Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

AHS PSA Lateral and Longitudinal Control Analysis

U.S. Department of Transportation
Federal Highway Administration

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FOREWORD

This report was a product of the Federal Highway Administration's Automated Highway System (AHS) Precursor Systems Analyses (PSA) studies. The AHS Program is part of the larger Department of Transportation (DOT) Intelligent Transportation Systems (ITS) Program and is a multi-year, multi-phase effort to develop the next major upgrade of our nation's vehicle-highway system.

The PSA studies were part of an initial Analysis Phase of the AHS Program and were initiated to identify the high level issues and risks associated with automated highway systems. Fifteen interdisciplinary contractor teams were selected to conduct these studies. The studies were structured around the following 16 activity areas:

> (A) Urban and Rural AHS Comparison, (B) Automated Check-In, (C) Automated Check-Out, (D) Lateral and Longitudinal Control Analysis, (E) Malfunction Management and Analysis, (F) Commercial and Transit AHS Analysis, (G) Comparable Systems Analysis, (H) AHS Roadway Deployment Analysis, (I) Impact of AHS on Surrounding Non-AHS Roadways, (J) AHS Entry/Exit Implementation, (K) AHS Roadway Operational Analysis, (L) Vehicle Operational Analysis, (M) Alternative Propulsion Systems Impact, (N) AHS Safety Issues, (O) Institutional and Societal Aspects, and (P) Preliminary Cost/Benefit Factors Analysis.

To provide diverse perspectives, each of these 16 activity areas was studied by at least three of the contractor teams. Also, two of the contractor teams studied all 16 activity areas to provide a synergistic approach to their analyses. The combination of the individual activity studies and additional study topics resulted in a total of 69 studies. Individual reports, such as this one, have been prepared for each of these studies. In addition, each of the eight contractor teams that studied more than one activity area produced a report that summarized all their findings.

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0.1 Methodology

To ensure practical and meaningful results from the analysis, a four step approach was adopted: (1) define system configurations according to the BAA guidelines, (2) define basic vehicle operations and maneuvers required for the defined system configurations, (3) perform generic analysis on each operation and maneuver, and (4) identify issues and risks from the analyses. Representative Systems Configurations (RSCs) are described. The basic operations and maneuvers required for the RSCs and discussed in the report are: headway maintenance including safety formulation; lane change maneuver including lane holding, lane entry/exit, and roadway entry/exit; platoon formation, obstacle avoidance, and automated traffic stream stability.

0.2 Summary of Results and Issues

Headway Maintenance Maneuvers

Issues and risks identified in this section are summarized below. Note that issues and risks are not necessarily concerns of the feasibility of the idea of AHS as the remedy for the next century's transportation problems but they are simply some technical subjects that ought to be thoroughly investigated in the future.

1. Safety distance between two vehicles depends upon many deterministic as well as random factors, e.g., velocity, road surface condition, tires, and weather. Should the safety distance be established upon the worst scenario (e.g., brick wall stop) or on a probability basis?

2. Can the safety distance between vehicles be preset realistically? If not, how do we establish it adaptively in real time?

3. To standardize longitudinal control systems of automated vehicles, the follow ing requirements need to be defined: ride comfort, the mobility of vehicles in an AHS, the nominal gap, the maximum tolerable gap variation, the maximum tolerable impact energy for platooning.

Analysis of Lane Change Maneuvers

The issues and risks identified in this section are summarized below. The issues and risks are subjects for future studies.

1. While the efficiency of an LCM can be optimized given a particular traffic condition, the optimization is often accomplished at the expense of system robustness. The trade off

between efficiency and robustness requires careful analysis, tuning, and tests in the future.

2. How much and when should the driver be given control of the vehicle to perform an LCM from an automated lane to a manual lane, and vice versa in the DE mechanization?

3. How do we estimate the necessary lead time to initiate an LCM which is constrained by the location and length of the opening of a physical barrier between an automated and transition lane as in a B+T mechanization?

4. Since lateral and longitudinal control systems are always operated simultaneously, and they are usually designed and analyzed separately, the possibility of adverse cross-axis interactions should be minimized to ensure the total system integrity. For example, the minimization of the effect of weight shift between front and rear tires on lateral maneuverability when the vehicle is accelerating longitudinally.

5. What is the effect of LCM on lane keeping? Biasing the vehicle's reference lateral position to, perhaps, the center line of the receiving lane?

Platoon Formation Task and Maneuver

There does not appear to be a compelling rationale for having the front platoon actively participate in the merge of two platoons. An active front platoon would imply system complexity beyond AICC with information simultaneously flowing both forward and rearward between the platoons. This would create two-way dynamic coupling that could be generally undesirable.

With a passive front platoon, merge involves only inter-platoon, not intra-platoon, dynamics. Consequently only the dynamics and control of the lead vehicle of the rear platoon need be treated explicitly.

It is important to distinguish between nominal merge conditions which would apply to the majority of platoon formations and special cases which will occur relatively rarely (emergency and failure cases). Platoon formation will always be an optional activity performed for traffic flow efficiency and not specifically to enhance safety. Thus aborting a platoon merge probably will be the correct strategy for many, if not most, off-nominal conditions. The nominal merge control design should not be compromised to allow platoon formation under off-nominal conditions where the maneuver could and should be aborted.

If the front platoon speed is much lower than the speed limit, or if it is decelerating rapidly, or if a third vehicle intrudes between the platoons, an off-nominal condition is indicated and platoon formation should not be initiated. This is particularly true without two-way inter-platoon communication. Further, the front platoon cannot accelerate significantly for long or the speed limit would be exceeded. Thus merging with an accelerating (or decelerating) front platoon should not be a system design issue.

Acceleration and jerk limits for platoon merges will be imposed for passenger comfort rather than safety and traffic flow. Thus these limits will likely be set by manufacturers (rather than the Government).

The nominal merge maneuver could be addressed as a constrained trajectory optimization problem, if a relevant cost function could be identified. A minimum time maneuver is a possibility, but not a compelling one since elapsed times for merge maneuvers will be much shorter than useful platoon "half-lives". Thus minimum time maneuvers are primarily of interest as reference maneuvers. Maximizing safety and passenger comfort is much more important.

Obstacle Avoidance Maneuvers

Currently the most important question concerning AHS obstacle avoidance is the discrete control strategy for determining if a vehicle should maneuver around an obstacle or simply remain in its current lane and brake.

The basic discrete lane change decision algorithm can be based on comparison of estimates of the expected costs of: (1) remaining in the lane and possibly impacting the object or, (2) maneuvering around the obstacle and possibly colliding with a vehicle in an adjacent lane.

The key uncertainties in the lane change decision problem, both for analysis and real-time systems, are the statistical distributions of the properties of the population of random objects that can be expected to appear on highways. The object properties of interest, in order of decreasing importance, are size, density, and effective structural stiffness. Relevant statistical data is not readily available.

The lane change decision problem for an automatic system is fundamentally the same as that for a human driver. However, in addition to simply detecting an object in the roadway, human drivers apparently apply, with various degrees of competence, subtle identification schemes to predict the danger of impacting the object. These probably involve cues from size, shape, color, and motion compared to a "knowledge-base" of likely highway objects. Achieving this capability in sensor processing for an automatic system can be expected to be a major challenge and a critical path in AHS development.

Even if an automated lane change decision capability can be developed and shown to equal or exceed human capability in tests, accidents with an automated system are probably more likely to result in lawsuits. This follows simply because of the "deeper pockets" of a system manufacturer compared to those of an individual driver.

The most sensitive object factor is size. Increased object size increases collision severity in the "no lane change" case by increasing object mass. It increases severity in the "lane change" case by increasing the expected relative velocity with respect to adjacent vehicles.

The most sensitive vehicle factor is the limit deceleration capability, but it effects only the "no lane change" case to a first approximation. Increasing the limit reduces the severity of "no lane change" accidents by decreasing the object impact speed. In lane changes some reduction in accident severity is achieved by increasing the effective side stiffness of the vehicle.

All of the AHS system parameters (lane speed, longitudinal vehicle separation, lane width, object detection range, and system effective time delay) are potentially significant. Reduction in longitudinal vehicle spacing and reduction in lane width from current nominals, possibilities that have been proposed as benefits from AHS and vehicle platooning, could have serious adverse impacts on the obstacle avoidance problem.

The primary need for future research in this area is better characterization of the population of random objects that can be expected to appear on highways (AHS highways in particular). Statistical distributions of (in order of decreasing importance) size, density, and effective stiffness should be obtained. Reasonable empirical data could probably be obtained from state highway departments and highway patrols.

When improved object statistics are available, the analytical procedure reported here should be refined to predict the variances of accident severity as well as expected severity. The lane change accident probabilities should also be refined. Ultimately the lane change model should be based on a vehicle dynamic simulation (which are currently available). However this step should be postponed, until a refined version of the closed form probabilistic model reported here has been thoroughly examined.

The problem of detecting and characterizing random roadway objects with machine systems should be studied as a distinct problem. This should begin with a study of human driver behavior and technique for object detection and classification. This could be done with integrated driver-in-the-loop simulation and field experiments. This effort can build on relevant technology developments for similar applications. New technologies in the area of artificial intelligence, machine vision, etc. should be examined. Developments could find application in collision warning systems (especially for night and foul weather) before AHS is operational.

Stream Stability

Perturbation amplification in strings of automated vehicles. There is a general consensus that if communications links are provided so that each vehicle in a platoon obtains continuous information regarding the motion of the lead vehicle, then stability of the platoon can be sustained indefinitely. There is an issue of the safety of the platoon in the event of sudden failure of the communications system, however, this does not appear to be insurmountable and back-up control algorithms have been designed. There is an issue of the cost of the communications system, including the use of the spectral bandwidth needed. It is not generally agreed that a longitudinal control system can be designed without the aid of communications that will both provide major benefits in flow capacity as well as provide guaranteed stable performance. However, some benefits are realizable, and it may be possible to impose constraints on the maximum platoon size (via a less expensive communications link from traffic management) that provides the necessary limits for safe and stable operation.

Impact of Entering and Exiting on Stream Stability. It has been found that the effect on the traffic flow of vehicles entering and exiting the AHS effects must be accounted for in deriving the potential flow capacity increase benefits of an AHS, as well as used in any on-ramp flow control (to ensure the system is not overloaded). However, these effects do not appear to impose an obstacle to implementation of the AHS. There are some approaches that have been investigated that indicate substantial mitigation of these detrimental effects by communicating information regarding exit destination and utilizing this in the behavior of the vehicles (viz., platoon formation and dissolution). However, these will bring issues both of cost of implementation such communications links and algorithms as well as the problem of privacy.

Complexity of Vehicle Interactions. The AHS, like any road traffic system, is representative of a complex dynamic system, in which many entities interact asychronously based on local information and nonlinear rules of operation. Analysis and prediction in such systems is generally intractable, much like predicting the weather (which can be chaotic in the sense of sensitive dependence on initial conditions). Newly emerging concepts in the field of complex systems theory will need to be applied to bound the problem of performance evaluation, and ensure stable conditions will prevail.

Effect of Automation on Vehicle Neighborhoods. It seems clear that in the AHS, the coupling among vehicles will necessarily be increased. Thus, when an incident occurs, the effects will be much more widespread both in the number affected and the spatial extent. While one approach is to emphasize the rapid removal of problems, we feel that at least concurrent with this must be a careful design that ensures that the AHS is not too brittle, wherein every small disturbance is felt by every vehicle in a large region.

1. INTRODUCTION

1.1 Description

The scope of this report is to document the study results obtained from the Lateral and Longitudinal Control Analysis (Lat/Long) performed by the Autonetics Electronics Systems Division of Rockwell in Anaheim, California. This effort was performed for the Federal Highway Administration (FHWA) during the period September 15, 1993, through November 30, 1994.

On November 27, 1992, FHWA issued a Broad Agency Announcement (BAA) that identified the need for analyses in the area of automated highway systems as part of the major initiative by the Department of Transportation (DOT) in the area of Intelligent Vehicle Highway Systems (IVHS).

The AHS development program is currently structured into three phases: analysis, demonstration, and operational test and evaluation. As part of the analysis phase of the program, the objective of this BAA is to identify issues and risks relating to an AHS by performing Precursor System Analyses (PSA) in sixteen different activity areas. Lateral and longitudinal control analysis is one of the areas of interest.

1.2 Objectives

The objectives of the Lat/Long Control Analysis are primarily (1) to perform system operational analyses in terms of safety and capacity, and (2) to identify issues and risks in various areas of vehicle control in a fully automated highway environment. In this report, the phrase "issues and risks" is applied in a broad sense to include those technical subjects that can not be fully studied at the precursor stage of the program but are desirable and/or necessary for future investigation as the AHS program matures.

1.3 Overall Approach

To ensure practical and meaningful results from the analysis, a four step approach was adopted: (1) define system configurations according to the BAA guidelines, (2) define basic vehicle operations and maneuvers required for the defined system configurations, (3) perform generic analysis on each operation and maneuver, and (4) identify issues and risks from the analyses. Representative Systems Configurations (RSCs) are described. The basic operations and maneuvers required for the RSCs and discussed in the report are: headway maintenance including safety formulation; lane change maneuver including lane holding, lane entry/exit, and roadway entry/exit; platoon formation, obstacle avoidance, and automated traffic stream stability.

2. ANALYSIS OF THE BASIC MANEUVERS

2.1 Objective

The objective of this section is to identity the basic vehicle maneuvers required in an AHS environment and the key parameters pertaining to the maneuvers.

2.2 Characteristics of the Basic Maneuvers

All of the various maneuvers that are possibly needed in an AHS can be decomposed into one or a combination of three basic maneuvers: speed change, longitudinal displacement, and lateral displacement.

The speed change maneuver is invoked when a free agent or the lead vehicle of a platoon is commanded, by either the infrastructure or other vehicles, to follow a certain desired velocity trajectory with or without constraints, e.g., vehicles approaching an exit or entry. The desired velocity is reached through the use of throttle control and braking control. It is possible that the desired velocity may not be reached within a time constraint, if any, for those vehicles with insufficient acceleration and/or brake capability from certain initial velocities. The key parameters associated with this maneuver are acceleration and brake capabilities including the tire rolling resistance, initial vehicle velocity, commanded velocity, and constraints, like time and/or distance.

The longitudinal displacement maneuver is invoked when (1) a vehicle needs to keep a minimum safe distance from the vehicle ahead, so that collision is prevented should the lead vehicle decelerate rapidly, or (2) a vehicle decides to platoon with another vehicle, or (3) a vehicle intends to change lanes, where longitudinal displacement maneuver is usually accompanied by lateral maneuver, or (4) a vehicle needs to make room in its own lane to accommodate another vehicle's maneuver. Time and/or distance constraints may be imposed to any one of the above situations. Regardless of which situation it may be, longitudinal displacement, like the speed change maneuver, is accomplished by throttle and brake control. The key parameters associated with this maneuver are acceleration and brake capabilities including tire rolling resistance, initial vehicle longitudinal position, commanded desirable displacement, and time and/or distance constraint.

The lateral displacement maneuver is invoked when (1) a vehicle needs to stay within its lane boundary (lane holding), or (2) a vehicle wishes to change lanes, or (3) a vehicle is trying to avoid an obstacle along its scheduled path. This maneuver is always performed simultaneously with non-zero vehicle longitudinal movement and it is accomplished by wheel steering, whereby a lateral force in the required direction is generated. The key parameters associated with this maneuver are the steering angle, the acceleration and brake capabilities including tire rolling resistance, initial vehicle lateral position, commanded lateral position, and time and/or distance constraints.

3. HEADWAY MAINTENANCE MANEUVERS

3.1 Objectives:

The objectives of this section are to (1) formulate safety criteria between two successive vehicles traveling in the same lane on an AHS, (2) investigate headway maintenance mechanism, (3) analyze the impact on the rear-end accident rate, and (4) identify the associated issues and risks.

3.2 Formulation of Safety Criteria

Safety enhancement compared with today's freeway system is one of the major demands of the AHS program. In practice, the overall AHS safety depends upon the design and reliability of infrastructure, vehicle control, traffic management, communications between infrastructure and vehicles, and among vehicles themselves. From the system operational point of view, safety can be accomplished by keeping following vehicles at safe distances from their lead vehicles, if any, in case the lead vehicle decelerates rapidly. There are many factors that affect the establishment of safe distance between two vehicles operating in an AHS. If the following six parameters are known, the safe distance can be calculated analytically: lead vehicle deceleration profile, lead vehicle velocity, relative velocity, reaction delay, braking capability and acceleration level of the following vehicle. The relative velocity and the acceleration are usually small, depending upon the control system mechanism, if the two vehicles are being operated in a headway maintenance mode.

Figure 3.1 illustrates the concept of the establishment of sa fe distance. V1 and V2 are the velocity profiles of the lead and following vehicles from the reference time of zero seconds, the time at which the lead vehicle decelerates according to curve V_1. The slope of each velocity curve represents each vehicle's braking capability. The following vehicle starts to react by applying its full brake capability after T_d seconds. Since the distance traveled by each vehicle is the area under its velocity curve, the difference, marked by the gray area enclosed by the two curves, indicates the minimum initial gap required in order to avoid a collision. In case of a "brick wall" stop of the lead vehicle, the entire area under V_2 becomes the minimum safety distance. Obviously, the smaller the ΔV and reaction time, and higher the following vehicle brake capability, the shorter the required safe distance becomes. By fixing three of the six parameter values and assigning one of the remaining three as the varying parameter, families of parametric curves can be thereby plotted. Figure 3.2 through 3.4 are some of the sample plots where 1 sec represents a possible reaction time for a manual vehicle, whereas .1 and .01 sec represents possible delays for an automated vehicle. Note that the term delay, as opposed to reaction time, is used for automated vehicles. Both terms describe the total elapsed time from the instant of the beginning of the lead vehicle's deceleration to the instant that the engine or brakes of the following vehicle generates the responsive force. Typically it includes sensing delay, sensor data processing delay, control processing delay, and actuator response time delay. The safe distance is basically linearly proportional to the delay and it can be shortened, as the case shown in Figure 3.2, by approximately 20 meters once the vehicles

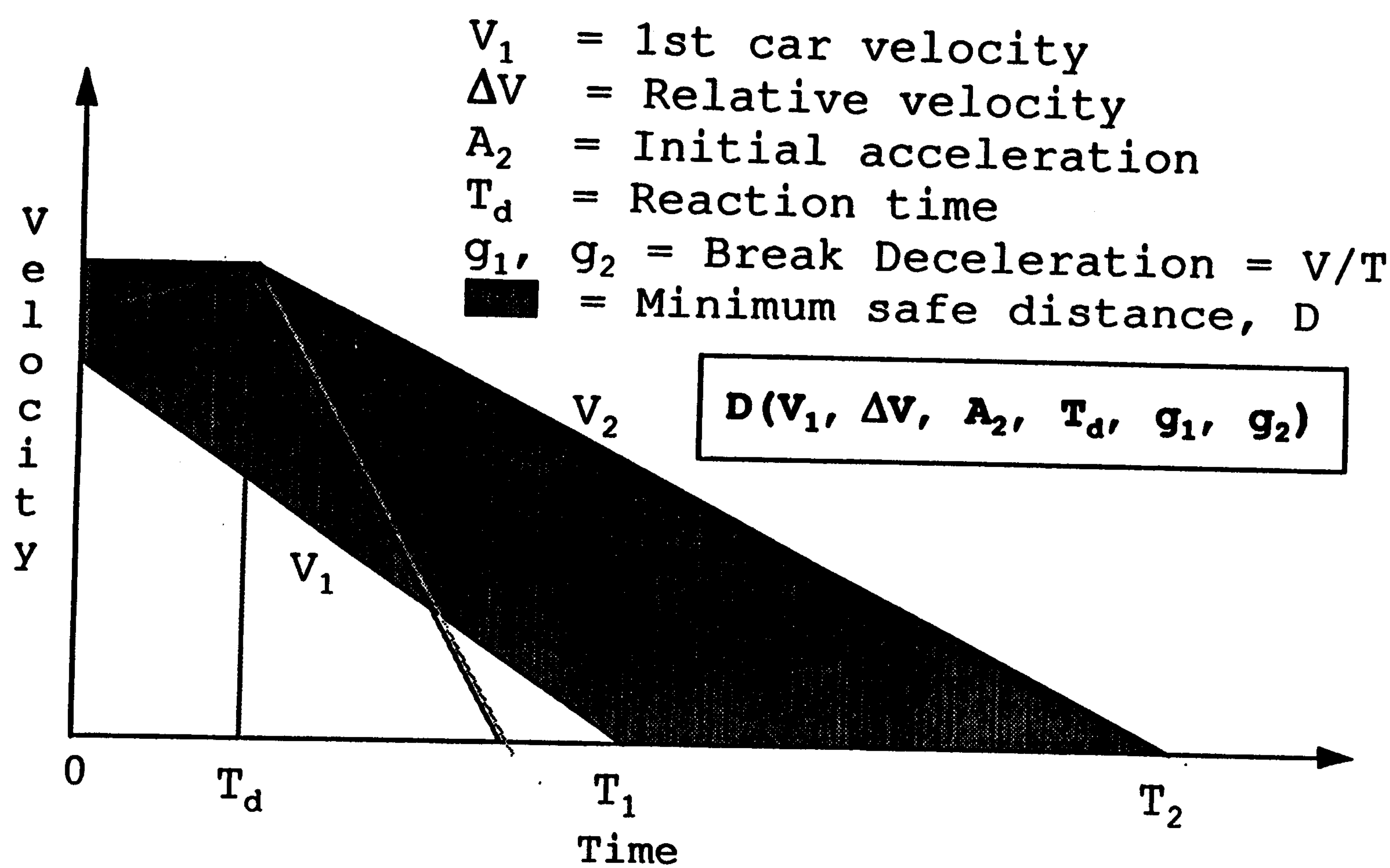


Figure 3.1. Safety Formulation

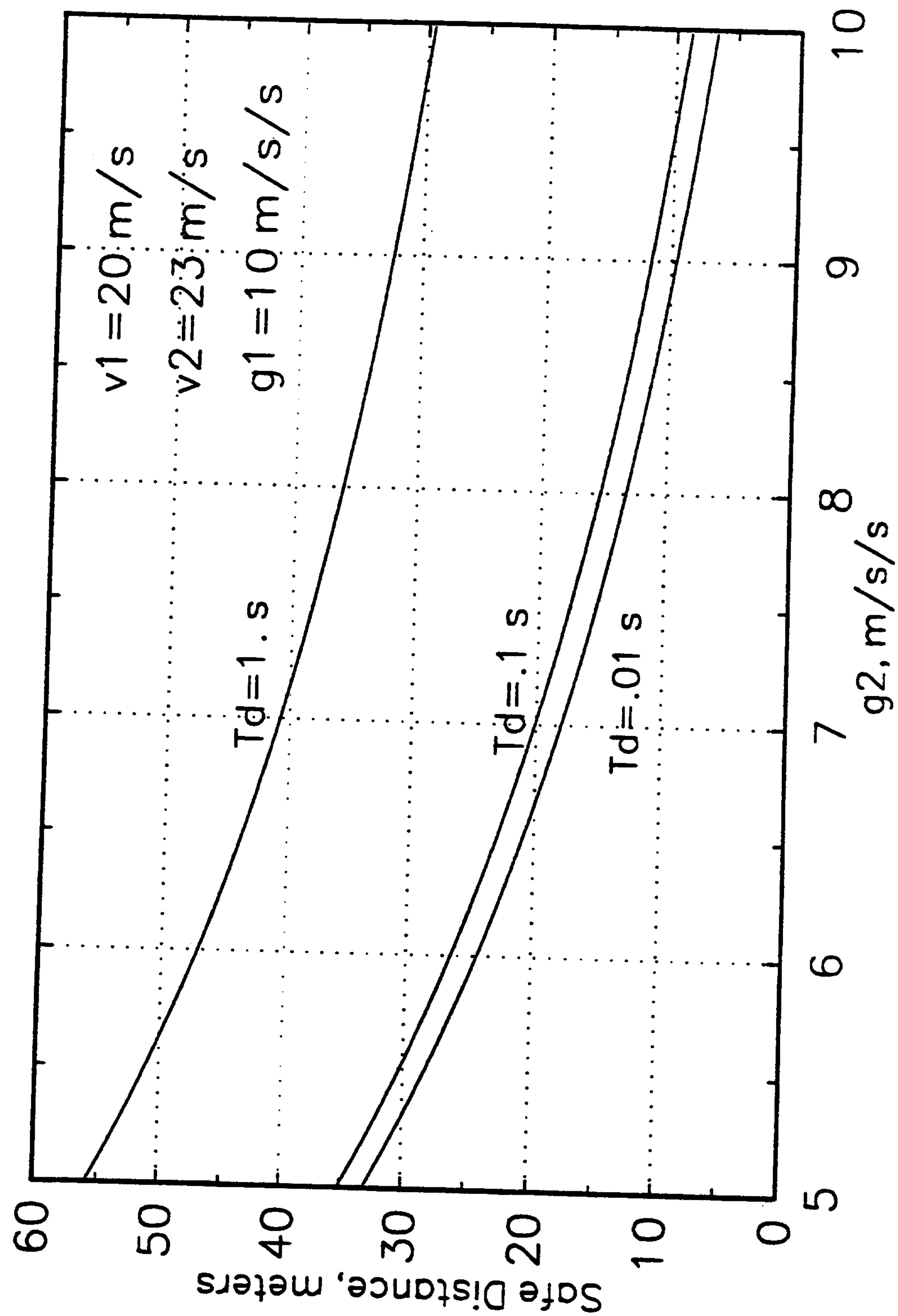


Figure 3.2. Safe Distance

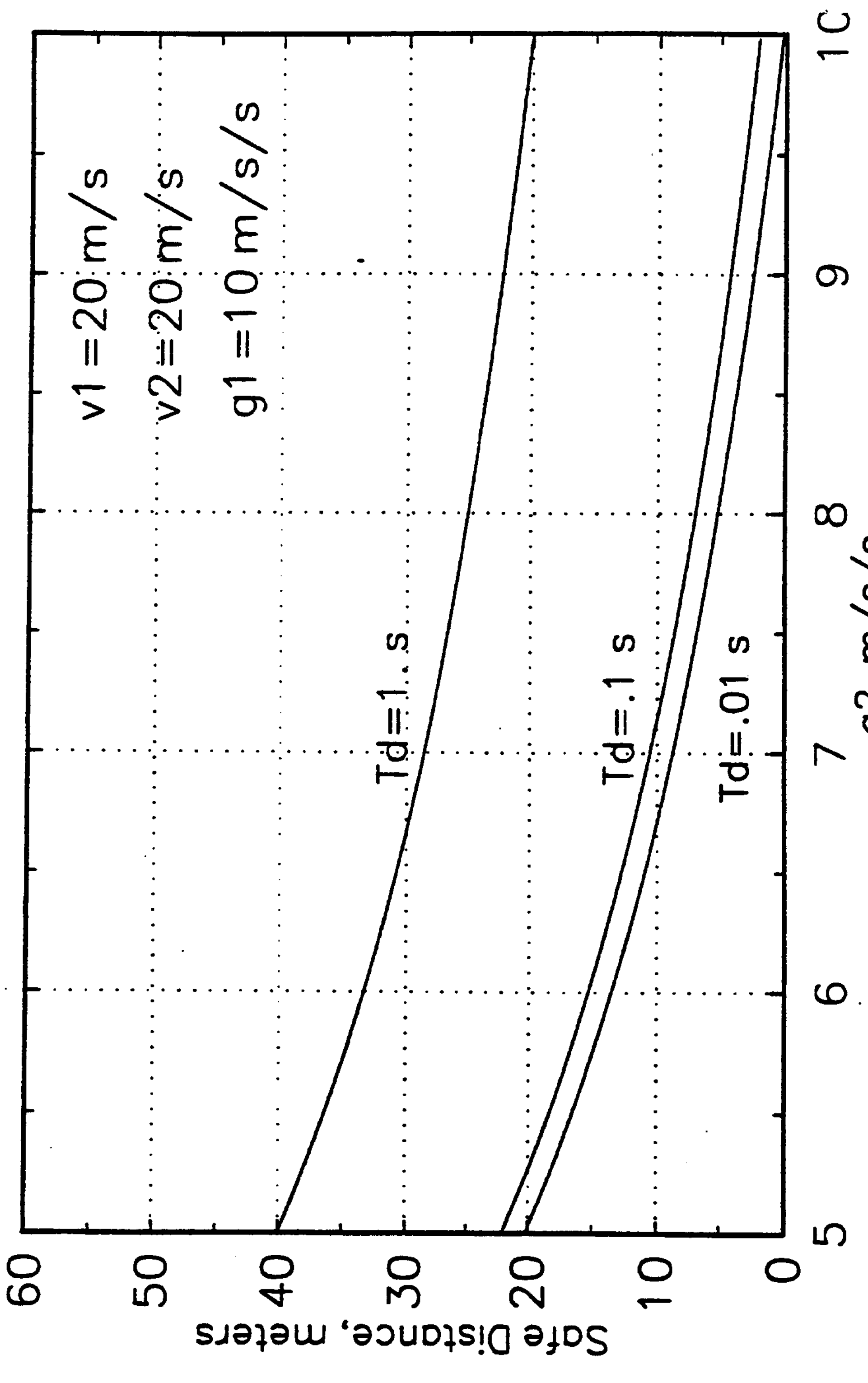


Figure 3.3. Safe Distance

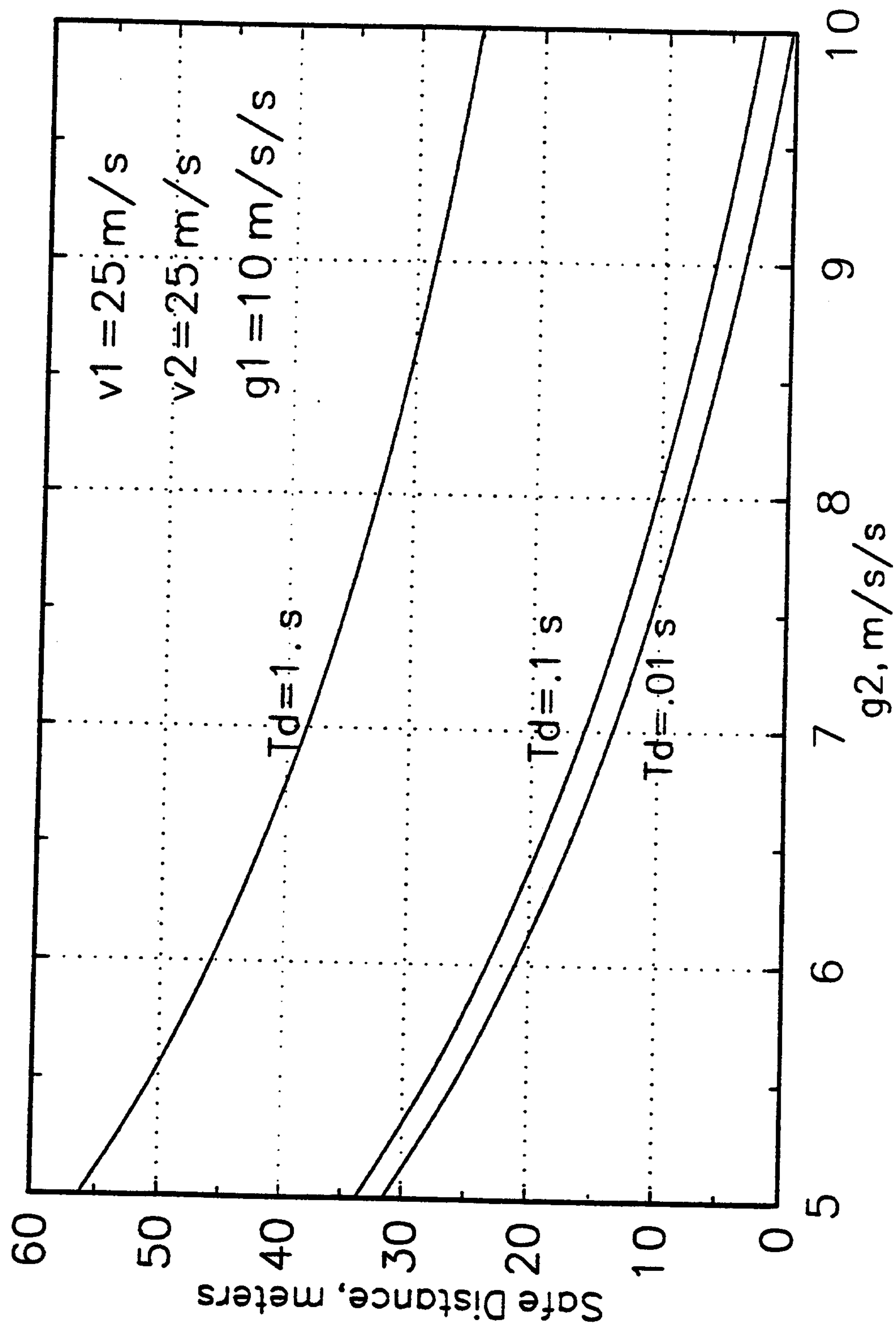


Figure 3.4. Safe Distance

are automated. Of course, the lane capacity will be increased accordingly. Using the theoretical equation

$$C = \frac{60*nv}{ns + (n-1)d + D}$$

where d is safe distance in meters, D is inter-platoon spacing in meters, s is vehicle length in meters, v is steady state speed in meters/second, and C the capacity in vehicles/lane/min., the relationship between capacity and gap can be calculated and is shown in Figure 3.5.

Another way to establish the safety criteria for AHS is based upon the maximum threshold impact energy that can be tolerated by both the vehicle and the driver. Figures 3.6 through 3.8 show the specific impact energy versus initial gap as functions of the six parameters. (As a point of interest, Figure 3.9 shows the relationship between impact velocity and gap.) The actual impact energy depends upon the vehicle mass. There are two crossing points on the energy curve with a low threshold. The initial gap at the far crossing point, on the right side of the hump, is the safe distance which is slightly shorter than the one that prevents body contacts as described in the previous paragraph. Since the gain of capacity is small, this safe distance is deemed as impractical. The other is the safe distance with the possibility of tolerable vehicle body contacts. The apparent advantage of this short safety criteria is that the lane capacity increases. In fact, this philosophy is the underlying rational for platooning. In this report we make a difference between vehicles operating at the long safety distance, without possibility of body contacts, and at the short safety distance, with possibility of tolerable body contacts, should the lead vehicle decelerate rapidly all of a sudden. The former is called headway maintenance, while the latter is called platooning. For headway maintenance the safety criteria is a minimum initial gap requirement, whereas for platooning, a maximum requirement. Therefore, if there is an error in gap measurement, for e.g. due to the inaccuracy of the sensor(s), the gap for headway maintenance needs to be set at the sum of the safe distance and the error, whereas for platooning it needs to be set at the difference. For example, at 25 m/s (approximately 55 mph) the gaps for headway maintenance and platooning are about 70 and 5 meters respectively. If the sensor uncertainty is 2 meters, than the gaps need to set at 70+2= 72 meters and 5-2= 3 meters respectively.

The safety formulation method described above assumes that safety only depends on the six parameters which are assumed to be well known, with certain accuracy, during the rapid deceleration period. In reality, however, there are many other factors that have not been considered, particularly those that affect the factual brake capability, e.g., road surface condition due to perhaps weather and tire condition. These uncertainty factors by no means make the above safety formulation method useless. If the parameter, brake capability in the analytical formula, is substituted with the effective brake capability (determined by other means) with all uncertainty factors considered, the resulting safe distance will still be useful. In fact this method can be used in real time if the effective brake capability can be somehow measured and verified.

