flow rates can be attained under different strategies.[74]

When considering the overall quality of a traffic facility, level of service can always be an effective index for evaluation. Level of service refers to the quality of driving conditions afforded a motorist by a particular facility. It generally includes the following factors: (1) driving safety, (2) speed and travel time, (3) traffic interruption, (4) freedom to maneuver, (5) motorist comfort, and (6) vehicular operating cost.

The level of service is the evaluation criterion from the user's point of view. In fact, all of the evaluation criteria have been widely used come from the factors of level of service, directly or indirectly. For the AVCS evaluation, we can use different factors of level of service as the criterion for different purposes and in different areas.

As the focus of this research is the headway control models for trucks operating on rural highways, where congestion is not major problem, safety and motorist comfort are more important issues, and therefore selected as the evaluation criteria.

Operating safety is the most important evaluation criterion for all AVCS technologies. It can be easily assessed when the headway control models are tested under the same operating scenario and conditions. With the same roadway conditions, time lags, and design speed, the maximum number of vehicles in a platoon, minimum spacing between vehicles, and maximum deceleration of leading vehicle can be determined through simulation and thus taken as the measure of safety of a headway control model.

Motorist comfort is complex index which is affected a variety of factors, such as traffic volume, roadway geometrics, and operating speed. A parameter that can comprehensively reflect motorist comfort must be selected as the evaluation index. As the varying nature of the roadway geometrics is accompanied by a varied degree of optimum speed, volume, and density for short successive sections of freeway, the evaluation parameter must reflect the qualitative efficiency of small roadway sections.

## 8.4 Acceleration Noise Approach

For the purpose of evaluation, motorist comfort must be quantified and then measured. In general, a motorist evaluates a facility by the speed at which he can operate his vehicle and the uniformity of speed. The amount of speed changes and the frequency of speed changes are undesirable factors which irritate the motorist. Thus the uniformity of speed is a very important index to the motorist comfort.

A traffic parameter referred to as acceleration noise[29] can be used to evaluate the uniformity of speed. The acceleration noise, which was used to evaluate traffic flow quality, is in fact a measurement of the smoothness of flow in a traffic stream. The acceleration noise is standard deviation of the accelerations. It can be considered as the

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disturbance of the vehicle's speed from a uniform speed. Acceleration noise reflects the amount of speed changes and the frequency of speed changes during a period. The greater the acceleration noise, the greater discomfort the motorist experiences.

Some tests have shown that in manual driving situations, the accelerations during a trip can be considered as random components of time, and the acceleration distributions essentially follow a normal distribution.[75] Although a motorist usually attempts to keep his vehicle at a comfortable speed when driving on a highway with very light traffic volume, but he accelerates and decelerates unconsciously and deviates from a uniform speed throughout the trip. When traffic volume increases, the motorist is perhaps forced to change lanes and increases speed, resulting in higher and more frequent deviations from a uniform speed. The smoothness of a trip can be described by the amount that the individual random accelerations disperse about the mean acceleration.

Drew proposed the following equations to estimate the acceleration noise of a vehicle for a trip of time T. [29]

$$\sigma = \left\{ \frac{1}{T} \int_0^T [a(t)]^2 \, dt - (a_{ave})^2 \right\}^{1/2} \tag{8.5}$$

$$a_{ave} = \frac{1}{T} [v(t) - v(0)] \tag{8.6}$$

where

$\sigma$ = acceleration noise

$a(t)$ = acceleration of the vehicle at time t

$a_{ave}$ = average acceleration of the vehicle for the trip

$v(t)$ = speed of the vehicle at time t

When a vehicle stops, the deviations of accelerations equal to zero. This situation would reduce the value of $\sigma$ even though it adds the annoyance of the motorist. Thus, $\sigma$ is measured only while vehicle is in motion, and therefore T is taken as the running time of the vehicle.

## 8.5 Automatic Headway Control Models Evaluation

Acceleration noise is generally used as a measurement of the smoothness of traffic flow, in which the vehicles are controlled by human drivers. The factors that influence the amount of acceleration noise include the behavior of driver, roadway geometric design, and traffic volume. The value of acceleration noise reflects potentially dangerous traffic conditions, roadway geometric qualities, and the degree of congestion. Some experiments obtained acceleration noise of 0.32 ft/sec$^2$ on a perfect roadbed without influence of

traffic, between 0.79 and 1.41 ft/sec$^2$ on winding country roads, and of 1.43 ft/sec$^2$ on a road with certain degree of congestion.[29]

In automated highway systems, vehicles are operated by automatic controller. The vehicles should travel under uniform speed, and thus the acceleration noise of a vehicle should be zero when it is traveling under normal situations. The discomfort a motorist may experience is the jerk that happens during the transient period of speed change or emergency braking. Although it is different from the original objective of evaluating the quality of traffic flow under manual driving situations, the acceleration noise can be applied to automatic headway control systems to evaluate the oscillation effects the motorists of individual vehicles would experience during certain speed changes. Under same operating scenario, various control models can be tested and the acceleration noises they would cause can be calculated.

The acceleration noise approach is implemented with the simulation tool and applied to evaluate automatic headway control models under different simulation scenarios. Since the evaluation is conducted only for speed transitional period and the simulation scenarios are very different from a uniform speed trip of manual driving situations, the values of the acceleration noises for this evaluation purpose should be much greater than the reference values above. For comparison purpose, the multiple-mode vehicle headway control model (MVHC) developed in this research and the duplicated PATH longitudinal

control model have been simulated with the same scenarios to measure the acceleration noise during the control procedure.

In the simulation, both control models were applied to a platoon of five vehicles with identical length, 18 feet, operating on an even grade highway. The simulation runs were conducted for two speed transition scenarios, acceleration and deceleration.

- **Scenario 1**

At initial state, the leading vehicle of the platoon began to accelerate from the speed of 60 mph, at the acceleration rate of 0.2g. When the speed reached 70 mph, it stopped accelerating and cruised at that speed. The following vehicles followed the leading vehicle's speed profile and accelerated respectively. At steady state, all the vehicles traveled at 70 mph.

- **Scenario 2**

At initial state, the leading vehicle of the platoon began to decelerate from the speed of 80 mph, at the deceleration rate of -0.2g. When the speed reached 70 mph, it stopped decelerating and cruised at that speed. The following vehicles followed the leading vehicle's speed profile and decelerated respectively. At steady state, all the vehicles traveled at 70 mph.

The acceleration noises of the control process were calculated and recorded for the speed transition period until both systems entered steady state. Figure 8.4 and Figure 8.5 show the acceleration noise simulation results of the MVHC model and the PATH longitudinal control model under simulation scenario 1. Figure 8.6 and Figure 8.7 show the acceleration noise simulation results of the two models under simulation scenario 2.

The simulation results show that the PATH control model causes higher acceleration noise during the control procedure than the MVHC model of this research. It should also be noticed that, in the PATH model, the acceleration noise increases as one goes upstream, i.e. the first vehicle experiences the lowest acceleration noise while the last vehicle experiences the highest acceleration noise. In contrast, in the MVHC model the first vehicle experiences the highest acceleration noise, while the last vehicle experiences the lowest acceleration noise. Although the PATH control model has the advantage of quicker response and smaller spacing between vehicles within a platoon, the MVHC model performs better under the criterion of motorist comfort.
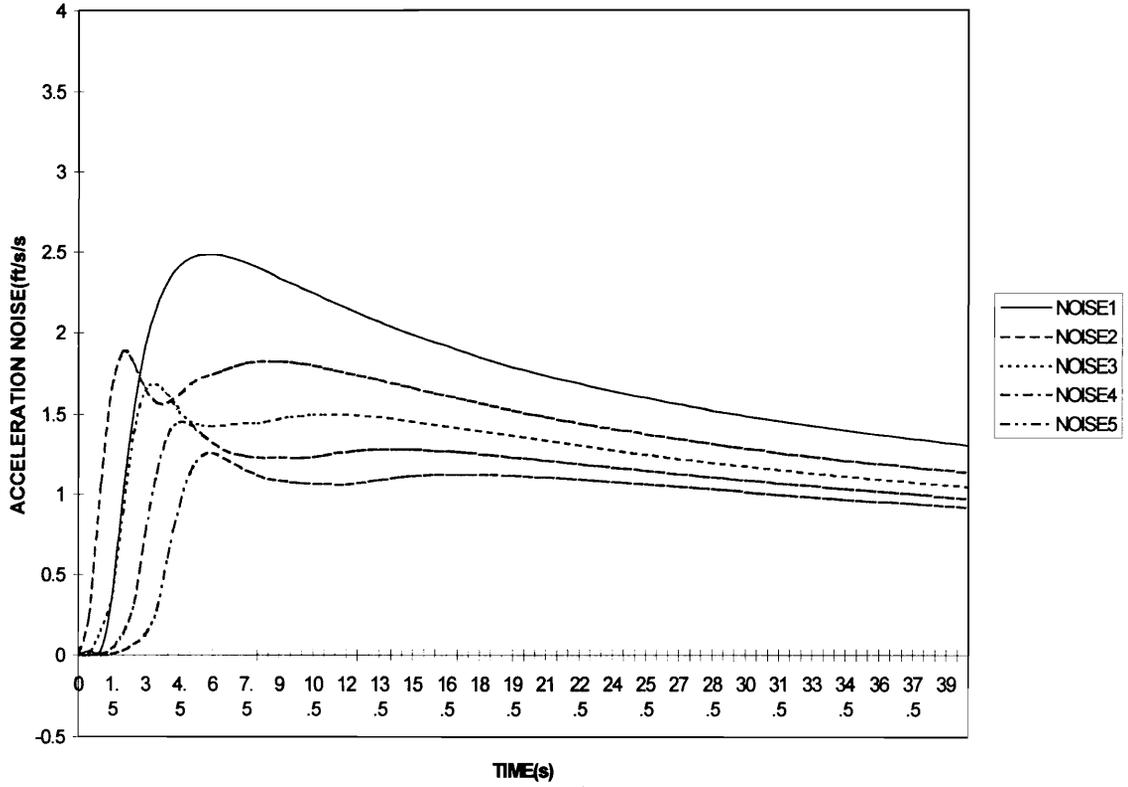
Figure 8.4 MVHC Model Acceleration Noise Graph (Scenario 1)
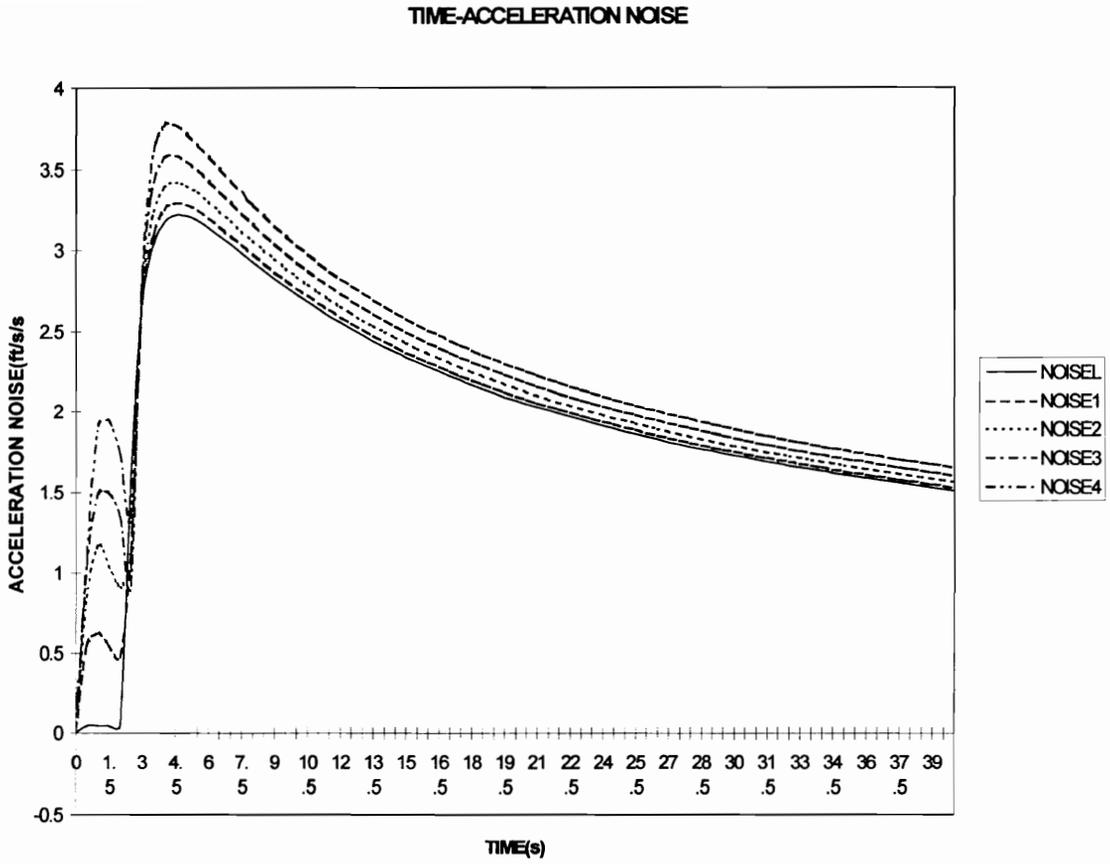
Figure 8.5  PATH Longitudinal Control Model Acceleration Noise Graph (Scenario 1)
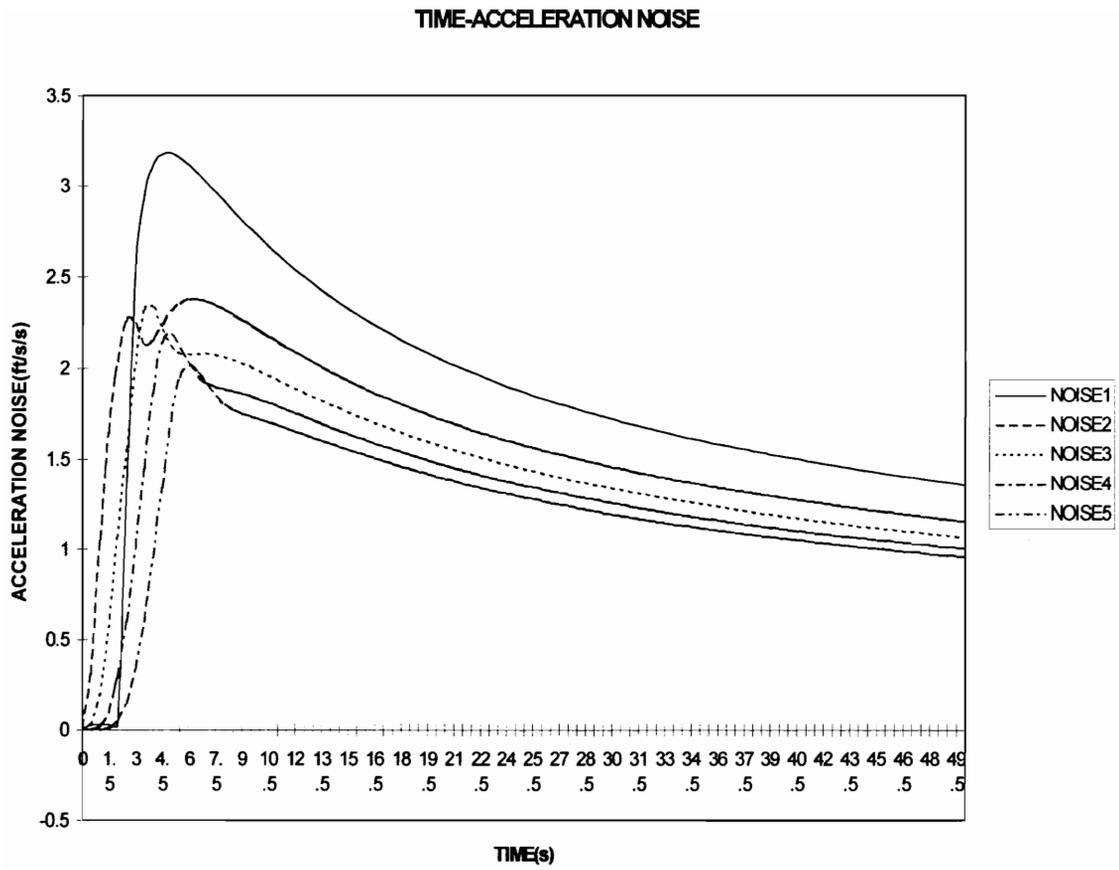
Figure 8.6 MVHC Model Acceleration Noise Graph (Scenario 2)