Two subjects for future study (repeated in Section 3.5 Issues and Risks) can be brought up at this point:

1. Should safety be established based upon the worst case (e.g., brick wall stop vs. 0.8 g deceleration) or statistical considerations (e.g., under certain weather and tire conditions the

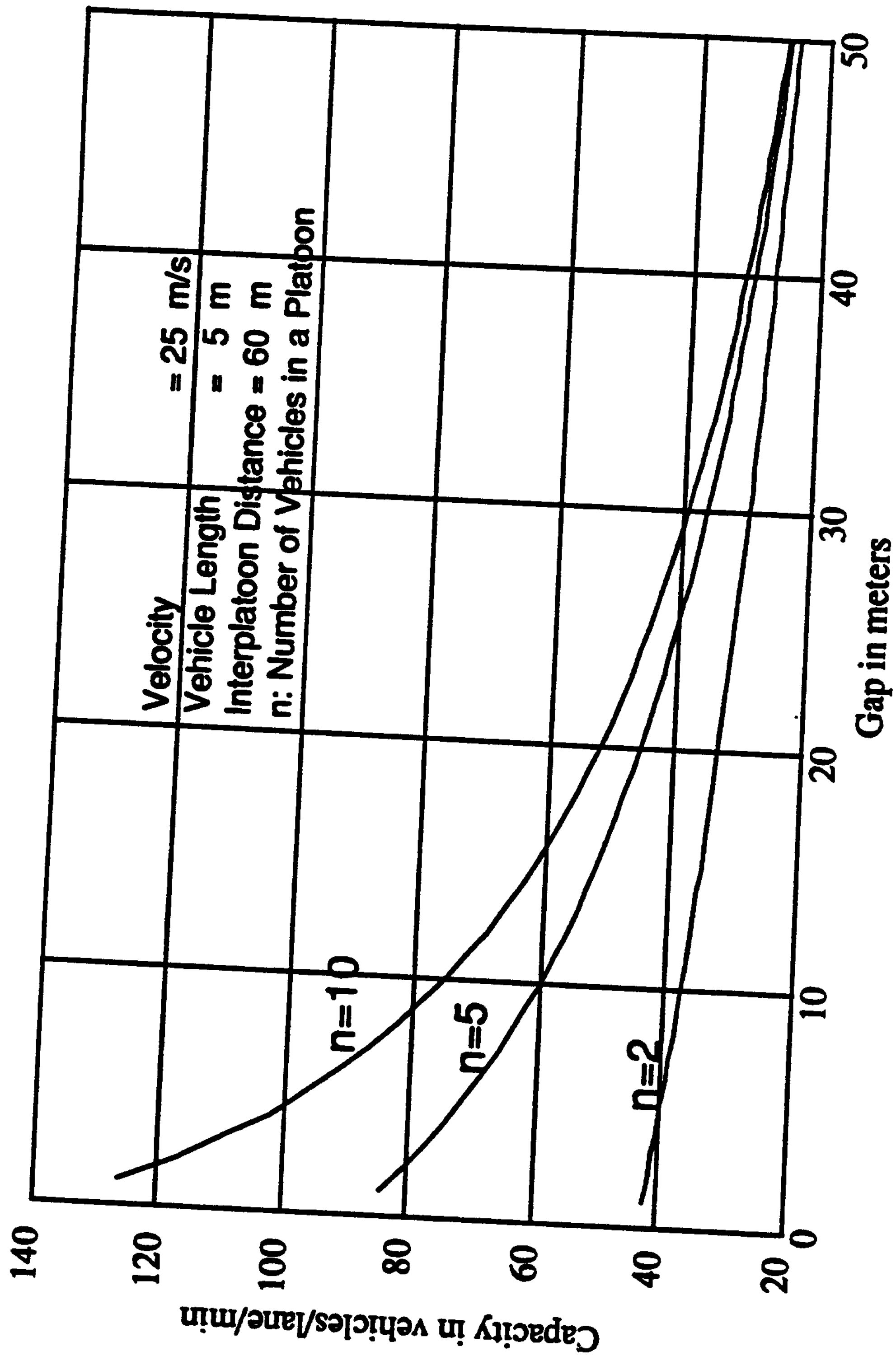


Figure 3.5. Capacity vs Gap

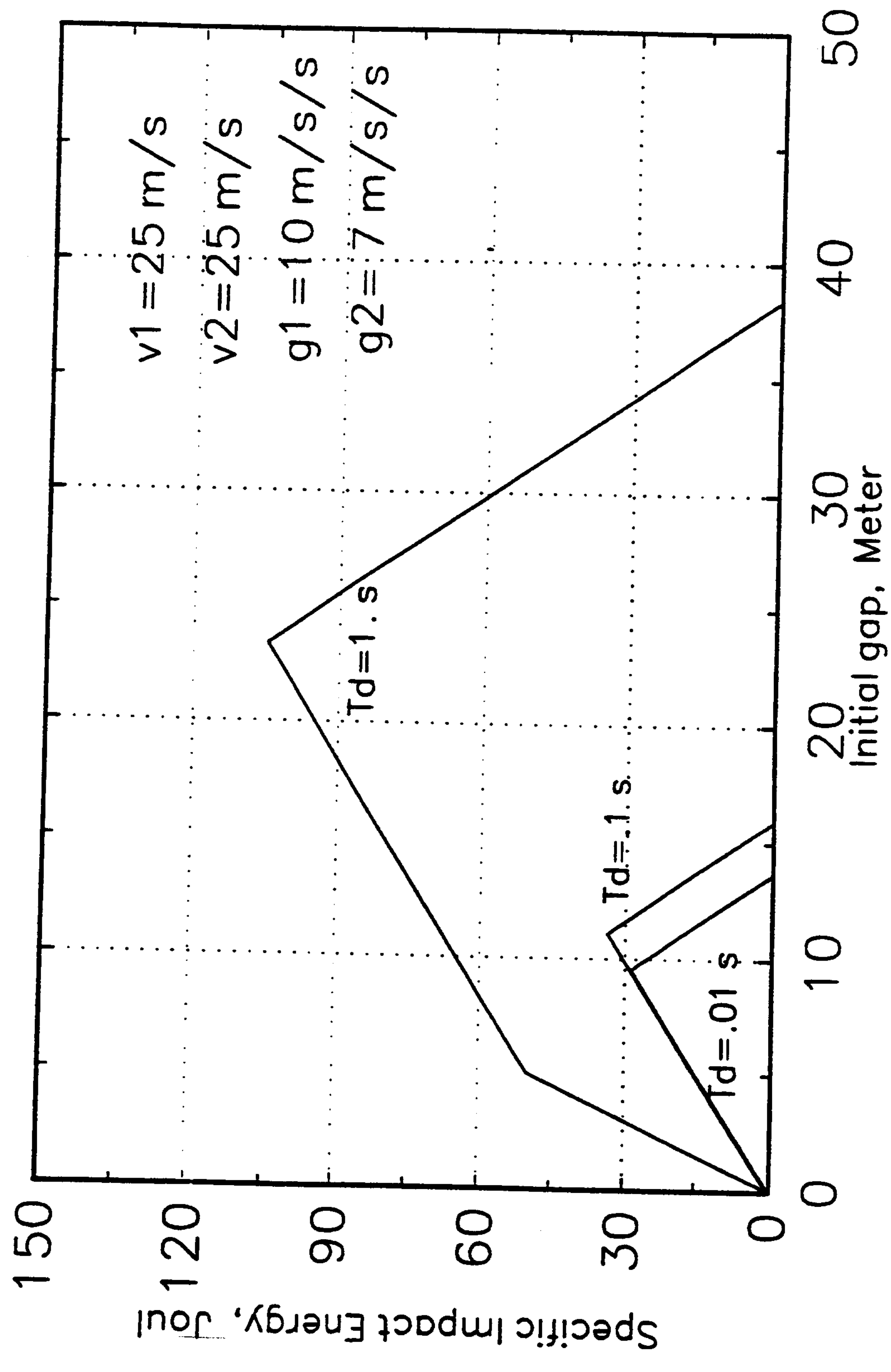


Figure 3.6. Impact Energy vs. Initial Gap

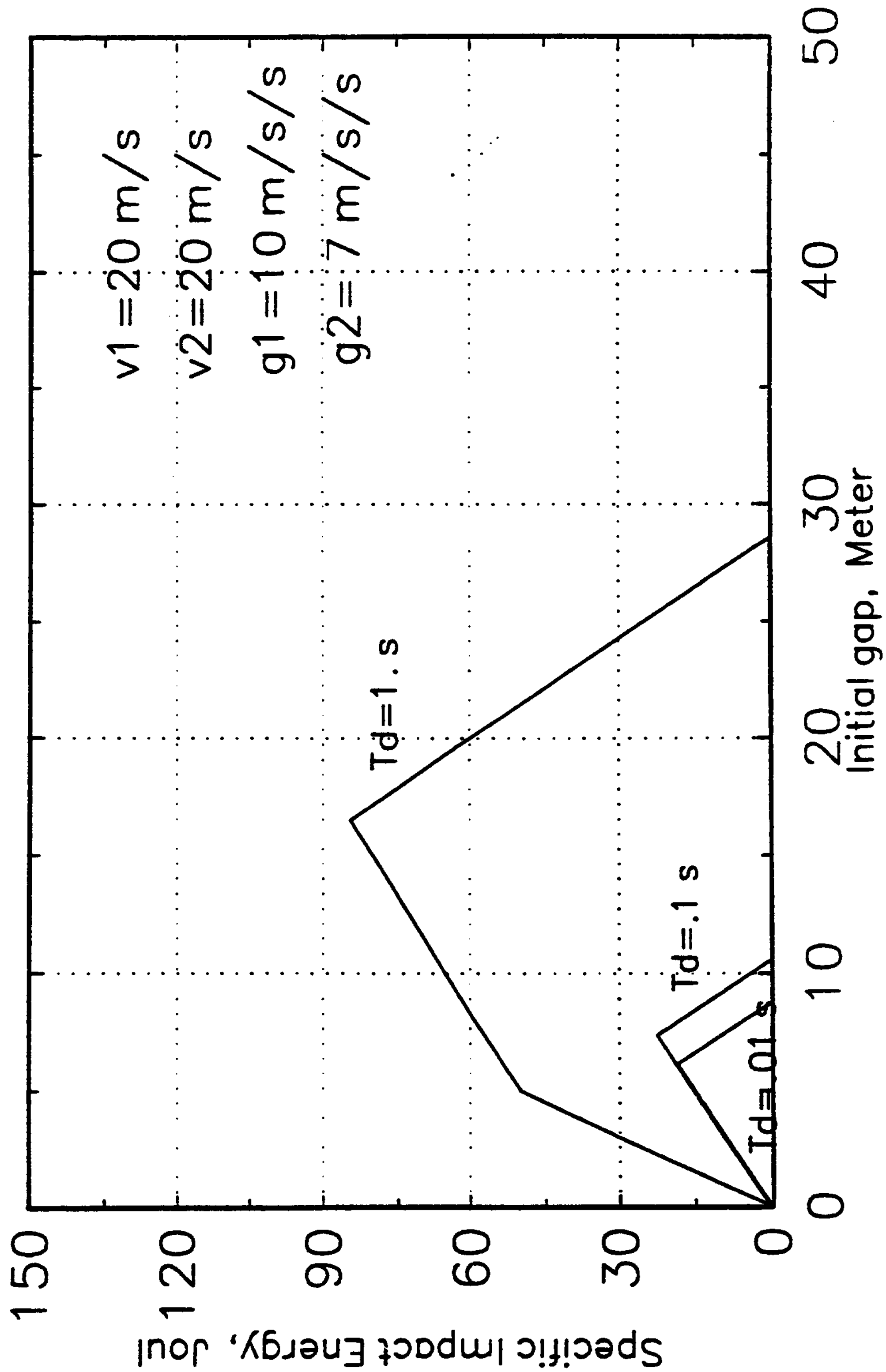


Figure 3.7. Impact Energy vs. Initial Gap

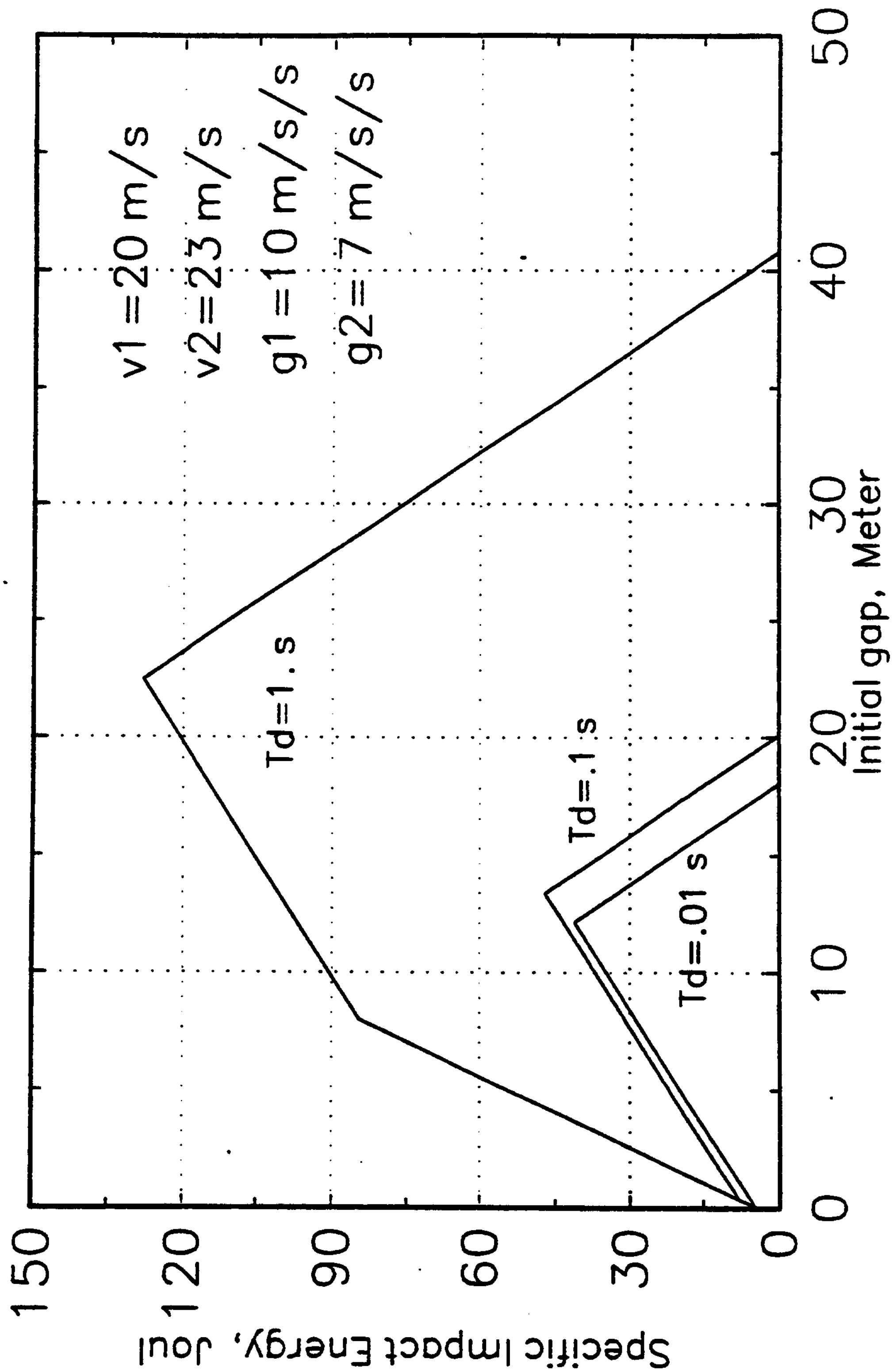


Figure 3.8. Impact Energy vs. Initial Gap

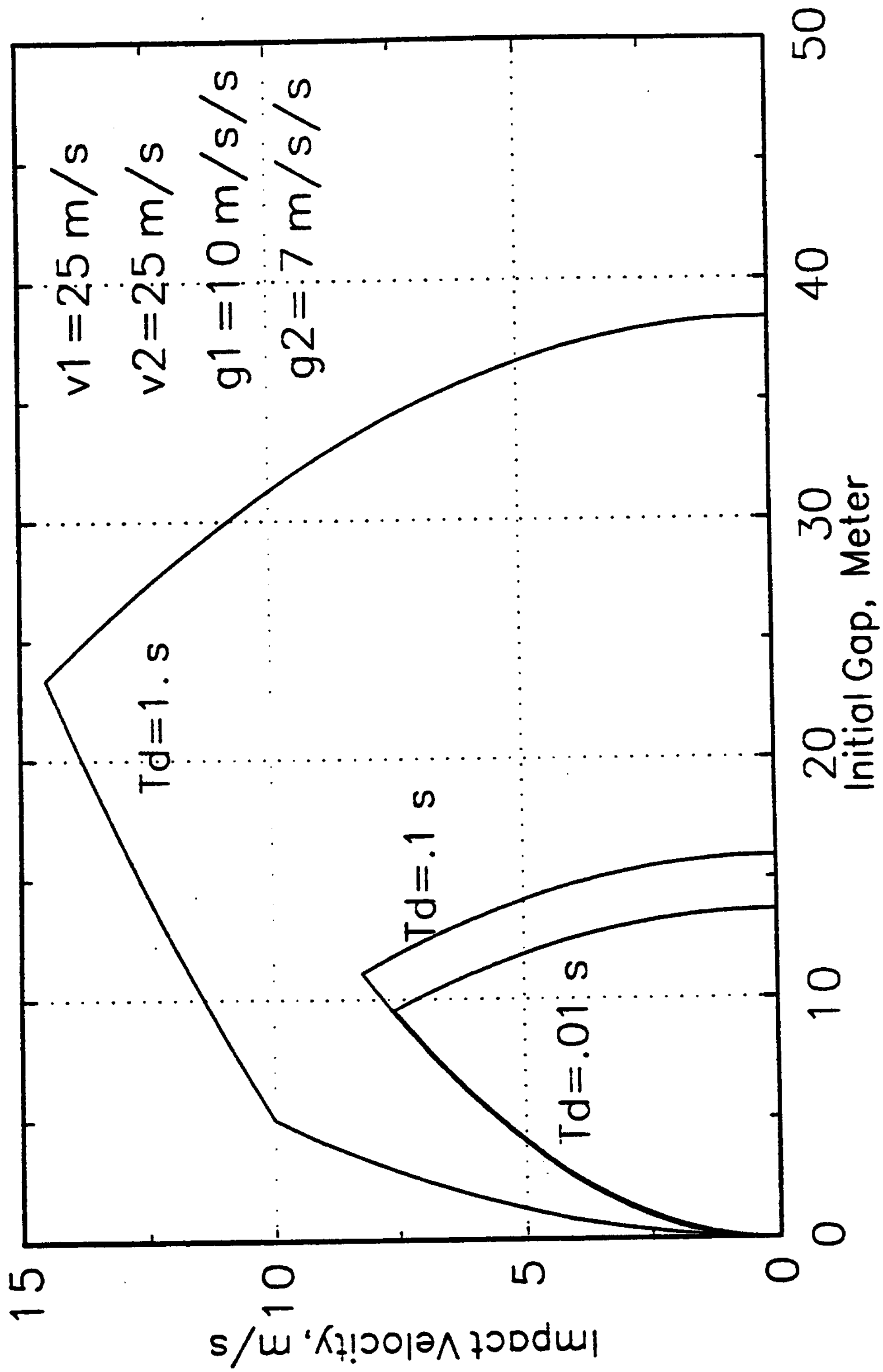


Figure 3.9. Impact Velocity vs. Initial Gap

effective brake capability is 1 g with a probability of .999) of each parameter, or a combination of the parameters?

Intuitively, if any one of the parameters can not be bound by a maximum or minimum value, then safe distance must be established statistically. Note that one of the parameters should be the probability of a sudden and rapid deceleration of a vehicle in an AHS environment. At this stage of the program, most of the parameters are unlikely to be analyzed with a reasonable level of confidence. They can however be best obtained by the scheduled 1997 AHS Dem/Val.

2. Can the safe distance between any two vehicles be preset realistically? If not, how do we establish the safe distance adaptively in real time for platooning?

   Due to the varieties of AHS qualified vehicles and the uncertainties of the effects of weather and tires, it does not seem to be realistic to preset safe distances. However, the idea of presetting should not be dismissed without careful trades against the alternatives. After all it is simple and does not require complex communications between vehicles.

3.3 Headway Maintenance Mechanism

As pointed out earlier, the focus of this study at this point of the program is to examine the effects of major lat/long parameters on AHS safety and capacity. To identify major control systems parameters and their effects on safety and capacity, a simple yet meaningful point mass vehicle model is used. To be exact, this model includes nonlinearities like acceleration, deceleration, and rate limits and small dead zones. A velocity limit, conceivably imposed by the AHS traffic management, is also incorporated. As a point of departure for comparative purposes, a set of control system data shown in Table 3.1, was used as a reference and the parameters perturbed so that the major influential parameters could be identified. Stochastically independent sensing is assumed in this model. For example, the target velocity derived by an imaging sensor by way of differentiating target image sizes at different frames is stochastically dependent on the target range; whereas the velocity sensed by a Doppler radar is independent of the range. This assumption does not affect the validity of the derived sensor requirements, it merely prohibits the model from reflecting the correlation among sensed signals for certain types of the sensors. After this process was carried out, plots from Figure 3.10 to Figure 3.19 were generated. and the following observations made:

1. To effectively maintain the headway, the control system requires sensing of the lead vehicle acceleration or its equivalent, the relative velocity, and the relative position. The sensing device can be either vehicle borne, as in a VWAM system configuration, or transmitted from the infrastructure, as in an IWSM system configuration. Either configuration should work as long as data accuracy and timing are within specification.

2. Based upon the reference system data, there are three major parameters that affect the gap variation while vehicles are operating in the headway maintenance mode: the lead vehicle motion profile (e.g., acceleration or velocity), the sensor noise, and data latency. In general smaller gaps restrict the lead vehicle motion more and demand more accurate sensors, and higher control system bandwidth allow shorter gaps but makes the headway maintenance more susceptible to noise. In other words, with maximum lead vehicle

mobility, capacity can only be increased by high performance sensing, control and communication systems.

Table 3.1 Reference Headway Maintenance Parameters

1. Vehicle Parameters

1.1 Initial States

	5m-Platoon	20m-Platoon	
Lead vehicle position	0.	0.	m
Lead vehicle velocity	25.	25.	m/s
Following vehicle position	-20.	-100.	m
Following vehicle velocity	-25.	25.	m/s

1.2 Vehicle Characteristics

Maximum acceleration	3	m/s/s
Maximum braking	-10	m/s/s
Maximum throttle/brake rate	.2	g/s

2. Environment

Lead vehicle acceleration profile	+/-Sin(0.1*t) + N(0, 0.2)	m/s/s
Velocity limit	0-35	m/s

3. Sensor Performance

Frame rate	100	Hz	
Range for 5m-platoon	20	m	
Range for 20m Hdwy Maint	100	m	
Relative position accuracy	1	m	(1 SD)
Relative velocity accuracy	2	m/s	(1 SD)
Acceleration accuracy	1	m/s/s	(1 SD)

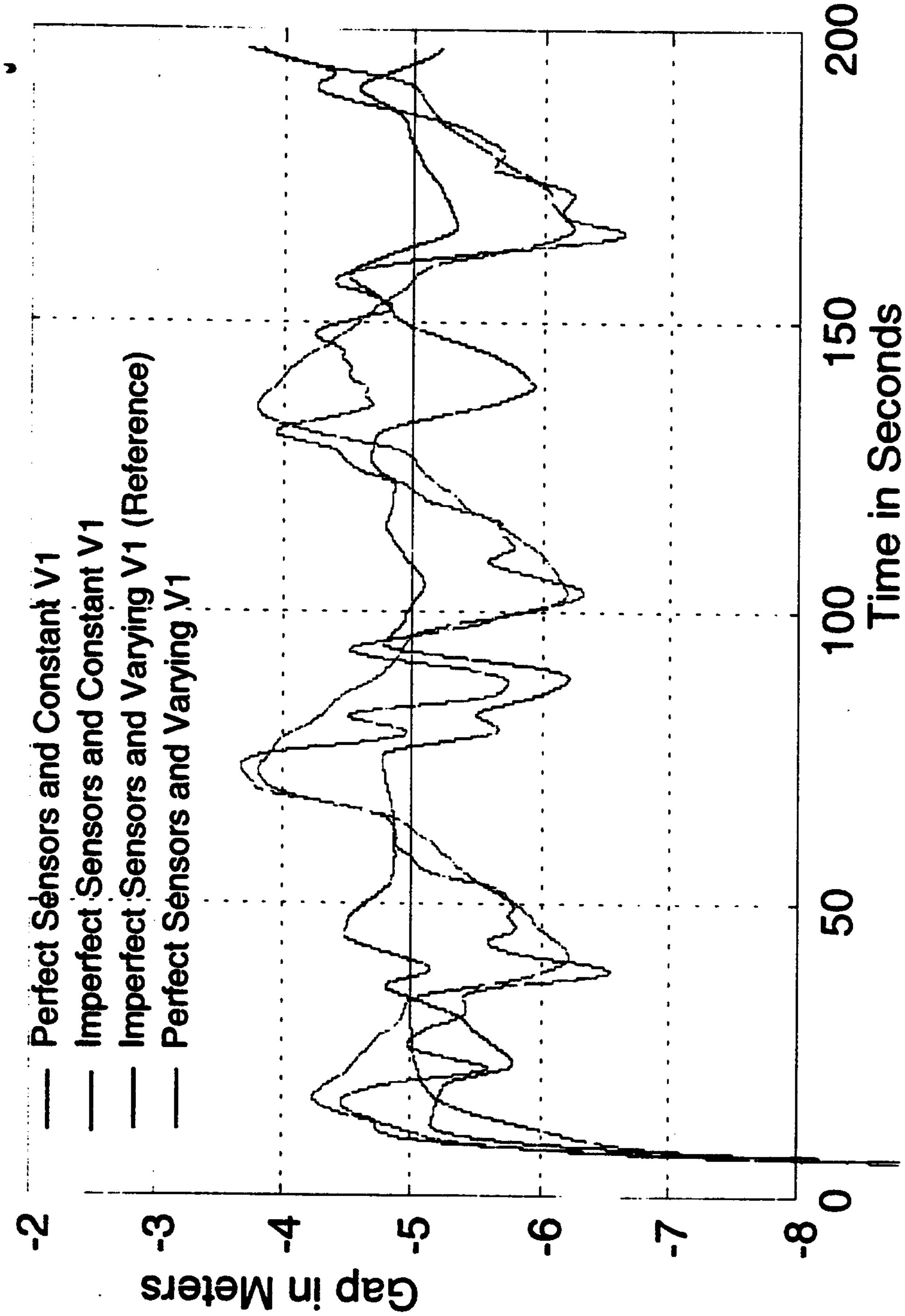


Figure 3.10. 5m Platoon

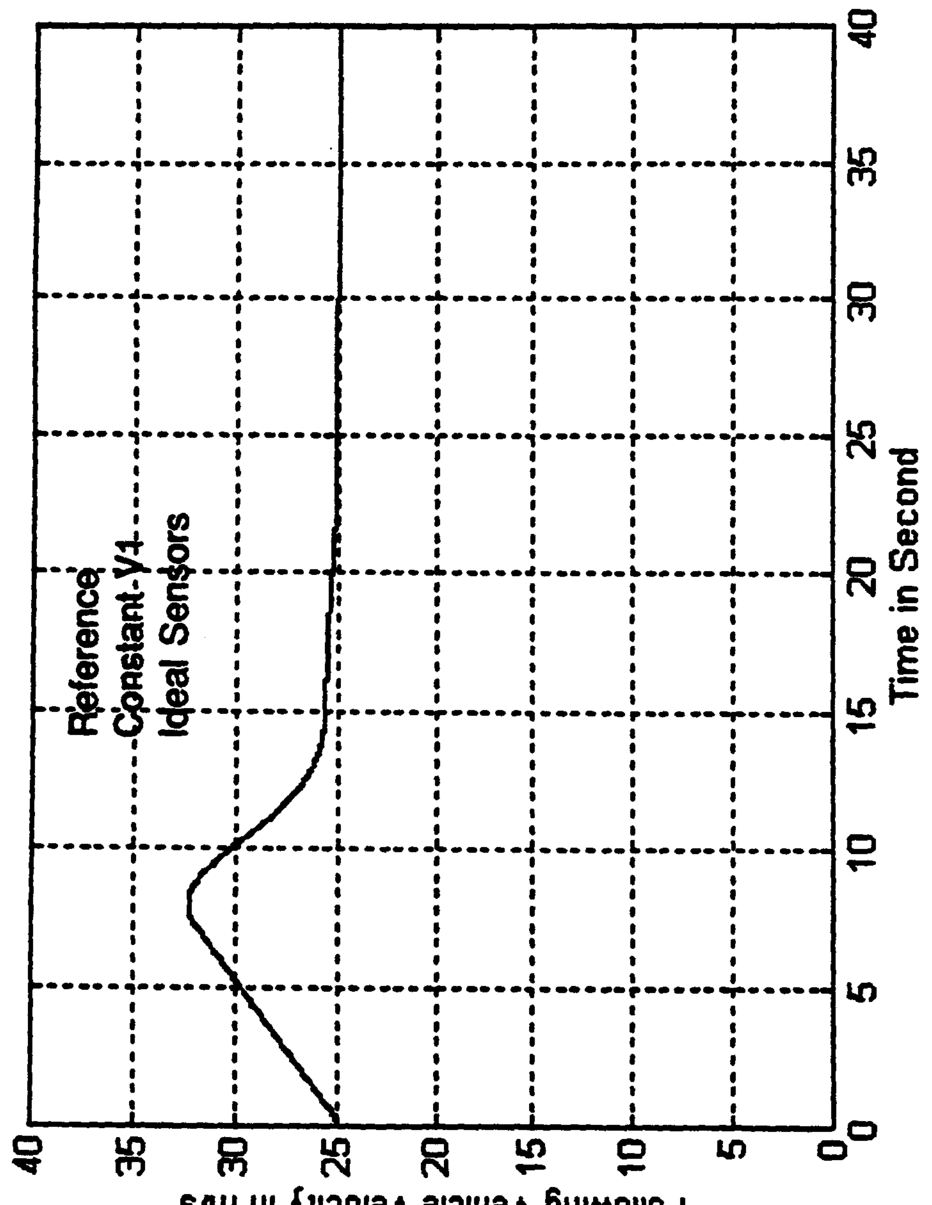


Figure 3.11. 5m Platoon Approach Velocity Profile

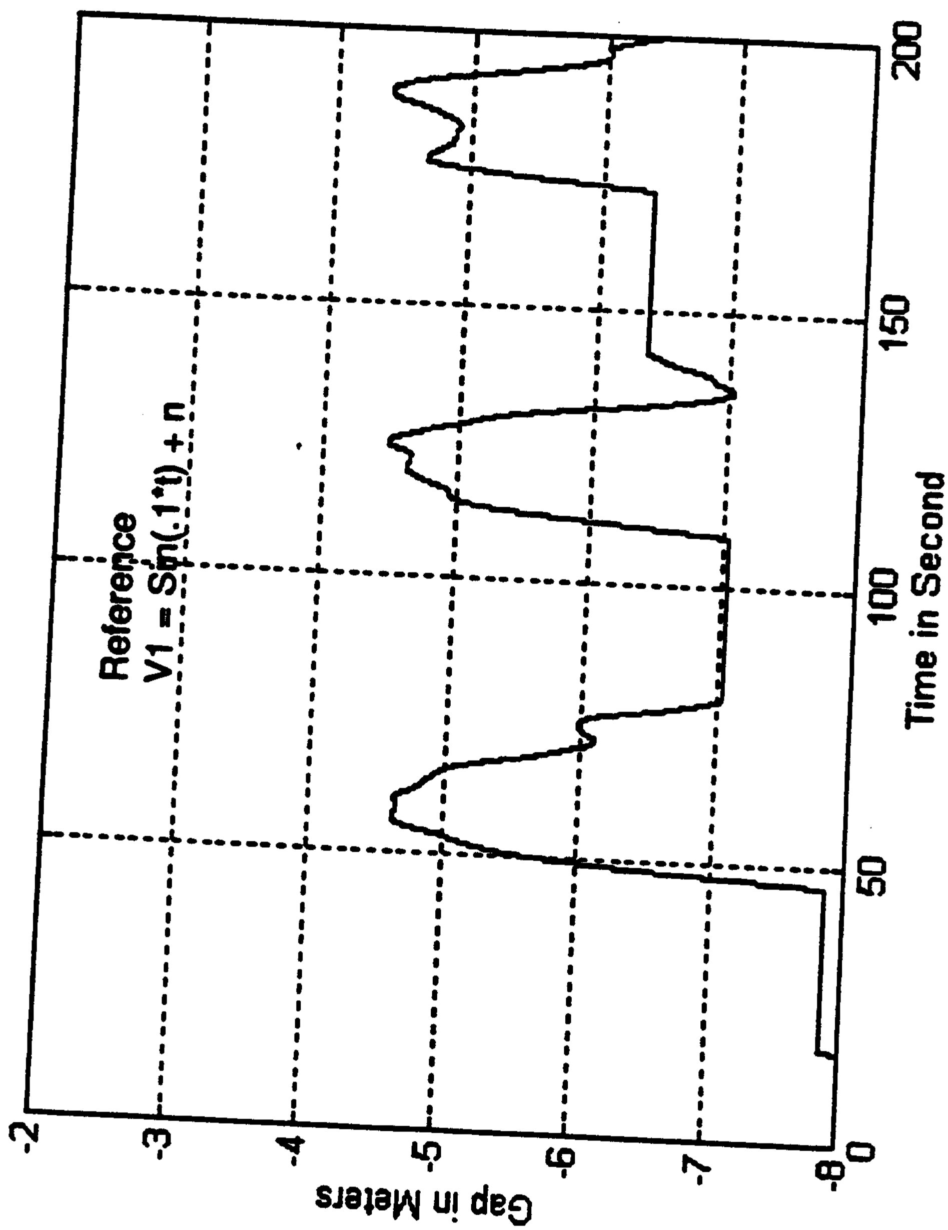


Figure 3.12. 5m Platoon

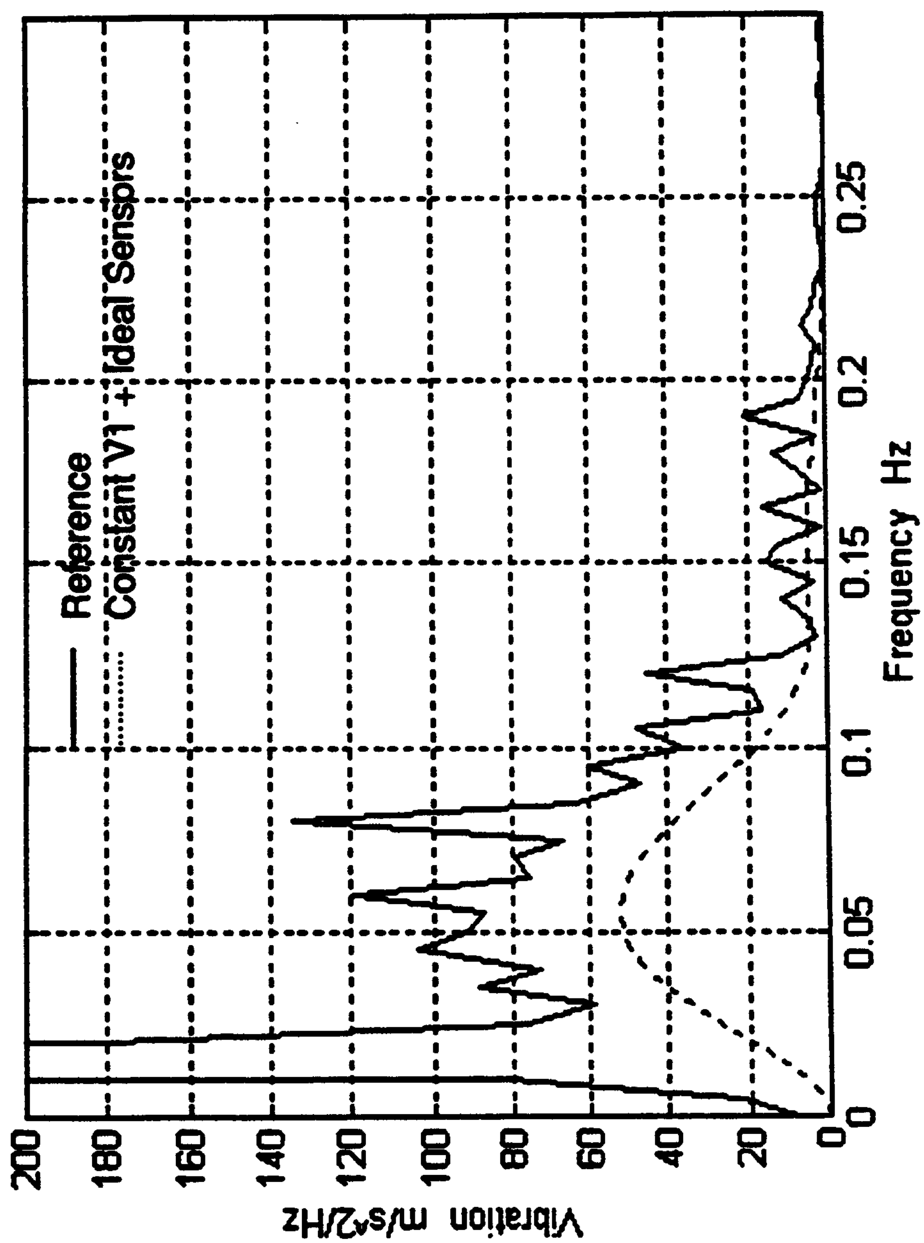


Figure 3.13. Ride Comfort of 5m Platoon

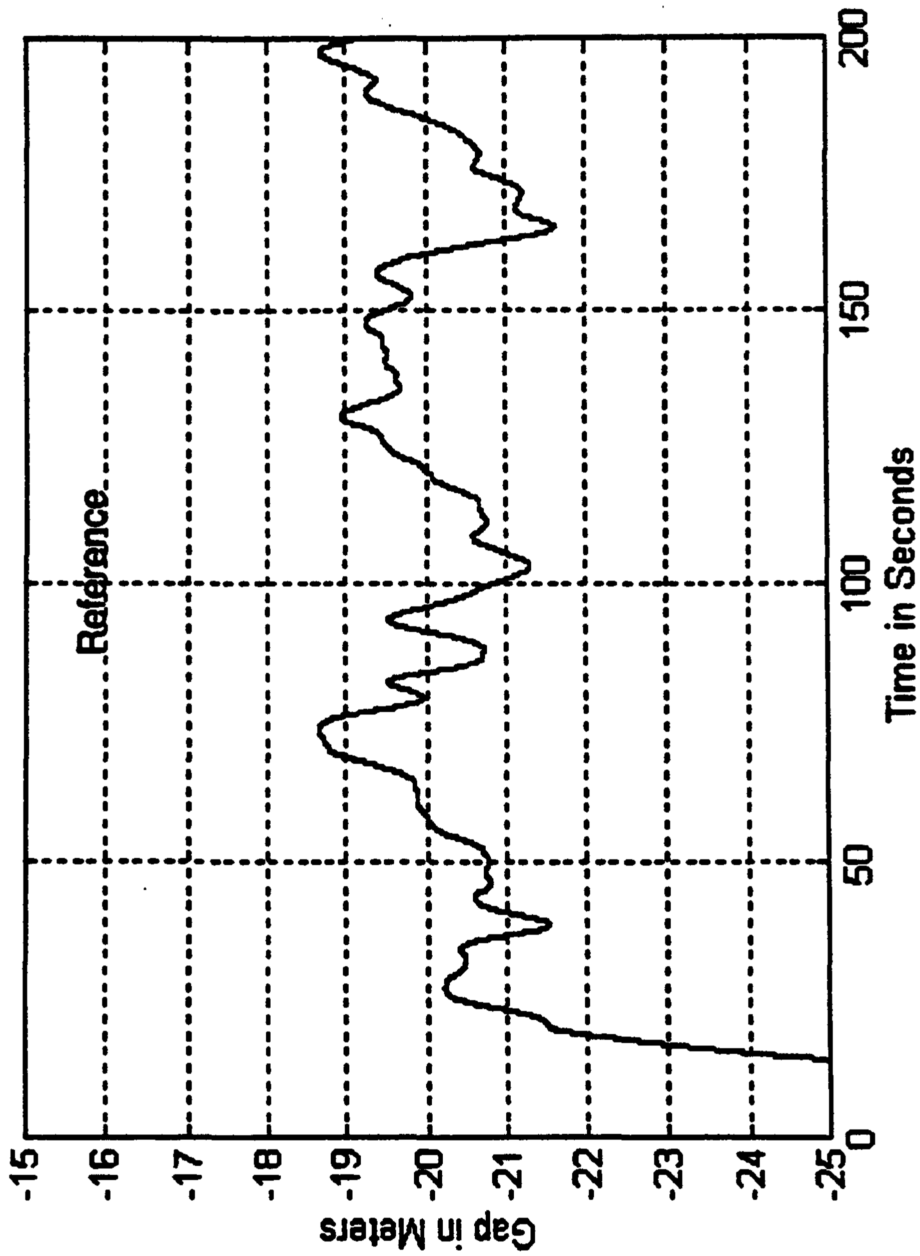


Figure 3.14. 20m Headway Maintenance

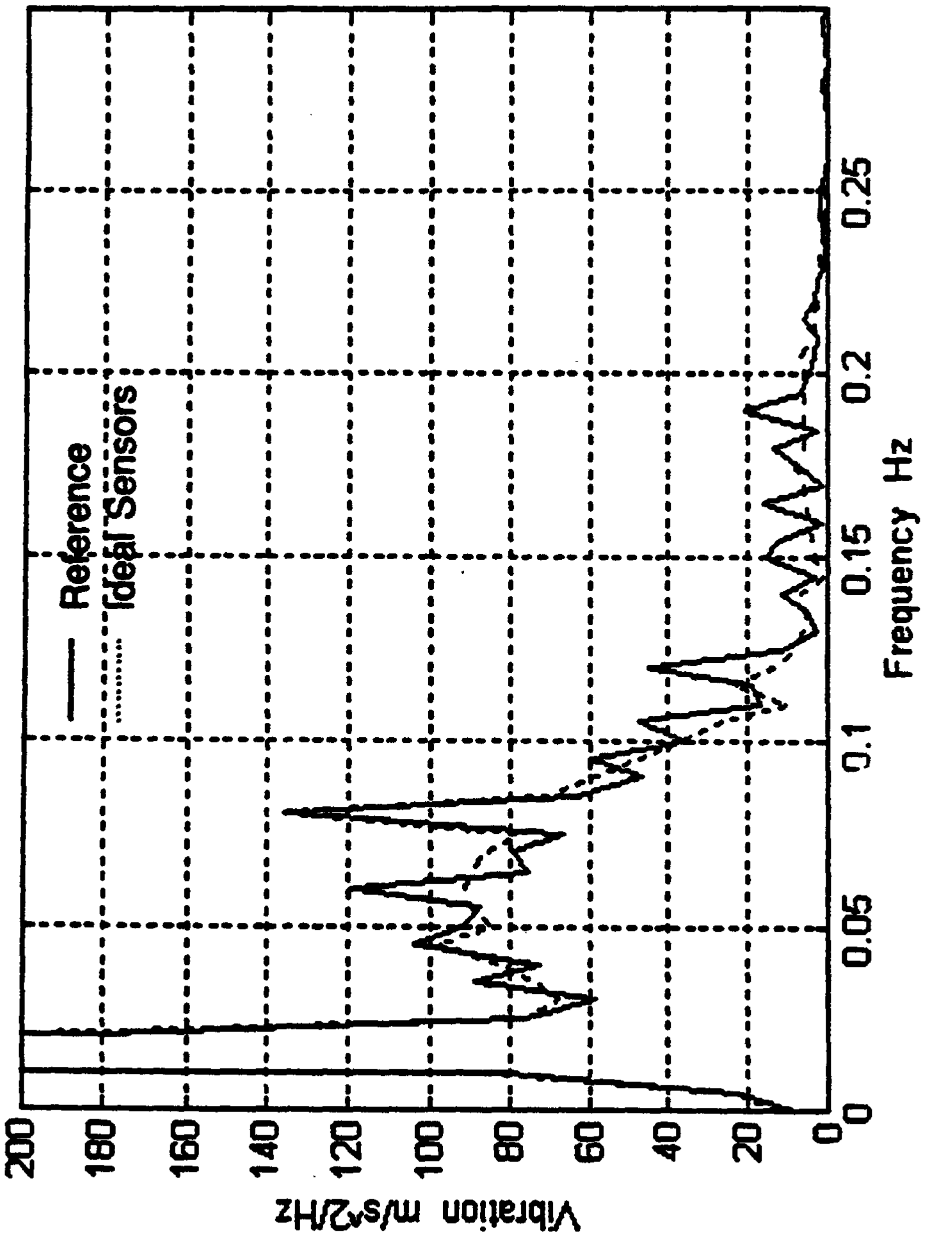


Figure 3.15. Ride Comfort of 5m Platoon

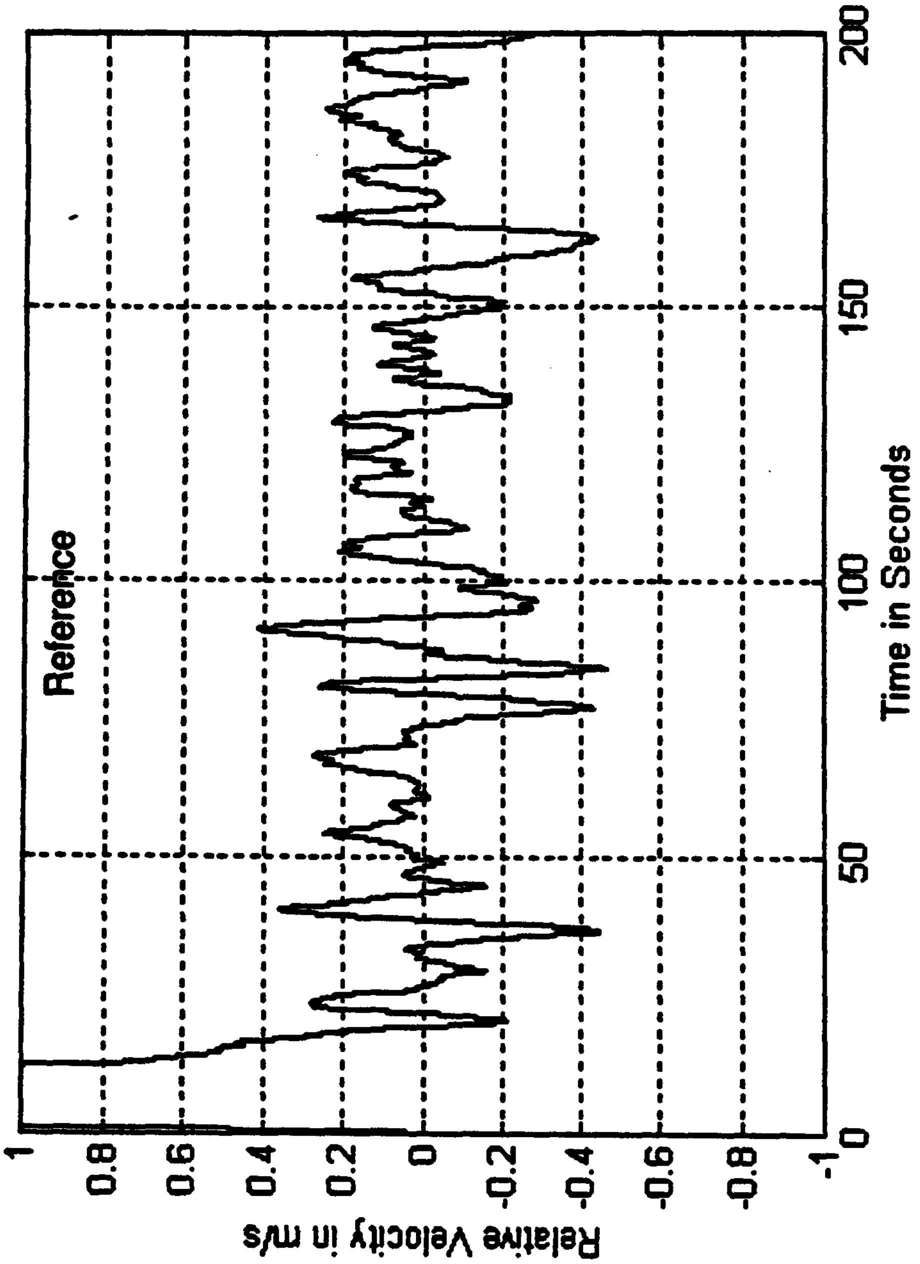


Figure 3.16. 5m Platoon

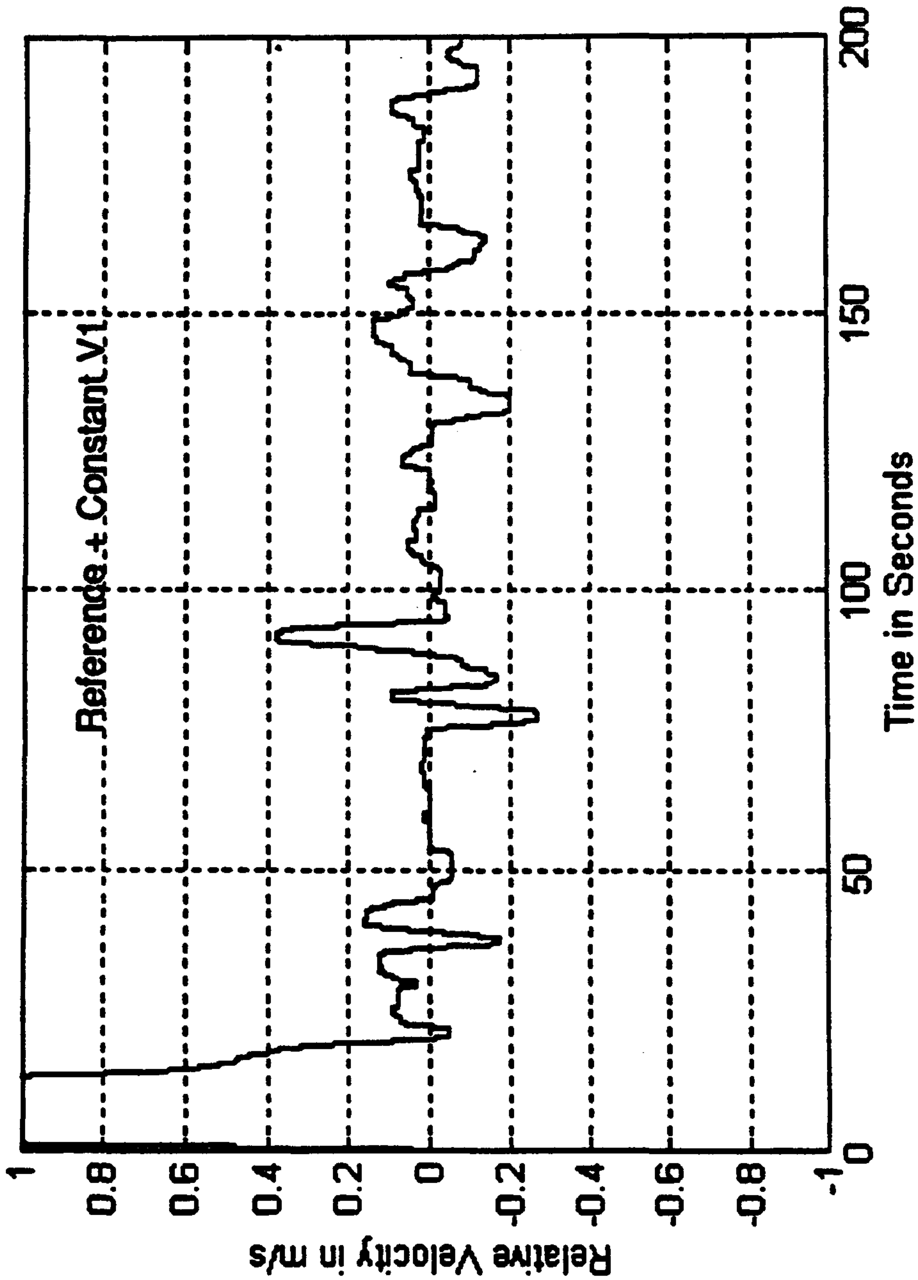


Figure 3.17. 5m Platoon

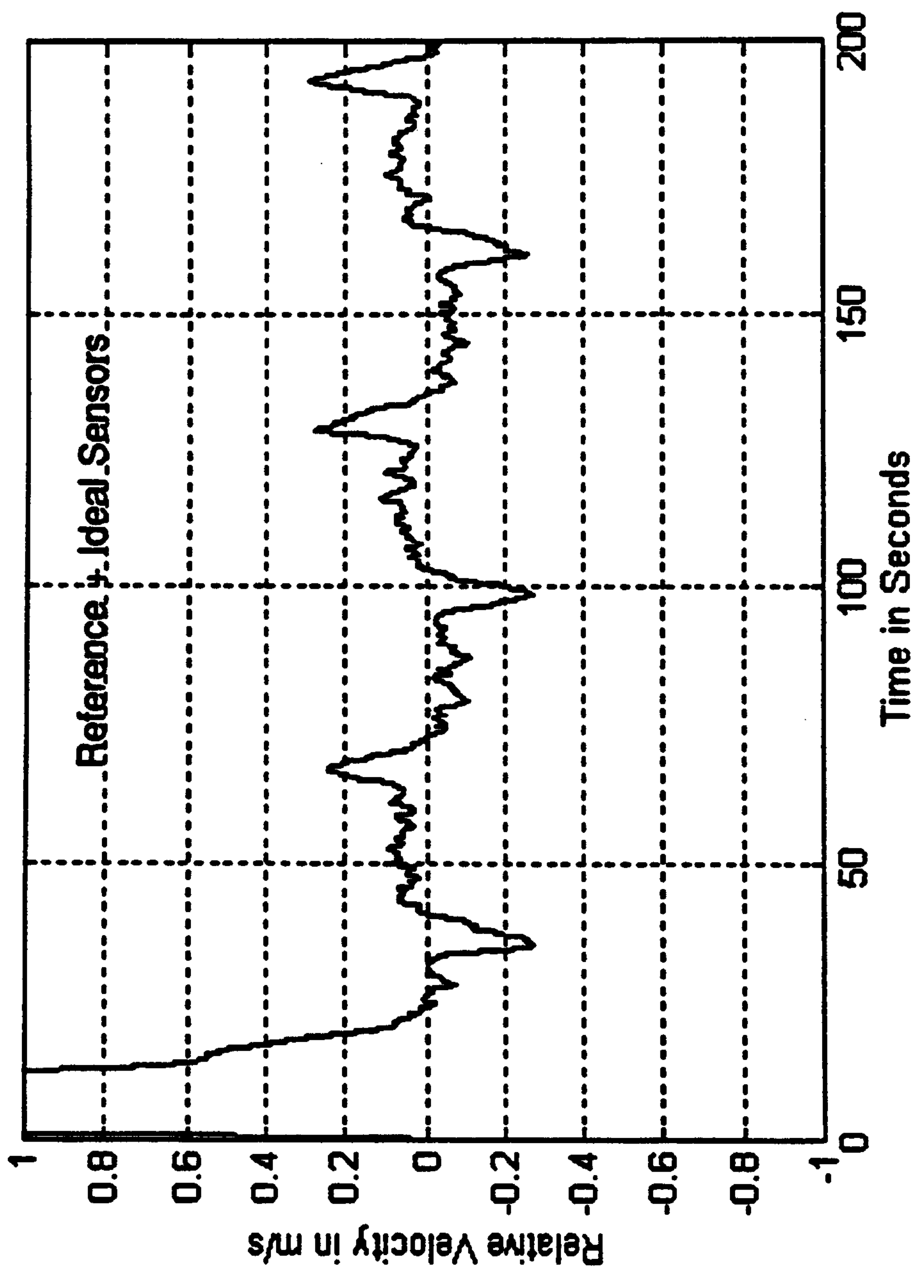


Figure 3.18. 5m Platoon

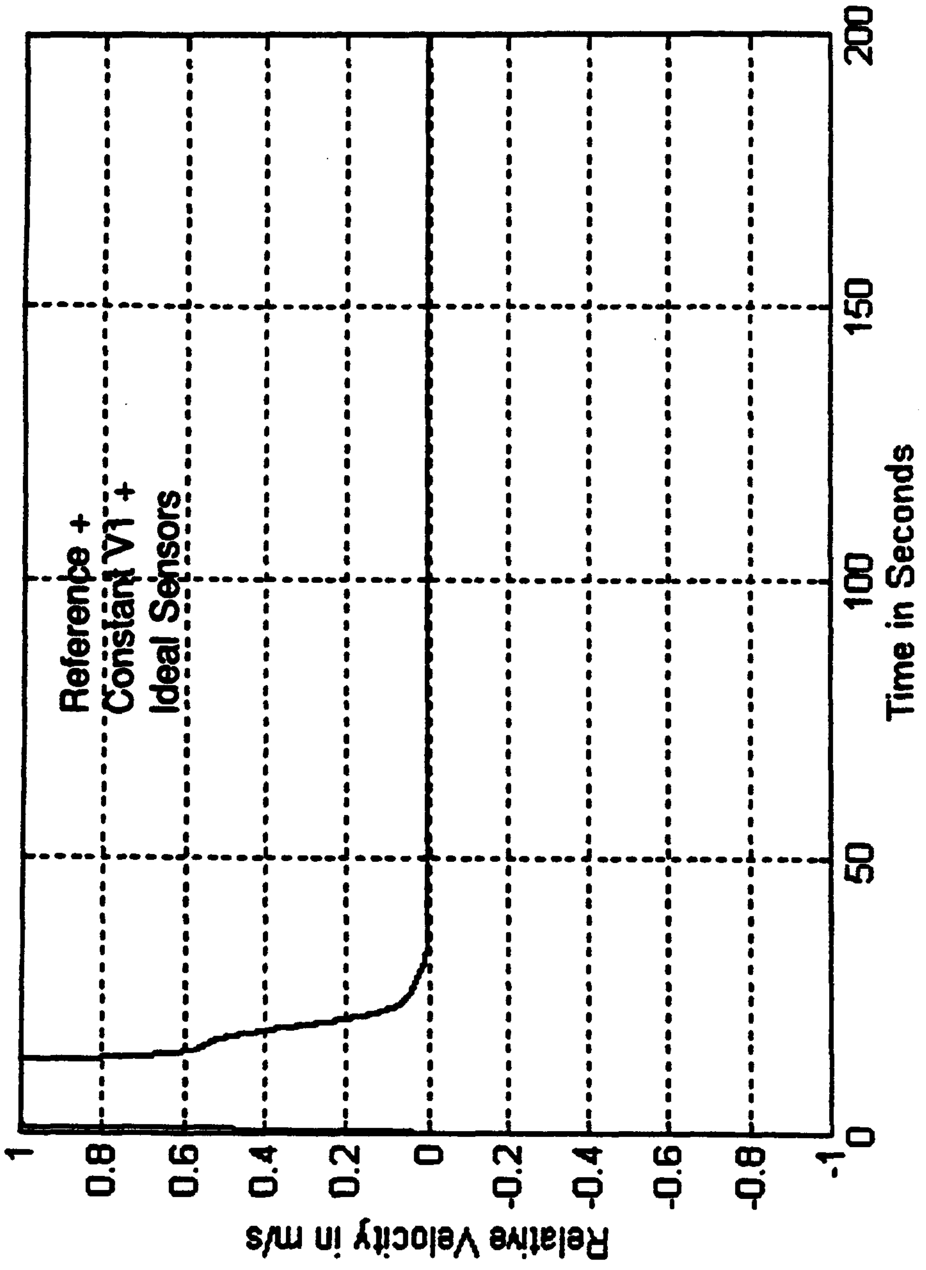


Figure 3.19. 5m Platoon

3. Sensor noise appears to be a significant source of ride discomfort. Of course we are referring to the vehicle longitudinal axis only.

4. Accurate sensors reduce relative velocity variation, thus allowing for smaller gaps.

5. Fast control cycle and sensor frame rates smooth the effects of sensor noise on gap control performance.

6. Vehicles capable of platooning may not be capable of headway maintenance, and vice versa, due to the disparity of sensor requirements, typically the range and accuracy requirements.

As a result of the headway maintenance analysis, the following issues and future study subjects pertaining to control system design requirements are raised:

1. What are the ride comfort requirements?

2. What are the minimum bandwidth of headway maintenance control systems?

3. What is the maximum tolerable gap variation? Is it statistically based?

4. What is the maximum tolerable impact energy for each class of vehicles?

3.4 Analysis of the Impact of Rear-End Accident Rate

Numerous sources of highway traffic safety data have been generated by various institutions. The data that was found to be of relevance to AHS safety assessment is interlaced with other general facts and figures. Many of the nationwide sources use sampling techniques and statistical analyses to arrive at the numerical figures provided. As such there are margins of uncertainty or variability in the figures from a number of sources. The numerical data varies depending on: the source, the area of the country (versus the whole country), the collection techniques, assumptions of the police reports, the categorizations made by the data analyst, the data excluded intentionally, and other factors. There are also estimates of unreported light impact incidents and accidents which may account for 20% to 50% of all accidents. These estimates would increase the numbers and percentages of the "property damage only" category, which is already the largest accident category.

A rear-end collision is defined as "a collision of the front of one vehicle with the rear of another." According to General Estimates System (GES) 1990, this type of accident is the second most common, making up approximately 35% of all accidents and 25% of severe/fatal accidents. Forty percent of the minor to moderate accidents are a result of rear-end collisions and 34% of the property damage. The categorization of rear-end impacts in this data requires that the two vehicles be nearly in line such that the rear car is the striking vehicle. In GES 1990, there may have been circumstances where an "angle collision" might have been considered as a rear-end collision, but because of a slightly larger angle at impact the statistic might have been grouped into the angle collision category, rather than the rear-end category.

Base upon a study by Rockwell in 1992, the rear-end accident rate would be reduced by 79.9%, 79.0%, and 60.0% respectively in the (1) property damage only, (2) minor to moderate, and (3) severe to fatal categories. The overall reduction is about 79%.

3.5 Conclusion, Issues and Risks

Issues and risks identified in this section are summarized below. Note that issues and risks are not necessarily concerns of the feasibility of the idea of AHS as the remedy for the next century's transportation problems but they are simply some technical subjects that ought to be thoroughly investigated in the future.

1. Safety distance between two vehicles depends upon many deterministic as well as random factors, e.g., velocity, road surface condition, tires, and weather. Should the safety distance be established upon the worst scenario (e.g., brick wall stop) or on a probability basis?

2. Can the safety distance between vehicles be preset realistically? If not, how do we establish it adaptively in real time?

3. To standardize longitudinal control systems of automated vehicles, the following requirements need to be defined: ride comfort, the mobility of vehicles in an AHS, the nominal gap, the maximum tolerable gap variation, the maximum tolerable impact energy for platooning.

4. LANE CHANGE MANEUVER

4.1 Objectives

The objectives of this section are to (1) identify major parameters of a lane change maneuver, (2) perform parametric analysis on lane entry and exit for both Direct-Entry (DE) and Barrier+Transition (BT) mechanizations, (3) perform parametric analysis on roadway entry and exit, (4) perform a top level examination of lane keeping maneuver, and (5) identify issues and risks.

4.2 Parameters of Lane Changing Maneuver

To understand the lane change maneuver (LCM) and identify its major parameters in an AHS, a simple point of departure lane change scenario, shown in Figure 4-1, has been developed as the basis for the analysis. Though it is simple, it serves the purpose well for identifying the major parameters and issues and risks. Because of the generality of this scenario, it may evolve into a more sophisticated lane change maneuver algorithm in the future. In this section, this scenario will be described as the Vehicle Weighted Autonomous Mechanization (VWAM) RSC. The same description is also applicable for the Infrastructure Weighted Synchronous Mechanization (IWSM) by shifting the intelligence from the vehicle to the infrastructure. This scenario should not be construed as Rockwell's position of the final LCM in any AHS RSC, since detailed trade off analyses is required.

An LCM can occur either from left to right (fast to slow) or from right to left (slow to fast). For illustration purposes, let us assume that the automated highway is configured as shown in Figure 4-2(a) prior to the maneuver in a UE (Unrestricted Entry) mechanization, where the vehicle wishing to make a lane change from left to right is named as the subject vehicle and is marked as C1s. This lane change scenario is briefly described as follows:

(1) Once the subject vehicle, C1s, has determined the need for a lane change, it first broadcasts a Lane Change Maneuver request along with time and/or distance constraints, if necessary.

(2) There are three possible responses to this request from its neighboring vehicles, if any:

[1] no response - This could mean either that there are no neighboring vehicle(s) or that the communication system is malfunctioning.. Whether to proceed the lane change or not is an issue in this case.

[2] negative response - Neighboring vehicles are unable to accommodate the request at this time. The subject vehicle needs to go back to step (1) and try later.

[3] positive response - Neighboring vehicles are able to accommodate the request at this time. Subject vehicle proceed the maneuver to the next step.