**TIME-ACCELERATION NOISE**
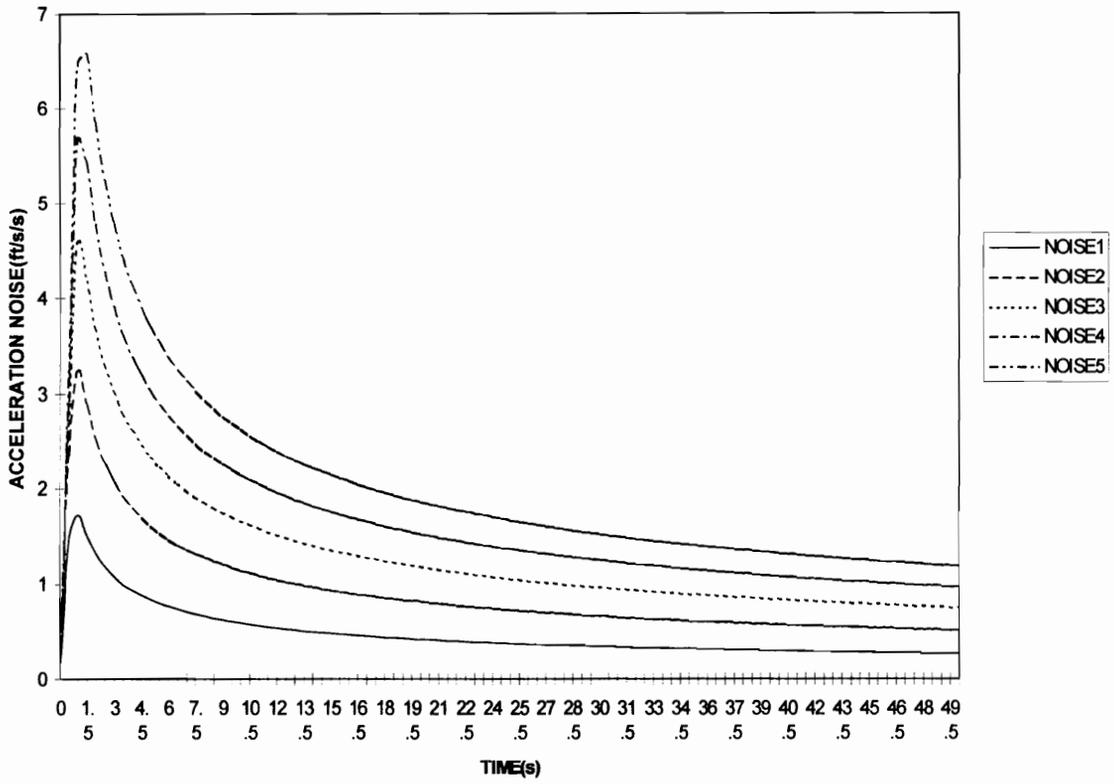
Figure 8.7  PATH Longitudinal Control Model Acceleration Noise Graph (Scenario 2)

# 9. Conclusions and Recommendations

## 9.1 Conclusions

The following work has been conducted in this study: manual driving process study and simulation; automatic vehicle headway control model development and simulation; establishing evaluation criteria for automatic headway control models for trucks operating on rural highways; and duplicating, testing and evaluating the existing automatic headway control models. In parallel, a simulation tool was developed using system dynamics that facilitated the above simulation tasks. The following conclusions can be drawn from the study.

1. Vehicle automatic headway control is a complicated process involving a variety of factors -- human, mechanical, environmental, and roadway. All these factors affect the properties of the control system greatly. It is very difficult to quantify all of the factors and determine their effects in an analytical model because many elements of the driving task are highly subjective. Simulation can afford a means of modeling control processes with various certain and uncertain factors, and therefore, it plays a key role in automatic headway control system design and development.

2.  Using a multiple modes controller in a vehicle headway control system to handle different operating situations, instead of using a uniform control algorithm, can improve the system control quality and realize quick and stable system responses to the state changes of surrounding traffic.

3.  A time lag imposes great influence in the vehicle headway control process. It brings an additional feedback loop into the control system, and thus increases the order of the system. Although in an automatic control system the delay is much smaller than in manual driving systems, it still causes oscillations in the control process. Therefore it must be given thorough and appropriate consideration in the system design.

As the underlying objective of this study is headway control for trucks operating on rural highways, safety has been given the first priority in system design. The MVHC model developed in this study incorporates a variety of factors existing in real world highway systems while enhancing vehicle operating safety and motorist comfort. On the other hand, there is no significant decrease in vehicle spacing by using this model. Therefore the MVHC contributes less to increasing lane capacity and solving the congestion problem than the PATH control model. The reasons for this are: (1) MVHC model considers time lags in control process, which increase the necessary safe distance between vehicles; (2) heavy trucks can not accelerate as fast as average passenger cars because of their dynamics, and thus the relative spacing of trucks with respect to the car ahead will increases when the whole platoon is accelerating; and (3) the design principle of MVHC

model is no accident in most situations while the PATH approach is not to design a system to have no rear-end collisions, but to design one in which the collisions have only minor effects. Based on the above consideration, MVHC model is more practical for trucks and cars mixed flow on rural highway systems.

## 9.2  Recommendations for Further Studies

The research was focused on the single lane car-following behavior of different types of vehicles within a platoon. To fulfill AVCS technologies evaluation and implementation, further studies should be conducted on the following aspects as the extension of this study:

1.    Conducting bounds and sensitivity analysis of varies time lags within an automatic headway control system.

2.    Simulating control strategies for more vehicles and platoons operating on a section of highway with different conditions.

3.    Accomplishing lane changing behavior and lateral control simulation.

4.    Incorporating traffic volume into the vehicle automatic control model to fulfill a whole automated highway system simulation.

5.    Establishing a set of evaluation criteria for different types of highway systems in order to select appropriate control models.

6. Reliability analysis for AVCS technologies must be conducted before the deployment of automatic headway control systems.

7. Conducting benefit-cost study of the automatic control systems.

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# Appendix A    Manual Driving Simulation Model Program


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NOTE    *********************************************************