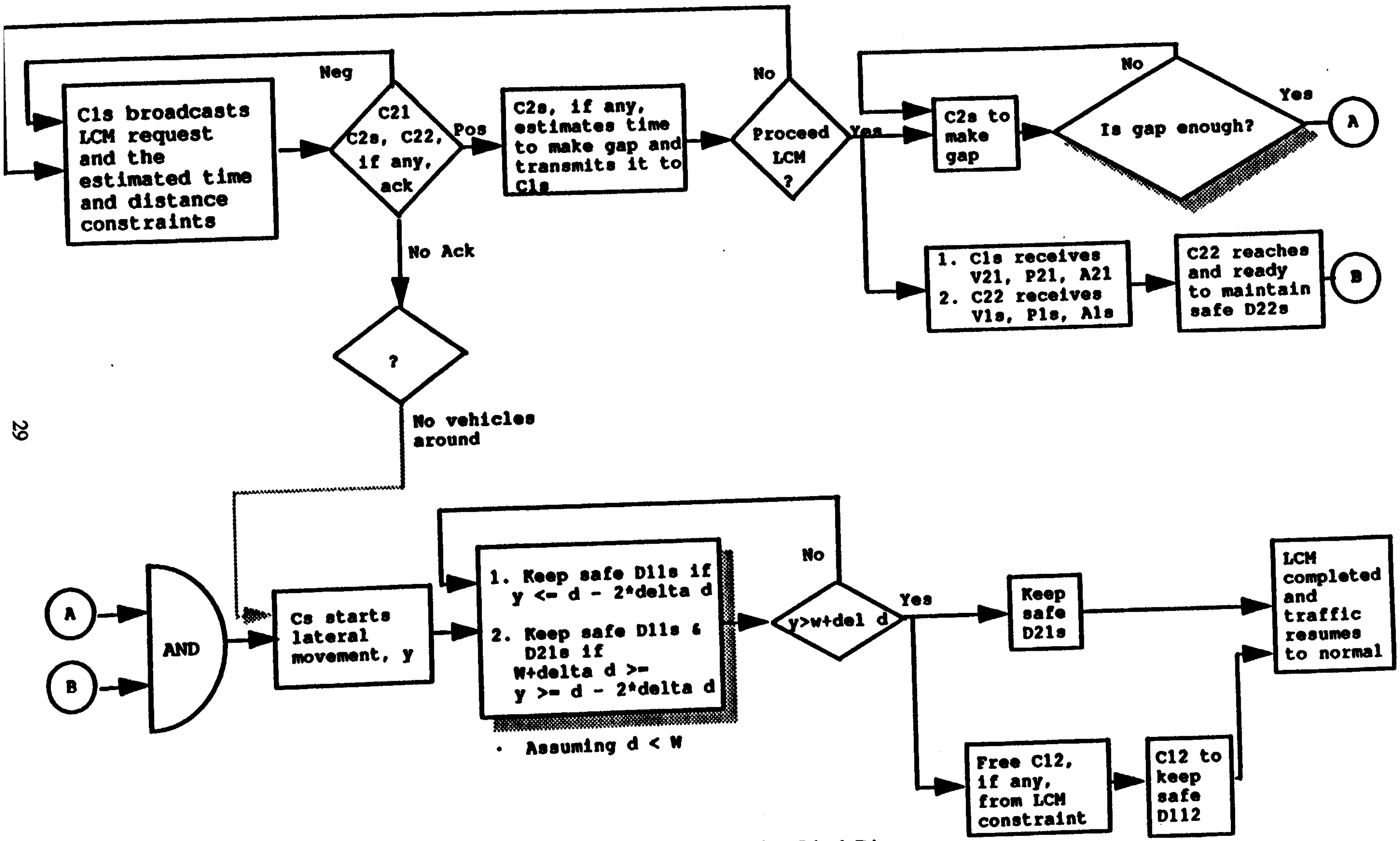


Figure 4.1. Lane Change Maneuver Flow Block Diagram

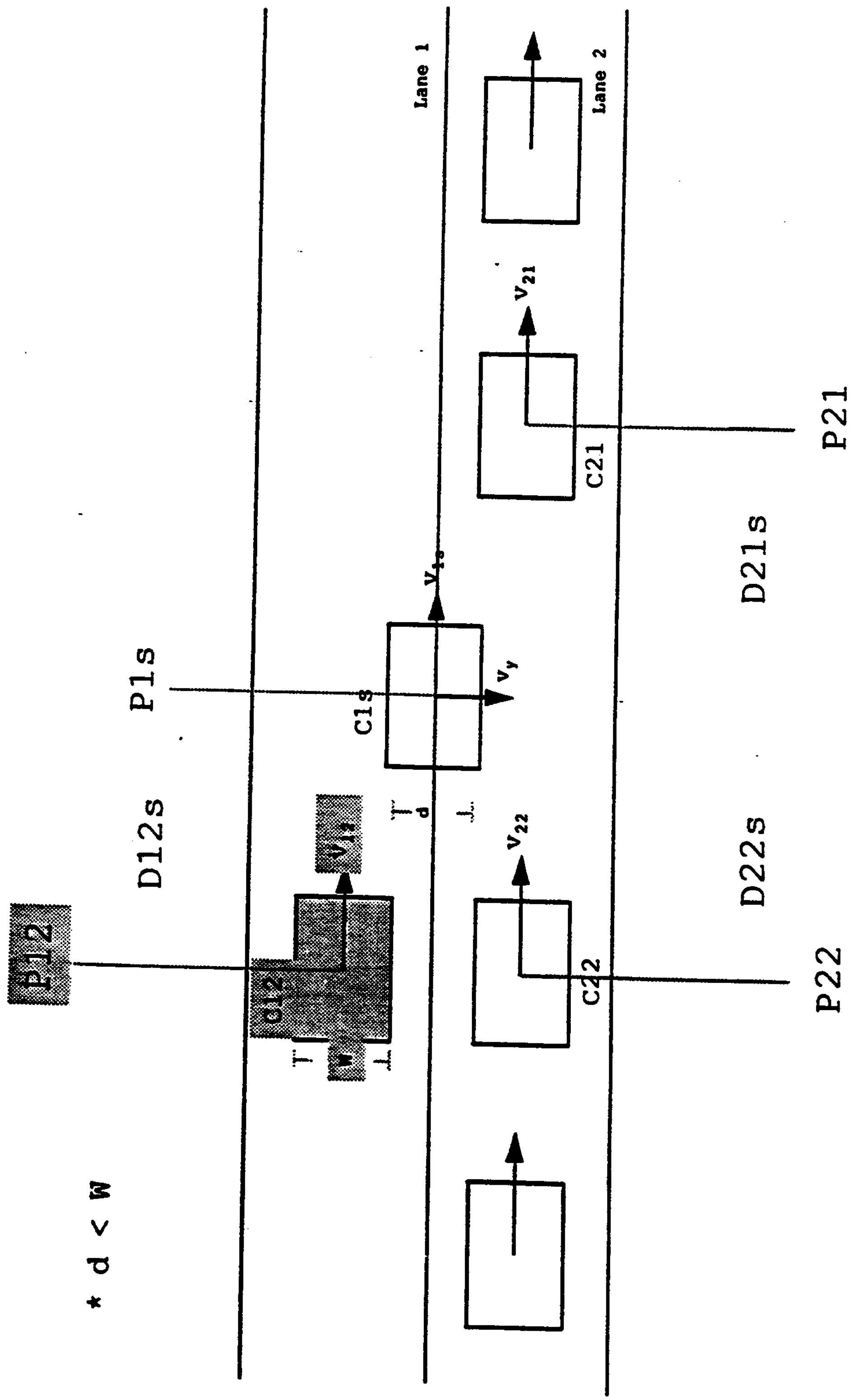


Figure 4.2a. Lane Change Maneuver Config 1: Left to Right - 1/5

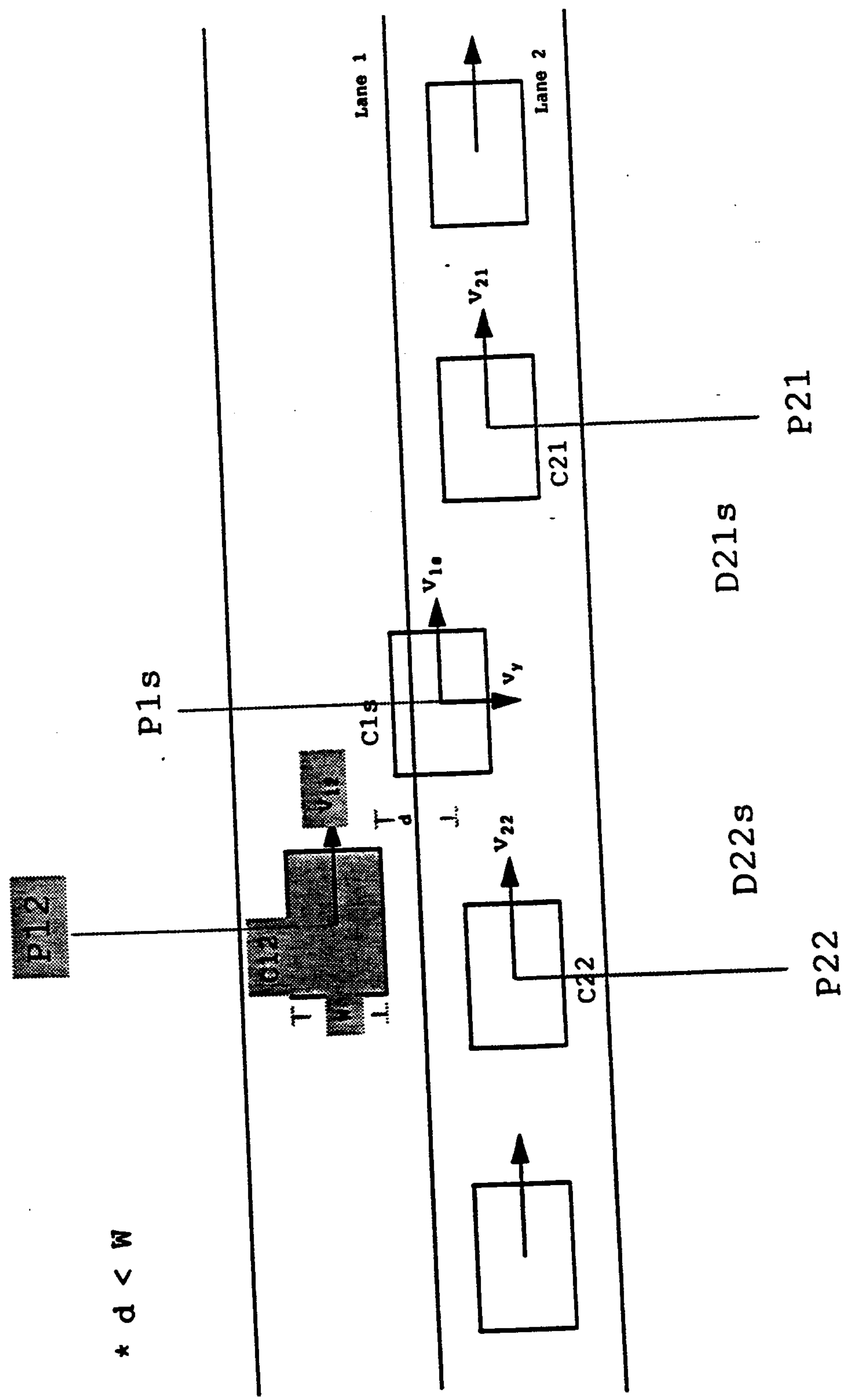


Figure 4.2b. Lane Change Maneuver Config 1: Left to Right - 2/5

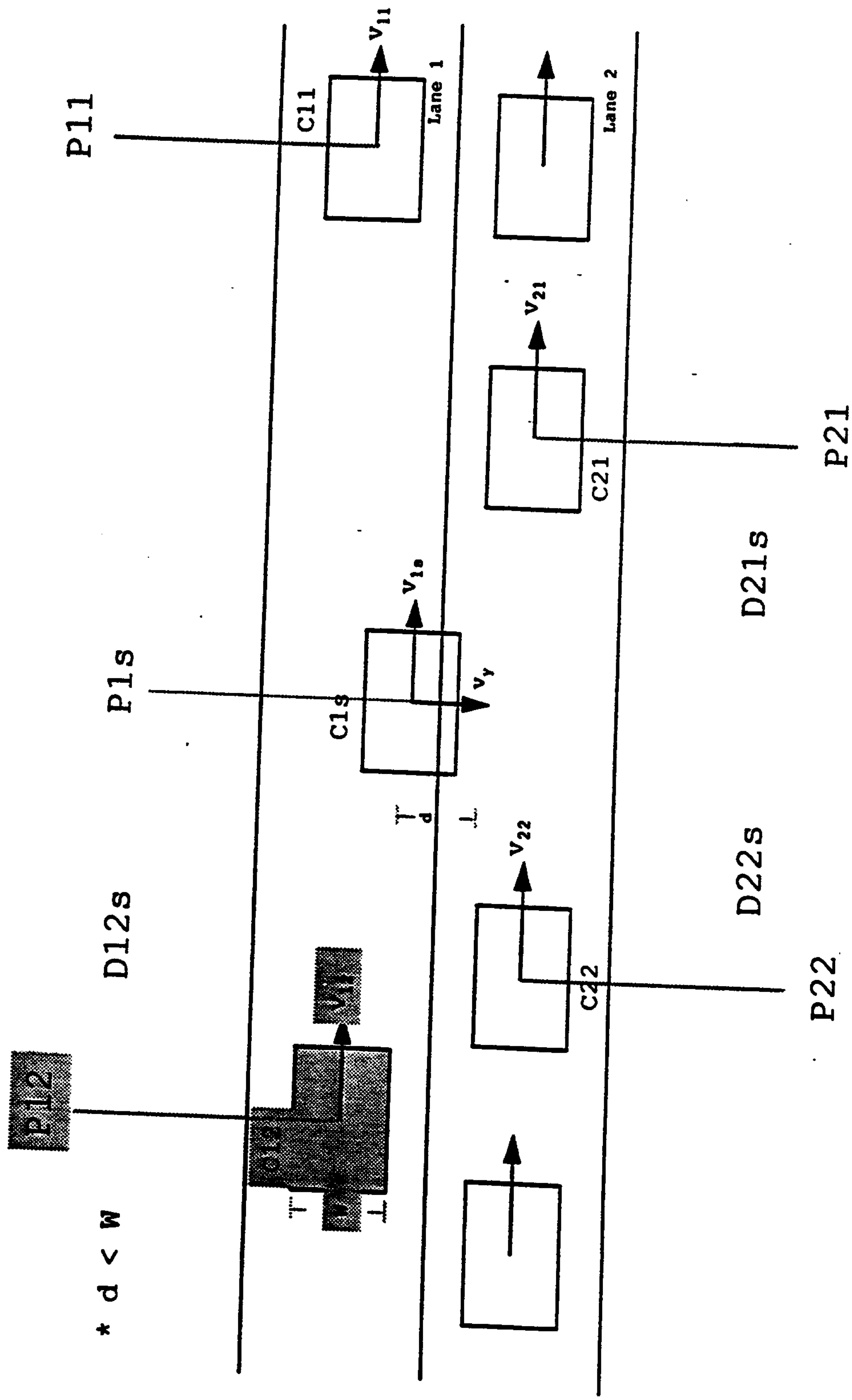


Figure 4.2c. Lane Change Maneuver Config 1: Left to Right - 3/5

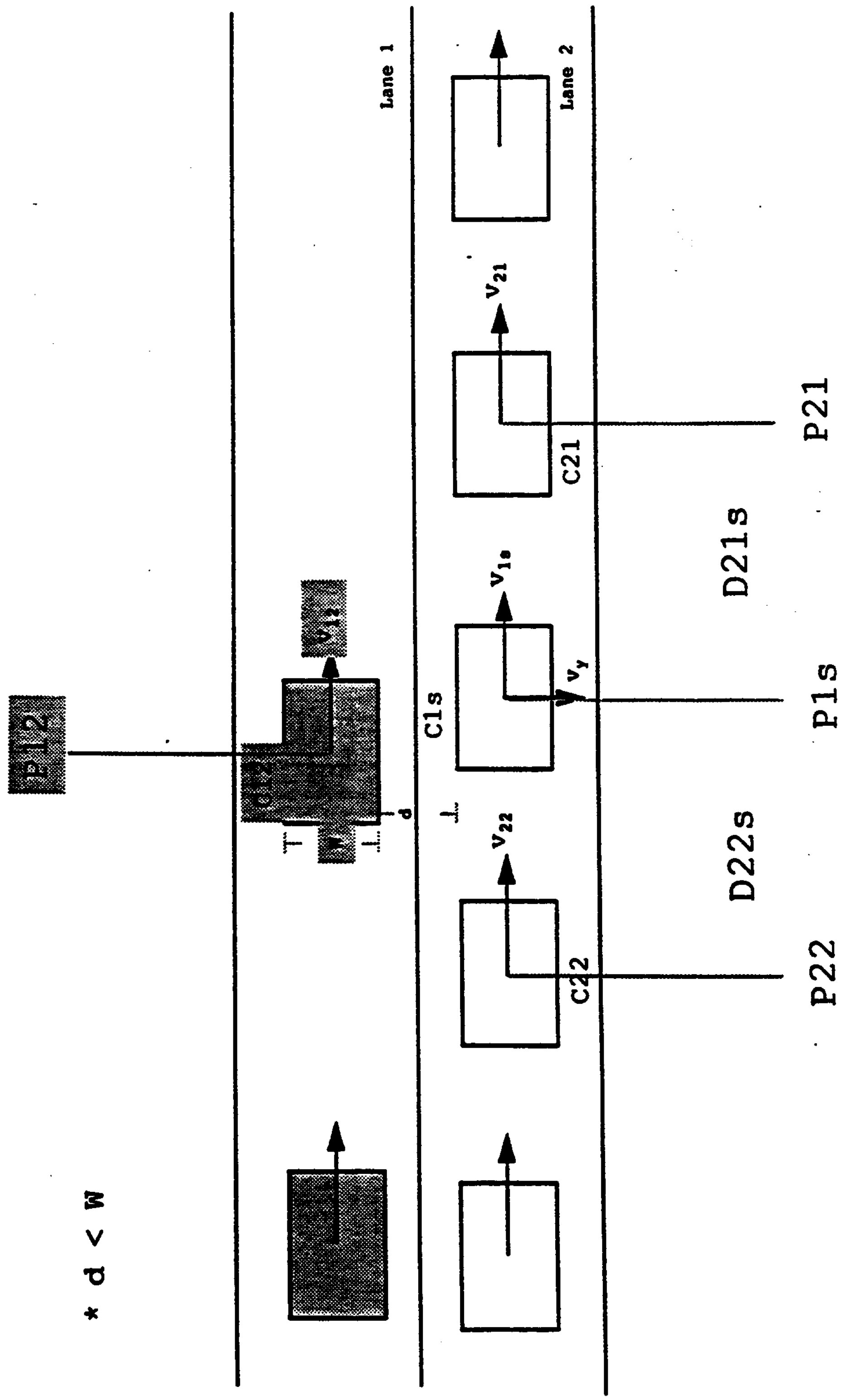


Figure 4.2d. Lane Change Maneuver Config 1: Left to Right - 4/5

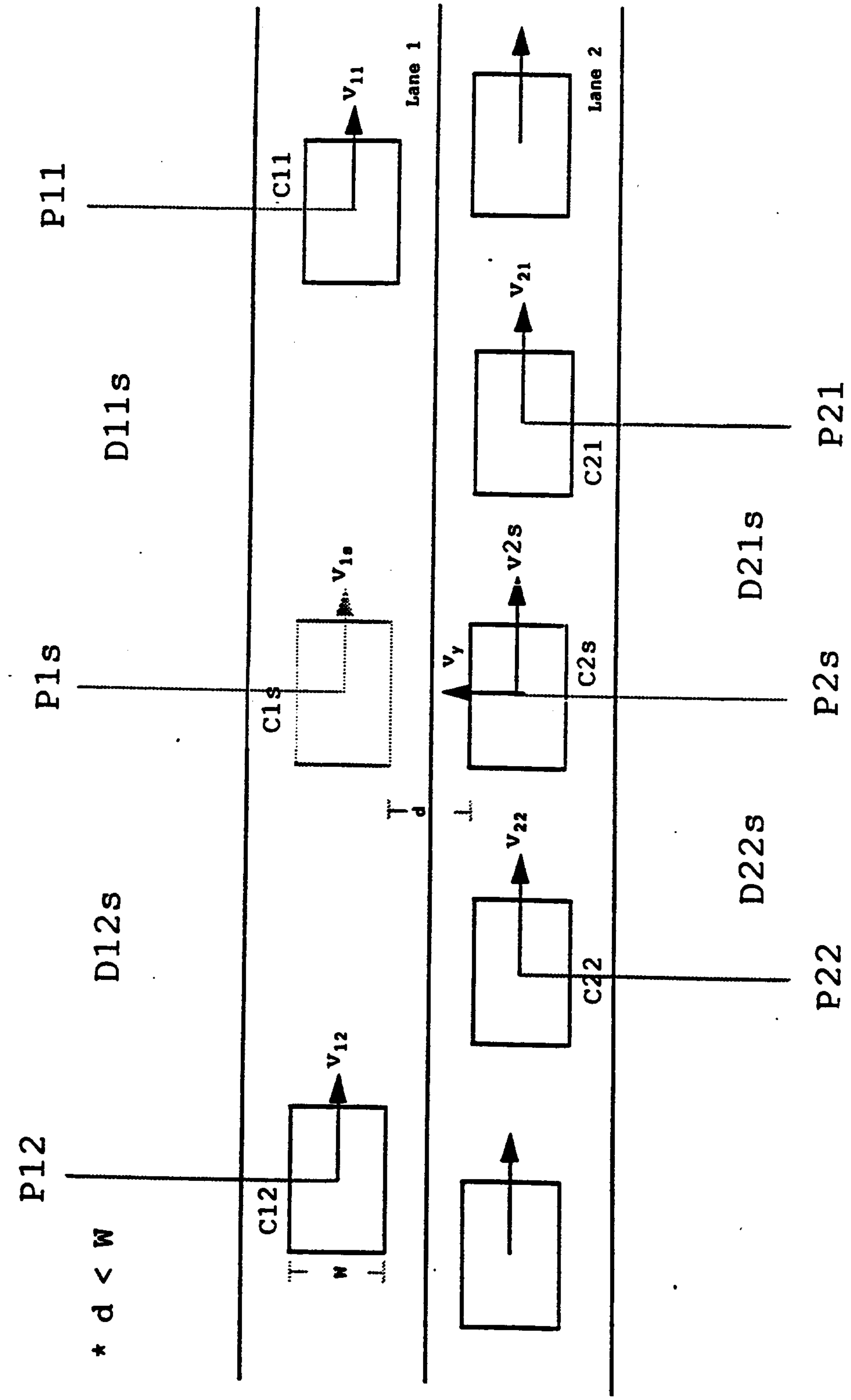


Figure 4.2e. Lane Change Maneuver Config 1: Left to Right - 5/5

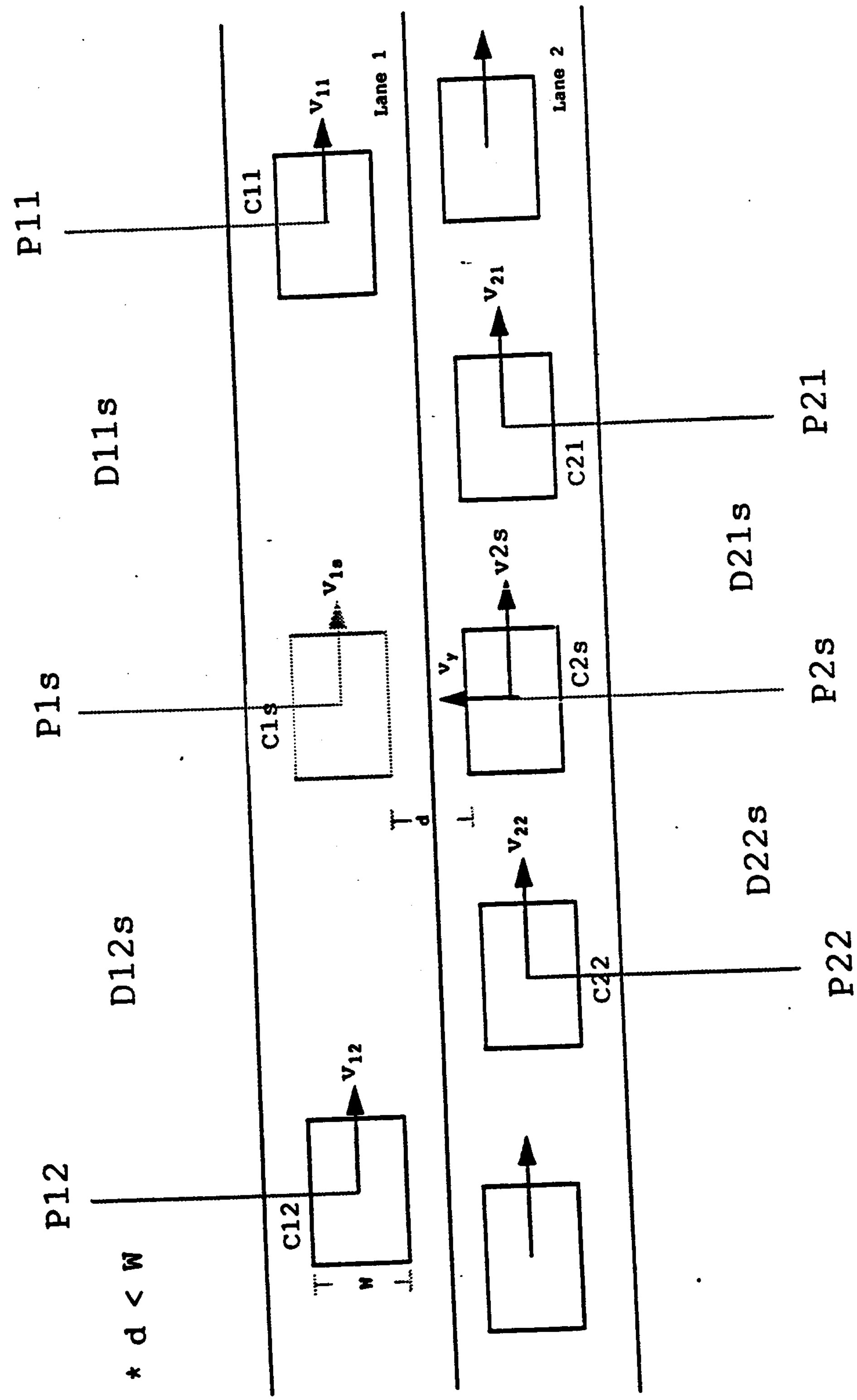


Figure 4.2f. Lane Change Maneuver Config 2: Right to Left - 1/5

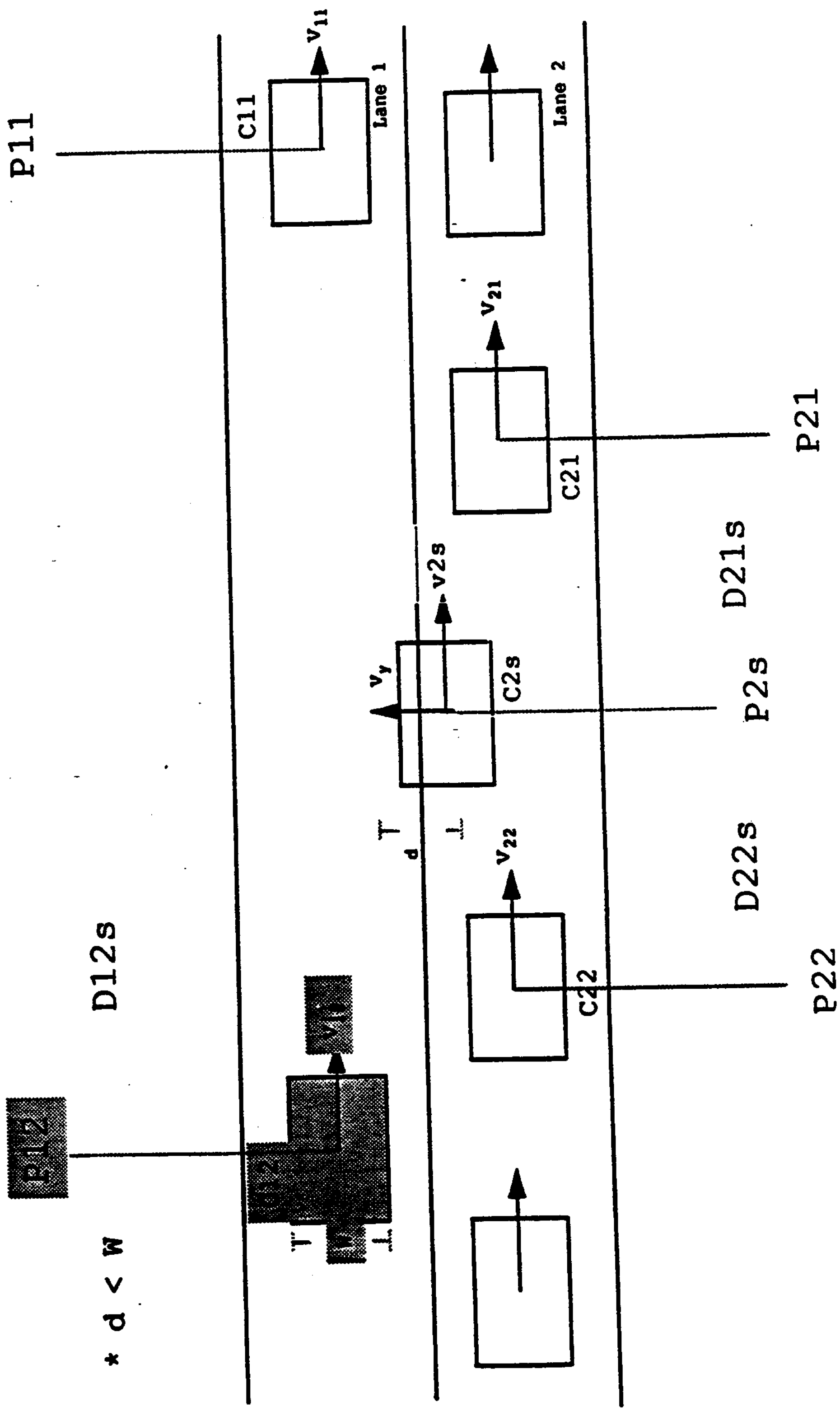


Figure 4.2g. Lane Change Maneuver Config 2: Right to Left - 2/5

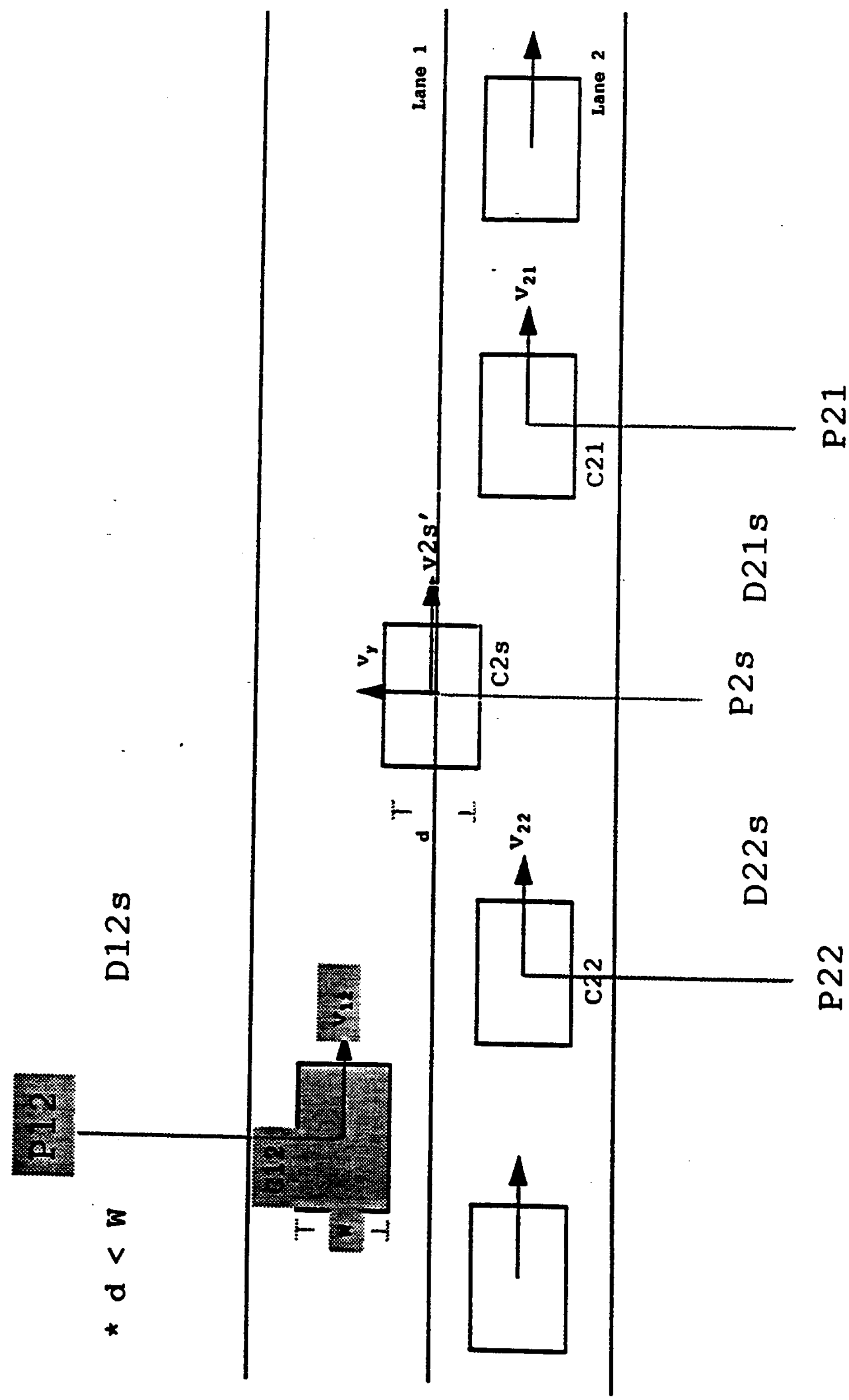


Figure 4.2h. Lane Change Maneuver Config 2: Right to Left - 3/5

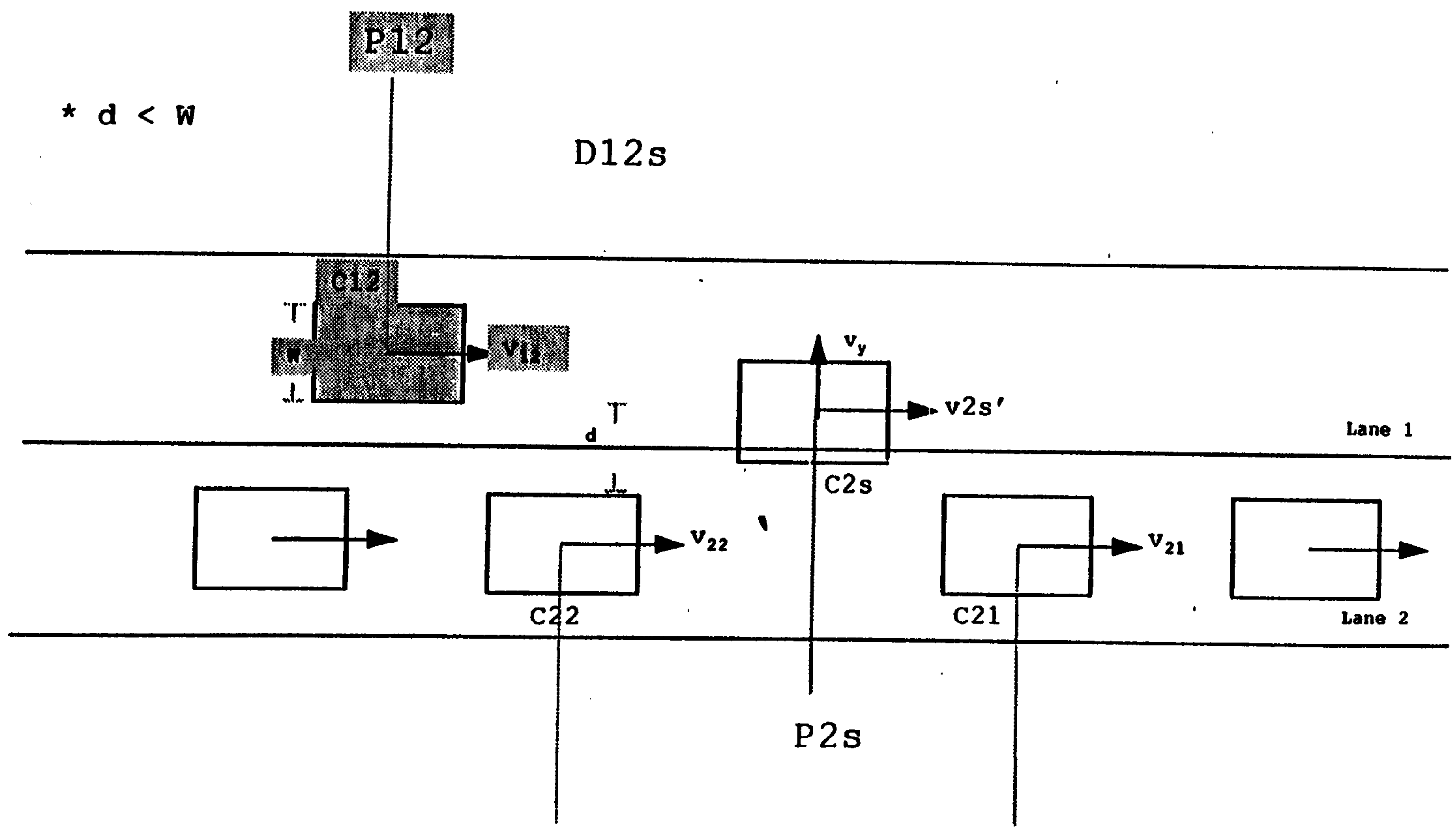


Figure 4.2i. Lane Change Maneuver Config 2: Right to Left - 4/5

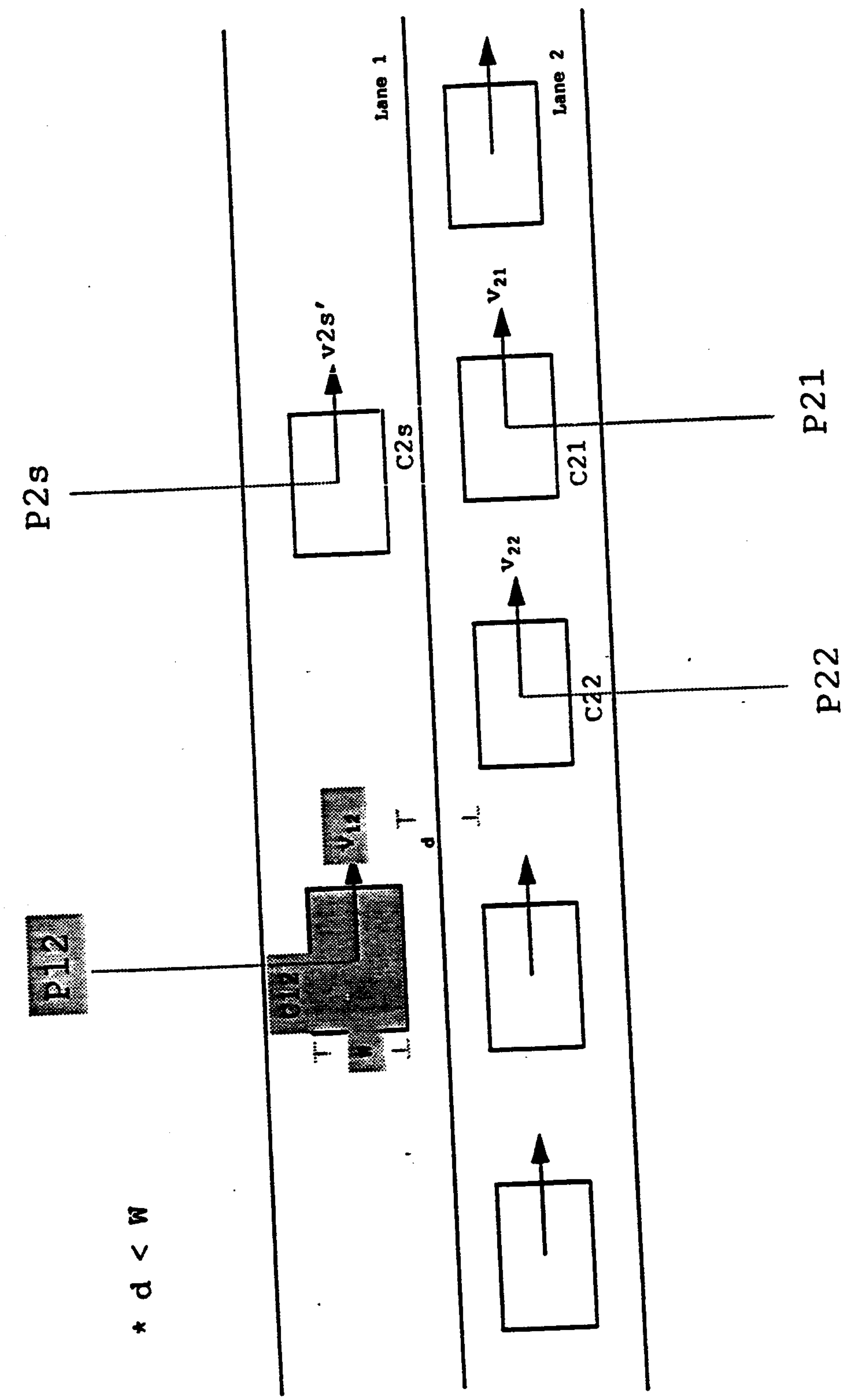


Figure 4.2j. Lane Change Maneuver Config 2: Right to Left - 5/5

It is conceivable that when conflicting requests arrive at the same vehicle, the urgency of the time or distance constraints may be used to prioritize these requests.

(3) If there is a vehicle, C2s, in the receiving lane, at the similar position as C1s, then vehicle C2s is requested to estimate the time required to make a gap for this LCM request and to transmit such information to C1s. When ambiguity arises about which vehicle in the receiving lane is deemed to be the "C2s", it is assumed that in this scenario the vehicle immediately behind C1s will be burdened to perform the estimate.

(4) Upon receiving the estimate from C2s, C1s starts to assess the possibility of completing the LCM within constraints, if any, and then determines whether to proceed with the LCM. If it decides not to proceed, C1s revokes the LCM request, frees the neighboring vehicles, and then goes back to step (1) to try later. If it decides to proceed, step (5) is executed.

(5) Three events are underway simultaneously at this step. [1] C2s is making a gap and checking if the gap is enough. [2] C1s receives the status (position, velocity, and acceleration) of vehicle C21, if any. [3] C22, if any, receives the status of C1s. Note that the status may not include the relative positions and velocities to C1s if the vehicle borne sensors are not capable of sensing vehicles in other lanes. In this case, the status needs to be obtained by other means, e.g., infrastructure sensing. When C2s has made a sufficient gap, and C1s and C22 are ready to maintain safe distances relative to C21 and C1s, the LCM is then ready to proceed to the next step. Note that if the gap is made by slowing down C2s, then C2s shall become C22 upon completion of gap making.

(6) C1s, renamed as Cs from this step on, starts the lateral movement by turning the steering wheel. Assuming all vehicles brake along straight lines, Cs needs to keep the minimum safe distance in case of platooning (or maximum in case of headway maintenance) from vehicles C11 or C21 or both, if any, until Cs is laterally positioned at the designated position in the receiving lane.

(7) C12 , if any, is freed from keeping safe distance from Cs whenever Cs is not straight ahead of C12.

(8) Cs broadcasts completion of LCM and frees all neighboring vehicles from its LCM request.

Obviously there are many areas in the above scenario where the maneuver efficiency in terms of its impact on traffic capacity can be optimized depending upon the system configuration, sensor capabilities, and the existence of some of the neighboring vehicles. For instance, a gap can be made by either speeding up or down, or a gap can be made or maintained ahead of C1s in order for it to catch up. However, any circumstantial optimization would necessitate more knowledge of the subject vehicle's surroundings via longer range and/or potentially more complex communications and sensing. Further more, from a system operational point of view, circumstantial optimization will subject more vehicles by the same single maneuver request, thus the entire system becomes more susceptible to anomalies and is consequently less robust. The trade off between maneuver efficiency and robustness will probably require detailed Monte Carlo simulations that is impossible at this point of the program due to budgetary and scheduling limitations.

As to the key parameters relating to a lane change, different scenarios yield diffe rent results. According to the above simple LCM scenario, the major parameters are: safe distance, time and/or distance constraints, identification of the existence of neighboring vehicles, vehicle states (position, velocity, and acceleration), sensing and communication among vehicles and with the infrastructure, and finally the vehicle lateral movement.

Some of the unique features of this scenario are worthwhile noting here: (1) It is inherently robust if gap making is done only by slowing down vehicles (i.e. C2s) in the receiving lane, if any, since by doing so no vehicles could be constrained by conflicting LCM requests. As a result, gap making by slowing down vehicles would be an excellent point of departure scenario to expand and fall back on if difficulties emerge. (2) It only requires short range communications between adjacent vehicles, (3) Gap and velocity matching between the subject vehicle and those in the receiving lane is guaranteed, (4) This scenario is not optimal in terms of efficiency.

4.3 Lane Entry and Exit

The above scenario assumes that all lanes are fully automated. In this section, LCM between automated and manual lanes are analyzed in two mechanizations: DE and B+T.

In the case of an automated vehicle entering an automated lane from a manual lane in the DE mechanization, the driver can switch to auto mode, upon the making of the LCM decision, and let the POD scenario finish the maneuver. However, in the case of exiting an automated lane to a manual lane the driver will need to take over control of his/her vehicle sometime after the LCM decision has been made. The maneuver can be accomplished manually like in today's freeway, by either gap matching or speed matching or a combination of both. Apparently the issue here is that during the period of time when auto and manual modes of operation are mixed in the automated lane, how much control (lateral only or both longitudinal and lateral) and exactly when the control should be relinquished to the driver. Without a transition lane the driver may have to abruptly accelerate or decelerate, while still in the automated lane, in order to complete the LCM in time. This abrupt acceleration and deceleration may well prohibit any platooning in the automated lane that is adjacent to a manual lane and/or simply prohibit any LCMs by vehicles in platoons.

Issue: How much and when should the driver be given control of the vehicle to perform an LCM from an automated lane to a manual lane?

In a B+T mechanization, whether the LCM is fr om auto to manual or manual to auto the request will be constrained by the location and length of the physical openings. One of the underlying ground rules of this mechanization is that under no circumstances will manual vehicles be allowed to get in the transition and automated lanes. It is reasonable, therefore, to assume vehicles in the transition lanes are capable of communicating among one another like in the automated lanes, and the vehicles in the transition lane are also equipped with certain range and range rate sensing devices. An automated vehicle entering or exiting an automated lane from or to a manual lane through a transition lane, the gap and the opening will automatically be synchronized by the POD LCM scenario because of the mandatory safe distance keeping. Of course, lane crossing sensing of the states of vehicles in adjacent lanes by sensors relying on Line-of-Sight (LOS) is impossible due to the physical barrier. Other means, e.g., radio communication, must be employed in such cases. The impact of LCM on capacity can not be quantified at this time. However, close examination of this LCM scenario shows that the major traffic interference due to the LCM is the forced slowing down of those vehicles behind the subject vehicle in the fast lane. This seems also to be true for a right-to-left LCM. Therefore, if those vehicles can be freed from the LCM request as soon as possible then the interference can be minimized.

Issue: How to estimate the necessary lead time to initiate an LCM constrained by the location and length of the opening of a physical barrier between an automated and transition lane?

4.4 Roadway Entry and Exit

Only a fully automated AHS is considered in this section. Conceptually, "roadway entry and exit" (REE) is similar to "lane entry and exit" (LEE) in a B+T mechanization. In both cases, the subject vehicle intends to merge into or exit from the automated lane with constraints of the location and length of the physical opening. However, they differ operationally in at least three areas: (1) Acceleration of the subject vehicle is usually required in REE. Should the merge fails, REE has no turning back unless a path is provided, (2) The merging geometry may be different between REE and LEE, (3) The queue in the exit lane may interfere with the AHS traffic. In fact, the transition between the automated and manual traffic is one of the key issues that may make or break the success of the overall traffic system including AHS, and surface streets. Intuitively, the impact on AHS capacity can be minimized if the entry/exit velocity of the subject vehicle is kept as close to the normal traffic as possible. The price paid for the minimal impact on capacity may be long entry/exit ramps and/or higher acceleration/deceleration capabilities. The three determining factors of REE are the length of the entry/exit lane, vehicle acceleration/deceleration capabilities, and the nominal traffic speed in the slow lane.

4.5 Lane Keeping

Lane keeping is a function of maintainin g vehicle lateral position within the lane being occupied along a reference lateral position, say, the center line of the lane. Like all control systems, this function requires vehicle lateral position sensing, processing of the sensed data, and the generation of a corresponding steering command thereby keeping the vehicle within some tolerance of the desired reference lateral position. Since lane keeping is always operated in conjunction with longitudinal control, and the control systems are, in practice, usually designed and analyzed in separate axes, the possibility of adverse cross-axis interactions should be minimized. For example, a vehicle's lateral maneuverability is generally reduced when in acceleration. As implied in Rockwell's proposal, the time lags around the loop is critical to lane keeping performance. Without doing extensive vehicle lateral dynamics modeling and control analysis, it is sufficient to state that, for PSA purposes the effect of time lags on lane keeping performance is measured by phase margins of the control systems. Typically the time lags include sensing, processing, and actuating lags. One interesting way of thinking of an LCM is considering it as a special lane keeping control with the vehicle's reference lateral position being shifted to, perhaps, the center line of the receiving lane. No technical difficulties are expected at this time, but this is a subject that needs to be examined in depth in the future.

One of the areas that most of the research done so far has focused on is the lateral sensing, e.g., magnetic nails and lane marking sensing. Table 4-1 lists a preliminary evaluation of lateral control technologies. At this time, no single method seems to be able to operate in all weather and road conditions. They are all subject to component failures or to unfavorable operating conditions, e.g., snow or fog. The question is how can the control system be ensured to be fail-operational or at least fail-safe? Two potential resolutions are being studied: redundancy and sensor fusion. Redundancy refers to the retaining f the functionality of the same or different kind of sensors, e.g., 2 image sensors; sensor fusion refers to the synergism and expansion of sensing capability by joining different types of sensors, e.g., combining magnetic nails and image sensors. The key issues are obviously: (1) what is the signature (target phenomenology) of a lateral deviation from the reference, so that the true or nearly true deviation can be extracted from the typically noisy data out of sensors? (2) how to and what to fuse the sensed lateral deviations from different types of sensors, so that all possible operating conditions are covered, and, in the mean time, hopefully the reliability and performance are enhanced while both (or all) sensors are in operation.

4.6 Conclusion, Issues and Risks

The issues and risks identified in this section are summarized below. The issues and risks are subjects for future studies.

1. While the efficiency of an LCM can be optimized given a particular traffic condition, the optimization is often accomplished at the expense of system robustness. The trade off between efficiency and robustness requires careful analysis, tuning, and tests in the future.

2. How much and when should the driver be given control of the vehicle to perform an LCM from an automated lane to a manual lane, and vice versa in the DE mechanization?

3. How do we estimate the necessary lead time to initiate an LCM which is constrained by the location and length of the opening of a physical barrier between an automated and transition lane as in a B+T mechanization?

4. Since lateral and longitudinal control systems are always operated simultaneously, and they are usually designed and analyzed separately, the possibility of adverse cross-axis interactions should be minimized to ensure the total system integrity. For example, the minimization of the effect of weight shift between front and rear tires on lateral maneuverability when the vehicle is accelerating longitudinally.

5. What is the effect of LCM on lane keeping? Biasing the vehicle's reference lateral position to, perhaps, the center line of the receiving lane?

Table 4-1 Lateral Control Technologies

Preliminary Evaluation of Lateral Control Technologies

Notation:
- ◎ desirable
- acceptable or improvement desired
- ○ unsatisfactory or enhancement required
- problematic or significant modification required
- ● unacceptable or technical barrier encountered
- ■ ~~unknown~~ N/A

	forward vision sensor with roadway lane lines	forward optical sensor with roadway reflective markers	forward vision sensor with frontal vehicle target	radar sensor with a reference wall	optical sensor with reflective beacons	magnetic sensor with discrete markers	optical sensor with reflective markers	magnetic sensors with energized wires	GPS for acquiring lat. and lon. positions
POTENTIAL FOR FAIL-SAFE	unsatisfactory	unsatisfactory	unacceptable	unacceptable	unacceptable	desirable	unsatisfactory	desirable	unacceptable
[redacted]									
POTENTIAL FOR HIGH RELIABLE ROADWAY	unsatisfactory	unsatisfactory	N/A	unsatisfactory	acceptable	desirable	unsatisfactory	problematic	N/A
POTENTIAL FOR HIGH RELIABLE SENSOR	problematic	problematic	acceptable	acceptable	problematic	desirable	problematic	desirable	desirable
POTENTIAL FOR LONG LIFE CYCLE ROADWAY	unsatisfactory	unsatisfactory	N/A	acceptable	acceptable	desirable	unsatisfactory	problematic	N/A
POTENTIAL FOR LONG LIFE CYCLE SENSOR	acceptable	acceptable	acceptable	desirable	acceptable	desirable	acceptable	desirable	desirable
[redacted]									
MEAN TIME TO RESTORE FOR ROADWAY FAILURE	desirable	desirable	N/A	problematic	acceptable	acceptable	desirable	unacceptable	N/A
MEAN TIME TO RESTORE FOR SENSOR FAILURE	unsatisfactory	acceptable	unsatisfactory	desirable	desirable	desirable	desirable	desirable	desirable
[redacted]									
LIFE CYCLE COST OF ROADWAY	desirable	desirable	N/A	unacceptable	problematic	unsatisfactory	desirable	unacceptable	N/A
LIFE CYCLE COST OF SENSOR	unacceptable	acceptable	unacceptable	acceptable	acceptable	desirable	acceptable	desirable	unsatisfactory
[redacted]									

5. ANALYSIS OF PLATOON FORMATION MANEUVERS

5.1 Objectives

The objectives of this activity are to (1) relate platoon formation maneuver performance (including safety and comfort) to control system implied requirements and vehicle dynamic constraints, and (2) identify the pertinent issues and risks.

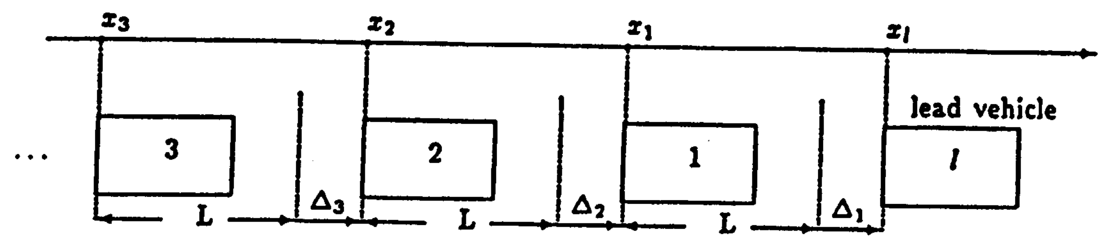
5.2 Analysis of Platoon Formation Maneuvers

The most extensive recent work, at least in the U.S., on vehicle platoon dynamics and control is that of the California PATH. Intra-platoon dynamics and control have been examined extensively by Sheikholeslam and Desoer (Ref. 11-16) using what amount to linear system analyses. Among the most important results of this work is the theoretical demonstration that a basically acceptable platoon control system can be structured as shown in Figure 5.1. In this structure the control system for each vehicle in the platoon operates only with information (from measurement or communication) on: (1) its own state, (2) the state of the vehicle immediately ahead, and (3) the state of the lead vehicle of the platoon. The inclusion of the lead vehicle state information is shown to be necessary, as well as sufficient, to avoid the "slinky" effect in which a perturbation in the lead vehicle motion can cause perturbations in the vehicle separations, Δ_i, which increase in magnitude from front to rear. Key results are that each vehicle does not need information on all other vehicles in the platoon and that information only need flow from front to rear in the platoon. This last point is important because it implies that each vehicle can "ignore" the vehicles behind it; the followers are "responsible" for maintaining the proper forward separation distance.

The Ref. 11-16 work on intra-platoon dynamics is only indirectly relevant to the work of this project which is focused on the inter-platoon dynamics of platoon formation. But directly relevant work on inter-platoon dynamics has also been done at PATH by Godbole and Lygeros (Ref. 20) and this work used the version of the Sheikholeslam and Desoer model documented in Reference 13. As noted in Reference 20, this problem is essentially similar to the Autonomous Intelligent Cruise Control (AICC) problem. The AICC problem has been addressed by Ioannou and Chien (Ref. 21) also using the same linearized vehicle model as in Reference 13. Other work on platoon dynamics has been done at PATH by Hedrick and others (Ref. 22), with general similarities in the approach and form of the vehicle models.

Thus the Sheikholeslam and Desoer vehicle plus control system model of Reference 13 is a key thread in much of the work to date in this area. Thus this model and the approach to modeling and analysis will be reviewed here as a reference point for the work of this study. The overall model including the control system is shown in Figure 5.2. The specific control law for the linear controller shown in Figure 5.2 is the inter-platoon control law of Reference 20, however the elements in the dashed box are the same as used in Ref. 13-15 and 21.

The "nonlinear plant" is the nonlinear longitudinal vehicle model diagrammed in Figure 5.3. The portion of the model to the right of the summing junction represents the longitudinal vehicle equation of



x_i is the abcissa of the i-th vehicle
x_l is the abcissa of the lead vehicle
This figure defines $\Delta_1, \Delta_2, \ldots,$ and L.

direction of motion

(a) Platoon of 4 vehicles

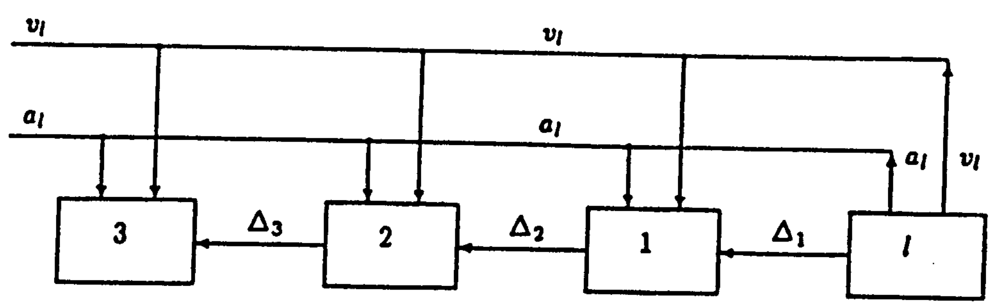
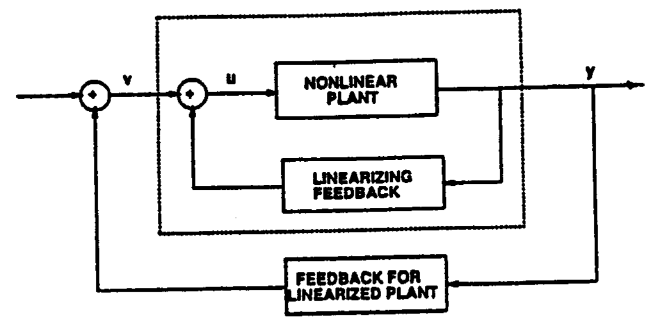


Figure 5.1. Platoon



Vehicle Model:

$$\dddot{x}_i = b_i(\dot{x}_i, \ddot{x}_i) + a_i(\dot{x}_i)u_i$$

Linearizing Feedback:

$$u = \frac{1}{a(\dot{x}_i)}\left[-b(\dot{x}_i, \ddot{x}_i) + v\right]$$

Linearized System:

$$\frac{d}{dt}\begin{bmatrix} x_i \\ \dot{x}_i \\ \ddot{x}_i \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} x_i \\ \dot{x}_i \\ \ddot{x}_i \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} v$$

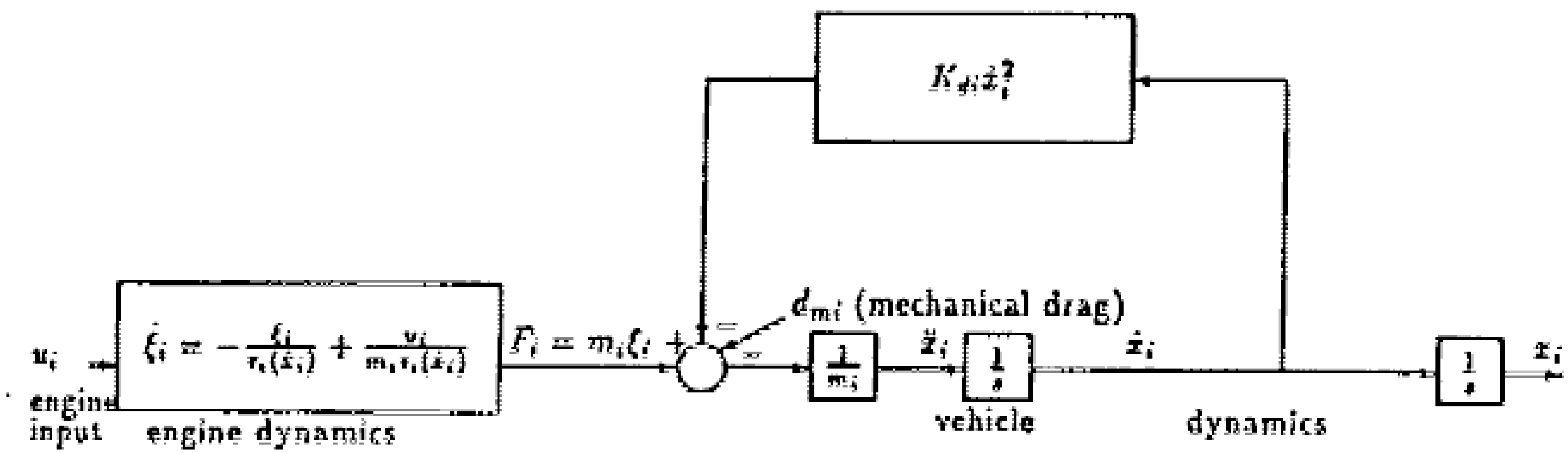
Linear Controller:

$$\dddot{x}_i = v = c_i \int e_i\, dt + c_p e_i + c_v \dot{e}_i + k_v(\dot{x}_i - \dot{x}_i(0)) + k_a(\ddot{x}_i - \ddot{x}_i(0))$$

Error Function:

$$e_i = x_{i-1} - x_i - L_{i-1} - (\lambda_v \dot{x}_i + \lambda_p) = d_i - D_i$$

Figure 5.2. Path Platoon Merge Control



F_i = engine force applied to vehicle i
ζ_i = commanded acceleration of vehicle i

Figure 5.3. Simplified Model of the i-th Vehicle in the Platoon

motion. This is in series with the engine dynamics which are modeled as a linear first order lag with time constant τ_i. This model is basically similar to the STI model (Ref. 23) used in this work, except that the STI model allows for nonlinear variation of rolling resistance with speed (this is a constant, d_{mi} in Figure 5.3) and includes a brake control point (input) not included in the Figure 5.3 model. This model is also basically similar to a vehicle model used by Hedrick (the three state model of Ref. 22) except that engine model is more detailed.

The only nonlinearity in this model is the aerodynamic drag which appears in the feedback loop in Figure 5.3. The variation of drag with dynamic pressure is a rather benign nonlinearity that has been treated routinely in aircraft flight control, from hover through orbital velocity, with gain scheduled linear control laws since October of 1903. A different approach, based on Ref. 24, was used in Reference 13. The vehicle model was inverted, by solving for u_i in terms of the jerk $\dddot{x}_i$, and the jerk was replaced with a control variable c_i (amounting to a "jerk command") to mechanize the "linearizing feedback" shown in Figure 5.4. The result is an infinite bandwidth linear system with respect to the jerk command point (bottom diagram in Fig. 5.4). At this point all of the vehicle dynamics have been removed from the problem and replaced with the equation at the bottom of Figure 5.4 which state that position is the integral of velocity, velocity is the integral of acceleration, and acceleration is the integral of jerk. The introduction of the nonlinear vehicle model in Figure 5.4 is not, of course, required to obtain the relationship between jerk, acceleration and velocity (final equation in Figure 5.4).

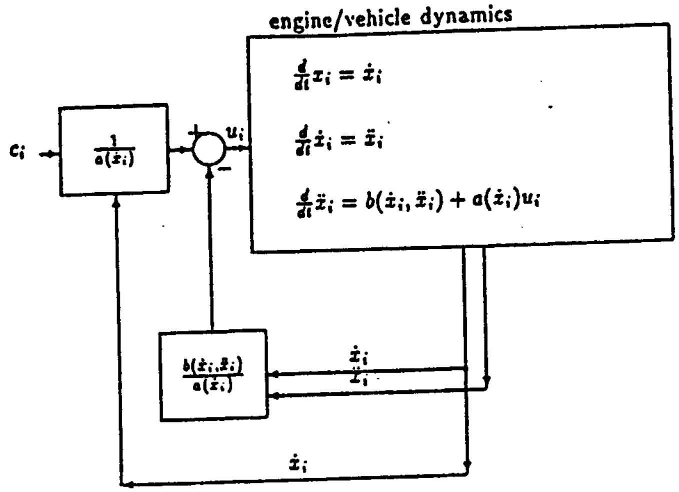
Certain issues were not addressed or even raised in the developments of Reference 13-15 which are important and will be addressed in part in the discussion in later sections. These include:

Significance of Nonlinear Vehicle Dynamics: the fact that the automobile longitudinal dynamics are nonlinear is not, in itself, significant. The key question is whether they are significantly nonlinear, i.e., whether they produce, for relevant values of the dependent variables, phenomena which are qualitatively different from what an approximating linear system would produce.

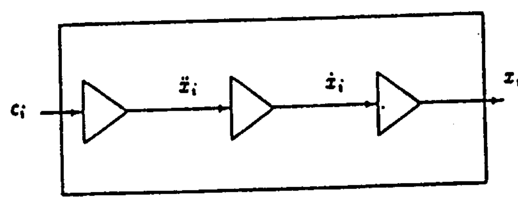
Robustness of the Linearizing Feedback: the linearizing feedback of Figures 5.2 and 5.4 effectively "exactly cancels" the vehicle dynamics. However, the a and b estimates in the linearizing feedback will inevitably be imperfect estimates of the actual vehicle a and b functions and thus exact cancellation will not occur. This potential robustness problem is the nonlinear version of a well known practical problem with certain linear optimal control schemes which effectively cancel undesirable poles with controller zeros instead of improving the pole placement. Plant uncertainty and variation lead to robustness problems in general and, more specifically, often lead to nuisance dipoles.

Performance of the Linearizing Feedback for Disturbance Inputs: even if the linearizing feedback performs adequately with respect to the jerk command, it is not designed to perform this function for other inputs -- specifically disturbances. The linearizing feedback will also not *linearize* the vehicle with respect to disturbances. However these particular problems may not be too critical since the longitudinal gust response of an automobile is much more benign than the corresponding disturbance in a lift generating vehicle (aircraft).

Pathologies due to Nonlinear Feedback: A more subtle issue is the possibility that the linearizing feedback, which is itself a nonlinear control law, could actually create nonlinear



Block diagram showing the linearizing state feedback for the i-th vehicle in the platoon; it is based on equations (4.4) to (4.6) and the linearizing state feedback (4.7). The result is the set of equations (4.8)-(4.10).



Input/Output point of view of the i-th vehicle's linearized model.

$$
\begin{aligned}
\frac{d}{dt}x_i &= \dot{x}_i \\
\frac{d}{dt}\dot{x}_i &= \ddot{x}_i \\
\frac{d}{dt}\ddot{x}_i &= c_i
\end{aligned}
$$

Figure 5.4. Input/Output Point of View of the i-th Vehicle's Linearized Model

phenomena more significant than those of the basic vehicle dynamics. A nonlinear control law may improve system performance for nominal conditions, but for certain input types significant nonlinear phenomena can appear and even result in closed loop instability for open loop plants which are linear and stable. A classic example is the Lewis servo, Ref. 19.

Control Effector Limiting: a real-world mechanization of the linearizing feedback will be affected by engine and brake torque limits and, at low speeds, force limits in the tire/road interface. If these limits are exceeded, the linearizing feedback will no longer function and the linear outer loop platoon controller will "see" a different (unaugmented) vehicle than that for which it was designed. Further, such saturation conditions will occur during limit maneuvering (e.g., emergency maximum deceleration) when control system performance is critical.

Effective Vehicle Bandwidth: normal platoon maneuvering will be done well within the vehicle and control system limits. However even in this range, the specific (infinite-bandwidth) characteristics of the final Figure 5.4 form cannot actually be obtained because of the finite bandwidth of sensors, actuators, and most importantly, the lags associated with the engine and brake dynamics. The actual bandwidth of the effective vehicle dynamics (between y and v in Figure 5.2) is a key factor in platoon maneuver performance and cost tradeoffs.

Thus the practical implications of the linearizing feedback approach need to be addressed. This raises the question of how linear the effective vehicle needs to be. This is closely connected to the question, raised above and addressed below, of how significant the vehicle nonlinearity, the drag variation with speed, is to the control problem. As was also noted above this problem has been routinely handled for many years in aircraft flight control system design using essentially linear control systems and simple gain scheduling[1] (Ref. 25).

This leads to a revised view of the Figure 5.2 control system structure in which the inner-loop linearizing feedback would be replaced by a traditional inner control loop and the outer platoon controller would be a traditional guidance loop. The inner control loop would shape the basic effective vehicle dynamics i.e., the speed and attitude response to command and disturbances. This loop also insures stability (although this is not critical in the automobile longitudinal dynamics), and treats significant nonlinearity. The aerodynamic nonlinearity will generally be treated adequately with simple gain scheduling[2] ; control effector limits, which are the most significant nonlinearities from the standpoint of the effective vehicle dynamics, are usually addressed with command limiters in the control system. The outer guidance loop can generally be designed based on simplified "equivalent system" models of the effective inner loop dynamics and definitions of ideal maneuvers.

This traditional guidance and control structure is, at the most basic level, consistent with the Figure 5.2 structure. The linearizing feedback approach is a "methods-driven", rather than a "problem-driven", approach. That is, the rigid requirement for strict linearity represented by the Figure 5.4

---

[1] The aircraft longitudinal problem is fundamentally more complex than the automotive problem because the lift as well as the drag depends on dynamic pressure. Further the induced drag varies with the square of the lift coefficient. Finally both the lift and drag are strongly dependent on the angle of attack which is determined by the pitch dynamics. None of these phenomena are significant for automobiles.

[2] For aircraft exceptions include transonic and high angle-of-attack phenomena. These are not problems which will be encountered in automobiles.

procedure is imposed by the design methodology (Ref. 24), not by any fundamental requirement of the problem. It is desirable that the inner loop effective vehicle dynamics be reasonably linear, but that is all -- seeking perfect linearity is counterproductive. Even with the usual vehicle nonlinearities, reasonable linearity can usually be achieved in the effective vehicle with simple linear feedback control systems. This is true because feedback, even linear feedback, intrinsically tends to linearize nonlinear systems (Ref. 25).

5.2.1 Platoon Formation Maneuvers

5.2.1.1 Maneuver Characteristics

Before control system issues can be addressed, the platoon formation task must be characterized. The basic possibilities have been examined by a number of groups including recent work by PATH (Ref. 26) and Rockwell (Ref. 27). As noted above, it is assumed that all platoon formation maneuvers are purely longitudinal maneuvers in a single lane. Lateral lane-keeping (not analyzed here), but not lateral maneuvering, will be part of platoon formation maneuvers. The basic inter-platoon geometry is shown in Figure 5.5. Distances are measured from some arbitrary reference that remains fixed throughout the maneuver. While only two platoons are shown, these could be an adjacent pair within a larger group of platoons. Further either or both platoons could consist of only a single vehicle.

Here it will be assumed that the leader vehicle of the rear platoon (which may be a free agent) is "responsible" for merging with the front platoon and that the front platoon is not required to perform any special maneuvers. Further it is not assumed that the front platoon has any information regarding the rear platoon and the formation maneuver. Consequently no communication between the platoons is assumed and all sensing is done by the rear leader. As noted in Reference 20 this implies that the rear leader control system can be classified as an Autonomous Intelligent Cruise Control (AICC) law. Other scenarios could be envisioned in which the front platoon is actively involved in the formation maneuver. However this would imply a control system architecture significantly more complex than AICC, but there does not appear to be clear advantages for platoon formation. Further this more complex architecture would have information simultaneously flowing both forward and rearward between the platoons resulting in a two-way dynamic coupling that may be generally undesirable. Thus this case will not be considered further here.

For platoon merge we are, strictly speaking, concerned only with inter-platoon, as distinct from intra-platoon, dynamics. More to the point we are, strictly speaking, concerned only with the dynamics and control of the lead vehicle of the rear platoon and not with the vehicles which follow it in the rear platoon. This view is valid as long as information only flows rearward in a platoon. This is the case in the intra-platoon architecture of Figure 5.1. The analyses of Ref. 11-13 indicates that this restricted architecture is basically adequate.

The range of operating conditions must also be defined. It is important to distinguish between nominal operating conditions which would apply to the majority of platoon formations and special cases which will occur relatively rarely. Emergency and failure cases must fall into the relatively rare category; otherwise the AHS would not be acceptable. While it is important to consider control system performance in certain emergency conditions, it must be recognized that platoon formation will always be an optional activity performed for traffic flow efficiency and not specifically to enhance safety. Thus aborting a platoon merge probably will the correct strategy for many, if not most, off-nominal conditions. The key

-- Longitudinal maneuver (no lateral motion)

-- Initial platoon separation = 100 ft (V_o dependent)

-- Desired separation after merge = 3 ft (constant)

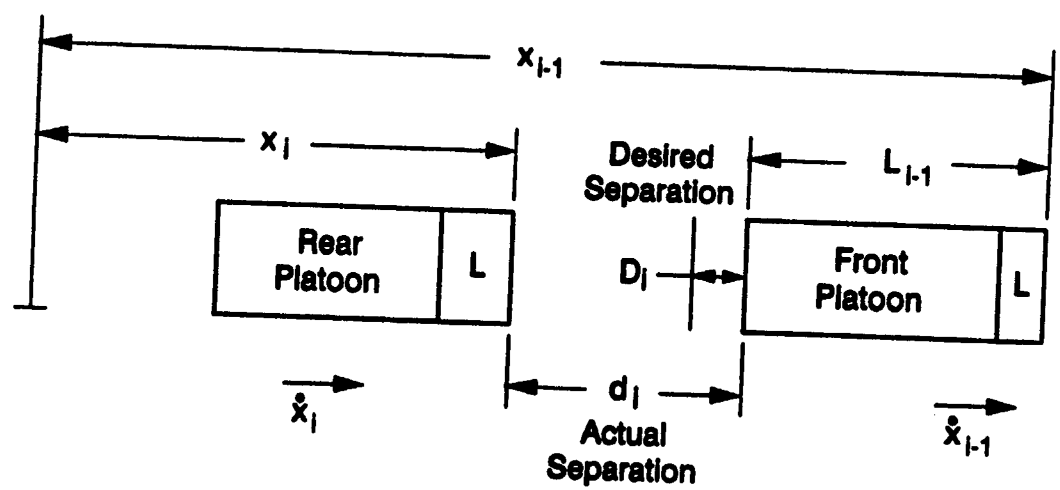


Figure 5.5. Platoon Merge Geometry

point here is that the nominal system design should not be compromised to allow platoon formation under off-nominal conditions where the maneuver should be aborted

The nominal conditions for initiating platoon formation will be assumed to be that both the front and rear platoons are moving at constant speed V_o which is less than, but close to the speed limit, V_{lim}. V_o must be close to V_{lim} to achieve traffic flow efficiency. The AHS at some level will define V_{lim} as a function of environmental conditions. Small differences from these conditions will not affect the issues of concern here; large differences will represent off-nominal conditions under which platoon formation probably should not be initiated. If the front platoon speed is much lower than the speed limit or if it is decelerating rapidly, this is an indication of an off-nominal condition and platoon formation should not be initiated. The fact that no communication is assumed between the front and rear platoons during most of the merge maneuver emphasizes the appropriateness of this strategy. Finally the front platoon cannot accelerate significantly for very long, with V_o close to V_{lim}, or V_{lim} would be exceeded. This implies that the problem of merging with an accelerating front platoon is not a significant issue.

The remaining off-nominal conditions are those arising after a merge maneuver is initiated. Likely scenarios include sudden emergency deceleration by the front platoon or intrusion of a third vehicle, from an adjacent lane, between the front and rear platoons. The last case certainly would represent a system error in the AHS coordination layer, because clearly the merge maneuver and the third vehicle lane change should not be allowed to occur simultaneously. In the system developed in Reference 20, the control laws were structured to accommodate these off-nominal conditions which considerably complicated the system. The position taken here is that this should not be done. Rather the merge maneuver should be aborted and the rear platoon should be returned to the "separated platoon" condition with $d_i = D_{i_o}$. When the situation stabilizes, the merge can be re-initiated. This should not require basic changes to the (feedback) control laws, rather the abort maneuver can be basically mechanized with discrete changes in commands and command limiters.

5.2.1.2 Motion Constraints

It will be assumed that there are limits on the velocity perturbation, v (from the initial reference velocity, V_o); acceleration, a; and jerk, $\dot{a}$ represented as follows:

$$v \le v_{lim} = V_{lim} - V_o \tag{5-1}$$

$$a_{limmin} \le a \le a_{limmax} \tag{5-2}$$

$$|\dot{a}| \le \dot{a}_{lim} \tag{5-3}$$

Any vehicle will have limits on speed and acceleration determined by physical capability, but the above limits represent constraints imposed on the maneuver for reasons of safety and passenger comfort. It will be assumed here that these limits are within the physical limits of vehicle performance, but this assumption will not be critical to the results which follow. While the absolute speed limit, V_{lim}, can be considered to be set by safety considerations, $v_{lim} = V_{lim} - V_o$ is really set (as low as practical) by traffic flow efficiency considerations. However, both of these limits would be set and enforced directly or indirectly by government agencies and thus should be considered firm constraints.

The situation is different for the acceleration and jerk limits because they are imposed for passenger comfort rather than safety and traffic flow. Thus it is assumed that these will be set by manufacturers rather than the government and may vary somewhat among manufacturers depending on their interpretation of market preference. It is not the purpose of this work to establish, or even propose, values for these limits, but rather the interest is in how such limits influence the maneuver and control system design. However, the following representative values will be used here.

$$a_{\text{limmax}} \approx 0.2\ g \approx 6\ \text{ft}/\text{sec}^2 \tag{5-4}$$

$$a_{\text{limmin}} \approx -0.5\ g \approx -16\ \text{ft}/\text{sec}^2 \tag{5-5}$$

$$\dot{a}_{\text{lim}} \approx 15\ \text{ft}/\text{sec}^3 \tag{5-6}$$

These values have been selected consistent with values used in PATH studies (Ref. 20) to facilitate comparisons. There is a considerable amount of data and precedent to support the acceleration data including differences between acceleration and deceleration. The jerk limits are less well defined.

5.2.1.3 Maneuver Definition

With the platoon formation task and constraints established as above, the details of the nominal merge maneuver can be developed. This could in principle be addressed as a constrained trajectory optimization problem, but only if a relevant cost function can be identified. One rather standard possibility would be to treat the problem as a minimum time maneuver. However it will be seen that elapsed times for merge maneuvers (not necessarily minimum time maneuvers) will be on the order of tens of seconds. To obtain traffic flow or other efficiencies, platoons will presumably have to remain in formation for much longer periods. Thus minimizing maneuver time is not critical; maximizing safety and passenger comfort is much more important. However cost functions for safety and passenger comfort are not firmly established as yet. Thus it is instructive to first examine the minimal time maneuver as a baseline for examination of other maneuver strategies.

Figure 5.5 diagrams the minimal time nominal merge maneuver under the speed, acceleration, and jerk constraints. Initially, time $t = 0$, the speed perturbation and acceleration are zero and thus not at their limits. It is assumed for this analysis (but not in later sections) that the jerk can be instantaneously commanded to any desired value satisfying the jerk constraint. This is comparable to the jerk command system of Figure 5.2. The time optimal solution requires that the jerk be set to its positive limit until either the acceleration or velocity constraint is reached. As will be explained below, and illustrated in Figure 5.5, the acceleration limit will likely be reached first. The solution will then move along the acceleration constraint boundary to time t_2, then again along the jerk boundary to time t_3 where the velocity constraint is reached. The solution will continue along the speed constraint for much of the maneuver to t_4 at which time deceleration will begin. It can be seen that a time optimal solution will always move along one of the three constraint boundaries.

In the sketch of Figure 5.6, the deceleration pulse does not reach the deceleration limit which is not as "tight" as for acceleration (see Eqn. 5-4 and 5-5). Thus there are two possible cases for the optimization depending on whether the acceleration pulse is "clipped" or not. Figure 5.7 shows clipping will occur when

$$v_{lim} \geq \frac{a_{lim}^2}{\dot{a}_{lim}} \tag{5-7}$$

$$= \frac{6^2}{15} = 2.4 \text{ ft / sec (1.6mph) accelerating}$$

$$= \frac{-16^2}{15} = 17.1 \text{ ft / sec (11.6 mph) decelerating}$$

It can be seen that the Figure 5.6 scenario is probably representative given the asymmetric nature of the acceleration limits.

As noted above, efficient traffic flow will tend to minimize v_{lim} which will lengthen maneuver time. Further as v_{lim} is reduced, the time in the limit speed section of the maneuver (t_3 to t_4 in Figure 5.6) will increase while the time for the acceleration pulses will decrease. It will be shown below that, to a useful first approximation, the time for the acceleration pulses can be neglected compared to the limit speed section which is equivalent to assuming instantaneous velocity changes for purposes of estimating maneuver time. Under this approximation the maneuver time is

$$\Delta t \approx \frac{D_{i_o} - D_{i_f}}{v_{lim}} \tag{5-8}$$

where D_{i_o} and D_{i_f} are, respectively, the nominal inter-platoon and intra-platoon separation distances. This relationship is shown graphically in Figure 5.8. A reference case will be used here with D_{i_o} = 100 ft, D_{i_o} = 3 ft, v_{lim} = 5 mph, V_o = 55 mph. It can be seen from Equation 5-5 through 5-8 and Figure 5.8, that the merge maneuver time is 13.2 sec assuming instantaneous velocity changes.

From Figure 5.7 it can be seen that the acceleration time history for the above reference case will be of the form of Figure 5.6, i.e., only the first pulse will be clipped. From the relations in Figure 5.7, the length of the first and second acceleration pulses will be 1.5 and 1.4 sec respectively. This confirms the assumption that Equation 5-8 and Figure 5.8, while not conservative, are adequate representations of the minimum time maneuver for this study.