NOTE    Manual Driving Simulation Model Program

NOTE    *********************************************************
NOTE RANDOM DESIRED SPEED GENERATOR
MACRO BETA(DUM)
A    $GA1.K=-LOGN(.5-NOISE())
A    $GA2.K=-LOGN(.5-NOISE())
A    $GA3.K=-LOGN(.5-NOISE())
A    $GA4.K=-LOGN(.5-NOISE())
A    $GA5.K=-LOGN(.5-NOISE())
A    $GM1.K=-LOGN(.5-NOISE())
A    $GM2.K=-LOGN(.5-NOISE())
A    $GM3.K=-LOGN(.5-NOISE())
A    $GM4.K=-LOGN(.5-NOISE())
A    $GM5.K=-LOGN(.5-NOISE())
A    $X.K=$GA1.K+$GA2.K+$GA3.K+$GA4.K+$GA5.K
A    $Y.K=$GM1.K+$GM2.K+$GM3.K+$GM4.K+$GM5.K
A    BETA.K=DUM.K*$X.K/($X.K+$Y.K)
MEND
NOTE  RANDOM DESIRED SPACING GENERATOR
MACRO BETS(DUM)
A    $G1.K=-LOGN(.5-NOISE())
A    $G2.K=-LOGN(.5-NOISE())
A    $G3.K=-LOGN(.5-NOISE())
A    $G4.K=-LOGN(.5-NOISE())
A    $H1.K=-LOGN(.5-NOISE())
A    $H2.K=-LOGN(.5-NOISE())
A    $H3.K=-LOGN(.5-NOISE())
A    $H4.K=-LOGN(.5-NOISE())
A    $X.K=$G1.K+$G2.K+$G3.K+$G4.K
A    $Y.K=$H1.K+$H2.K+$H3.K+$H4.K
A    BETS.K=DUM.K*$X.K/($X.K+$Y.K)
MEND
NOTE  VEHICLE LENGTH SELECTION
MACRO VLF(X)
A    VLF.K=TABHL(VLFTAB,X.K,15,75,15)
T    VLFTAB=0/.1/.2/.25/.3
MEND
NOTE ACCELERATION GAIN GENERATOR
MACRO  ADJ2(X)
A    ADJ2.K=CLIP(Y1,Y2,X.K,STPD)
C    Y1=-.6
C    Y2=-.9
C    STPD=8
MEND
```

NOTE  TRACTIVE FORCE FUNCTION
MACRO TE(P,V)
A    TE.K=2650*P*RATE1/(V.K+$PD.K)
A    $PD.K=CLIP(0,1,V.K,1)
C    RATE1=.81
MEND
NOTE  AIR RESISTANCE FUNCTION
MACRO RA(A,V,G)
C    DRAG=.5
C    RATE2=0.002385
A    RA.K=1.075*RATE2*DRAG*A*V.K*V.K/G
NOTE  RA--AIR RESISTANCE
MEND
NOTE  GRADE RESISTANCE FUNCTION
MACRO RG(W,G)
A    RG.K=W*G/100
NOTE  RG-- GRADE RESISTANCE
MEND
NOTE  ROLLING RESISTANCE FUNCTION
MACRO RR(V,W,L)
A    RR.K=CLIP($RRT.K,$RRC.K,L,SVL)
NOTE  RR--ROLLING RESISTANCE
A    $RRT.K=W*(CA+1.47*CB*V.K)
NOTE  $RRT--ROLLING RESISTANCE TO TRUCK
A    $RRC.K=W*(CRS+2.15*CRV*V.K*V.K)
NOTE  $RRC.K--ROLLING RESISTANCE TO CAR
C    CA=.2445
C    CB=0.00044
C    CRS=.012
C    CRV=.65E-6
C    SVL=80
MEND
NOTE  DESCRIPTION OF FIRST VEHICLE
L    X1.K=X1.J+(DT)(XX1.JK)
NOTE  X1--THE POSITION OF FIRST VEHICLE(FT)
N    X1=XN1
C    XN1=600
R    XX1.KL=MAX(0,V1.K)
NOTE  XX1--SPEED RATE OF FIRST VEHICLE(FT/S)
L    V1.K=V1.J+(DT)(A1R.JK)
NOTE  V1--VELOCITY OF FIRST VEHICLE
N    V1=VN1
C    VN1=44.01
R    A1R.KL=DELAY1(A1I.KL,PTRT)
NOTE  A1R-- ACCELERATION FIRST VEHICLE REALIZED
R    A1I.KL=CLIP(A12.K,A11.K,TIME.K,STRT)
NOTE  A1I--ACCELERATION FIRST VEHICLE INITIALIZED
A    A11.K=MIN(AMAX1.K,AC11*(DS1.K-V1.K))
NOTE  A11--ACCELERATION OF FIRST VEHICLE AT FIRST STAGE
A    A12.K=CLIP(A1D.K,0,V1.K,0)
NOTE  A12--ACCELERATION OF FIRST VEHICLE AT SECOND STAGE
A    A1D.K=MAX(A1DM,RAMP(-JMX,STRT))

NOTE  A1D--FIRST VEHICLE DECELERATION FUNCTION
C    A1DM=-8.05
C    JMX=16.1
NOTE  JMX--MAXIMUM JERK
C    STRT=30
A    DS1.K=SAMPLE(DB.K,60,RN1.K)
NOTE  DS1--DESIRED SPEED OF FIRST VEHICLE
A    DB.K=NORMRN(50,8)
A    RN1.K=88.002+29.334*BETA(1)
C    AC11=.2
NOTE  AC11--ACCELERATION COEFFICIENT
A    AMAX1.K=MIN(GRAV,GRAV*(TE1.K-R1.K)/WT1)
NOTE  AMAX1--MAXIMUM ACCELERATION OF FIRST VEHICLE
A    TE1.K=TE(P1,XX1.KL)
NOTE  TE1--TRACTIVE FORCE  OF FIRST VEHICLE
A    R1.K=RR1.K+RG1.K+RA1.K
NOTE  R1--TOTAL RESISTANCE OF FIRST VEHICLE
A    RR1.K=RR(XX1.KL,WT1,VL1)
A    RG1.K=RG(WT1,GRAD)
A    RA1.K=RA(A1,XX1.KL,GRAV)
NOTE  DESCRIPTION OF SECOND VEHICLE
L    X2.K=X2.J+(DT)(XX2.JK)
NOTE  X2--POSITION OF SECOND VEHICLE
N    X2=XN1-ISP-VL1
R    XX2.KL=MAX(0,V2.K)
NOTE  XX2--SPEED RATE OF SECOND VEHICLE
L    V2.K=V2.J+(DT)(A2R.JK)
NOTE  V2==VELOCITY OF SECOND VEHICLE(FT/S)
N    V2=VN2
C    VN2=44.01
R    A2R.KL=DELAY1(A2I.KL,PTRT)
NOTE  A2R--ACCELERATION THE SECOND VEHICLE REALIZED(FT/S/S)
C    PTRT=.1
NOTE  PTRT--POWER TRAIN RESPONSE TIME
R    A2I.KL=MIN(AMAX2.K,MIN(A2ICR.K,A2II.K))
NOTE  A2I--ACCELERATION SECOND VEHICLE INITIATED
A    AMAX2.K=MIN(GRAV,GRAV*(TE2.K-R2.K)/WT2)
NOTE  AMAX2--MAXIMUM ACCELERATION OF SECOND VEHICLE
A    TE2.K=TE(P2,XX2.KL)
NOTE  TE2--TRACTIVE FORCE  OF SECOND VEHICLE
A    R2.K=RR2.K+RA2.K+RG2.K
NOTE  R2--TOTAL RESISTANCE OF SECOND VEHICLE
A    RR2.K=RR(XX2.KL,WT2,VL2)
A    RG2.K=RG(WT2,GRAD)
A    RA2.K=RA(A2,XX2.KL,GRAV)
A    A2II.K=CLIP(A2I1.K,A2I2.K,DA1.K,0)
A    A2I2.K=CLIP(A2IT.K,A2I1.K,TDJ2.K,TB2.K)
A    A2IT.K=CLIP(A2ITT.K,A2ITS.K,DSPAC12.K,STPD2)
A    A2ITS.K=CLIP(A2I1.K,A2IDJ.K,A2IDJ.K,2*DA1.K)
A    A2ITT.K=CLIP(A2IDJ.K,A2ISW.K,TDJ2.K,2.5*TB2.K)
A    A2ISW.K=CLIP(A2I1.K,A2IDJ.K,A2IDJ.K,DA1.K)
A    A2IDJ.K=CLIP(ADJ1*XX2.KL+ADJ2(DSPAC12.K),0,V2.K,0)

A   TDJ2.K=DSPAC12.K/(XX2.KL+.1)
A   TB2.K=(ADJ3*XX2.KL)/(-DMAX)
A   SD21.K=SCF1*SD2.K
C   STPD2=15
C   SCF1=2.4
A   SD2.K=VL1*(1+SS2.K*VLF(VL1))+0.068*SS2.K*AVL*PXX2.K
NOTE  SD2--SAFETY DISTANCE BETWEEN VEHICLES FOR DRIVER 2
A   PXX2.K=DELAY1(XX2.KL,PRT)
C   AVL=15
A   SS2.K=SAMPLE(SR,60,RS2.K)
C   SR=60
A   RS2.K=Z1+Z2*BETS(1)
C   Z1=.6
C   Z2=.4
A   A2I1.K=MAX(DMAX,CLIP(A2IFW.K,A2IBF.K,SWDX12.K,SD23.K))
A   SD23.K=MAX(SD24.K,SCF3*SD2.K)
C   SCF3=1.3
A   A2IFW.K=CLIP(A2IF1.K,A2IBF.K,DV12.K,CRV1)
A   A2IF1.K=CLIP(A2IAB.K,A2IDC.K,A2IAB.K,0)
A   A2IDC.K=CLIP(A2IAB.K,0,V2.K,0)
A   A2IAB.K=AC21.K*W2.K*(SWDV12.K/SWDX12.K)+AS2.K
C   DMAX=-16.1
NOTE  A2I1--ACCELERATION BASED ON THE VEHICLE AHEAD
A   AS2.K=CLIP(0,AS21.K,-V1.K,0)
NOTE  AS2.K--ACCELERATION BASED ON SAFETY DISTANCE
A   AS21.K=CLIP(0,ACS*(1-(SD2.K/SWDX12.K)),-V2.K,0)
A   AC21.K=TABHL(AC21TAB,DSPAC12.K,5,145,20)
NOTE  AC21--ACCELERATION COEFFICIENT
T   AC21TAB=4/5/7/8.5/9/9.5/9.8/10.2
A   W2.K=TABHL(W2TAB,DV12.K,-21,18,3)
T   W2TAB=14/13/12.2/11.5/10.5/9.5/8.5/8/8/8.5/9/9.5/10/12
C   ACS=8
A   SWDV12.K=CLIP(SADV12.K,DV12.K,V2.K,CRV3)
A   SWDX12.K=CLIP(SADX12.K,ADX12.K,V2.K,CRV3)
A   SADV12.K=CLIP(SDV12.K,DV12.K,DA1.K,-ACV)
A   SADX12.K=CLIP(SDX12.K,ADX12.K,DA1.K,-ACV)
A   A2IBF.K=CLIP(A2IFF.K,A2IF.K,DA1.K,-ACV)
A   A2IFF.K=CLIP(A2IF1.K,A2IF.K,DDA1.K,-ACV)
A   A2IF.K=CLIP(A2IF2.K,A2IBD.K,DX12.K,SD24.K)
A   A2IF2.K=CLIP(A2IFD.K,0,V2.K,0)
A   A2IFD.K=FV2.K*FH2.K*DV12.K/PRT
A   FV2.K=TABHL(FV2TAB,V2.K,0,100,25)
T   FV2TAB=.5/.7/.9/1.1/1.3
A   FH2.K=TABHL(FH2TAB,DSPAC12.K,0,140,20)
T   FH2TAB=2/1.7/1.2/.8/.5/.3/.22/.2
A   DA1.K=DELAY1(A1I.KL,PRT)
A   DDA1.K=DELAY1(A1I.KL,DPRT)
A   SA1.K=SAMPLE(DA1.K,SINV,DA1.K)
A   FA1.K=CLIP(DA1.K,SA1.K,V1.K,0)
A   A2IBD.K=CLIP(A2IF2.K,A2IBK.K,DV12.K,CRV2)
A   A2IBK.K=MAX(A2IBK1.K,A2IBK2.K)
A   A2IBK1.K=CLIP(BV2*(V1.K*V1.K-V2.K*V2.K)/ADX12.K,0,V2.K,0)

```
A    A2IBK2.K=CLIP(DMAX,0,V2.K,0)
C    BV=.114
C    CRV3=58.68
C    BV2=2.5
C    SINV=5
C    DPRT=1
C    ACV=4.03
C    CRV1=-2.92
C    CRV2=-22
A    SD24.K=SCF4*VL1
C    SCF4=2
A    ADX12.K=MAX(DX12.K,-DX12.K)
A    ABDV12.K=MAX(DV12.K,-DV12.K)
A    A2ICR.K=CLIP(A2ID1.K,A2ID2.K,DX23.K,SDB)
NOTE A2I2--ACCELERATION BASED ON DESIRED SPEED AND VEHICLE BEHIND
A    A2ID1.K=AC23*(DS2.K-V2.K)
A    A2ID2.K=MAX(A2ID1.K,AC24*((SDB/DX23.K)-1))
C    AC23=.2
C    AC24=3
C    SDB=25
NOTE SDB --SAFETY DISTANCE WITH THE VEHICLE BEHIND
A    DS2.K=SAMPLE(DB.K,60,RN2.K)
NOTE DS2--DESIRED SPEED OF SECOND VEHICLE
A    RN2.K=88.002+29.334*BETA(1)
A    SDX12.K=SAMPLE(ADX12.K,XINV,ADX12.K)
A    DX12.K=DELAY1(RX12.KL,PRT)
NOTE DX12--PERCEIVED RELATIVE SPACE BETWEEN 1ST AND 2ND VEHICLES
R    RX12.KL=X1.K-X2.K
NOTE RX12--RELATIVE SPACE BETWEEN 1ST AND 2ND VEHICLE
C    PRT=.7
NOTE PRT--PERCEPTION REACTION TIME
C    XINV=1
A    SDV12.K=SAMPLE(DV12.K,XINV,DV12.K)
A    DV12.K=DELAY1(RV12.KL,PRT)
NOTE DV12--PERCEIVED RELATIVE VELOCITY
R    RV12.KL=XX1.KL-XX2.KL
NOTE RV12--RELATIVE VELOCITY OF 1ST AND 2ND VEHICLE
L    X3.K=X3.J+(DT)(XX3.JK)
NOTE X3--POSITION OF THIRD VEHICLE
N    X3=XN1-2*ISP-VL1-VL2
R    XX3.KL=MAX(0,V3.K)
NOTE XX3--SPEED RATE OF THIRD VEHICLE
L    V3.K=V3.J+(DT)(A3R.JK)
NOTE V3--VELOCITY OF THIRD VEHICLE
N    V3=VN3
C    VN3=44.01
R    A3R.KL=DELAY1(A3I.KL,PTRT)
NOTE A3R--ACCELERATION THIRD VEHICLE REALIZED
R    A3I.KL=MIN(AMAX3.K,MIN(A3ICR.K,A3II.K))
NOTE A3I--ACCELERATION THIRD VEHICLE INITIATED
A    AMAX3.K=MIN(GRAV,GRAV*(TE3.K-R3.K)/WT3)
A    TE3.K=TE(P3,XX3.KL)
```

A   R3.K=RR3.K+RA3.K+RG3.K
A   RR3.K=RR(XX3.KL,WT3,VL3)
A   RG3.K=RG(WT3,GRAD)
A   RA3.K=RA(A3,XX3.KL,GRAV)
A   A3II.K=CLIP(A3I1.K,A3I2.K,DA2.K,0)
A   A3I2.K=CLIP(A3IT.K,A3I1.K,TDJ3.K,TB3.K)
NOTE  A3I2--ACCELERATION BASED IN DESIRED SPEED AND VEHICLE BEHIND(FT/S/S)
A   A3IT.K=CLIP(A3ITT.K,A3ITS.K,DSPAC23.K,STPD2)
A   A3ITS.K=CLIP(A3I1.K,A3IDJ.K,A3IDJ.K,2*DA2.K)
A   A3ITT.K=CLIP(A3IDJ.K,A3ISW.K,TDJ3.K,2*TB3.K)
A   A3ISW.K=CLIP(A3I1.K,A3IDJ.K,A3IDJ.K,DA2.K)
A   A3IDJ.K=CLIP(ADJ1*XX3.KL+ADJ2(DSPAC23.K),0,V3.K,0)
A   TDJ3.K=DSPAC23.K/(XX3.KL+.1)
A   TB3.K=(ADJ3*XX3.KL)/(-DMAX)
A   SD31.K=SCF1*SD3.K
A   SD3.K=VL2*(1+SS3.K*VLF(VL2))+0.068*SS3.K*AVL*PXX3.K
A   PXX3.K=DELAY1(XX3.KL,PRT)
A   SS3.K=SAMPLE(SR,60,RS3.K)
A   RS3.K=Z1+Z2*BETS(1)
A   A3I1.K=MAX(DMAX,CLIP(A3IFW.K,A3IBF.K,SWDX23.K,SD33.K))
NOTE  A3I1--ACCELERATION BASED ON THE VEHICLES AHEAD(FT/S/S)
A   SD33.K=MAX(SD34.K,SCF3*SD3.K)
A   A3IFW.K=CLIP(A3IF1.K,A3IBF.K,DV23.K,CRV1)
A   A3IF1.K=CLIP(A3IAB.K,A3IDC.K,A3IAB.K,0)
A   A3IDC.K=CLIP(A3IAB.K,0,V3.K,0)
A   A3IAB.K=CLIP(A3IAB2.K,A3IAB1.K,VL2,30)
A   A3IAB1.K=A3IAB11.K+A3IAB12.K+AS3.K
A   A3IAB11.K=AC31.K*W3.K*(.9*SWDV23.K/SWDX23.K)
A   A3IAB12.K=AC31.K*W3.K*(.1*SWDV13.K/SWDX13.K)
A   A3IAB2.K=AC31.K*W3.K*(SWDV23.K/SWDX23.K)+AS3.K
A   AS3.K=CLIP(0,AS31.K,-V2.K,0)
A   AS31.K=CLIP(0,ACS*(1-(SD3.K/ADX23.K)),-V3.K,0)
A   W3.K=TABHL(W3TAB,DV23.K,-21,18,3)
T   W3TAB=14/13/12.2/11.5/10.5/9.5/8.5/8/8/8.5/9/9.5/10/12
A   SD32.K=3*SD3.K
A   AC31.K=TABHL(AC31TAB,DSPAC23.K,5,145,20)
T   AC31TAB=4/5/7/8.5/9/9.5/9.8/10.2
A   SWDV23.K=CLIP(SADV23.K,DV23.K,V3.K,CRV3)
A   SWDV13.K=CLIP(SDV13.K,DV13.K,V3.K,CRV3)
A   SWDX23.K=CLIP(SADX23.K,ADX23.K,V3.K,CRV3)
A   SWDX13.K=CLIP(SDX13.K,DX13.K,V3.K,CRV3)
A   SADV23.K=CLIP(SDV23.K,DV23.K,DA2.K,-ACV)
A   SADX23.K=CLIP(SDX23.K,ADX23.K,DA2.K,-ACV)
A   A3IBF.K=CLIP(A3IFF.K,A3IF.K,DA2.K,-ACV)
A   A3IFF.K=CLIP(A3IF1.K,A3IF.K,DDA2.K,-ACV)
A   A3IF.K=CLIP(A3IF2.K,A3IBD.K,DX23.K,SD34.K)
A   A3IF2.K=CLIP(A3IFD.K,0,V3.K,0)
A   A3IFD.K=FV3.K*FH3.K*DV23.K/PRT
A   FV3.K=TABHL(FV3TAB,V3.K,0,100,25)
T   FV3TAB=.5/.7/.9/1.1/1.3
A   FH3.K=TABHL(FH3TAB,DSPAC23.K,0,140,20)
T   FH3TAB=1.6/1.3/1/.7/.5/.3/.22/.2