5.2.2 IDEALIZED MERGE CONTROL SYSTEM

5.2.2.1 Basic Architecture

Formulation of a platoon formation (merge) control system begins with the controlled variable. This is the separation error, e_i, defined as the difference between the actual separation, d_i, and the desired separation, D_i, of the i^{th} and $i\text{-}1^{st}$ platoons (Fig. 5.5). As noted above, consideration will be limited to the two platoon case where the rear platoon executes a merge with a passive front platoon. Further there is no communication between the platoons until the merge is essentially complete so that all information flows

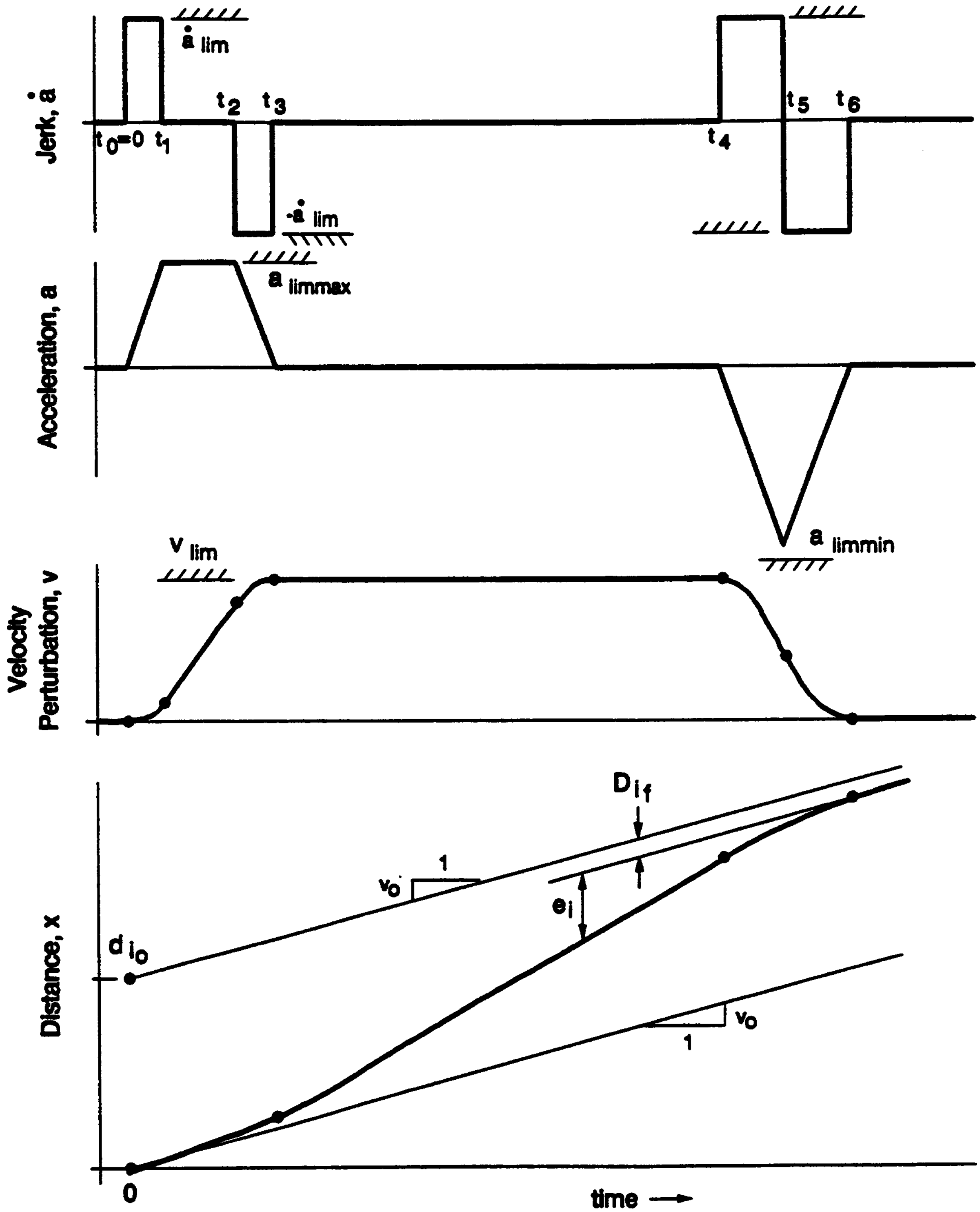
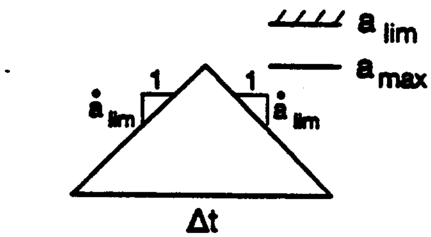


Figure 5-6. Minimum Time Platoon Merge

Case I No Clipping

no clipping if $a_{lim} > a_{max}$

$$= \frac{1}{2}\,\dot{a}_{lim}\,\Delta t$$



$$v_{lim} = \frac{1}{2}\,a_{max}\,\Delta t$$

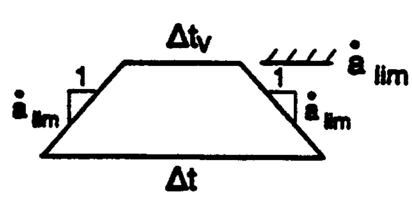
$$= \frac{1}{4}\,\dot{a}_{lim}\,\Delta t^2$$

$$\Delta t = \sqrt{\frac{4v_{lim}}{\dot{a}_{lim}}}$$

no clipping if $a_{lim} \geq \sqrt{\dot{a}_{lim}\, v_{lim}}$

Case II Clipping

clipping if $a_{lim} < \sqrt{\dot{a}_{lim}\, v_{lim}}$



$$\Delta t = \frac{v_{lim}}{a_{lim}} + \frac{a_{lim}}{\dot{a}_{lim}}$$

Figure 5-7. Interaction of Constraints in Acceleration Pulses for Minimum Time Platoon Merge Maneuvers

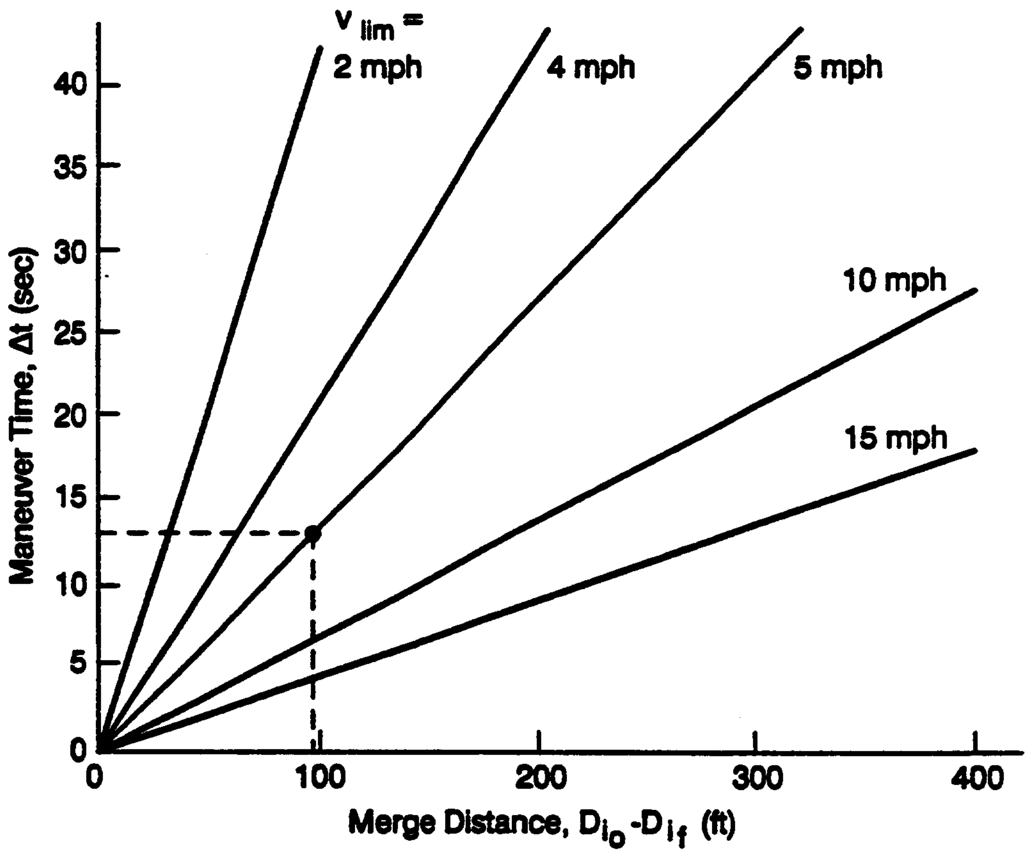


Figure 5-8. Maneuver Times for Idealized Minimum time Maneuvers

rearward and the merge controller acts like an AICC. Before the merge is initiated the desired separation is taken to be the inter-platoon minimum here set at

$$D_i = 1.0V + 19.3 \quad \text{ft} \tag{5-9}$$

At highway speeds the speed dependent term dominates and the relationship is essentially a constant 1 second headway. This is comparable to the rule of Reference 20 and the California rule (Ref. 21). The merge maneuver is to conclude with D_i set to the intra-platoon separation distance here taken to be 3 feet. It is not the purpose of this analysis to determine what the inter- and intra-platoon D_i should be, rather the interest is in relating these task parameters to control system implied requirements.

The basic control law is based on feeding back the separation error to an appropriate control point on the vehicle as indicated in Figure 5.9. This structure assumes a sensor on the rear leader capable of ranging the rear of the front platoon. The availability of range rate is not assumed. A key element of this structure is the assumption of inner control loops around the vehicle. The effective vehicle dynamics of the augmented vehicle in response to commands, i.e., it's "response-type", is thus a key factor in the merge controller design. From the standpoint of inner loop equalization for the outer loop, the effective vehicle response type should, ideally, be "k/s-like". This implies a velocity command response-type as indicated in Figure 5.9. This is achieved by a velocity command system, detailed below, which creates a low-pass characteristic, with unity low frequency gain, in the augmented speed to speed command response.

In the Figure 5.9 merge control system, the separation error command, e_{ic}, is always zero and thus the reference speed, V_o, is injected ahead of the velocity command, V_c, to insure that the nominal speed will be maintained even when the separation error returns to zero at the conclusion of a merge. This treatment is the simplest approach, consistent with our emphasis of minimal systems, but is a first approximation of more sophisticated treatments. These could include "follow-up trim" integrators and feedforward loops from the error command to the velocity command. This issue is considered further below, but here it can be noted that this issue would be of concern primarily for tracking a lead platoon which is maneuvering. However the basic merge task definition presented above calls for abort of the merge when there is significant maneuvering by the lead platoon so that the simple V_o injection is adequate for a minimal system. It should be noted that the reference speed can be varied as part of the control strategy and this would be done in emergency situations. The final element in the Figure 5.9 design is the merge controller which provides equalization for the error loop as required. The requirements for G_e will be addressed below.

5.2.2.2 Comparison with Alternative Merge Control Systems

It is useful to compare the Figure 5.9 architecture to the Figure 5.2 system. Although there are important differences, the linearized vehicle (dashed box in Fig. 5.2) can be compared to the velocity command system in Figure 5.9 and the "feedback for linearized plant" in Figure 5.2 can be compared to the separation error feedback in Figure 5.9. The response-type of the linearized plant in Figure 5.2 (between v and y) is an infinite bandwidth jerk command system. Such an infinite bandwidth system is, of course physically unrealizable, but this approximation is useful for initial consideration of the outer loop design.

Selection of the inner loop response-type is a more important consideration. The rationale behind the selection of jerk command is not discussed in Ref. 20, but it does, in principle, allow the jerk limit to be treated with a command limiter. However a command limiter is not explicit in the Figure 5.2 system. For

-- Based on inner-loop velocity command system

-- Outer-loop is separation error feedback

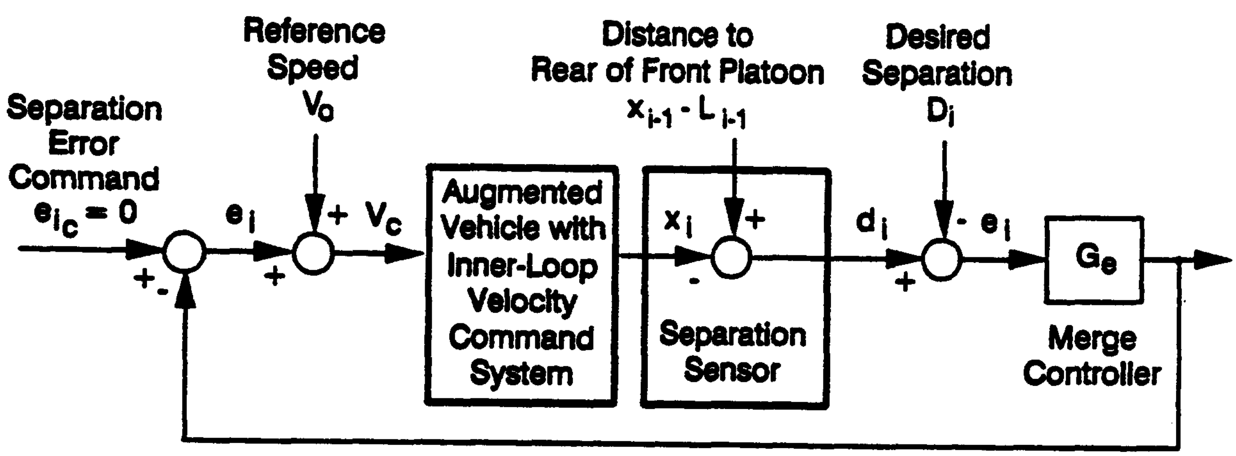


Figure 5-9. Merge Control System (Outer-Loop)

a purely automatic system, the inner loop response-type issue is not so critical and jerk, acceleration, and velocity command could each be used in some form. However there will be differences in response to noise in the outer command or outer loop feedback paths and higher derivative response-types will tend to accentuate command noise.

The AHS vehicle will be dual mode and while the manual and automatic modes could be implemented with a high degree of independence, cost considerations will tend to dictate commonality. In the manual mode the response to the accelerator pedal must appear reasonably conventional to the human driver, i.e., it must be nominally an acceleration command response-type. For the Figure 5.9 speed command system, this can be implemented by lagging (pseudo-integrating) the accelerator pedal signal to generate a V_c command. For the Figure 5.2 jerk command system this would require leading (pseudo-differentiating) the accelerator pedal signal which could result in accentuated noise problems.

Another difference between the Figure 5.9 and Figure 5.2 designs is in the treatment of the speed dependence in the desired separation function, D_i (Eqn. 5-9). In the Figure 5.2 design this speed dependence is explicitly incorporated into the feedback control law. This effectively applies the speed dependence to infinite bandwidth, i.e., D_i is treated as dependent even on high frequency disturbances in vehicle speed. There is no known empirical or theoretical basis for this interpretation; the relation can be reasonably said to apply only to the low frequency, average speed. Thus in the Figure 5.9 design, D_i is taken to be a function of V_0, a low bandwidth interpretation. This removes the D_i speed dependence from the error feedback and avoids unwarranted complexity in the control law. In actual practice this would be treated with speed scheduling using a low sample rate and/or low pass filtered speed measurement. The issue of the bandwidth of physical various relationships is generally important in this problem and will be addressed further below. However this issue is often not addressed adequately because it is inconvenient to do this using time domain methods (e.g., as used in Ref. 13 and 20). This problem is readily treated with the frequency domain methods used here.

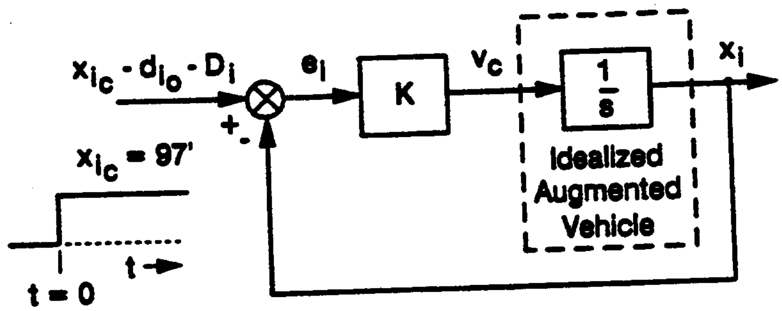
5.2.2.3 Infinite Bandwidth Assessment

It is useful to make an initial assessment of the Figure 5.9 minimal system outer error loop closure assuming an infinite bandwidth velocity command system. This is consistent with the analyses of Ref. 13 and 20 and removes the real vehicle dynamics from the problem to focus on the outer loop dynamics. With this simplification, the Figure 5.9 system becomes essentially linear and can be replaced with the linear equivalent in Figure 5.10a. The system survey sketch (Fig. 5.10b) shows that the open loop (augmented) vehicle has the ideal k/s form (90^o phase margin and no gain margin constraint) such that no compensation is required and the merge controller G_e can take the form of a pure gain K_e. It can be seen that at this level that K_e is the only control system parameter and that the closed loop bandwidth (also the crossover frequency) is K_e.

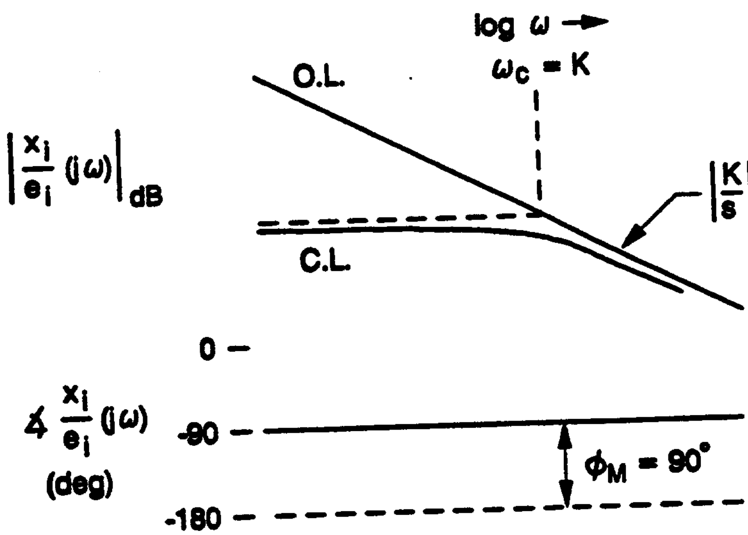
Further the closed loop separation error (Fig. 5.10c) has zero steady state gain implying zero steady state error for the step command of interest. If the lead platoon was accelerating or decelerating, there would be a steady state error, however, the task definition above calls for abort of the merge when the lead platoon maneuvers significantly. However, if the purpose here was to actually design a merge controller, the pure gain controller K_e would simply be replaced with a PI controller

$$v_c = \frac{(K_{p_e} s + K_{i_e})}{s} \tag{5-10}$$

a. Pure Gain System Block Diagram



b. Open-Loop Transfer Function, $\frac{x_i}{e_i} = \frac{K}{s}$



c. Closed-Loop Error, $\frac{e_i}{x_{i_c}}(s) = \frac{1}{1 + K/s} = \frac{s}{s + K}$

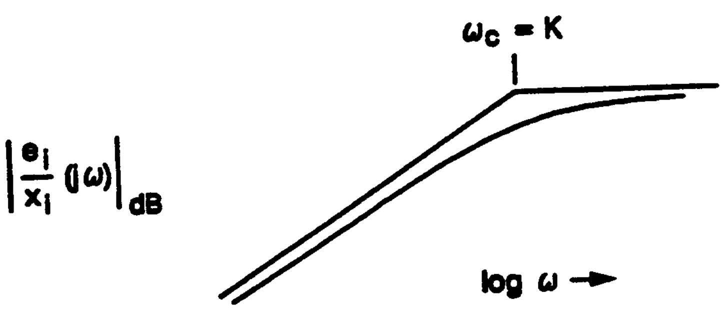


Figure 5-10. Platoon Merge Control Minimal System Pure Gain Controller with Idealized Velocity Command

where K_{ie}/K_{pe} would be set well below the crossover frequency which in turn sets the approximate closed loop bandwidth K_{pe}.

However, in keeping with the requirements focus, assessment will be limited to the minimal system of Figure 5.10. Figure 5.11 shows the system response in a merge maneuver initiated from the minimum separation distance at 55 mph. This corresponds to a step change in D_i from the 100 foot inter-platoon separation to the 3 foot intra-platoon separation. It can be seen that general character of the maneuver is exponential as is to be expected from a first order system. The exponential separation error decay is desirable in that it avoids overshoot that could lead to collision. The exponential character of the speed response is distinctly different from that of the minimum time solution (Fig. 5.6). The time for the maneuver (roughly 3-4 time constants or 15-20 sec) is somewhat longer the idealized minimum time maneuver (Fig. 5.8) if the comparison is made based on the maximum speed perturbation in Figure 5.11.

However, it was noted above that the minimum time solution is a reference point but not a design objective. The fact that the Figure 5.11 maneuver time is short compared to platoon "dwell" time is more important. As should be expected the maneuver time can be reduced by increasing the system bandwidth by increasing the gain K_e. But this will also increase the peak velocity. Further the Equation 5-1 v_{lim} implies a limit on the peak velocity perturbation

$$v_{peak} = v(0^+) = K_e(d_{i0} - D_{if}) \tag{5-11}$$

which in turn implies a limit on the bandwidth (K_e). However it will be shown below that this problem may be readily dealt with command limiters which are standard control system elements.

The acceleration and jerk are well within their respective limits except at t = 0 where both are infinite. This latter situation is an artifact of the infinite bandwidth approximation of the augmented vehicle model. This will not occur with a realistic vehicle model as will be seen shortly. The peak (for t > 0) acceleration and jerk increase with, respectively, the square and cube of the bandwidth. Further peak acceleration and jerk will both increase roughly with the nominal speed V_o due to the D_{io} speed dependence. However, as will be seen shortly, these variables are quite sensitive to real vehicle effects.

5.2.3 VELOCITY COMMAND SYSTEM

5.2.3.1 Linear Analysis and Design

The initial development of the platoon merge control system (Fig. 5.9) assumed that the inner loop velocity command system was ideal with infinite bandwidth. This idealization will now be relaxed so that the effects of the vehicle dynamics can be introduced and examined. This will be done first with a linear model and frequency domain analysis to identify the key relationships. Then the nonlinear vehicle effects will be considered systematically.

The nonlinear longitudinal equation of motion from Ref. 23, Table 1, can be linearized about the steady reference condition ($V = V_o$) resulting in

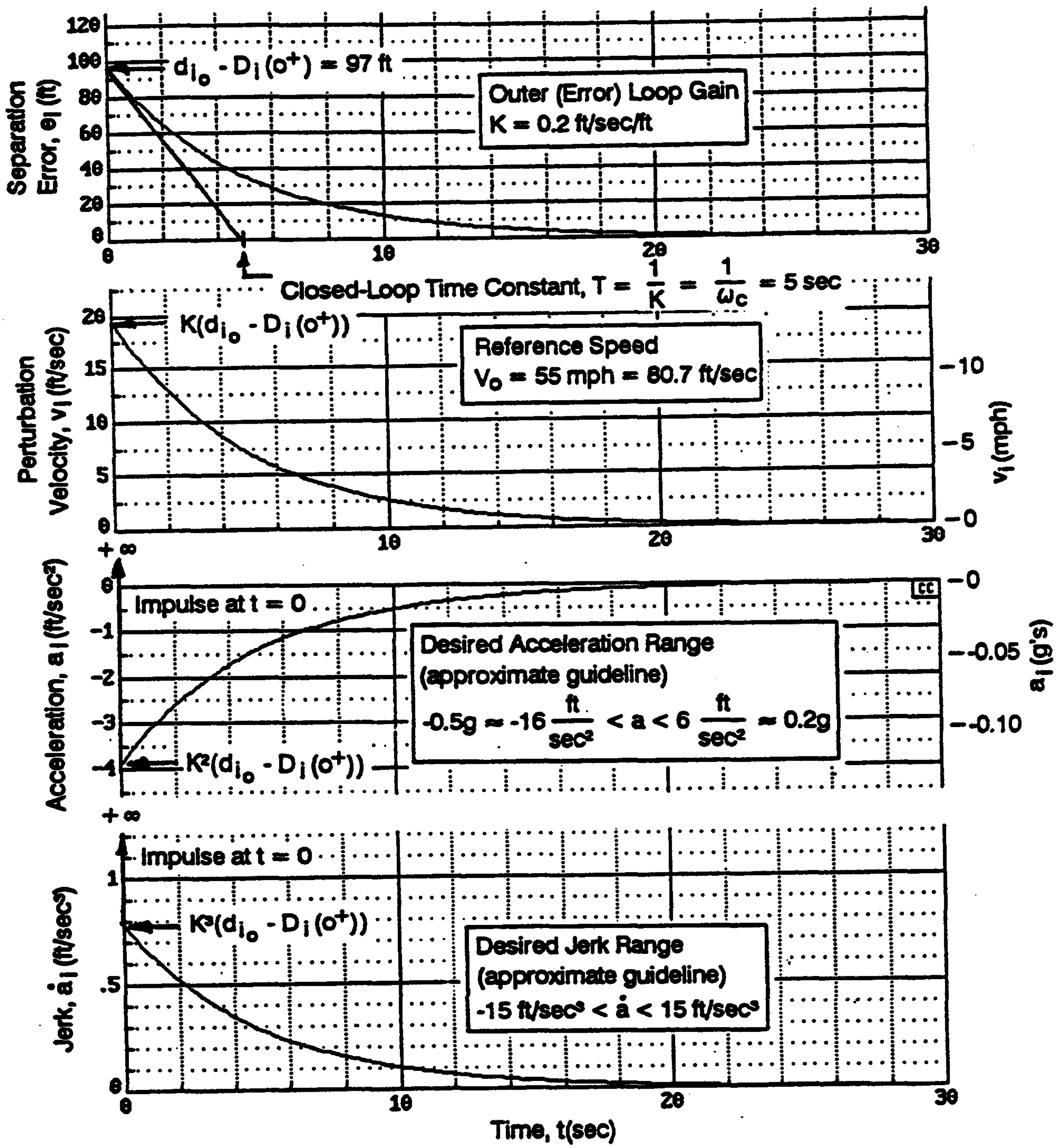


Figure 5-11. Platoon Merge Maneuver with an Ideal (Infinite Bandwidth) Velocity Command System (Variables are for the Leader of the Merging Platoon)

$$\dot{v} = X_v v + X_{\Delta T_d} \Delta T_d + X_{\Delta T_b} \Delta T_b \quad \text{where}$$

$$X_v = -4gbcV_o^{c-1} - \frac{V_o A_f C_D}{mh}$$
$$X_{\Delta T_d} = \frac{1}{mh}$$
$$X_{\Delta T_b} = -\frac{1}{mh} \qquad (5\text{-}12)$$

The speed to drive torque transfer function is obtained by LaPlace transforming the above equation.

$$\frac{v}{\Delta T_d}(s) = \frac{X_{\Delta T_d}}{(s - X_v)} \qquad (5\text{-}13)$$

A first order transfer function approximation of the engine/drivetrain dynamics is

$$\frac{\Delta T_d}{T}(s) = \frac{R_g T_{e\max}}{(T_T s + 1)} \qquad (5\text{-}14)$$

Thus the linearized unaugmented longitudinal vehicle dynamics can be summarized as in Figure 5.12. The essence of the longitudinal vehicle dynamics is characterized by the speed mode, the first order pole (eigenvalue) at X_v in the Bode plot. Whatever nonlinearities or uncertainties exist in the vehicle dynamics can be viewed, to a first approximation, as movement in the speed mode pole. In general the speed mode will be well below the engine mode frequency.

The essence of the vehicle dynamics can thus be seen in the literal factor for the speed mode (Fig. 5.12). This is determined from the derivatives of the drag forces, aerodynamic drag and rolling resistance, with respect to speed as shown in Figure 5.13a. The variation of the rolling resistance with speed is more uncertain than that of the aerodynamic drag and the variation shown in Figure 5.13a is probably extreme. The X_v stability derivative is plotted as a function of speed in Figure 5.13b. This shows that the first order effect of the drag nonlinearities is to increase the speed mode frequency as the nominal speed increases.

The velocity command system design can now be examined with linear analysis (Fig. 5.14). From the open loop frequency response of the speed to throttle transfer function ($|G(j\ \ )|$ and its associated asymptotes in the "system survey" of Figure 5.14.) it can be seen that there is a fairly broad region of k/s between the speed and engine modes. A pure gain speed loop closure is thus a possibility in this region. The first consideration is the required closed loop bandwidth for the velocity loop. Establishing this bandwidth requirement, in some generic form, will be a key requirement issue for AHS. From general experience with vehicle control we can expect that this bandwidth requirement should be below 1 rad/sec. It can be seen, e.g., from the Bode root locus, $|G(\ \ )|$, (Ref. 25) in Figure 5.14, that bandwidths up to 1 rad/sec can be supported with negligible coupling between the speed and engine modes. Higher bandwidths could be achieved, but the speed and engine modes would couple to form a second order mode. Additional

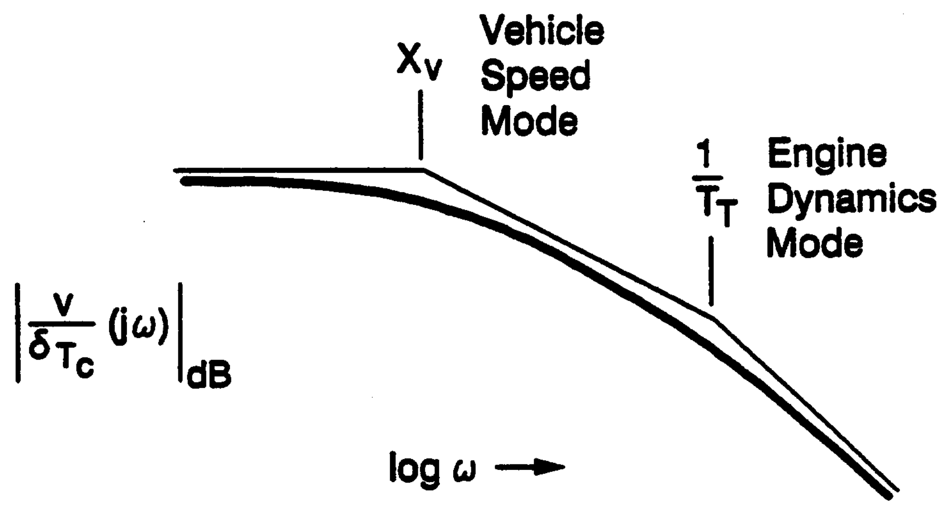
- **Transfer Function**

$$\frac{V}{\delta_{T_C}}(s) = \frac{X_{\delta_T}/T_T}{(s + X_V)(s + 1/T_T)}$$

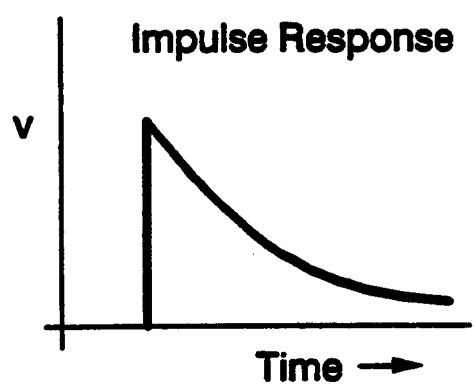
- **Literal Approximate Factors**

$$X_V = -4gbcV_o^{c-1} - \rho V_o A_f C_D/m$$

- **Bode (Magnitude) Sketch/Frequency Response**



- **Time Histories**



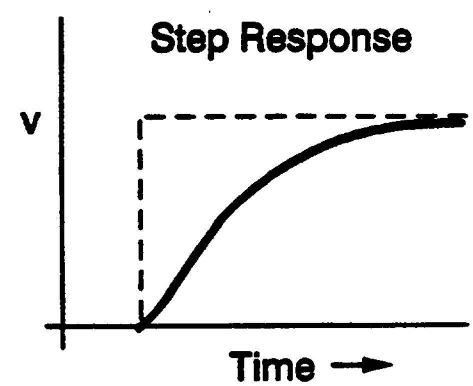
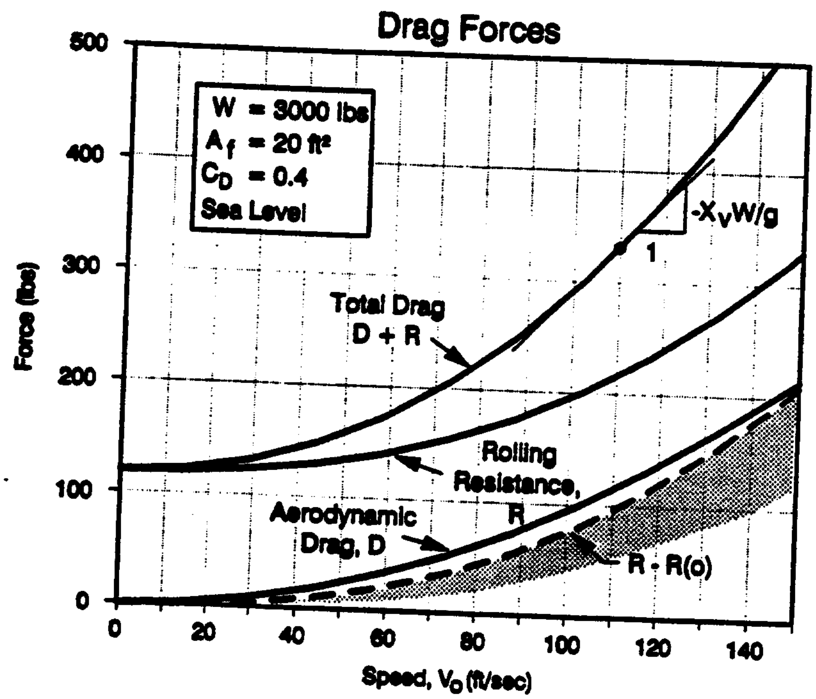


Figure 5-12. Linearized Speed-to-Throttle Response Dynamics for "Bare" Car

a. Both Aerodynamic and Rolling Drag Vary With Speed



b. The Speed Mode in the Linear Model is Related to the Slope of the Drag vs Speed Curve

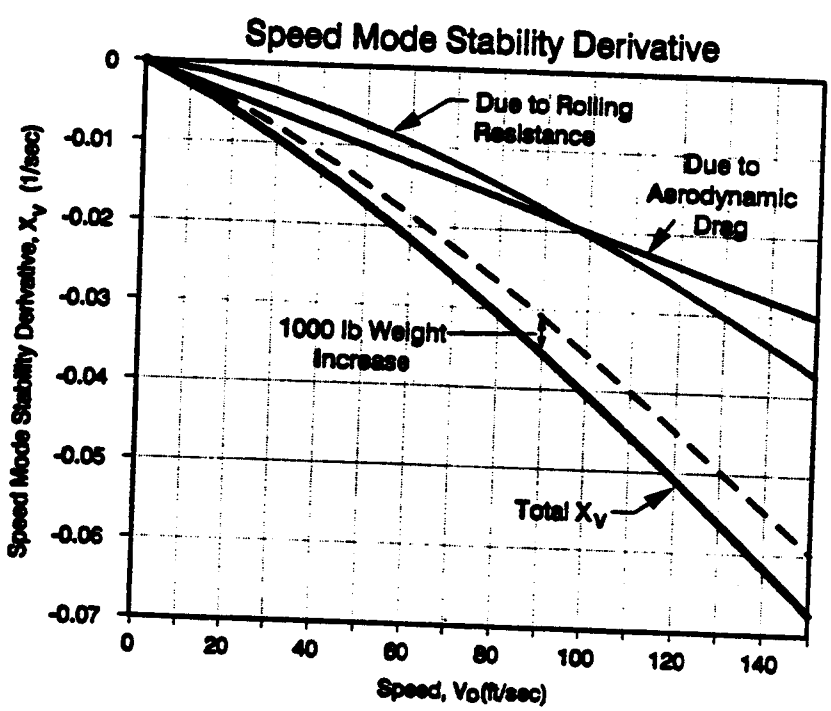
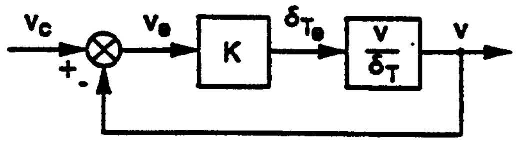


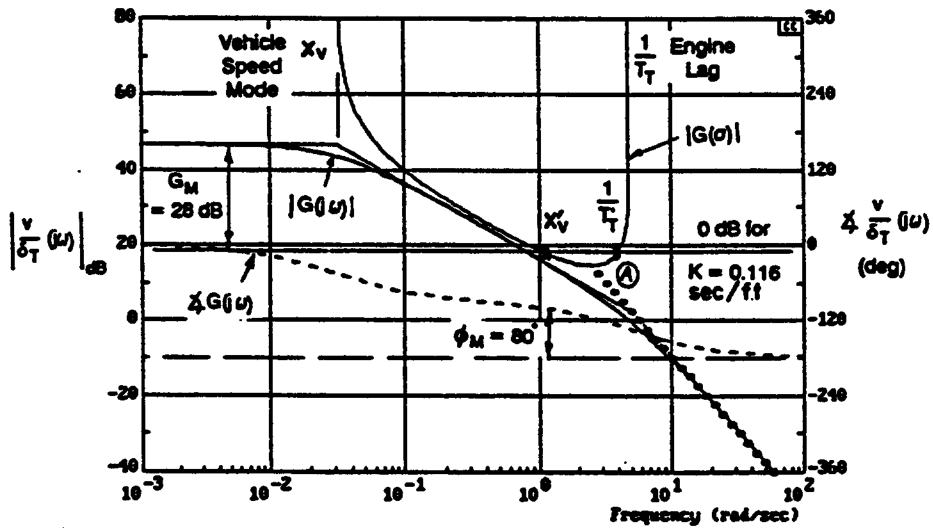
Figure 5-13. Effect of Drag Forces on Vehicle Dynamic Speed Mode

- Block Diagram



$$G(s) = \frac{V}{\delta_T}(s)\Big|_{O.L} = \frac{33.44}{(s + 0.0312)(s + 5)}$$

- Bode Root Locus



- Conventional Root Locus

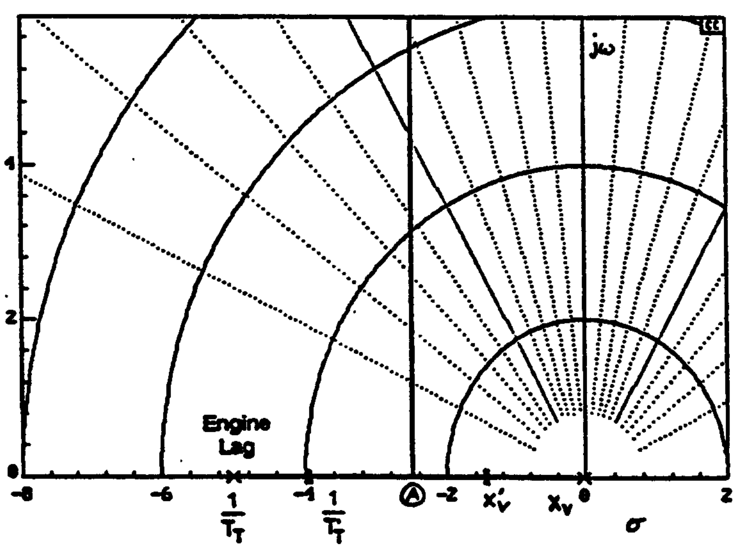


Figure 5-14. System Survey of Pure Gain Speed Command System

high frequency lags could reduce the phase margin enough to create an undesirable low damping ratio. These considerations set implied requirements on any inner loop engine control, but the 5 rad/sec engine lag here does not appear problematical.

The "shelf" in $|G(j\ \ )|$ below the speed mode indicates a potential command following problem for a pure gain closure. If the purpose here was to actually design a speed controller, this problem would be treated routinely with a PI controller replacing the pure gain K_v. The lead in the PI would be roughly scheduled with the speed based on the literal factor and everything would work just fine. But in keeping with the "minimal system" approach to requirements issues, the pure gain speed loop will be maintained. The problem then becomes setting a compromise between low frequency gain margin and bandwidth. The compromise shown, K_v = 0.116 sec/ft, has enough potential problems to be worth pursuing in a requirements investigation.

The closed loop response of the pure gain velocity command system to a 1 ft/sec velocity command step (Fig. 5.15) shows the basic connections between the frequency and time domain. The rise time is roughly the inverse of the bandwidth as would be expected. The steady state droop is due to the finite low frequency gain margin ($G_M(0)$ = 28 dB in Fig. 5.14).

5.2.3.2 Inner Loops for the Velocity Command System

There is an additional aspect of inner loop control which is very important in modeling the vehicle dynamics of automobiles for platoon control studies, but which has not been routinely addressed in any of the models presented in Ref. 13, 20, 21, or 22. These are the specialized control systems which have been introduced into production automobiles in recent years. Specifically these include anti-lock braking systems (ABS), active traction control (Acceleration Slip Regulation, ASR) and a variety of engine management systems. There are other specialized systems, such as active suspension, but these generally have only secondary influence on the longitudinal control problem.

ABS initially appeared on higher priced cars, but are currently moving toward standard equipment status for almost all cars. ASR is now at the point where ABS was several years ago and can be expected to follow a similar growth of market acceptance. While ABS and ASR are fundamentally intended to address problems of vehicle dynamics, engine management systems address a range of issues besides vehicle dynamics, particularly emission control and fuel economy.