```
A    DA2.K=DELAY1(A2R.KL,PRT)
A    DDA2.K=DELAY1(A2R.KL,DPRT)
A    SA2.K=SAMPLE(DA2.K,SINV,DA2.K)
A    FA2.K=CLIP(DA2.K,SA2.K,V2.K,0)
A    A3IBD.K=CLIP(A3IF2.K,A3IBK.K,DV23.K,CRV2)
A    A3IBK.K=MAX(A3IBK1.K,A3IBK2.K)
A    A3IBK1.K=CLIP(BV2*(V2.K*V2.K-V3.K*V3.K)/ADX23.K,0,V3.K,0)
A    A3IBK2.K=CLIP(DMAX,0,V3.K,0)
A    SD34.K=SCF4*VL2
A    ABDV23.K=MAX(DV23.K,-DV23.K)
A    SDX23.K=SAMPLE(ADX23.K,XINV,ADX23.K)
A    DX23.K=DELAY1(RX23.KL,PRT)
A    ADX23.K=MAX(DX23.K,-DX23.K)
NOTE DX23--PERCEIVED RELATIVE SPACE BETWEEN 2ND AND 3RD VEHICLE
R    RX23.KL=X2.K-X3.K
NOTE RX23--RELATIVE SPACE BETWEEN 2ND AND 3RD VHEICLE
A    SDX13.K=SAMPLE(DX13.K,XINV,DX13.K)
A    DX13.K=DELAY1(RX13.KL,PRT)
NOTE DX13--PERCEIVED RELATIVE SPACE BETWEEN 1ST AND 3RD VEHICLE
R    RX13.KL=X1.K-X3.K
NOTE RX13--RELATIVE SPACE BETWEEN 1ST AND 3RD VEHICLE
A    DV23.K=DELAY1(RV23.KL,PRT)
A    SDV23.K=SAMPLE(DV23.K,XINV,DV23.K)
R    RV23.KL=XX2.KL-XX3.KL
NOTE RV23--RELATIVE VELOCITY OF 2ND AND 3RD VEHICLE
A    DV13.K=DELAY1(RV13.KL,PRT)
A    SDV13.K=SAMPLE(DV13.K,XINV,DV13.K)
R    RV13.KL=XX1.KL-XX3.KL
NOTE RELATIVE VELOCITY OF 1ST AND 3RD VEHICLE
A    A3ICR.K=CLIP(A3ID1.K,A3ID2.K,DX34.K,SDB)
A    A3ID1.K=AC33*(DS3.K-V3.K)
A    A3ID2.K=MAX(A3ID1.K,AC34*((SDB/DX34.K)-1))
A    DS3.K=SAMPLE(DB.K,60,RN3.K)
NOTE DS3--DESIRED SPEED OF THIRD VEHICLE
A    RN3.K=88.002+29.334*BETA(1)
C    AC33=.2
C    AC34=3
L    X4.K=X4.J+(DT)(XX4.JK)
NOTE X4--POSITION OF FORTH VEHICLE
N    X4=XN1-3*ISP-VL1-VL2-VL3
R    XX4.KL=MAX(0,V4.K)
NOTE XX4--SPEED RATE OF 4TH VEHICLE
L    V4.K=V4.J+(DT)(A4R.JK)
NOTE V4--VELOCITY OF 4TH VEHICLE(FT/S)
N    V4=VN4
C    VN4=44.01
R    A4R.KL=DELAY1(A4I.KL,PTRT)
NOTE A4R--ACCELERATION 4TH VEHICLE REALIZED(FT/S/S)
R    A4I.KL=MIN(AMAX4.K,MIN(A4ICR.K,A4II.K))
NOTE A4I--ACCELERATION 4TH VEHICLE INITIATED(FT/S/S)
A    AMAX4.K=MIN(GRAV,GRAV*(TE4.K-R4.K)/WT4)
A    TE4.K=TE(P4,XX4.KL)
```

```
A    R4.K=RR4.K+RG4.K+RA4.K
A    RR4.K=RR(XX4.KL,WT4,VL4)
A    RG4.K=RG(WT4,GRAD)
A    RA4.K=RA(A4,XX4.KL,GRAV)
A    A4II.K=CLIP(A4I1.K,A4I2.K,DA3.K,0)
A    A4I2.K=CLIP(A4IT.K,A4I1.K,TDJ4.K,TB4.K)
A    A4IT.K=CLIP(A4ITT.K,A4ITS.K,DSPAC34.K,STPD2)
A    A4ITS.K=CLIP(A4I1.K,A4IDJ.K,A4IDJ.K,2*DA3.K)
A    A4ITT.K=CLIP(A4IDJ.K,A4ISW.K,TDJ4.K,2.5*TB4.K)
A    A4ISW.K=CLIP(A4I1.K,A4IDJ.K,A4IDJ.K,DA3.K)
A    A4IDJ.K=CLIP(ADJ1*XX4.KL+ADJ2(DSPAC34.K),0,V4.K,0)
A    TDJ4.K=DSPAC34.K/(XX4.KL+.1)
A    TB4.K=(ADJ3*XX4.KL)/(-DMAX)
A    SD41.K=SCF1*SD4.K
A    SS4.K=SAMPLE(SR,60,RS4.K)
A    SD4.K=VL3*(1+SS4.K*VLF(VL3))+.068*SS4.K*AVL*PXX4.K
A    PXX4.K=DELAY1(XX4.KL,PRT)
A    RS4.K=Z1+Z2*BETS(1)
A    A4I1.K=MAX(DMAX,CLIP(A4IFSW.K,A4IBF.K,SWDX34.K,SD43.K))
A    SD43.K=SCF3*SD4.K
A    A4IFSW.K=CLIP(A4IAB.K,A4IFW.K,SWDX34.K,SD41.K)
A    A4IFW.K=CLIP(A4IF1.K,A4IBF.K,DV34.K,CRV1)
A    A4IF1.K=CLIP(A4IAB.K,A4IDC.K,A4IAB.K,0)
A    A4IDC.K=CLIP(A4IAB.K,0,V4.K,0)
A    A4IAB.K=CLIP(A4IAB2.K,A4IAB1.K,VL3,30)
A    A4IAB1.K=A4IAB11.K+A4IAB12.K+AS4.K
A    A4IAB11.K=AC41.K*W4.K*(.9*SWDV34.K/SWDX34.K)
A    A4IAB12.K=AC41.K*W4.K*(.1*SWDV24.K/SWDX24.K)
A    A4IAB2.K=AC41.K*W4.K*(SWDV34.K/SWDX34.K)+AS4.K
NOTE  A4I1--ACCELERATION BASED ON THE VEHICLE AHEAD(FT/S/S)
A    W4.K=TABHL(W4TAB,DV34.K,-21,18,3)
T    W4TAB=14/13/12.2/11.5/10.5/9.5/8.5/8/8/8.5/9/9.5/10/12
A    AC41.K=TABHL(AC41TAB,DSPAC34.K,5,145,20)
T    AC41TAB=4/5/7/8.5/9/9.5/9.8/10.2
A    SWDV34.K=CLIP(SADV34.K,DV34.K,V4.K,CRV3)
A    SWDV24.K=CLIP(SDV24.K,DV24.K,V4.K,CRV3)
A    SWDX34.K=CLIP(SADX34.K,ADX34.K,V4.K,CRV3)
A    SWDX24.K=CLIP(SDX24.K,DX24.K,V4.K,CRV3)
A    SADV34.K=CLIP(SDV34.K,DV34.K,DA3.K,-ACV)
A    SADX34.K=CLIP(SDX34.K,ADX34.K,DA3.K,-ACV)
A    ABDV34.K=MAX(DV34.K,-DV34.K)
A    AS4.K=CLIP(0,AS41.K,-V3.K,0)
A    AS41.K=CLIP(0,ACS*(1-(SD4.K/ADX34.K)),-V4.K,0)
A    SD42.K=3*SD4.K
A    A4IBF.K=CLIP(A4IFF.K,A4IF.K,DA3.K,-ACV)
A    A4IFF.K=CLIP(A4IF1.K,A4IF.K,DDA3.K,-ACV)
A    A4IF.K=CLIP(A4IF2.K,A4IBD.K,DX34.K,SD44.K)
A    A4IF2.K=CLIP(A4IFD.K,0,V4.K,0)
A    A4IFD.K=FV4.K*FH4.K*DV34.K/PRT
A    FV4.K=TABHL(FV4TAB,V4.K,0,100,25)
T    FV4TAB=.5/.7/.9/1.1/1.3
A    FH4.K=TABHL(FH4TAB,DSPAC34.K,0,140,20)
```

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T    FH4TAB=1.6/1.3/1/.7/.5/.3/.22/.2
A    DA3.K=DELAY1(A3R.KL,PRT)
A    DDA3.K=DELAY1(A3R.KL,DPRT)
A    SA3.K=SAMPLE(DA3.K,SINV,DA3.K)
A    FA3.K=CLIP(DA3.K,SA3.K,V3.K,0)
A    A4IBD.K=CLIP(A4IF2.K,A4IBK.K,DV34.K,CRV2)
A    A4IBK.K=MAX(A4IBK1.K,A4IBK2.K)
A    A4IBK1.K=CLIP(BV2*(V3.K*V3.K-V4.K*V4.K)/ADX34.K,0,V4.K,0)
A    A4IBK2.K=CLIP(DMAX,0,V4.K,0)
A    SD44.K=SCF4*VL3
A    ADX34.K=MAX(DX34.K,-DX34.K)
A    SDX34.K=SAMPLE(ADX34.K,XINV,ADX34.K)
A    DX34.K=DELAY1(RX34.KL,PRT)
NOTE DX34--PERCEIVED RELATIVE SPACE BETWEEN 3RD AND 4TH VEHICLE
R    RX34.KL=X3.K-X4.K
NOTE RX34--RELATIVE SPACE BETWEEN 3RD AND 4TH VEHICLE
A    DX24.K=DELAY1(RX24.KL,PRT)
A    SDX24.K=SAMPLE(DX24.K,XINV,DX24.K)
R    RX24.KL=X2.K-X4.K
A    SDV34.K=SAMPLE(DV34.K,XINV,DV34.K)
A    DV34.K=DELAY1(RV34.KL,PRT)
NOTE  DV34--PERCEIVED RELATIVE VELOCITY OF 3RD AND 4TH VEHICLE
R    RV34.KL=XX3.KL-XX4.KL
NOTE RV34--RELATIVE VELOCITY OF 3RD AND 4TH VEHICLE
A    DV24.K=DELAY1(RV24.KL,PRT)
A    SDV24.K=SAMPLE(DV24.K,XINV,DV24.K)
R    RV24.KL=XX2.KL-XX4.KL
A    A4ICR.K=AC43*(DS4.K-V4.K)
NOTE A4I2--ACCELERATION BASED ON DESIRED SPEED
A    DS4.K=SAMPLE(DB.K,60,RN4.K)
NOTE  DS4--DESIRED SPEED OF 4TH VEHICLE
A    RN4.K=88.002+29.334*BETA(1)
C    AC43=.2
NOTE  CALCULATING THE JERK OF VEHICLES
A    DLYA1.K=DELAY1(A1R.KL,DT)
A    DLYA2.K=DELAY1(A2R.KL,DT)
A    DLYA3.K=DELAY1(A3R.KL,DT)
A    DLYA4.K=DELAY1(A4R.KL,DT)
NOTE  JERK OF VEHICLES
A    J1.K=(A1R.KL-DLYA1.K)/DT
A    J2.K=(A2R.KL-DLYA2.K)/DT
A    J3.K=(A3R.KL-DLYA3.K)/DT
A    J4.K=(A4R.KL-DLYA4.K)/DT
NOTE  SPACINS BETWEEN VEHICLES
R    SPAC12.KL=RX12.KL-VL1
R    SPAC23.KL=RX23.KL-VL2
R    SPAC34.KL=RX34.KL-VL3
C    ADJ1=-.4
C    ADJ3=1.5
C    VL1=15
C    VL2=45
C    VL3=75
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C    VL4=25
C    GRAV=32.2
C    GRAD=0
NOTE  WEIGHTS OF VEHICLES
C    WT1=3500
C    WT2=15000
C    WT3=60000
C    WT4=8000
NOTE  FRONT AREAS OF VEHICLES
C    A1=17.5
C    A2=21
C    A3=25
C    A4=19
NOTE  POWER OF VEHICLES
C    P1=105
C    P2=175
C    P3=325
C    P4=125
C    ISP=70
NOTE  ISP--INITIAL SPACING BETWEEN VEHICLES
A    DSPAC12.K=DELAY1(SPAC12.KL,PRT)
A    DSPAC23.K=DELAY1(SPAC23.KL,PRT)
A    DSPAC34.K=DELAY1(SPAC34.KL,PRT)
SPEC  DT=.0625/LENGTH=60/PLTPER=1/SAVPER=.5/NS_SEED=131
SAVE  A1R,V1,V2,V3,V4,X1,X2,X3,X4
SAVE  XX1,XX2,XX3,XX4,RX12,RX23,RX34,A2R,A3R,A4R
SAVE  SPAC12,SPAC23,SPAC34
SAVE  J1,J2,J3,J4
SAVE  AMAX1,AMAX2,AMAX3,AMAX4
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## Appendix B   Multi-mode Vehicle Headway Control Model Program

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NOTE   ***************************************************************

NOTE   Multi-mode Vehicle Headway Control Model Program

NOTE   ***************************************************************
NOTE  TRACTIVE EFFORT FUNCTION
MACRO TE(P,V)
A    TE.K=2650*P*RATE1/(V.K+$PD.K)
NOTE  TE--TRACTIVE EFFORT OF VEHICLE
A    $PD.K=CLIP(0,1,V.K,1)
C    RATE1=.81
MEND
NOTE  AIR RESISTANCE FUNCTION
MACRO RA(A,V,G)
A    RA.K=1.075*RATE2*DRAG*A*V.K*V.K/G
NOTE  RA--AIR RESISTANCE
C    DRAG=.5
C    RATE2=.002385
MEND
NOTE  GRADE RESISTANCE FUNCTION
MACRO RG(W,G)
A    RG.K=W*G/100
NOTE  RG-- GRADE RESISTANCE
MEND
NOTE  ROLLING RESISTANCE FUNCTION
MACRO RR(V,W,L)
A    RR.K=CLIP($RRT.K,$RRC.K,L,SVL)
NOTE  RR--ROLLING RESISTANCE
A    $RRT.K=W*(CA+1.47*CB*V.K)
NOTE  $RRT--ROLLING RESISTANCE TO TRUCK
A    $RRC.K=W*(CRS+2.15*CRV*V.K*V.K)
NOTE  $RRC.K--ROLLING RESISTANCE TO CAR
C    CA=.2445
C    CB=.00044
C    CRS=.012
C    CRV=.65E-6
C    SVL=80
MEND
NOTE  CRUISE MODE ACCELERATION GAIN
MACRO ACG1(V)
A    ACG1.K=TABHL(ACG1TAB,V.K,0,120,20)
T    ACG1TAB=.12/.18/.25/.41/.6/.85/1
MEND
NOTE  ACCELERATION SENSTIVE FUNCTION
MACRO ASF(SPACE,RV)
A    ASF.K=$ACG2.K*$ACG3.K*(RV.K/($ASPACE.K+ABSC))
A    $ACG2.K=TABHL(ACG2TAB,SPACE.K,5,145,20)
T    ACG2TAB=4/5/7/8.5/9/9.5/9.8/10.2
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A    $ACG3.K=TABHL(ACG3TAB,RV.K,-21,18,3)
T    ACG3TAB=14/13/12.2/11.5/10.5/9.6/8.8/10/10.8/11.5/12.3/13.2/13.8/14.5
A    $ASPACE.K=MAX(SPACE.K,-SPACE.K)
C    ABSC=20
MEND
NOTE  MAXIMUM DECELERATION FUNCTION
MACRO MAXDEC(WT,FR)
A    MAXDEC.K=CLIP($DECT.K,$DECC.K,WT,10000)
A    $DECT.K=CLIP(YT1,YT2,FR,.5)
NOTE  $DECT--DECELERATION RATE OF TRUCK
A    $DECC.K=CLIP(YC1,YC2,FR,.5)
NOTE  $DECC--DECELERATION RATE OF CAR
C    YT1=19.32
C    YT2=9.66
C    YC1=22.54
C    YC2=12.88
MEND
NOTE  SLOW HEADWAY ADJUSTMENT FUNCTION
MACRO ADJF(V,SPACE)
A    ADJF.K=CLIP((ADJ1*V.K/(2*SPACE.K+BS))+$ADJ2.K,0,V.K,0)
A    $ADJ2.K=CLIP(Y1,$Y2.K,$ASPACE.K,STPD1)
A    $ASPACE.K=MAX(SPACE.K,-SPACE.K)
A    $Y2.K=CS*($ASPACE.K-STPD2)
C    Y1=1
C    CS=.3
C    BS=200
C    ADJ1=-60
C    STPD1=20
C    STPD2=7
MEND
NOTE  SPACE ADJUSTMENT PARAMETER
MACRO FS(SPACE)
A    FS.K=TABHL(FSTAB,SPACE.K,0,140,20)
T    FSTAB=1.8/1.4/1/.7/.5/.3/.22/.2
MEND
NOTE  VELOCITY ADJUSTMENT PARAMETER
MACRO FV(V)
A    FV.K=TABHL(FVTAB,V.K,0,100,25)
T    FVTAB=1.0/1.1/1.2/1.4/1.6
MEND
NOTE  SAFE DISTANCE FUNCTION
MACRO SD(VI,VJ,DMAXJ,VLI)
A    SD.K=CLIP($SD1.K,$SD2.K,VJ.K,VI.K)
A    $SD1.K=(B1*VJ.K*VJ.K/DMAXJ.K)-(B2*VI.K*VI.K/BE)+1.25*VLI
A    $SD2.K=B3*VJ.K+VLI
C    BE=25.67
C    B1=.5
C    B2=.5
C    B3=.5
MEND
NOTE  DESCRIPTION OF FIRST VEHICLE
L    X1.K=X1.J+(DT)(XX1.JK)
```

NOTE  X1--POSITION OF FIRST VEHICLE
N    X1=XN1
C    XN1=600
NOTE  XN1--INITIAL POSITION OF FIRST VEHICLE
R    XX1.KL=MAX(0,V1.K)
NOTE  XX1--SPEED OF FIRST VEHICLE
L    V1.K=V1.J+(DT)(A1R.JK)
NOTE  V1--VELOCITY OF FIRST VEHICLE
N    V1=VN1
R    A1R.KL=SMOOTH(A1I.KL,PTRT)
NOTE  A1R--ACCELERATION FIRST VEHICLE REALIZED
R    A1I.KL=CLIP(A1I2.K,A1I1.K,TIME.K,STRT)
NOTE  A1I--ACCELERATION FIRST VEHICLE INITIALIZED
A    A1I1.K=MIN(AMAX1.K,ACG1(XX1.KL)*(DSPEED-V1.K))
NOTE  A1I1--FIRST STAGE ACCELERATION OF FIRST VEHICLE
A    A1I2.K=CLIP(DECE1.K,0,V1.K,0)
NOTE  A1I2--SECOND STAGE ACCELERATION OF FIRST VEHICLE
A    DECE1.K=MAX(DMD,RAMP(-MAXJK,STRT))
NOTE  DECE1--DECELERATION OF FIRST VEHICLE
A    AMAX1.K=MIN(MAXACC,GRAV*(TE1.K-R1.K)/WT1)
NOTE  AMAX1--MAXIMUM ACCELERATION OF FIRST VEHICLE
A    TE1.K=TE(P1,XX1.KL)
NOTE  TE1--TRACTIVE EFFORT OF FIRST VEHICLE
A    R1.K=RR(XX1.KL,WT1,VL1)+RG(WT1,GRAD)+RA(A1,XX1.KL,GRAV)
NOTE  R1--RESISTANCE TO MOTION OF FIRST VEHICLE
A    PA1.K=DELAY1(A1R.KL,SENTM)
NOTE  PA1--PECEIVED ACCELERATION OF FIRST VEHICLE
A    FA1.K=DELAY1(A1R.KL,PCT)
NOTE  DESCRIPTION OF SECOND VEHICLE
L    X2.K=X2.J+(DT)(XX2.JK)
NOTE  X2--POSITION OF SECOND VEHICLE
N    X2=XN1-VL1-ISP
R    XX2.KL=MAX(0,V2.K)
NOTE  XX2--SPEED OF SECOND VEHICLE
L    V2.K=V2.J+(DT)(A2R.JK)
NOTE  V2--VELOCITY OF SECOND VEHICLE
N    V2=VN2
R    A2R.KL=SMOOTH(A2I.KL,PTRT)
NOTE  A2R--ACCELERATION SECOND VEHICLE REALIZED
R    A2I.KL=MIN(AMAX2.K,CLIP(A2C1.K,A2PC.K,SSPAC12.K,SD21.K))
NOTE  A2I--ACCELERATION SECOND INITIALIZED
A    AMAX2.K=MIN(MAXACC,GRAV*(TE2.K-R2.K)/WT2)
NOTE  MAXIMUM ACCELERATION OF SECOND VEHICLE
A    TE2.K=TE(P2,XX2.KL)
NOTE  TE2--TRACTIVE EFFORT OF SECOND VEHICLE
A    R2.K=RR(XX2.KL,WT2,VL2)+RG(WT2,GRAD)+RA(A2,XX2.KL,GRAV)
NOTE  R2--RESISTANCE TO MOTION OF SECOND VEHICLE
A    A2C1.K=CLIP(A2C2.K,A2PC.K,V2.K,VT1)
NOTE  A2C1--ACCELERATION OF SECOND VEHICLE IN CASE 1
A    A2C2.K=CLIP(A2CRU.K,A2PC.K,SRV12.K,CRV3)
NOTE  A2C2--ACCELERATION OF SECOND VEHICLE IN CASE 2
A    A2CRU.K=ACG1(XX2.KL)*(DSPEED-V2.K)

NOTE  A2CRU--ACCELERATION OF SECOND IN CRUISE CONTROL MODE
A    A2PC.K=CLIP(A2PC1.K,A2PC2.K,PA1.K,0)
NOTE  A2PC--ACCELERATION OF SECOND IN PLATOON CONTROL MODE
A    A2PC1.K=MAX(-MAXDC2.K,CLIP(A2PC11.K,A2PC12.K,SSPAC12.K,SD22.K))
A    MAXDC2.K=MAXDEC(WT2,FR)
NOTE  MAXDC2.K--MAXIMUM DECELERATION OF SECOND VEHICLE
A    A2PC11.K=CLIP(A2FM.K,A2PC12.K,SRV12.K/(SSPAC12.K+2),CRVS)
A    A2FM.K=CLIP(A2FF.K,A2DC.K,A2FF.K,0)
NOTE  A2FM--ACCELERATION OF SECOND VEHICLE IN FOLLWINF MODE
A    A2FF.K=ASF(SSPAC12.K,SRV12.K)+A2HD.K
NOTE  A2FF--SECOND VEHICLE FOLLOWING MODE FUNCTION
A    A2HD.K=CLIP(0,A2HDF.K,-XX2.KL,0)
NOTE  A2HD--ACCELERATION OF SECOND BASED ON HEADWAY
A    A2HDF.K=ACG4*(1-(SD2.K/SSPAC12.K))
A    A2DC.K=CLIP(A2FF.K,0,V2.K,0)
A    A2PC12.K=CLIP(A2FD.K,A2DB.K,PA1.K,DCV)
A    A2FD.K=CLIP(A2FM.K,A2DB.K,FA1.K,DCV)
NOTE  A2FD--ACCELERATION OF SECOND VEHICLE FOLLOWING OR DECELERATION MODE
A    A2DB.K=CLIP(A2DB1.K,A2DB2.K,SSPAC12.K,SD23.K)
NOTE  A2DB--ACCELERATION OF SECOND VEHICLE DECELERATION OR BRAKING MODE
A    A2DB1.K=CLIP(A2ND.K,0,V2.K,0)
A    A2ND.K=FV(V2.K)*FS(SSPAC12.K)*SRV12.K
NOTE  A2ND--ACCELERATION OF SECOND NORMAL DECELERATION MODE
A    A2DB2.K=CLIP(A2DB1.K,A2BK.K,SRV12.K,CRV2)
A    A2BK.K=MAX(A2BK1.K,A2BK2.K)
NOTE  A2BK--ACCELERATION OF SECOND EMERGANCY BRAKING MODE
A    A2BK1.K=CLIP(BV1*(V1.K*V1.K-V2.K*V2.K)/(SSPAC12.K+10),0,V2.K,0)
A    A2BK2.K=CLIP(-MAXDC2.K,0,V2.K,0)
A    A2PC2.K=CLIP(A2SD.K,A2PC1.K,TDJ2.K,TB2.K)
A    A2SD.K=CLIP(A2SD1.K,A2SD2.K,SSPAC12.K,STPD)
NOTE  A2SD--ACCELERATION OF SECOND IN SLOW DECELERATION
A    A2SD1.K=CLIP(A2ADJ.K,A2SW.K,TDJ2.K,ADV*TB2.K)
A    A2SW.K=CLIP(ADJ5*A2ADJ.K,A2PC1.K,SRV12.K/(SSPAC12.K+2),CRVS)
A    A2ADJ.K=CLIP(ADJF(V2.K,SSPAC12.K),0,V2.K,0)
NOTE  A2ADJ--ACCELERATION OF SECOND SPACE ADJUSTMENT FUNCTION
A    A2SD2.K=CLIP(A2PC1.K,A2ADJ.K,A2ADJ.K,2*PA1.K)
A    TDJ2.K=SSPAC12.K/(XX2.KL+.5)
NOTE  TDJ2.K--SAFE STOPPING TIME AT CURRENT SPEED OF SECOND VEHICLE
A    TB2.K=(ADJ3*XX2.KL)/MAXDC2.K
NOTE  TB2--STOPPING AT MAXIMUM DECELERATION OF SECOND VEHICLE
A    SRV12.K=DELAY1(RV12.KL,SENTM)
NOTE  SRV12--SENSORED RELATIVE VELOCITY OF IST AND 2ND VEHICLES
R    RV12.KL=XX1.KL-XX2.KL
NOTE  RV12--RELATIVE VELOCITY OF 1ST AND 2ND VEHICLE
A    SSPAC12.K=DELAY1(SPAC12.KL,SENTM)
NOTE  SSPAC12--SENSORED SPACING BETWEEN FIRST AND SECOND VEHICLE
R    SPAC12.KL=X1.K-X2.K-VL1
NOTE  SPAC12--SPACING BETWEEN FIRST AND SECOND VEHICLE
A    SD2.K=SD(V1.K,V2.K,MAXDC2.K,VL1)
NOTE  SD2--SAFE DISTANCE FOR SECOND VEHICLE
A    SD21.K=SCF1*SD2.K
A    SD22.K=SCF2*SD2.K