It can be expected that these systems will evolve and become as accepted as the automatic transmission by the time AHS systems are introduced. Because they fundamentally affect vehicle dynamics they must be accounted for in AHS vehicle dynamic models. However, the current systems are designed for manually controlled vehicles, so a critical question is how these systems should be designed for dual mode vehicles which will operate under both manual and automatic control.

It can be reasonably expected that these systems will be modified and extended to support AHS as well as manual operation. It is speculated here that this will evolve to an active powertrain torque command system that will integrate many of the current ABS, ASR, and engine management functions plus support AHS by providing ideal inner loop equalization for a velocity command system. The ideal equalization results because vehicle speed is the integral of powertrain torque to a first approximation. In the following sections the pertinent features of ABS, ASR and engine management function will be briefly

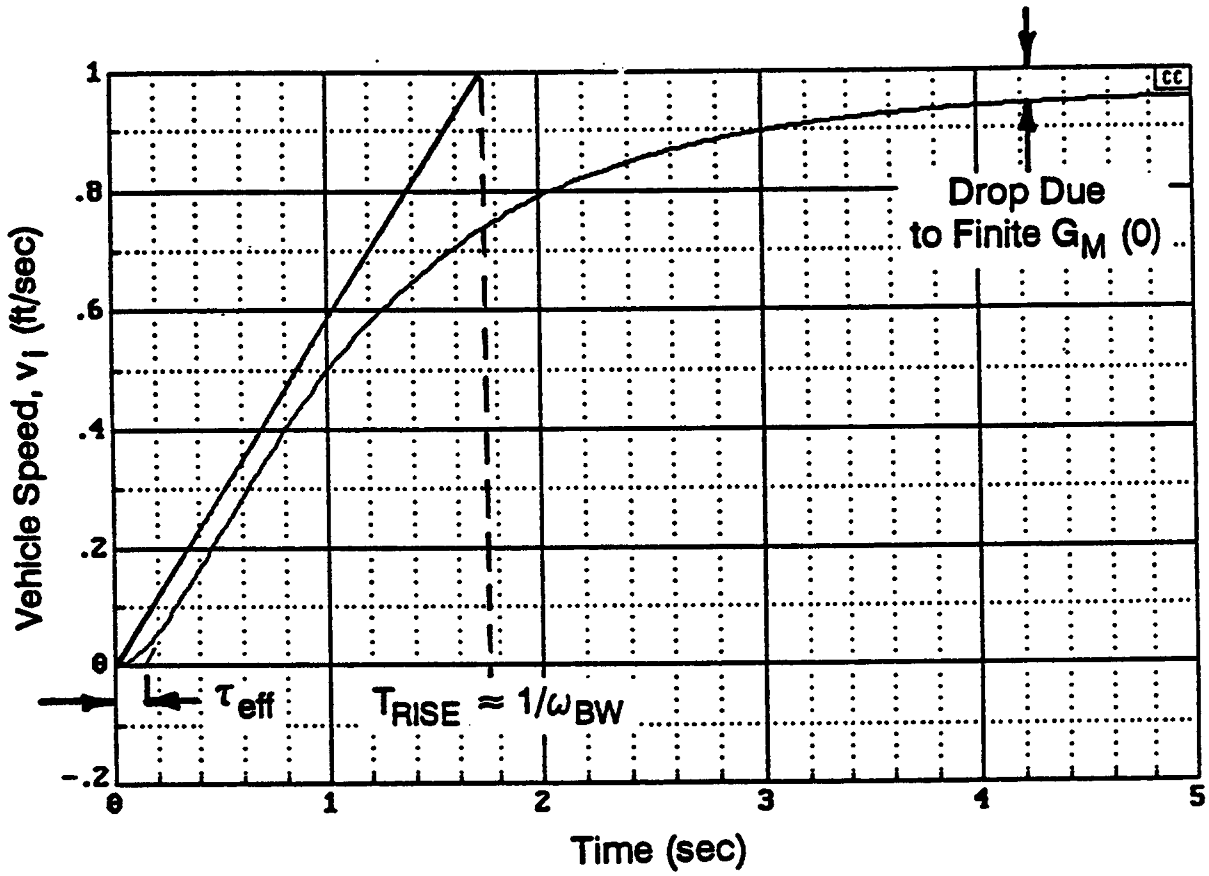


Figure 5-15. Vehicle Speed Response to a 1 ft/sec Speed Command with the Pure Gain Speed Command System

reviewed and then the basic architectural features and requirements for an integrated powertrain torque command system will be considered.

a. Engine Modeling and Dynamics

Figure 5.16 displays a representative dynamic model of a gasoline automobile engine similar to models in Ref. 22, 28-30). Certain elements are functions of several variables and/or strongly nonlinear. Certain engine management and other features less relevant here, such as exhaust gas recirculation and exhaust oxygen sensing are not shown. The Figure 5.16 model has three states: one associated with lag in the fuel supply, one associated with the influence of manifold pressure on flow through the throttle, and one associated with the engine rotational dynamics. The throttle is the primary control because it directly controls manifold pressure which in turn controls brake mean effective (cylinder) pressure (BMEP) and thus the basic torque function. The air-fuel ratio and spark advance are normally controlled automatically to optimize performance and fuel economy and to avoid detonation.

Detailed modeling and analysis of reciprocating engines is a complex and highly empirical process beyond on the scope of this work. The modeling problem is even more complex if the dynamics are to be accurately characterized. This follows because many of the key relationships are defined only under steady-state conditions and even then largely empirically. The corresponding frequency responses (or describing functions for strongly nonlinear functions) are rarely determined. For example the engine friction function in Figure 5.16 is shown to be a function of engine speed, but the data supporting such empirical functions would generally be traceable to engine dynamometer tests where measurements would be made at a series of steady engine speeds. Thus while these steady-state functions of engine speed are included in engine models (Ref. 28, 29) there is no guarantee that they will adequately represent higher frequency engine dynamics.

b. Engine Torque Control

The essence of an engine torque control system would involve feedback of an engine net torque measurement/estimate to the throttle control point and perhaps to fuel and ignition control points as well. Measuring engine net torque is problematical. Loadcells for torque measurement are readily available, but these would have to be mounted in the rotating drivetrain between the flywheel and torque converter. It would probably be more practical to use a model-based torque estimate exploiting more readily-obtained measurements. These might include measurements currently available in engine management systems such as engine speed, manifold pressure, throttle position, vehicle speed, and transmission gear. These might be augmented with specialized measurements such as longitudinal acceleration and engine mount loads.

Closure of the torque-to-throttle loop might be facilitated with an inner manifold pressure-to-throttle loop. The key measurement, manifold absolute pressure (MAP), is readily available in engine management measurements. The major complexity in designing an inner pressure control loop is the strongly nonlinear pressure ratio influence (PRI) function (Fig. 5.16). However, this function is well understood in terms of basic gas dynamics (Ref. 29) and essentially a function of the controlled variable, MAP, alone. Thus the PRI function constitutes a simple, frequency invariant (Ref. 19) nonlinearity which might be practical to linearize with inverse model strategies. It is reasonable to expect that the closed loop bandwidth of a MAP command inner loop could be set well above the basic engine speed mode which is fundamentally determined by the engine rotational inertia. This follows because the throttle/manifold dynamics depend on gas dynamics (the throttle butterfly inertia is negligible compared to the engine rotational inertia) and high bandwidth pressure sensors are readily available.

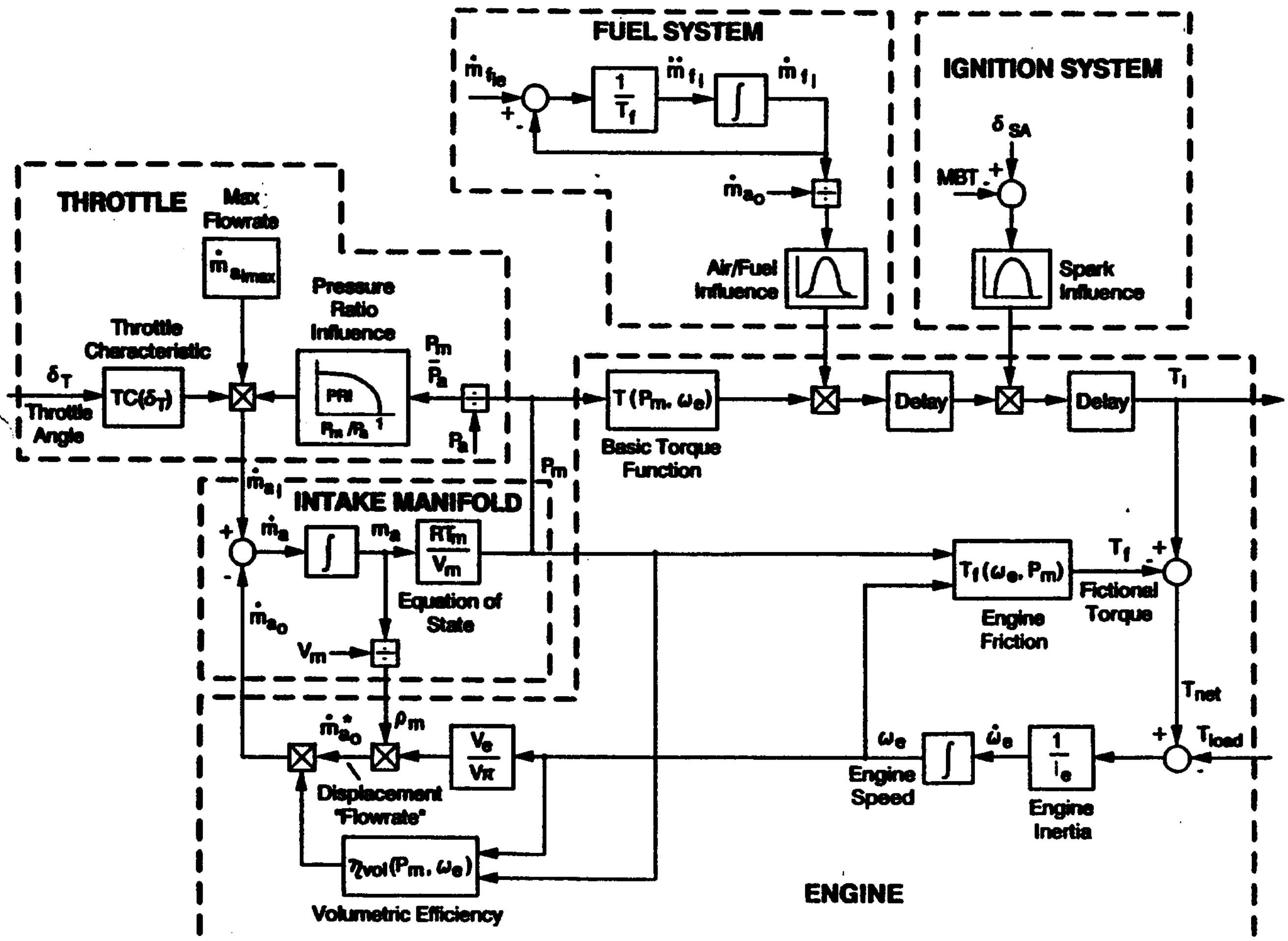


Figure 5-16. Basic Elements of Automotive Engine Model

Thus it appears feasible that an engine torque command system could be developed, likely using an inner manifold pressure loop. Perfect linearity of the closed loop torque response to command would not be required. It might be feasible to set the bandwidth of the torque command system somewhat above the open loop engine speed mode frequency. However it is not clear that this would be either necessary or desirable. Rather, the primary value of the torque command system is in essentially eliminating the variation, uncertainty, and nonlinearity in control effectiveness of the open loop torque to throttle transfer function. That is, with a torque command inner loop, the velocity command loop will "see" a nearly ideal 1/s open loop frequency response out to the torque command bandwidth.

c. ABS/ASR

Antilock Brake Systems (ABS) (Ref. 31, 32, 33) operate by reducing the brake torque on wheels that exceed a specified slip (or "skid") ratio. This function is particularly valuable when the road surface friction coefficient is reduced due to rain, snow, ice or other environmental conditions. ABS mechanizations vary in detail and complexity but there are certain common basic features. Sensors mounted near the wheels determine wheel rotational rate and compare this with an estimate of what the rate, including time rate of change, should be. The estimate of the nominal wheel speed is generally based on averages for the other wheels. If the rotation speed of a given wheel is sufficiently low and/or decelerating such as to indicate that the slip ratio limit will be exceeded, the ABS reduces the brake pressure to the wheel at high frequency to avoid lockup.

Active traction control (ASR) (Ref. 31, 34, 35) has some basic similarities and even commonality with ABS. ASR systems effectively estimate longitudinal slip ratio at each drive wheel during acceleration. If the slip ratio exceeds the level at which wheel spin would occur, the ASR reduces the torque to the wheel momentarily. Some ASR reduce wheel torque by applying the brakes, but other options are available and are used in various combinations. These include actuation of differential locks, ignition spark retard, fuel injection cutout, and throttle modulation. Thus ASR tend to be more complex, and hence more expensive, than ABS and require greater integration with the engine management system.

Both ABS and ASR are active limiting systems, i.e., they operate only when the vehicle reaches some limit representing significantly nonlinear behavior and extreme operational conditions. Under the more normal conditions of routine vehicle operation, which would include nominal AHS platoon maneuvers, ABS and ASR systems have no effect. Even under the conditions (e.g., icy roads) that cause ABS/ASR to operate, they do not eliminate the influence of low surface coefficient. Braking and acceleration performance will still be reduced as the surface coefficient is reduced, but for any given coefficient ABS/ASR will insure that the vehicle can achieve performance near the theoretical limits. Thus the AHS system, at some level, would have to accommodate weather induced reductions in surface coefficient by reducing the speed limit. The presence of ABS and ASR also have a direct impact on vehicle dynamic modeling. Specifically they insure that the common assumption (e.g., Ref. 22, 23) of negligible wheel slip is justified.

d. Powertrain Torque Command

Because ABS/ASR systems are limiters, they are distinctly different from the powertrain torque command system of envisioned here for AHS applications. The torque command system will affect the torque response to command over the entire range of the command whereas the ABS/ASR acts only at the control limit[3]. However the control effectors, and, to a lessor extent, the sensors required to

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[3] Analogies and precedents exist in modern fly-by-wire aircraft flight control systems such as those on the F16 fighter. Stall or angle of attack limiters are analogous to the ABS/ASR function. Stability

mechanize ABS/ASR should be very similar to those required to extend the torque command system from the engine output (discussed above) all the way to the drive wheel torque. Direct control of drive wheel torque provides the ideal inner loop for implementing velocity command system. Again a key difficulty will be the measurement/estimation of the wheel torque. As for the net engine torque at the flywheel, adequate model-based estimates of wheel torque can probably be made based on available ASR/ABS, engine and transmission measurements (e.g., wheel speed) plus some special measurements, e.g., structural stress measurements near the brake caliper mounts and/or longitudinal acceleration.

It would probably be possible to develop adequate AHS control systems without the use of wheel torque command systems for inner loop equalization. However, since actuators, effectors and sensors, which would be largely suitable for mechanizing torque command, will be available from engine management and ABS/ASR, torque command is likely to be a desirable and cost effective strategy for mechanizing AHS control systems. Without this commonality, torque command mechanization might well not be cost effective. A key advantage of a torque command system is that it would deal with the key uncertainties, variations and nonlinearities in the vehicle dynamics in the inner most loops making the outer loop design problem relatively simple and straightforward. This is consistent with long established good practice in vehicle control system design.

Since most of the complexity of AHS control system design would be in the torque command system under this strategy, the development of such systems would be a significant activity. Thus the torque command system cannot be developed or described in detail here. But from the requirements perspective here this is not critical. Instead the concern is with characterizing the implied requirements for the torque command system. Fundamentally the torque command system will have a basic "servo characteristic", i.e., it will be reasonably linear and the wheel torque-to-torque command frequency response will be close to unity from zero frequency to some bandwidth beyond which the torque will roll off. The details of the behavior beyond the closed loop bandwidth are not critical other than that there should not be lightly damped, second order modes (e.g., problematic structural modes are a possibility in a drivetrain).

This torque-to-torque command characteristic can be represented with a first order lag transfer function with a unity low frequency gain. Phase lag from any high frequency dynamics beyond the first order lag can be represented with a pure time delay. The key nonlinearities within the torque command system, including all of those in the engine, drive train and the wheel roadway interface (except rolling resistance), can be represented with command limits on the torque command. The adequacy of this representation is implied by the general linearizing effect of feedback and the limiting function of ABS/ASR systems. Thus the torque command system can be represented as

$$T_W = \begin{cases} T_{W\max} & \text{if } T_{Wc} > T_{W\max} \\ \dfrac{T_{Wc}(s)e^{-\tau s}}{(T_T s + 1)} & \text{if } T_{W\min} \le T_{Wc} \le T_{W\max} \\ T_{W\min} & \text{if } T_{Wc} < T_{W\min} \end{cases} \tag{5-15}$$

Long experience with vehicle control system requirements definition indicates that, if an inner loop cannot be approximated as above, the actual inner loop design likely will not be satisfactory.

5.2.3.3 Nonlinear Assessment of the Velocity Command System

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and Command Augmentation Systems (SCAS) are analogous to the automotive torque command system.

a. Nonlinear Model and Simulation

A simulation of the minimal platoon formation control system, with pure gain velocity command and powertrain torque command inner loops, was developed for assessment of the effect of nonlinearity. The velocity command with torque command inner loop is shown in Figure 5.17. The longitudinal vehicle dynamics includes the nonlinear aerodynamic drag and rolling resistance functions. The torque command system is set to a 5 rad/sec bandwidth (T_T = 0.2 sec) with zero time delay so that it is equivalent dynamically to the open loop powertrain model used above (Fig. 5.12). In principle the open loop engine would exhibit greater uncertainty, variation, and nonlinearity, but this was not treated above because a powertrain torque command system would significantly reduce these problems.

The K_v gain in the Figure 5.17 simulation is set to produce a speed loop closure corresponding to that in Figure 5.14. Accounting for the differences in the low frequency gains between the open loop and closed loop (torque command) powertrains, K_v = 72.34 ft-lb/ft/sec when the torque command system is used (Fig. 5.17). The velocity command system must provide for trimming the torque command as the velocity error goes to zero. If the purpose here was to design an actual velocity command system, a trim mechanization involving an appropriate combination of velocity command feedforward to the torque command point and/or a follow-up trim integrator would be used. In keeping with the minimal system requirements perspective, here (Fig. 5.17) the trim torque at the reference speed is simply injected before the wheel torque command. This is consistent with the treatment of velocity trim (Fig. 5.9).

b. Velocity Command System Assessment Without Torque and Speed Command Limits

For the initial assessment, the wheel torque and velocity command limits are opened (removed). Figure 5.18 compares the nonlinear and linearized closed loop velocity command system responses to 1 ft/sec and 10 ft/sec step velocity commands. The linearized response is comparable to Fig. 5.11. It can be seen that, even at the larger amplitude command (v_c = 10 ft/sec), there is negligible quantitative difference between the linear and nonlinear response. More importantly there is no qualitative difference between the linear and nonlinear responses. This is to be expected since the only nonlinearities at this point are the drag variation with speed, which as noted above, are particularly benign in their dynamic effect.

However nonlinear systems can be quite sensitive to the specifics of their inputs and/or initial conditions. Thus examination of a few step responses may not reveal the true character of a nonlinear system. A more insightful assessment, which can be made for this second order velocity command system, is a phase plane diagram (Ref. 19). Figure 5.19a compares the phase planes of the linear and nonlinear velocity command systems. The corresponding nonlinear time histories are shown in Figure 5.19b for reference. It can be seen from the phase plane that there is no significant quantitative difference between the linear and nonlinear systems. More importantly there are no qualitative differences indicating a characteristic nonlinear phenomena such as a limit cycle.

Since the nonlinearities are speed dependent, the phase planes were generated over the range of reference speeds from the design case, V_o = 55 mph, to V_o = 115 mph as shown in Figure 5.20. It should be noted that the velocity command system parameters were not scheduled with speed, they remained

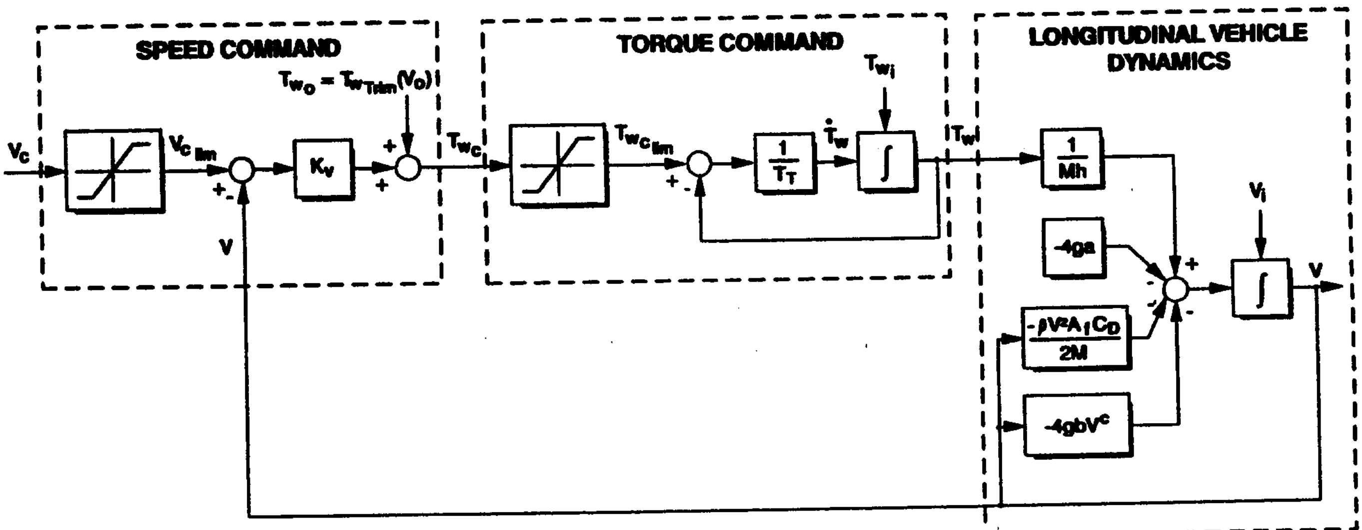


Figure 5-17. Complete Velocity Command System

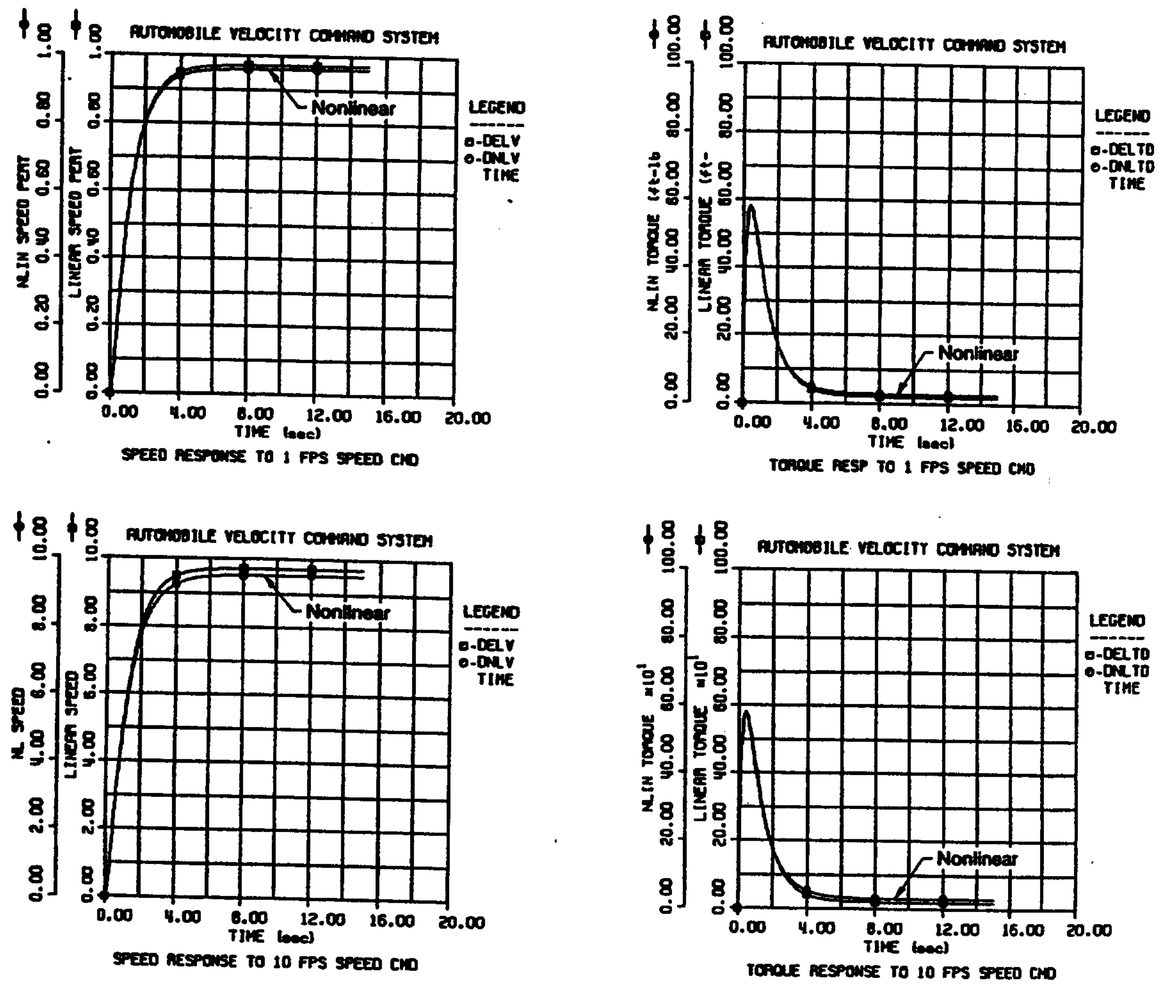


Figure 5-18. Comparison of Nonlinear and Linear Command Responses Velocity Command System without Torque or Velocity Limits

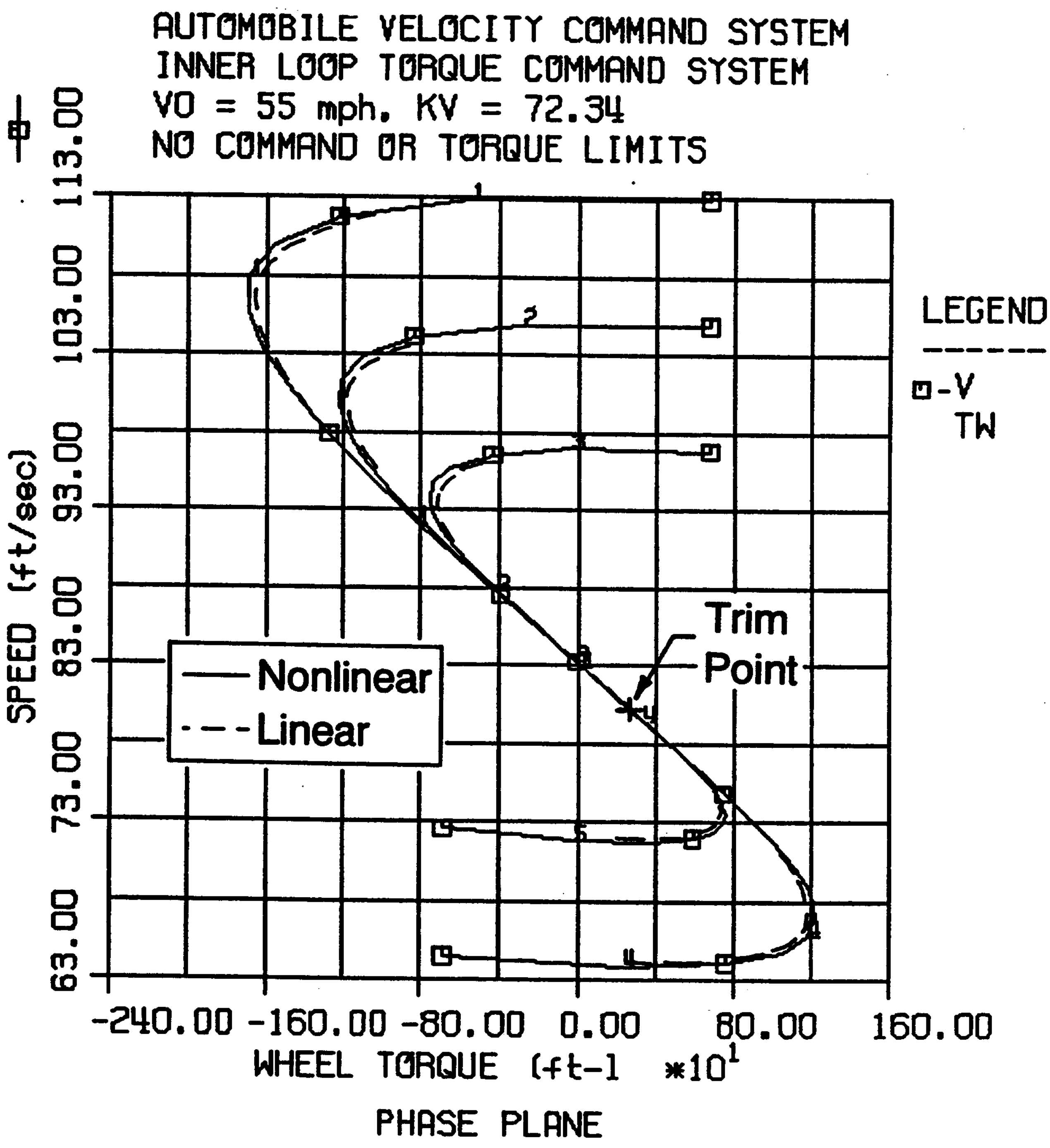


Figure 5-19a. Phase Plane Analysis of Aerodynamic Drag and Rolling Resistance Nonlinearities

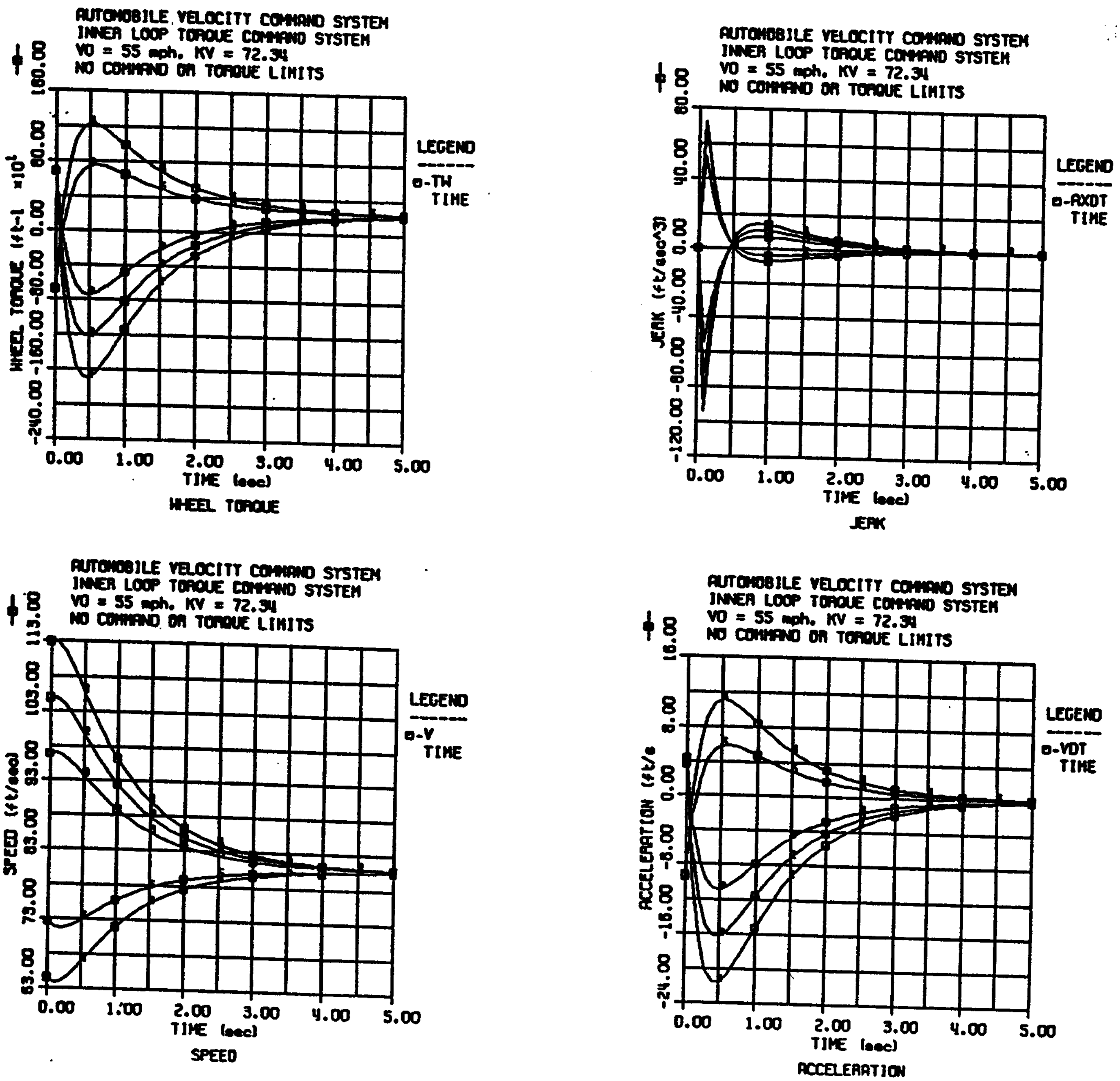

AUTOMOBILE VELOCITY COMMAND SYSTEM
INNER LOOP TORQUE COMMAND SYSTEM
VO = 55 mph. KV = 72.34
NO COMMAND OR TORQUE LIMITS
WHEEL TORQUE (ft-l ×10¹
-240.00 -160.00 -80.00 0.00 80.00 160.00
0.00 1.00 2.00 3.00 4.00 5.00
TIME (sec)
LEGEND
□-TW
TIME
WHEEL TORQUE
AUTOMOBILE VELOCITY COMMAND SYSTEM
INNER LOOP TORQUE COMMAND SYSTEM
VO = 55 mph. KV = 72.34
NO COMMAND OR TORQUE LIMITS
JERK (ft/sec^3)
-120.00 -80.00 -40.00 0.00 40.00 80.00
0.00 1.00 2.00 3.00 4.00 5.00
TIME (sec)
LEGEND
□-AXDT
TIME
JERK
AUTOMOBILE VELOCITY COMMAND SYSTEM
INNER LOOP TORQUE COMMAND SYSTEM
VO = 55 mph. KV = 72.34
NO COMMAND OR TORQUE LIMITS
SPEED (ft/sec)
63.00 73.00 83.00 93.00 103.00 113.00
0.00 1.00 2.00 3.00 4.00 5.00
TIME (sec)
LEGEND
□-V
TIME
SPEED
AUTOMOBILE VELOCITY COMMAND SYSTEM
INNER LOOP TORQUE COMMAND SYSTEM
VO = 55 mph. KV = 72.34
NO COMMAND OR TORQUE LIMITS
ACCELERATION (ft/s
-24.00 -16.00 -8.00 0.00 8.00 16.00
0.00 1.00 2.00 3.00 4.00 5.00
TIME (sec)
LEGEND
□-VDT
TIME
ACCELERATION

Figure 5-19b.

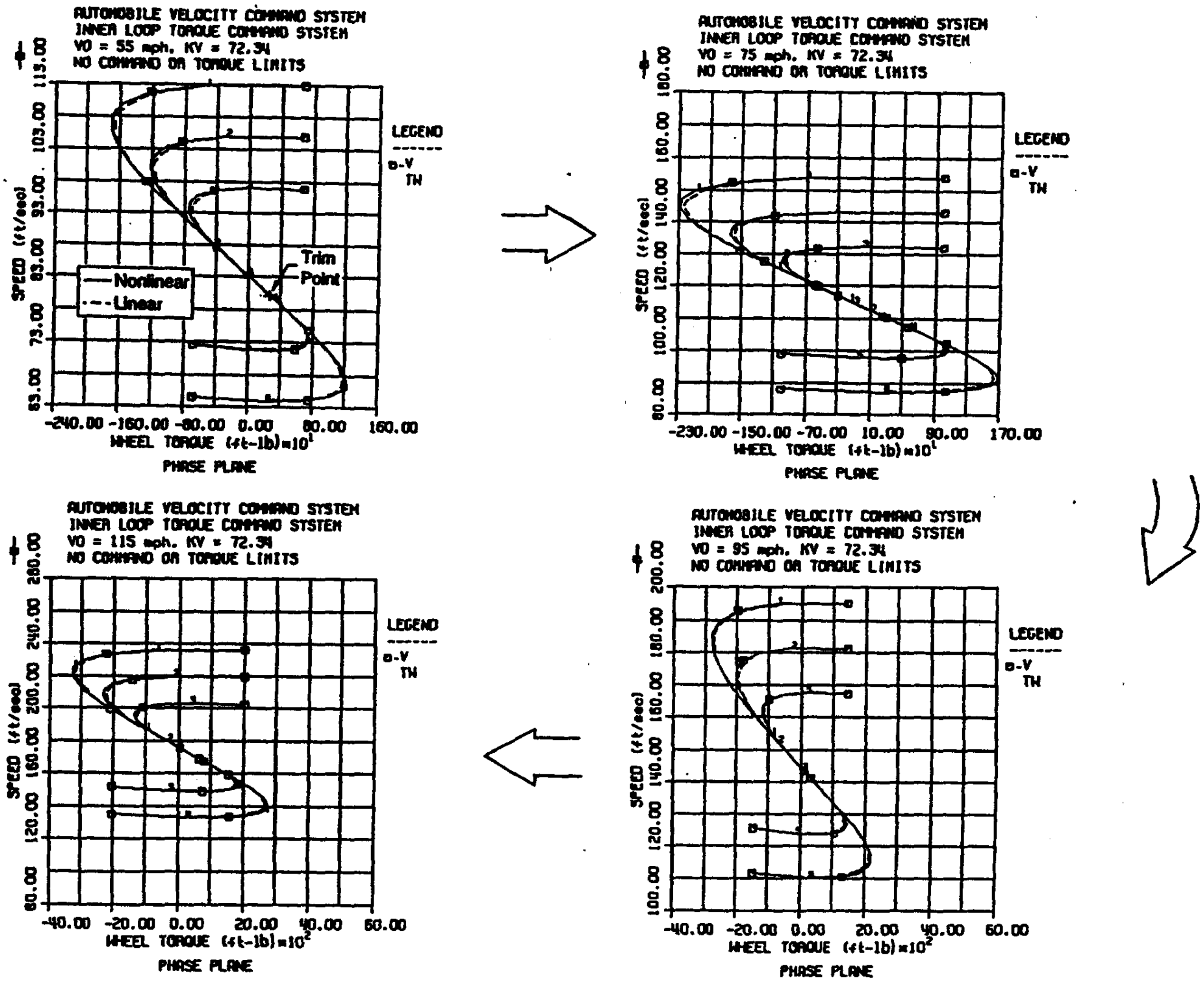


Figure 5-20. Phase Plane Diagrams of the Nonlinear and Linear Velocity Command System Without Limits

constant at the values determined for the 55 mph case. However it can be seen from Figure 5.20, that no fundamentally nonlinear phenomena arise as the speed increases and the differences between the nonlinear and linear systems remain negligible over the phase plane and over the speed range. This is in part an example of the linearizing effect of an appropriate linear feedback applied to a (mildly) nonlinear system. The assessments of Figure 5.19 and 5.20 support the view that the specific characteristics of a nonlinear system should always be carefully assessed before treating the nonlinearity with a special control system solution.