A    SD23.K=SCF3*SD2.K
A    PA2.K=DELAY1(A2R.KL,SENTM)
NOTE  PA2--PECEIVED ACCELERATION OF SECOND VEHICLE
A    FA2.K=DELAY1(A2R.KL,PCT)
NOTE  DESCRIPTION OF THIRD VEHICLE
L    X3.K=X3.J+(DT)(XX3.JK)
NOTE  X3--POSITION OF THIRD VEHICLE
N    X3=XN1-VL1-VL2-2*ISP
R    XX3.KL=MAX(0,V3.K)
NOTE  XX3--SPEED OF THIRD VEHICLE
L    V3.K=V3.J+(DT)(A3R.JK)
NOTE  V3--VELOCITY OF SECOND VEHICLE
N    V3=VN3
R    A3R.KL=SMOOTH(A3I.KL,PTRT)
NOTE  A3R--ACCELERATION THIRD VEHICLE REALIZED
R    A3I.KL=MIN(AMAX3.K,CLIP(A3C1.K,A3PC.K,SSPAC23.K,SD31.K))
NOTE  A3I--ACCELERATION THIRD INITIALIZED
A    AMAX3.K=MIN(MAXACC,GRAV*(TE3.K-R3.K)/WT3)
NOTE  AMAX3--MAXIMUM ACCELERATION OF THIRD VEHICLE
A    TE3.K=TE(P3,XX3.KL)
NOTE  TE3--TRACTIVE EFFORT OF THIRD VEHICLE
A    R3.K=RR(XX3.KL,WT3,VL3)+RG(WT3,GRAD)+RA(A3,XX3.KL,GRAV)
NOTE  R3--RESISTANCE TO MOTION OF THIRD VEHICLE
A    A3C1.K=CLIP(A3C2.K,A3PC.K,V3.K,VT1)
NOTE  A3C1--ACCELERATION OF THIRD VEHICLE IN CASE 1
A    A3C2.K=CLIP(A3CRU.K,A3PC.K,SRV23.K,CRV3)
NOTE  A3C2--ACCELERATION OF THIRD VEHICLE IN CASE 2
A    A3CRU.K=ACG1(XX3.KL)*(DSPEED-V3.K)
NOTE  A3CRU--ACCELERATION OF THIRD IN CRUISE CONTROL MODE
A    A3PC.K=CLIP(A3PC1.K,A3PC2.K,PA2.K,0)
NOTE  A3PC--ACCELERATION OF THIRD IN PLATOON CONTROL MODE
A    A3PC1.K=MAX(-MAXDC3.K,CLIP(A3PC11.K,A3PC12.K,SSPAC23.K,SD32.K))
A    MAXDC3.K=MAXDEC(WT3,FR)
NOTE  MAXDC3.K--MAXIMUM DECELERATION OF THIRD VEHICLE
A    A3PC11.K=CLIP(A3FM.K,A3PC12.K,SRV23.K/(SSPAC23.K+2),CRVS)
A    A3FM.K=CLIP(A3FF.K,A3DC.K,A3FF.K,0)
NOTE  A3FM--ACCELERATION OF THIRD VEHICLE IN FOLLWINF MODE
A    A3FF.K=ASF(SSPAC23.K,SRV23.K)+A3HD.K
NOTE  A3FF--SECOND VEHICLE FOLLOWING MODE FUNCTION
A    A3HD.K=CLIP(0,A3HDF.K,-XX3.KL,0)
NOTE  A3HD--ACCELERATION OF THIRD VEHICLE BASED ON HEADWAY
A    A3HDF.K=ACG4*(1-(SD3.K/SSPAC23.K))
A    A3DC.K=CLIP(A3FF.K,0,V3.K,0)
A    A3PC12.K=CLIP(A3FD.K,A3DB.K,PA2.K,DCV)
A    A3FD.K=CLIP(A3FM.K,A3DB.K,FA2.K,DCV)
NOTE  A3FD--ACCELERATION OF THIRD VEHICLE FOLLOWING OR DECELERATION MODE
A    A3DB.K=CLIP(A3DB1.K,A3DB2.K,SSPAC23.K,SD33.K)
NOTE  A3DB--ACCELERATION OF THIRD VEHICLE DECELERATION OR BRAKING MODE
A    A3DB1.K=CLIP(A3ND.K,0,V3.K,0)
A    A3ND.K=FV(V3.K)*FS(SSPAC23.K)*SRV23.K
NOTE  A3ND--ACCELERATION OF THIRD NORMAL DECELERATION MODE
A    A3DB2.K=CLIP(A3DB1.K,A3BK.K,SRV23.K,CRV2)

A    A3BK.K=MAX(A3BK1.K,A3BK2.K)
NOTE  A3BK--ACCELERATION OF THIRD EMERGANCY BRAKING MODE
A    A3BK1.K=CLIP(BV1*(V2.K*V2.K-V3.K*V3.K)/(SSPAC23.K+10),0,V3.K,0)
A    A3BK2.K=CLIP(-MAXDC3.K,0,V3.K,0)
A    A3PC2.K=CLIP(A3SD.K,A3PC1.K,TDJ3.K,TB3.K)
A    A3SD.K=CLIP(A3SD1.K,A3SD2.K,SSPAC23.K,STPD)
NOTE  A3SD--ACCELERATION OF THIRD IN SLOW DECELERATION
A    A3SD1.K=CLIP(A3ADJ.K,A3SW.K,TDJ3.K,ADV*TB3.K)
A    A3SW.K=CLIP(ADJ5*A3ADJ.K,A3PC1.K,SRV23.K/(SSPAC23.K+2),CRVS)
A    A3ADJ.K=CLIP(ADJF(V3.K,SSPAC23.K),0,V3.K,0)
NOTE  A3ADJ--ACCELERATION OF THIRD SPACE ADJUSTMENT FUNCTION
A    A3SD2.K=CLIP(A3PC1.K,A3ADJ.K,A3ADJ.K,2*PA2.K)
A    TDJ3.K=SSPAC23.K/(XX3.KL+.5)
NOTE  TDJ3--SAFE STOPPING TIME AT CURRENT SPEED OF THIRD VEHICLE
A    TB3.K=(ADJ3*XX3.KL)/MAXDC3.K
NOTE  TB3--STOPPING AT MAXIMUM DECELERATION OF THIRD VEHICLE
A    SRV23.K=DELAY1(RV23.KL,SENTM)
NOTE  SRV23--SENSORED RELATIVE VELOCITY OF 2ND AND 3RD VEHICLES
R    RV23.KL=XX2.KL-XX3.KL
NOTE  RV23--RELATIVE VELOCITY OF 2ND AND 3RD VEHICLE
A    SSPAC23.K=DELAY1(SPAC23.KL,SENTM)
NOTE  SSPAC23--SENSORED SPACING BETWEEN 2ND AND 3RD VEHICLE
R    SPAC23.KL=X2.K-X3.K-VL2
NOTE  SPAC23--SPACING BETWEEN 2ND AND 3RD VEHICLE
A    SD3.K=SD(V2.K,V3.K,MAXDC3.K,VL2)
NOTE  SD3--SAFE DISTANCE FOR THIRD VEHICLE
A    SD31.K=SCF1*SD3.K
A    SD32.K=SCF2*SD3.K
A    SD33.K=SCF3*SD3.K
A    PA3.K=DELAY1(A3R.KL,SENTM)
NOTE  PA3--PECEIVED ACCELERATION OF THIRD VEHICLE
A    FA3.K=DELAY1(A3R.KL,PCT)
NOTE  DESCRIPTION OF FOURTH VEHICLE
L    X4.K=X4.J+(DT)(XX4.JK)
NOTE  X4--POSITION OF FOURTH VEHICLE
N    X4=XN1-VL1-VL2-VL3-3*ISP
R    XX4.KL=MAX(0,V4.K)
NOTE  XX4--SPEED OF FOURTH VEHICLE
L    V4.K=V4.J+(DT)(A4R.JK)
NOTE  V4--VELOCITY OF FOURTH VEHICLE
N    V4=VN4
R    A4R.KL=SMOOTH(A4I.KL,PTRT)
NOTE  A4R--ACCELERATION FOURTH VEHICLE REALIZED
R    A4I.KL=MIN(AMAX4.K,CLIP(A4C1.K,A4PC.K,SSPAC34.K,SD41.K))
NOTE  A4I--ACCELERATION FOURTH INITIALIZED
A    AMAX4.K=MIN(MAXACC,GRAV*(TE4.K-R4.K)/WT4)
NOTE  AMAX4--MAXIMUM ACCELERATION OF FOURTH VEHICLE
A    TE4.K=TE(P4,XX4.KL)
NOTE  TE4--TRACTIVE EFFORT OF FOURTH VEHICLE
A    R4.K=RR(XX4.KL,WT4,VL4)+RG(WT4,GRAD)+RA(A4,XX4.KL,GRAV)
NOTE  R4--RESISTANCE TO MOTION OF FOURTH VEHICLE
A    A4C1.K=CLIP(A4C2.K,A4PC.K,V4.K,VT1)

NOTE  A4C1--ACCELERATION OF FOURTH VEHICLE IN CASE 1
A    A4C2.K=CLIP(A4CRU.K,A4PC.K,SRV34.K,CRV3)
NOTE  A4C2--ACCELERATION OF FOURTH VEHICLE IN CASE 2
A    A4CRU.K=ACG1(XX4.KL)*(DSPEED-V4.K)
NOTE  A4CRU--ACCELERATION OF FOURTH IN CRUISE CONTROL MODE
A    A4PC.K=CLIP(A4PC1.K,A4PC2.K,PA3.K,0)
NOTE  A4PC--ACCELERATION OF FOURTH IN PLATOON CONTROL MODE
A    A4PC1.K=MAX(-MAXDC4.K,CLIP(A4PC11.K,A4PC12.K,SSPAC34.K,SD42.K))
A    MAXDC4.K=MAXDEC(WT4,FR)
NOTE  MAXDC4.K--MAXIMUM DECELERATION OF FOURTH VEHICLE
A    A4PC11.K=CLIP(A4FM.K,A4PC12.K,SRV34.K/(SSPAC34.K+2),CRVS)
A    A4FM.K=CLIP(A4FF.K,A4DC.K,A4FF.K,0)
NOTE  A4FM--ACCELERATION OF FOURTH VEHICLE IN FOLLWING MODE
A    A4FF.K=ASF(SSPAC34.K,SRV34.K)+A4HD.K
NOTE  A4FF--FOURTH VEHICLE FOLLOWING MODE FUNCTION
A    A4HD.K=CLIP(0,A4HDF.K,-XX4.KL,0)
NOTE  ACCELERATION OF FOURTH VEHICLE BASED ON HEADWAY
A    A4HDF.K=ACG4*(1-(SD4.K/SSPAC34.K))
A    A4DC.K=CLIP(A4FF.K,0,V4.K,0)
A    A4PC12.K=CLIP(A4FD.K,A4DB.K,PA3.K,DCV)
A    A4FD.K=CLIP(A4FM.K,A4DB.K,FA3.K,DCV)
NOTE  A4FD--ACCELERATION OF FOURTH VEHICLE FOLLOWING OR DECELERATION MODE
A    A4DB.K=CLIP(A4DB1.K,A4DB2.K,SSPAC34.K,SD43.K)
NOTE  A4DB--ACCELERATION OF FOURTH VEHICLE DECELERATION OR BRAKING MODE
A    A4DB1.K=CLIP(A4ND.K,0,V4.K,0)
A    A4ND.K=FV(V4.K)*FS(SSPAC34.K)*SRV34.K
NOTE  A4ND--ACCELERATION OF FOURTH NORMAL DECELERATION MODE
A    A4DB2.K=CLIP(A4DB1.K,A4BK.K,SRV34.K,CRV2)
A    A4BK.K=MAX(A4BK1.K,A4BK2.K)
NOTE  A4BK--ACCELERATION OF FOURTH VEHICLE EMERGANCY BRAKING MODE
A    A4BK1.K=CLIP(BV1*(V3.K*V3.K-V4.K*V4.K)/(SSPAC34.K+10),0,V4.K,0)
A    A4BK2.K=CLIP(-MAXDC4.K,0,V4.K,0)
A    A4PC2.K=CLIP(A4SD.K,A4PC1.K,TDJ4.K,TB4.K)
A    A4SD.K=CLIP(A4SD1.K,A4SD2.K,SSPAC34.K,STPD)
NOTE  A4SD--ACCELERATION OF FOURTH IN SLOW DECELERATION
A    A4SD1.K=CLIP(A4ADJ.K,A4SW.K,TDJ4.K,ADV*TB4.K)
A    A4SW.K=CLIP(ADJ5*A4ADJ.K,A4PC1.K,SRV34.K/(SSPAC34.K+2),CRVS)
A    A4ADJ.K=CLIP(ADJF(V4.K,SSPAC34.K),0,V4.K,0)
NOTE  A4ADJ--ACCELERATION OF FOURTH SPACE ADJUSTMENT FUNCTION
A    A4SD2.K=CLIP(A4PC1.K,A4ADJ.K,A4ADJ.K,2*PA3.K)
A    TDJ4.K=SSPAC34.K/(XX4.KL+.5)
NOTE  TDJ4--SAFE STOPPING TIME AT CURRENT SPEED OF FOURTH VEHICLE
A    TB4.K=(ADJ3*XX4.KL)/MAXDC4.K
NOTE  TB4--STOPPING AT MAXIMUM DECELERATION OF FOURTH VEHICLE
A    SRV34.K=DELAY1(RV34.KL,SENTM)
NOTE  SRV34--SENSORED RELATIVE VELOCITY OF 3RD AND 4TH VEHICLES
R    RV34.KL=XX3.KL-XX4.KL
NOTE  RV34--RELATIVE VELOCITY OF 3RD AND 4TH VEHICLE
A    SSPAC34.K=DELAY1(SPAC34.KL,SENTM)
NOTE  SSPAC34--SENSORED SPACING BETWEEN 3RD AND 4TH VEHICLE
R    SPAC34.KL=X3.K-X4.K-VL3
NOTE  SPAC34--SPACING BETWEEN 3RD AND 4TH VEHICLE

A   SD4.K=SD(V3.K,V4.K,MAXDC4.K,VL3)
NOTE  SD4--SAFE DISTANCE FOR FOURTH VEHICLE
A   SD41.K=SCF1*SD4.K
A   SD42.K=SCF2*SD4.K
A   SD43.K=SCF3*SD4.K
A   PA4.K=DELAY1(A4R.KL,SENTM)
NOTE  PA4--PECEIVED ACCELERATION OF FOURTH VEHICLE
A   FA4.K=DELAY1(A4R.KL,PCT)
NOTE  DESCRIPTION OF FIFRTH VEHICLE
L   X5.K=X5.J+(DT)(XX5.JK)
NOTE  X5--POSITION OF FIFTH VEHICLE
N   X5=XN1-VL1-VL2-VL3-VL4-4*ISP
R   XX5.KL=MAX(0,V5.K)
NOTE  XX5--SPEED OF FIFTH VEHICLE
L   V5.K=V5.J+(DT)(A5R.JK)
NOTE  V5--VELOCITY OF FIFTH VEHICLE
N   V5=VN5
R   A5R.KL=SMOOTH(A5I.KL,PTRT)
NOTE  A5R--ACCELERATION FIFTH VEHICLE REALIZED
R   A5I.KL=MIN(AMAX5.K,CLIP(A5C1.K,A5PC.K,SSPAC45.K,SD51.K))
NOTE  A5I--ACCELERATION FIFTH INITIALIZED
A   AMAX5.K=MIN(MAXACC,GRAV*(TE5.K-R5.K)/WT5)
NOTE  AMAX5--MAXIMUM ACCELERATION OF FIFTH VEHICLE
A   TE5.K=TE(P5,XX5.KL)
NOTE  TE5--TRACTIVE EFFORT OF FIFTH VEHICLE
A   R5.K=RR(XX5.KL,WT5,VL5)+RG(WT5,GRAD)+RA(A5,XX5.KL,GRAV)
NOTE  R5--RESISTANCE TO MOTION OF FIFTH VEHICLE
A   A5C1.K=CLIP(A5C2.K,A5PC.K,V5.K,VT1)
NOTE  A5C1--ACCELERATION OF FOURTH VEHICLE IN CASE 1
A   A5C2.K=CLIP(A5CRU.K,A5PC.K,SRV45.K,CRV3)
A   A5CRU.K=ACG1(XX5.KL)*(DSPEED-V5.K)
NOTE  A5CRU--ACCELERATION OF FIFTH IN CRUISE CONTROL MODE
A   A5PC.K=CLIP(A5PC1.K,A5PC2.K,PA4.K,0)
NOTE  A5PC--ACCELERATION OF FOURTH IN PLATOON CONTROL MODE
A   A5PC1.K=MAX(-MAXDC5.K,CLIP(A5PC11.K,A5PC12.K,SSPAC45.K,SD52.K))
A   MAXDC5.K=MAXDEC(WT5,FR)
NOTE  MAXDC5--MAXIMUM DECELERATION OF FIFTH VEHICLE
A   A5PC11.K=CLIP(A5FM.K,A5PC12.K,SRV45.K/(SSPAC45.K+2),CRV1)
A   A5FM.K=CLIP(A5FF.K,A5DC.K,A5FF.K,0)
NOTE  A5FM--ACCELERATION OF FIFTH VEHICLE IN FOLLWING MODE
A   A5FF.K=ASF(SSPAC45.K,SRV45.K)+A5HD.K
NOTE  A5FF--FIFTH VEHICLE FOLLOWING MODE FUNCTION
A   A5HD.K=CLIP(0,A5HDF.K,-XX5.KL,0)
NOTE  ACCELERATION OF FIFTH VEHICLE BASED ON HEADWAY
A   A5HDF.K=ACG4*(1-(SD5.K/SSPAC45.K))
A   A5DC.K=CLIP(A5FF.K,0,V5.K,0)
A   A5PC12.K=CLIP(A5FD.K,A5DB.K,PA4.K,DCV)
A   A5FD.K=CLIP(A5FM.K,A5DB.K,FA4.K,DCV)
NOTE  A5FD--ACCELERATION OF FIFTH VEHICLE FOLLOWING OR DECELERATION MODE
A   A5DB.K=CLIP(A5DB1.K,A5DB2.K,SSPAC45.K,SD53.K)
NOTE  A5DB--ACCELERATION OF FIFTH VEHICLE DECELERATION OR BRAKING MODE
A   A5DB1.K=CLIP(A5ND.K,0,V5.K,0)

A    A5ND.K=FV(V5.K)*FS(SSPAC45.K)*SRV45.K
NOTE  A5ND--ACCELERATION OF FIFTH NORMAL DECELERATION MODE
A    A5DB2.K=CLIP(A5DB1.K,A5BK.K,SRV45.K,CRV2)
A    A5BK.K=MAX(A5BK1.K,A5BK2.K)
NOTE  A5BK--ACCELERATION OF FIFTH VEHICLE EMERGANCY BRAKING MODE
A    A5BK1.K=CLIP(BV1*(V4.K*V4.K-V5.K*V5.K)/(SSPAC45.K+10),0,V5.K,0)
A    A5BK2.K=CLIP(-MAXDC5.K,0,V5.K,0)
A    A5PC2.K=CLIP(A5SD.K,A5PC1.K,TDJ5.K,TB5.K)
A    A5SD.K=CLIP(A5SD1.K,A5SD2.K,SSPAC45.K,STPD)
NOTE  A5SD--ACCELERATION OF FIFTH IN SLOW DECELERATION
A    A5SD1.K=CLIP(A5ADJ.K,A5SW.K,TDJ5.K,ADV*TB5.K)
A    A5SW.K=CLIP(ADJ5*A5ADJ.K,A5PC1.K,SRV45.K/(SSPAC45.K+2),CRVS)
A    A5ADJ.K=CLIP(ADJF(V5.K,SSPAC45.K),0,V5.K,0)
NOTE  A5ADJ--ACCELERATION OF FIFTH SPACE ADJUSTMENT FUNCTION
A    A5SD2.K=CLIP(A5PC1.K,A5ADJ.K,A5ADJ.K,2*PA4.K)
A    TDJ5.K=SSPAC45.K/(XX5.KL+.5)
NOTE  TDJ5--SAFE STOPPING TIME AT CURRENT SPEED OF FIFTH VEHICLE
A    TB5.K=(ADJ3*XX5.KL)/MAXDC5.K
NOTE  TB5--STOPPING AT MAXIMUM DECELERATION OF FIFTH VEHICLE
A    SRV45.K=DELAY1(RV45.KL,SENTM)
NOTE  SRV45--SENSORED RELATIVE VELOCITY OF 4TH AND FIFTH VEHICLES
R    RV45.KL=XX4.KL-XX5.KL
NOTE  RV45--RELATIVE VELOCITY OF 4TH AND 5TH VEHICLE
A    SSPAC45.K=DELAY1(SPAC45.KL,SENTM)
NOTE  SSPAC45--SENSORED SPACING BETWEEN 4TH AND 5TH VEHICLE
R    SPAC45.KL=X4.K-X5.K-VL4
NOTE  SPAC45--SPACING BETWEEN 4TH AND 5TH VEHICLE
A    SD5.K=SD(V4.K,V5.K,MAXDC5.K,VL4)
NOTE  SD5--SAFE DISTANCE FOR FOURTH VEHICLE
A    SD51.K=SCF1*SD5.K
A    SD52.K=SCF2*SD5.K
A    SD53.K=SCF3*SD5.K
A    PA5.K=DELAY1(A5R.KL,SENTM)
NOTE  PA5--PECEIVED ACCELERATION OF FIFTH VEHICLE
A    FA5.K=DELAY1(A5R.KL,PCT)
NOTE  HEADWAY CALCULATION
A    HW12.K=X1.K-X2.K
A    HW23.K=X2.K-X3.K
A    HW34.K=X3.K-X4.K
A    HW45.K=X4.K-X5.K
NOTE  JERK CLACULATION
A    DLYA1.K=DELAY1(A1R.KL,DT)
A    DLYA2.K=DELAY1(A2R.KL,DT)
A    DLYA3.K=DELAY1(A3R.KL,DT)
A    DLYA4.K=DELAY1(A4R.KL,DT)
A    DLYA5.K=DELAY1(A5R.KL,DT)
A    J1.K=(A1R.KL-DLYA1.K)/DT
A    J2.K=(A2R.KL-DLYA2.K)/DT
A    J3.K=(A3R.KL-DLYA3.K)/DT
A    J4.K=(A4R.KL-DLYA4.K)/DT
A    J5.K=(A5R.KL-DLYA5.K)/DT
NOTE  PARAMETERS OF CONTROL MODEL

```
C    PTRT=.1
NOTE  PTRT--POWER TRAIN RESPONSE TIME
C    SENTM=.2
NOTE  SENTM--SENTOR TIME
C    ISP=80
C    PCT=1
C    STRT=25
NOTE  STRT--START CHANGING CONTROL MODE TIME
C    DSPEED=103
NOTE  DSPEED--DESIGN SPEED
C    MAXJK=16.1
NOTE  MAXJK--MAXIMUM JERK
C    DMD=-8.05
NOTE  DMD--DESIRED MAXIMUM DECELERATION
C    MAXACC=6.44
NOTE  MAXACC--MAXIMUM ACCELERATION
C    GRAV=32.2
NOTE  GRAV--GRAVITY ACCELERATION
C    GRAD=0
NOTE  GRAD--GRADE OF ROADWAY
C    FR=1
NOTE  FR--FRICTION CODE OF ROADWAY
C    ACG4=1.8
NOTE  ACCELERATION GAIN NO.4
C    ADV=2.5
C    BV1=2.5
C    CRV1=-2.92
NOTE  CRV1--CRITICAL RELATIVE VELOCITY NO. 1
C    CRV2=-22
NOTE  CRV2--CRITICAL RELATIVE VELOCITY NO.2
C    CRV3=-14.67
C    CRV4=-4.4
C    CRVS=-.3
C    DCV=-4.03
NOTE  DCV--CRITICAL DECELERATION VALUE
C    ADJ3=1.5
NOTE  ADJ3--ACCELERATION ADJUSTMENT PARAMETER 3
C    ADJ5=1.8
C    VT1=14.4
C    SCF1=3
C    SCF2=1.5
C    SCF3=.9
C    STPD=15
NOTE  INITIAL VELOCITY OF VEHICLES
C    VN1=73.35
C    VN2=73.35
C    VN3=73.35
C    VN4=73.35
C    VN5=73.35
NOTE  POWER OF VEHICLES
C    P1=105
C    P2=175
```

C    P3=125
C    P4=325
C    P5=105
NOTE  LENGTH OF VEHICLES
C    VL1=15
C    VL2=35
C    VL3=20
C    VL4=70
C    VL5=18
NOTE  WEIGHT OF VEHICLES
C    WT1=3500
C    WT2=9000
C    WT3=4500
C    WT4=50000
C    WT5=5000
NOTE  FRONT AREAS OF VEHICLES
C    A1=17.5
C    A2=21
C    A3=19
C    A4=24
C    A5=18.5
NOTE  ACCELERATION NOISE EVALUATION
L    NOISEA1.K=NOISEA1.J+(DT)(SQA1.JK)
N    NOISEA1=0
NOTE  NOISEA1--ACCELERATION NOISE ITEM A OF FIRST VEHICLE
R    SQA1.KL=A1R.KL*A1R.KL
A    NOISEB1.K=(XX1.KL-VN1)*(XX1.KL-VN1)/(TTIME.K*TTIME.K)
NOTE  NOISEB1--ACCELERATION NOISE ITEM B OF FIRST VEHICLE
A    NOISE1.K=(NOISEA1.K/TTIME.K)-NOISEB1.K
NOTE  NOISE1--ACCELERATION NOISE OF FIRST VEHICLE
A    TTIME.K=CLIP(TIME.K+.01,TIME.K,-TIME.K,0)
L    NOISEA2.K=NOISEA2.J+(DT)(SQA2.JK)
N    NOISEA2=0
NOTE  NOISEA2--ACCELERATION NOISE ITEM A OF SECOND VEHICLE
R    SQA2.KL=A2R.KL*A2R.KL
A    NOISEB2.K=(XX2.KL-VN2)*(XX2.KL-VN2)/(TTIME.K*TTIME.K)
NOTE  NOISEB2--ACCELERATION NOISE ITEM B OF SECOND VEHICLE
A    NOISE2.K=(NOISEA2.K/TTIME.K)-NOISEB2.K
NOTE  NOISE2--ACCELERATION NOISE OF SECOND VEHICLE
L    NOISEA3.K=NOISEA3.J+(DT)(SQA3.JK)
N    NOISEA3=0
NOTE  NOISEA3--ACCELERATION NOISE ITEM A OF SECOND VEHICLE
R    SQA3.KL=A3R.KL*A3R.KL
A    NOISEB3.K=(XX3.KL-VN3)*(XX3.KL-VN3)/(TTIME.K*TTIME.K)
NOTE  NOISEB3--ACCELERATION NOISE ITEM B OF THIRD VEHICLE
A    NOISE3.K=(NOISEA3.K/TTIME.K)-NOISEB3.K
NOTE  NOISE3--ACCELERATION NOISE OF THIRD VEHICLE
L    NOISEA4.K=NOISEA4.J+(DT)(SQA4.JK)
N    NOISEA4=0
NOTE  NOISEA4--ACCELERATION NOISE ITEM A OF FOURTH VEHICLE
R    SQA4.KL=A4R.KL*A4R.KL
A    NOISEB4.K=(XX4.KL-VN4)*(XX4.KL-VN4)/(TTIME.K*TTIME.K)

NOTE  NOISEB4--ACCELERATION NOISE ITEM B OF FOURTH VEHICLE
A     NOISE4.K=(NOISEA4.K/TTIME.K)-NOISEB4.K
NOTE  NOISE4--ACCELERATION NOISE OF FOURTH VEHICLE
L     NOISEA5.K=NOISEA5.J+(DT)(SQA5.JK)
N     NOISEA5=0
NOTE  NOISEA5--ACCELERATION NOISE ITEM A OF FIFTH VEHICLE
R     SQA5.KL=A5R.KL*A5R.KL
A     NOISEB5.K=(XX5.KL-VN5)*(XX5.KL-VN5)/(TTIME.K*TTIME.K)
NOTE  NOISEB5--ACCELERATION NOISE ITEM B OF FIFTH VEHICLE
A     NOISE5.K=(NOISEA5.K/TTIME.K)-NOISEB5.K
NOTE  NOISE5--ACCELERATION NOISE OF FIFTH VEHICLE
SPEC  DT=.0625/LENGTH=60/SAVPER=.5/PLTPER=1
SAVE  A1R, XX1, X1, AMAX1, NOISE1, NOISE2, NOISE3, NOISE4, NOISE5
SAVE  A2R, XX2, X2, AMAX2
SAVE  SPAC12, SPAC23, SPAC34, SPAC45
SAVE  A3R, XX3, X3, AMAX3
SAVE  A4R, XX4, X4, AMAX4
SAVE  A5R, XX5, X5, AMAX5
SAVE  J1 ,J2, J3, J4, J5

## Appendix C    Duplicated PATH Longitudinal Control Model Program

NOTE    ****************************************************************

NOTE    Duplicated PATH Longitudinal Control Model Program

NOTE    ****************************************************************

NOTE  DRIVING PROCESS OF LEADING VEHICLE
L     PSNL.K=PSNL.J+(DT)(SPDL.JK)
NOTE  PSNL--POSITION OF LEADING VEHICLE
N     PSNL=PSNLN
C     PSNLN=100
R     SPDL.KL=VL.K
L     VL.K=VL.J+(DT)(ALR.JK)
N     VL=VLN
C     VLN=58.68
R     ALR.KL=AL.K
A     AL.K=CLIP(0,ACE,VL.K,VUP)
A     DAL.K=DELAY1(ALR.KL,DT)
A     JL.K=(AL.K-DAL.K)/DT
A     DVL.K=VL.K-VLN
NOTE  DRIVING PROCESS OF FIRST VEHICLE IN PLATOON
L     DPSN1.K=DPSN1.J+(DT)(DSPD1.JK)
N     DPSN1=DSNSP
R     DSPD1.KL=DV1.K
L     DV1.K=DV1.J+(DT)(DA1R.JK)
N     DV1=DV1N
C     DV1N=0
R     DA1R.KL=DA1.K
L     DA1.K=DA1.J+(DT)(DJ1R.JK)
N     DA1=DA1N
C     DA1N=0
R     DJ1R.KL=DJ1.K
A     DJ1.K=JL.K-KA1*AL.K-KV1*VL.K-CA*DA1.K-CV*DV1.K-CP*DPSN1.K
A     PSN1.K=PSNL.K-DPSN1.K-L
A     V1.K=VL.K-DV1.K
A     A1.K=AL.K-DA1.K
NOTE  DRIVING PROCESS OF SECOND VEHICLE IN PLATOON
L     DPSN2.K=DPSN2.J+(DT)(DSPD2.JK)
N     DPSN2=DSNSP
R     DSPD2.KL=DV2.K
L     DV2.K=DV2.J+(DT)(DA2R.JK)
N     DV2=DV2N
C     DV2N=0
R     DA2R.KL=DA2.K
L     DA2.K=DA2.J+(DT)(DJ2R.JK)
N     DA2=DA2N
C     DA2N=0

R DJ2R.KL=DJ2.K
A DJ2.K=KA*DA1.K+KV*DV1.K+CP*(DPSN1.K-DPSN2.K)-CA*DA2.K-CV*DV2.K
A PSN2.K=PSN1.K-DPSN2.K-L
A V2.K=V1.K-DV2.K
A A2.K=A1.K-DA2.K
NOTE DRIVING PROCESS OF THIRD VEHICLE IN PLATOON
L DPSN3.K=DPSN3.J+(DT)(DSPD3.JK)
N DPSN3=DSNSP
R DSPD3.KL=DV3.K
L DV3.K=DV3.J+(DT)(DA3R.JK)
N DV3=DV3N
C DV3N=0
R DA3R.KL=DA3.K
L DA3.K=DA3.J+(DT)(DJ3R.JK)
N DA3=DA3N
C DA3N=0
R DJ3R.KL=DJ3.K
A DJ3.K=KA*DA2.K+KV*DV2.K+CP*(DPSN2.K-DPSN3.K)-CA*DA3.K-CV*DV3.K
A PSN3.K=PSN2.K-DPSN3.K-L
A V3.K=V2.K-DV2.K
A A3.K=A2.K-DA3.K
NOTE DRIVING PROCESS OF FOURTH VEHICLE IN PLATOON
L DPSN4.K=DPSN4.J+(DT)(DSPD4.JK)
N DPSN4=DSNSP
R DSPD4.KL=DV4.K
L DV4.K=DV4.J+(DT)(DA4R.JK)
N DV4=DV4N
C DV4N=0
R DA4R.KL=DA4.K
L DA4.K=DA4.J+(DT)(DJ4R.JK)
N DA4=DA4N
C DA4N=0
R DJ4R.KL=DJ4.K
A DJ4.K=KA*DA3.K+KV*DV3.K+CP*(DPSN3.K-DPSN4.K)-CA*DA4.K-CV*DV4.K
A PSN4.K=PSN3.K-DPSN4.K-L
A V4.K=V3.K-DV4.K
A A4.K=A3.K-DA4.K
NOTE DRIVING PROCESS OF FIFTH VEHICLE IN PLATOON
L DPSN5.K=DPSN5.J+(DT)(DSPD5.JK)
N DPSN5=DSNSP
R DSPD5.KL=DV5.K
L DV5.K=DV5.J+(DT)(DA5R.JK)
N DV5=DV5N
C DV5N=0
R DA5R.KL=DA5.K
L DA5.K=DA5.J+(DT)(DJ5R.JK)
N DA5=DA5N
C DA5N=0
R DJ5R.KL=DJ5.K
A DJ5.K=KA*DA4.K+KV*DV4.K+CP*(DPSN4.K-DPSN5.K)-CA*DA5.K-CV*DV5.K
A PSN5.K=PSN4.K-DPSN5.K-L
A V5.K=V4.K-DV5.K

A   A5.K=A4.K-DA5.K
NOTE  DRIVING PROCESS OF SIXTH VEHICLE IN PLATOON
L   DPSN6.K=DPSN6.J+(DT)(DSPD6.JK)
N   DPSN6=DSNSP
R   DSPD6.KL=DV6.K
L   DV6.K=DV6.J+(DT)(DA6R.JK)
N   DV6=DV6N
C   DV6N=0
R   DA6R.KL=DA6.K
L   DA6.K=DA6.J+(DT)(DJ6R.JK)
N   DA6=DA6N
C   DA6N=0
R   DJ6R.KL=DJ6.K
A   DJ6.K=KA*DA5.K+KV*DV5.K+CP*(DPSN5.K-DPSN6.K)-CA*DA6.K-CV*DV6.K
A   PSN6.K=PSN5.K-DPSN6.K-L
A   V6.K=V5.K-DV6.K
A   A6.K=A5.K-DA6.K
NOTE  ACCELERATION NOISE EVALUATION
A   TTIME.K=CLIP(TIME.K+.01,TIME.K,-TIME.K,0)
L   NOISEAL.K=NOISEAL.J+(DT)(SQAL.JK)
N   NOISEAL=0
R   SQAL.KL=AL.K*AL.K
A   NOISEBL.K=(VL.K-VLN)*(VL.K-VLN)/(TTIME.K*TTIME.K)
A   NOISEL.K=(NOISEAL.K/TTIME.K)-NOISEBL.K
L   NOISEA1.K=NOISEA1.J+(DT)(SQA1.JK)
N   NOISEA1=0
R   SQA1.KL=A1.K*A1.K
A   NOISEB1.K=(V1.K-VLN)*(V1.K-VLN)/(TTIME.K*TTIME.K)
A   NOISE1.K=(NOISEA1.K/TTIME.K)-NOISEB1.K
L   NOISEA2.K=NOISEA2.J+(DT)(SQA2.JK)
N   NOISEA2=0
R   SQA2.KL=A2.K*A2.K
A   NOISEB2.K=(V2.K-VLN)*(V2.K-VLN)/(TTIME.K*TTIME.K)
A   NOISE2.K=(NOISEA2.K/TTIME.K)-NOISEB2.K
L   NOISEA3.K=NOISEA3.J+(DT)(SQA3.JK)
N   NOISEA3=0
R   SQA3.KL=A3.K*A3.K
A   NOISEB3.K=(V3.K-VLN)*(V3.K-VLN)/(TTIME.K*TTIME.K)
A   NOISE3.K=(NOISEA3.K/TTIME.K)-NOISEB3.K
L   NOISEA4.K=NOISEA4.J+(DT)(SQA4.JK)
N   NOISEA4=0
R   SQA4.KL=A4.K*A4.K
A   NOISEB4.K=(V4.K-VLN)*(V4.K-VLN)/(TTIME.K*TTIME.K)
A   NOISE4.K=(NOISEA4.K/TTIME.K)-NOISEB4.K
L   NOISEA5.K=NOISEA5.J+(DT)(SQA5.JK)
N   NOISEA5=0
R   SQA5.KL=A5.K*A5.K
A   NOISEB5.K=(V5.K-VLN)*(V5.K-VLN)/(TTIME.K*TTIME.K)
A   NOISE5.K=(NOISEA5.K/TTIME.K)-NOISEB5.K
L   NOISEA6.K=NOISEA6.J+(DT)(SQA6.JK)
N   NOISEA6=0
R   SQA6.KL=A6.K*A6.K

```
A    NOISEB6.K=(V6.K-VLN)*(V6.K-VLN)/(TTIME.K*TTIME.K)
A    NOISE6.K=(NOISEA6.K/TTIME.K)-NOISEB6.K
C    L=18
C    DSNSP=1
C    KA1=-5.15
C    KV1=0
C    KA=12.41
C    KV=80.96
C    CP=91.99
C    CV=80.96
C    CA=17.56
C    TF=20
C    VUP=88.02
C    ACE=6.44
C    DCE=-8.05
SPEC  DT=.0125/LENGTH=50/SAVPER=.5
SAVE  PSNL,PSN1,PSN2,PSN3,PSN4,PSN5,PSN6,VL,V1,V2,V3,V4,V5,V6
SAVE  DPSN1,DPSN2,DPSN3,DPSN4,DPSN5,DPSN6,AL,A1,A2,A3,A4,A5,A6
SAVE  NOISEL,NOISE1,NOISE2,NOISE3,NOISE4,NOISE5,NOISE6
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# Vita

Ming Lu was born in Tianjin, P. R. China on June 25, 1956. She attended Tianjin University (Tianjin, P. R. China) in February, 1978, where she received her Bachelor degree in Electrical Engineering in May, 1982 and Master degree in Systems Engineering in December, 1984. She joined the faculty of Institute of Systems Engineering at Tianjin University since November, 1984. She completed her Ph.D. degree in Civil Engineering at Virginia Polytechnic Institute and State University in May, 1996.