Figure 5.21 compares the acceleration and jerk characteristics corresponding to the phase plane trajectories of Figure 5.20 at V_o = 55 and 115 mph. The desired limits for acceleration and jerk are often exceeded, however the phase plane trajectories correspond to more extreme conditions than what would be encountered in normal merge maneuvers. Further the introduction of wheel torque limits, examined next, will significantly reduce jerk and acceleration response.

c. Velocity Command System Assessment With Torque Command Limits

The maximum wheel torque is the product of the maximum engine torque and the overall drivetrain gear ratio at a given speed. It is assumed here that the gear ratio is optimized to set the engine speed at the speed for maximum (full throttle) torque and that the transmission does not shift during maneuvers. The torque-engine speed curve is sufficiently flat for automotive engines so that this is not a very sensitive assumption. Under this assumption the maximum wheel torque becomes

$$\begin{aligned} T_{W_{max}} &= T_{e_{max}} R_g \\ &= \frac{T_{e_{max}} \;\; {}^{*}_{e} h}{V_o} \\ &= \frac{67{,}021}{V_o} \quad \text{ft - lb} \end{aligned} \tag{5-16}$$

The minimum wheel torque is determined by the maximum braking torque available. For normal road surface coefficients, the minimum wheel torque can be set from the assumption of a representative maximum (low speed) deceleration rate taken as 0.8 g here. For the example vehicle used here,

$$T_{W_{min}} = 2400 \;\; \text{ft - lb} \tag{5-17}$$

With significant reductions in the road surface friction coefficient under adverse environmental conditions, the above limits would ultimately be reduced even with ABS/ASR, however this situation will not be considered explicitly here.

When a velocity command system is operating within a platoon merge controller, it will probably be desirable to limit the torque command authority to levels well below the above physical limits. The idea is to set the effective torque limits to be adequate for normal maneuvering while leaving margins, particularly

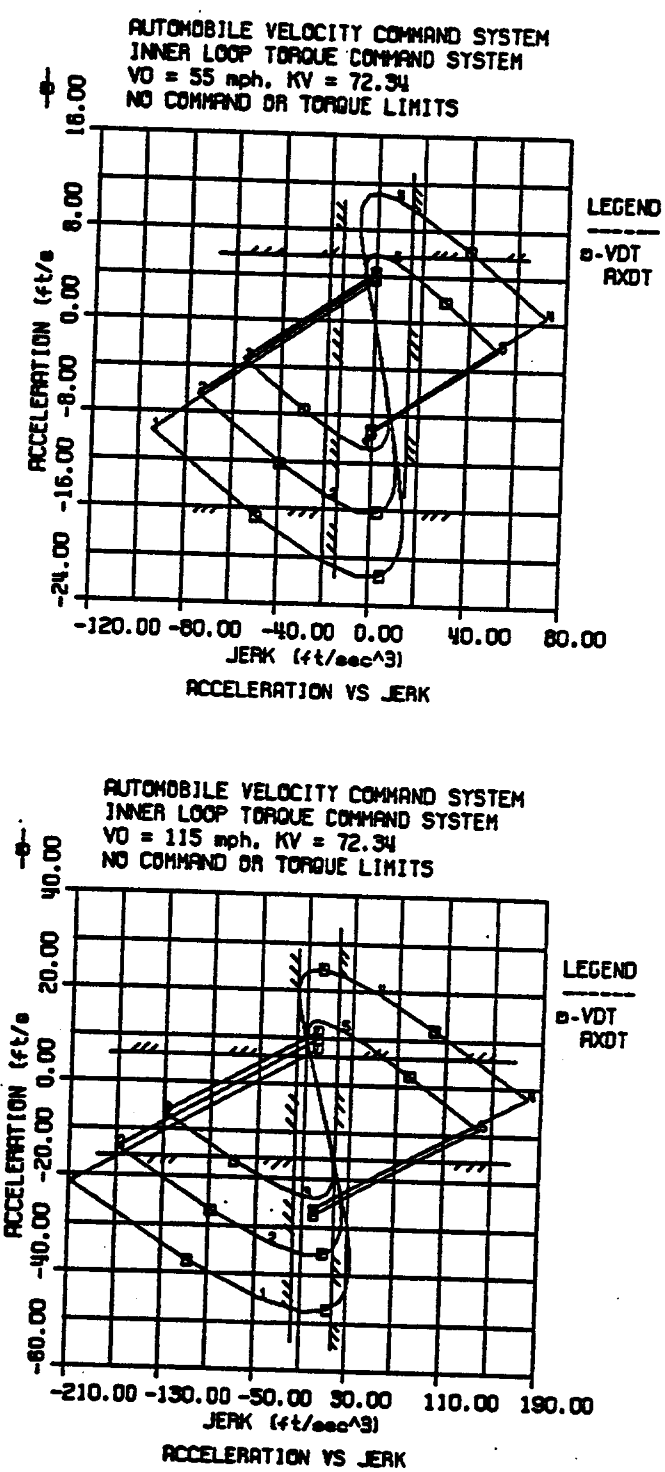


Figure 5-21. Acceleration and Jerk Trajectories

for emergency braking. In the following analyses a single authority fraction will be applied to the above physical limits; in an actual design differences in positive and negative authority would be likely.

Figure 5.22a shows the speed-torque phase plane with the physical torque limits and a 40% torque command authority compared to the unlimited case (Figure 5.19). Figure 5.22b shows the corresponding 40% authority time histories. It can be seen, as should be expected, that the control effector (torque) limits have a much greater effect on the effective vehicle dynamics than did the drag nonlinearities. However, the torque limits do not produce any nonlinear pathologies such as limit cycles. This is consistent with general experience in vehicle control that the usual problem, if any, with effector limiting is reduced performance. If the open loop vehicle were unstable (e.g., as in an actively stabilized, relaxed static stability aircraft), effector limiting could be more of a problem, but this will not be the case for automotive speed command systems.

The acceleration and jerk extremes corresponding to the torque-limited phase plane trajectories (Figure 5.22a) are reduced from those in Figure 5.22c, but they still exceed the desired levels. However, as noted above, the phase plane maneuvers are more extreme than the normal merge maneuvers which will be examined next.

5.2.4 Merge Controller with Inner Loop Speed Command

5.2.4.1 Linear Assessment

When the idealized, infinite bandwidth speed command system in the merge control system of Figure 5.10 is replaced with the linearized system of Figure 5.14, the result is as shown in Figure 5.23. It can be seen that the dynamics are somewhat more complex, and that, ultimately, the outer loop error mode would couple with the inner loop speed mode. However the effect is small at the original gain of K_e = 0.2 ft/sec/ft and this closure is still satisfactory. However the Figure 5.23 system survey does imply a minimum bandwidth for the speed command loop.

Figure 5.24 compares the time histories of the merge maneuver comparable to Figure 5.11. It can be seen that the finite speed command bandwidth has little effect on the error response and the time for the maneuver. The speed perturbation response is more physically realistic in that it starts at zero. The acceleration and jerk response in the first few seconds are more complex, but these responses will be significantly affected by the torque limits addressed next.

5.2.4.2 Nonlinear Assessment with Torque Command Limits

Figure 5.25 shows the complete platoon merge control system with the nonlinear elements including a speed command limiter. Figure 5.26a shows the time histories of the 55 mph merge maneuver for three levels of torque limit/command authority: no torque limits (corresponding to the Figure 5.24 responses), full (100%) authority, and 50% authority. The reduction from 100% to 50% authority generally has a greater effect on the maneuver than the original imposition of the physical torque limits. Reducing command authority increases maneuver time, but even with only 50% authority the increase in maneuver time is not very significant. The maximum acceleration and jerk magnitudes are directly reduced as the command authority is reduced.

Figure 5.26b shows the variation of speed with separation error. This plot is not actually a phase plane plot because the dynamics are higher than second order. The corresponding variation of acceleration

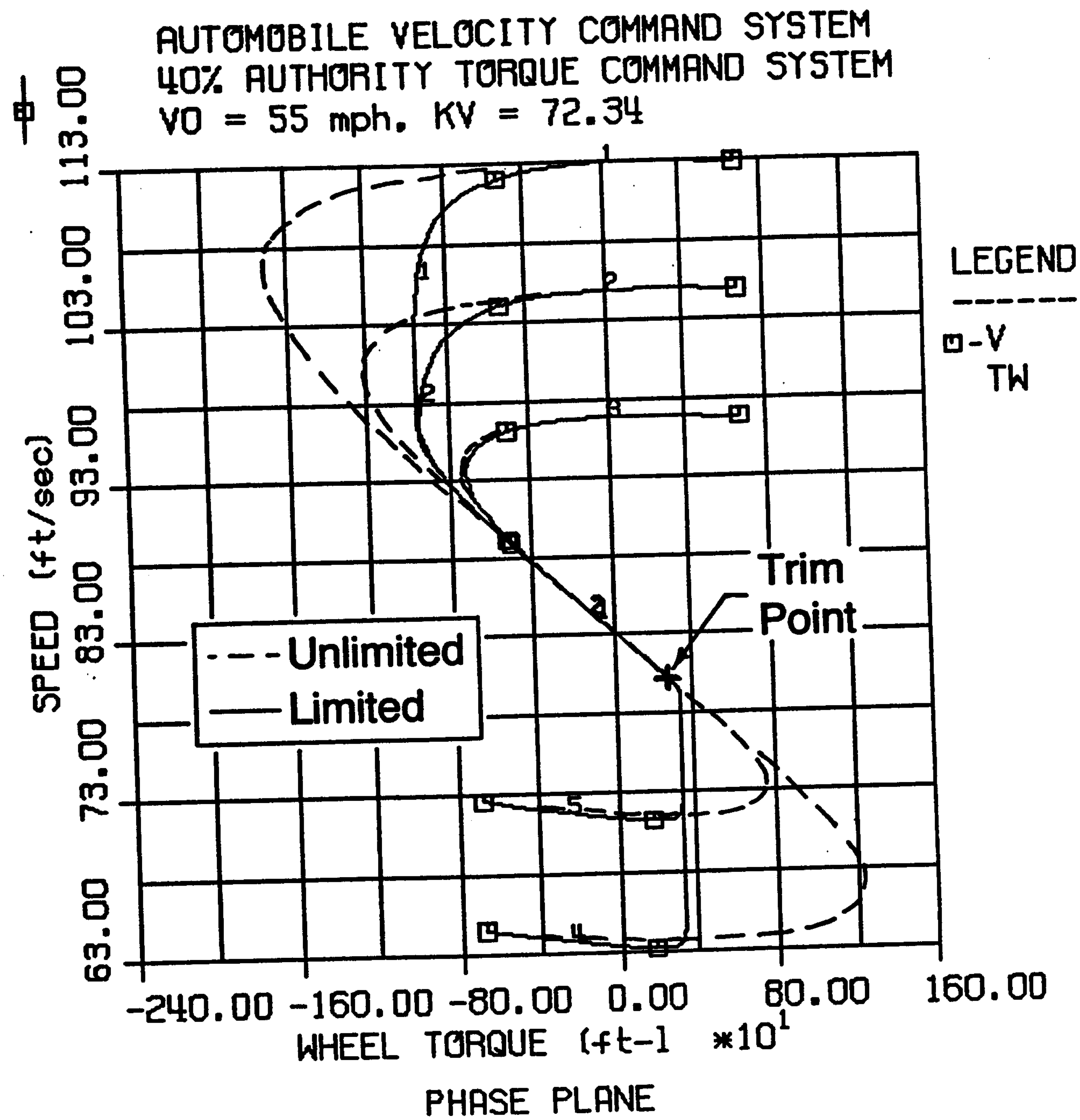


Figure 5-22a. Phase Plane Diagram Showing the Effect of Torque Command Limits.

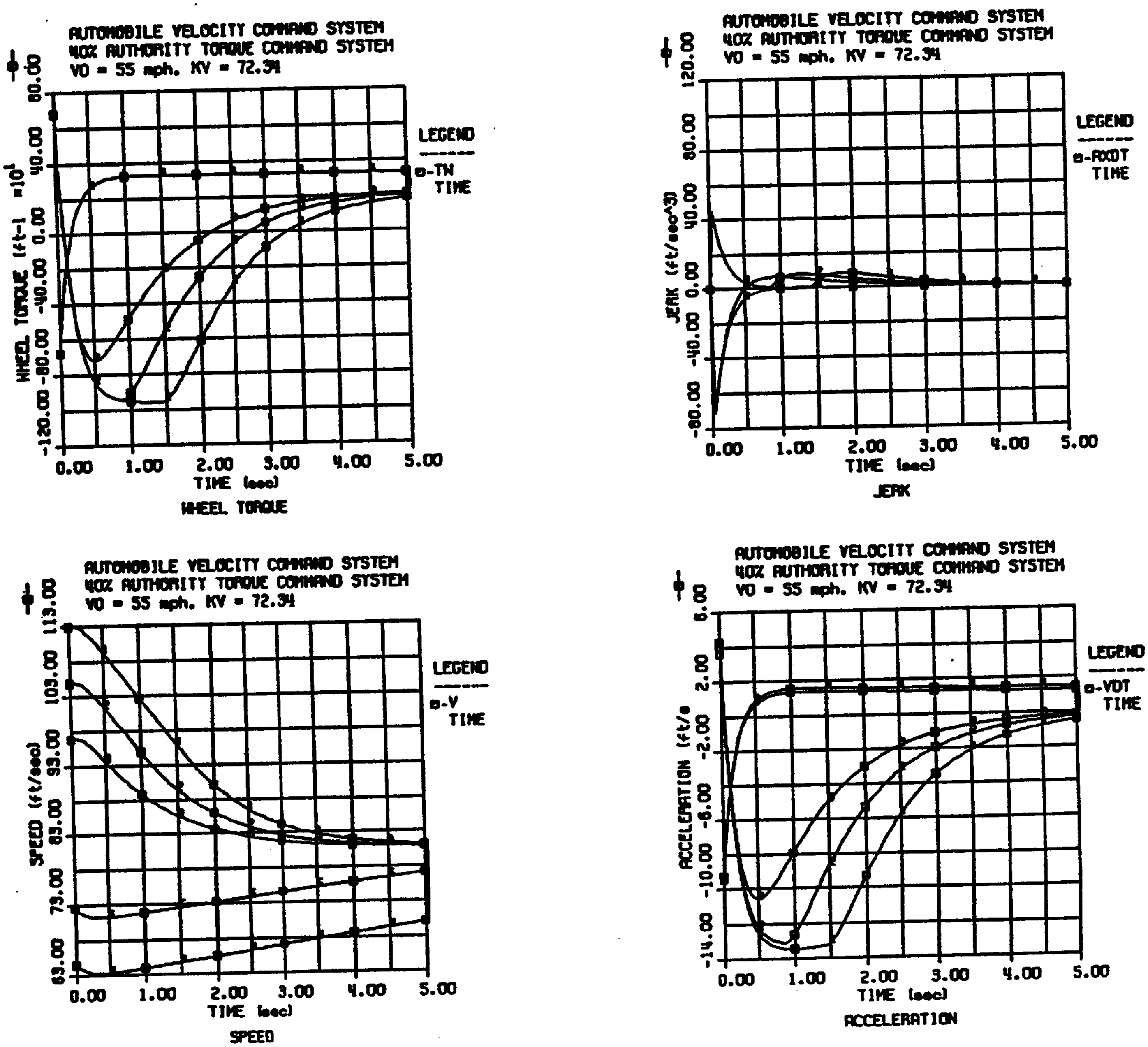

AUTOMOBILE VELOCITY COMMAND SYSTEM
40% AUTHORITY TORQUE COMMAND SYSTEM
VO = 55 mph, KV = 72.34
WHEEL TORQUE (ft-l ×10¹)
LEGEND
TW
TIME
TIME (sec)
WHEEL TORQUE
AUTOMOBILE VELOCITY COMMAND SYSTEM
40% AUTHORITY TORQUE COMMAND SYSTEM
VO = 55 mph, KV = 72.34
JERK (ft/sec^3)
LEGEND
AXDT
TIME
TIME (sec)
JERK
AUTOMOBILE VELOCITY COMMAND SYSTEM
40% AUTHORITY TORQUE COMMAND SYSTEM
VO = 55 mph, KV = 72.34
SPEED (ft/sec)
LEGEND
V
TIME
TIME (sec)
SPEED
AUTOMOBILE VELOCITY COMMAND SYSTEM
40% AUTHORITY TORQUE COMMAND SYSTEM
VO = 55 mph, KV = 72.34
ACCELERATION (ft/s
LEGEND
VDT
TIME
TIME (sec)
ACCELERATION

Figure 5-22b.

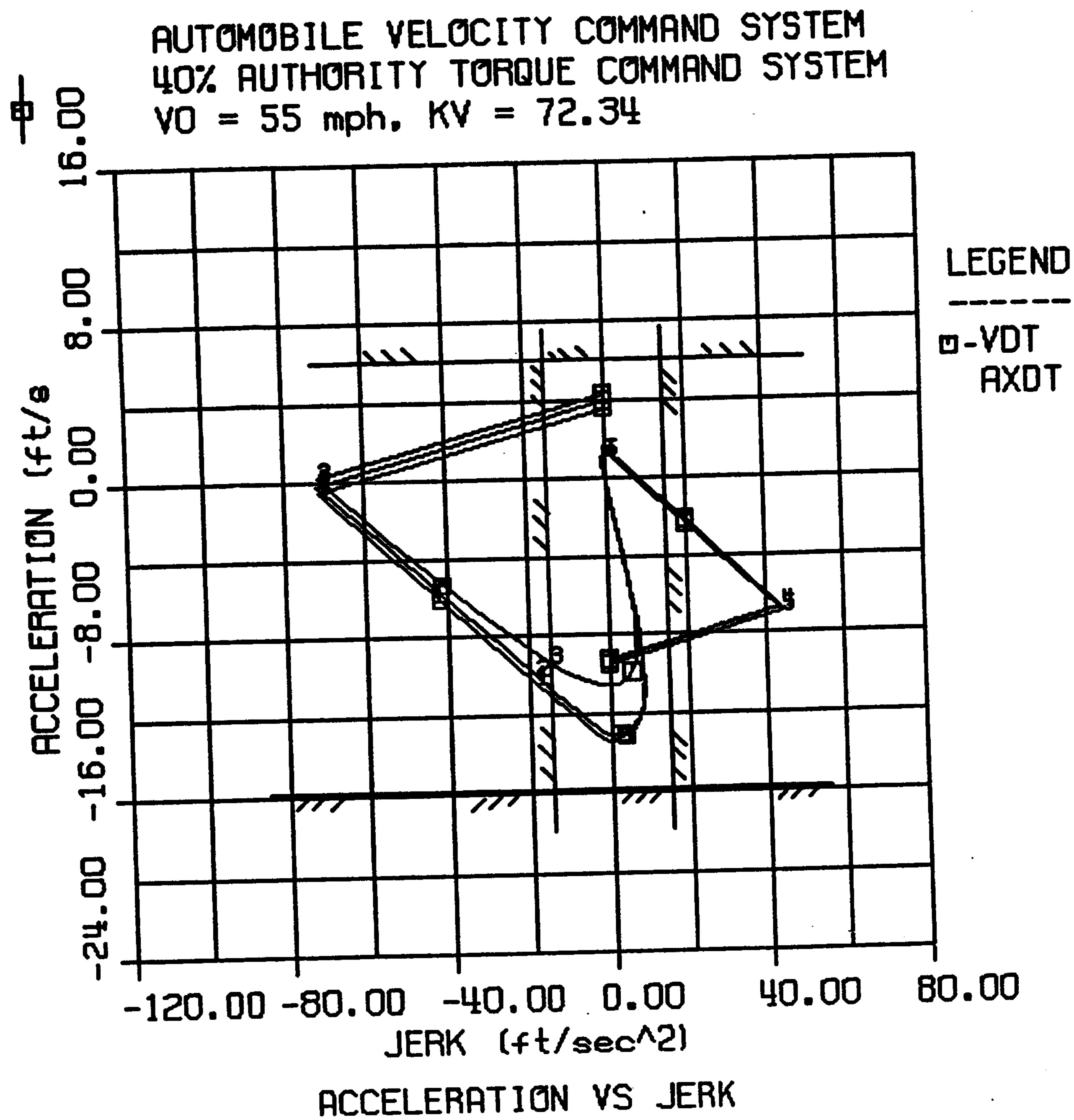
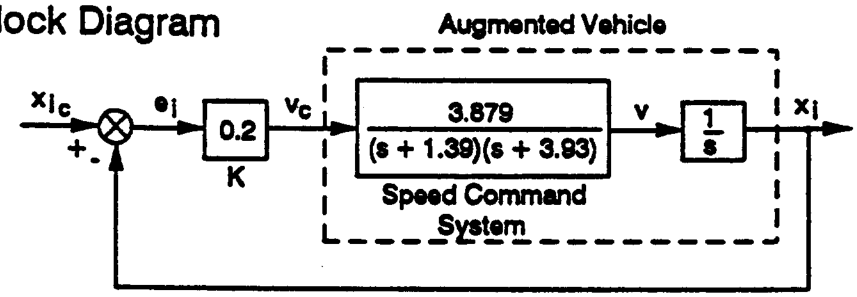
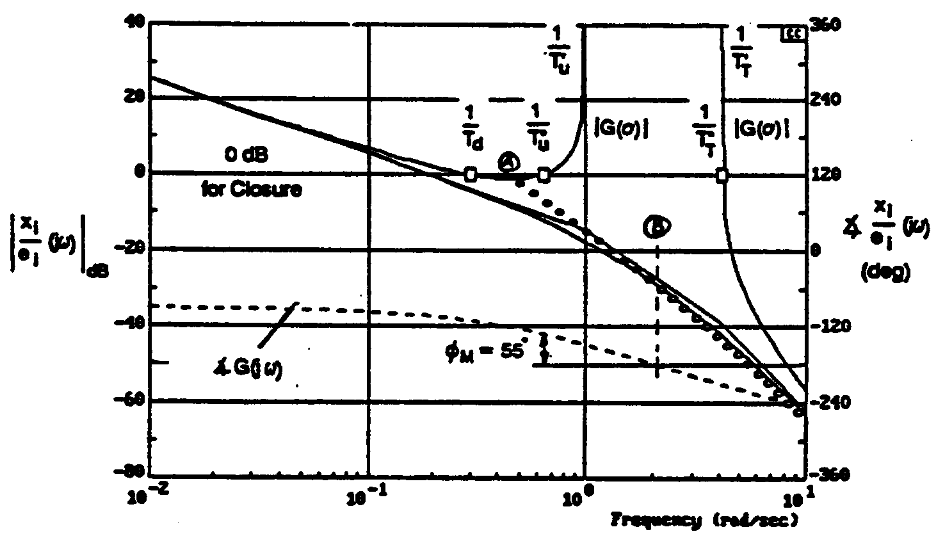

AUTOMOBILE VELOCITY COMMAND SYSTEM
40% AUTHORITY TORQUE COMMAND SYSTEM
VO = 55 mph, KV = 72.34
ACCELERATION (ft/s
16.00
8.00
0.00
-8.00
-16.00
-24.00
-120.00
-80.00
-40.00
0.00
40.00
80.00
JERK (ft/sec^2)
ACCELERATION VS JERK
LEGEND
-VDT
AXDT

Figure 5-22c.

- Block Diagram



- Bode Root Locus



- Conventional Root Locus

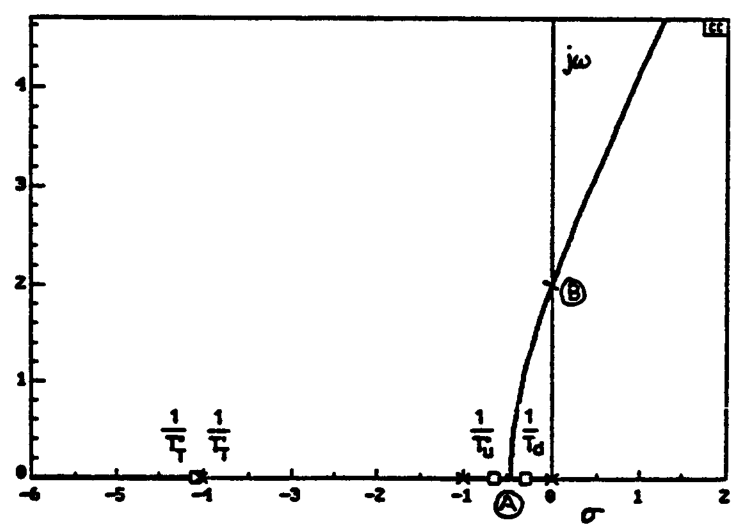


Figure 5-23. System Survey of Merge Control System Closure with Actual Vehicle and Speed Command System

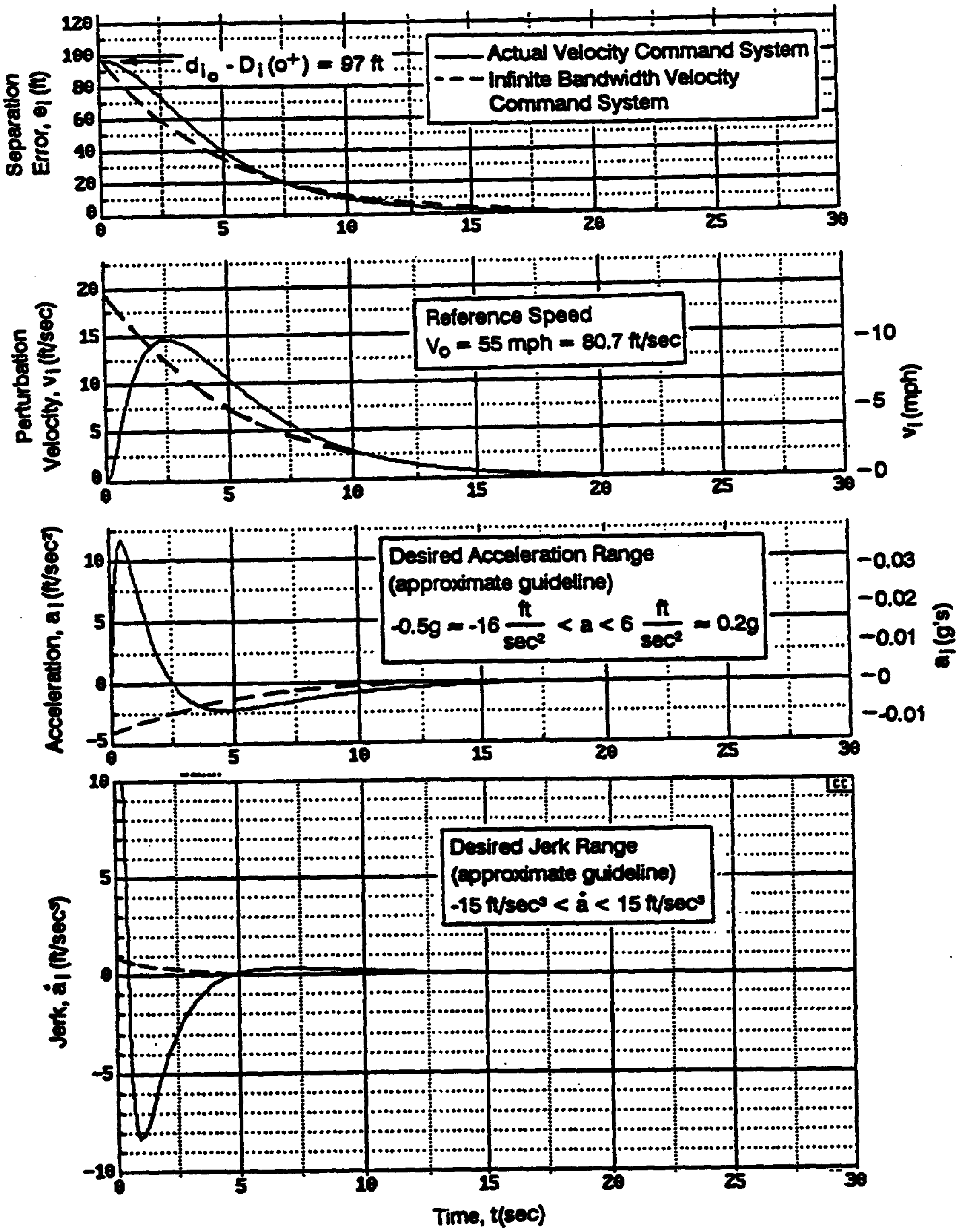


Figure 5-24. Platoon Merge Maneuver with Actual Velocity Command System (Variables are for the Leader of the Merging Platoon

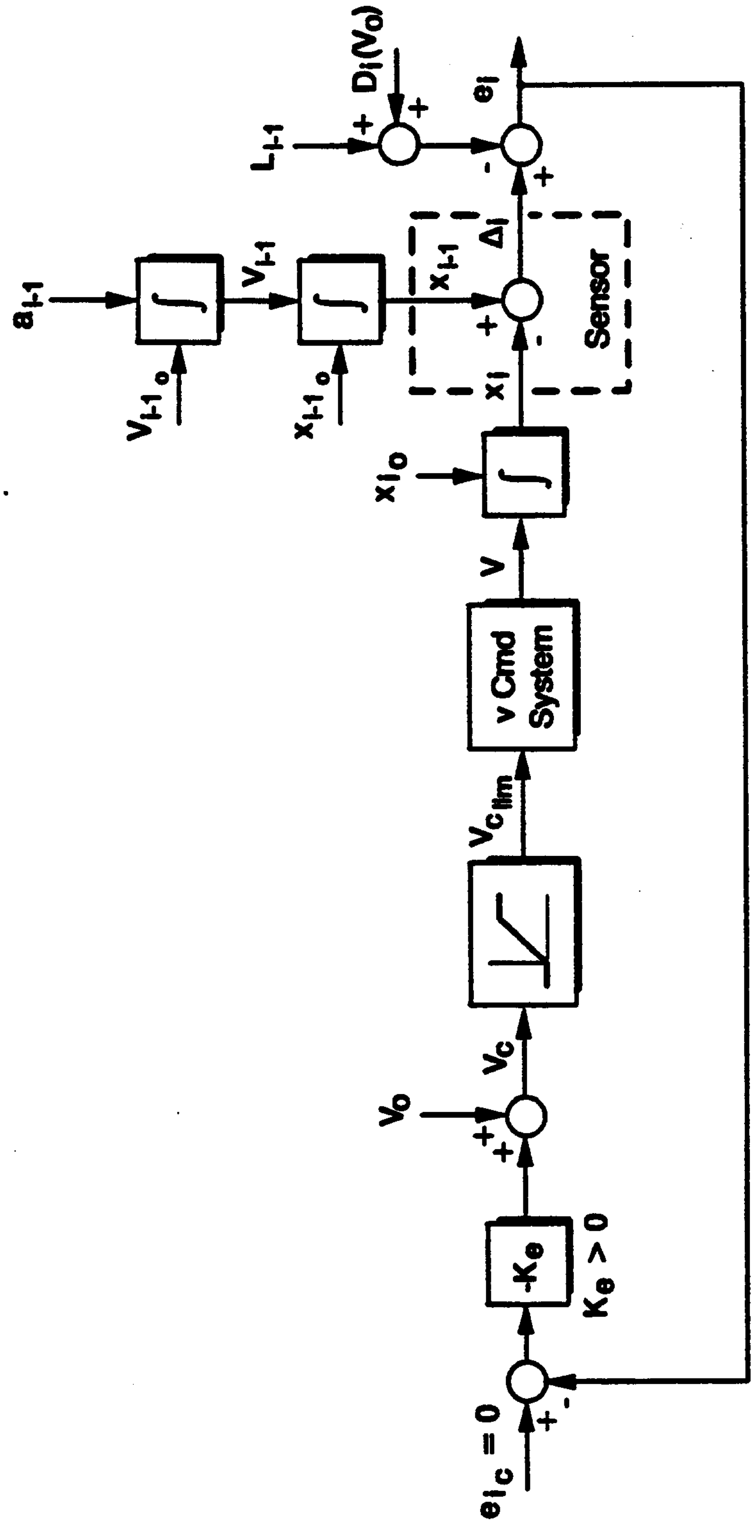


Figure 5-25. Platoon Merge Control System

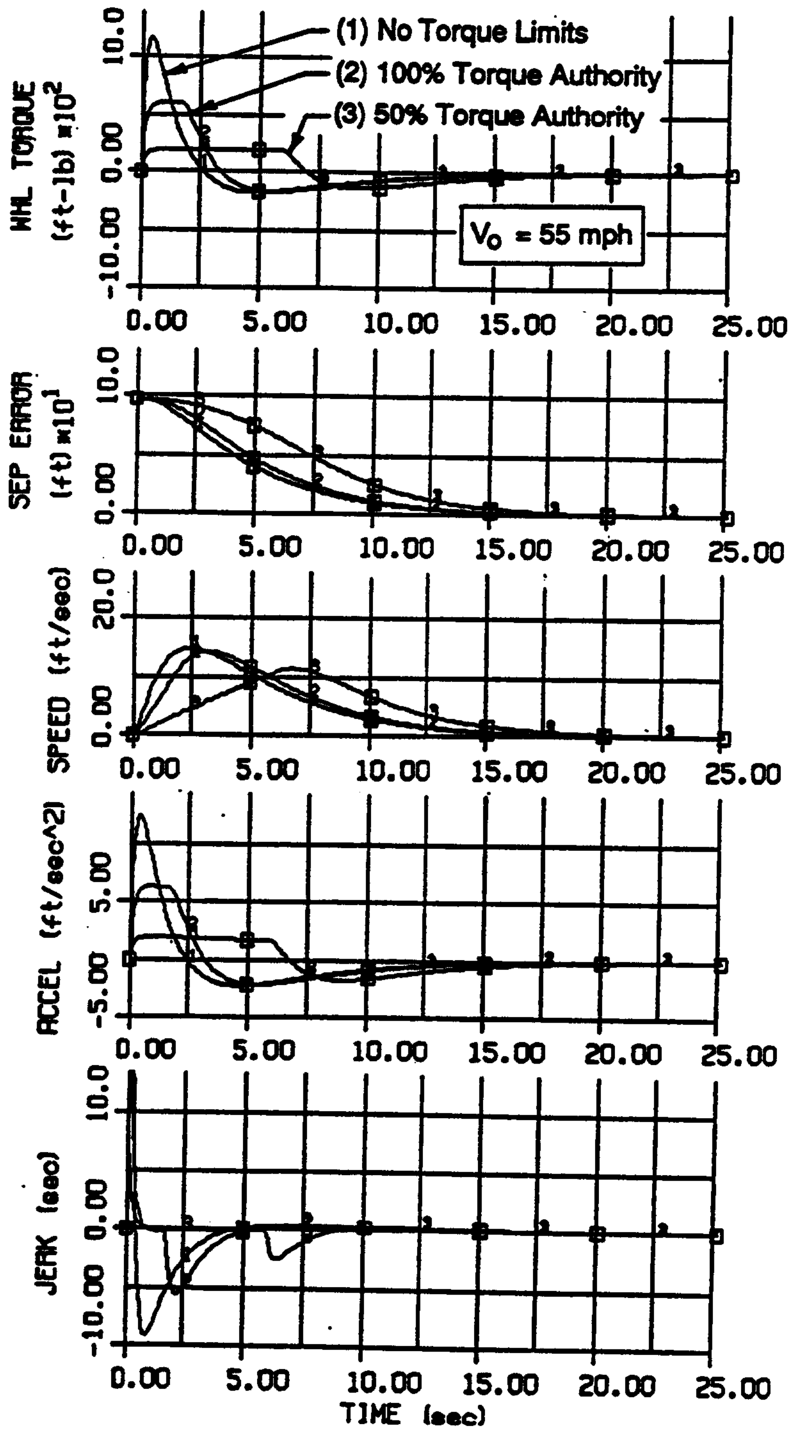
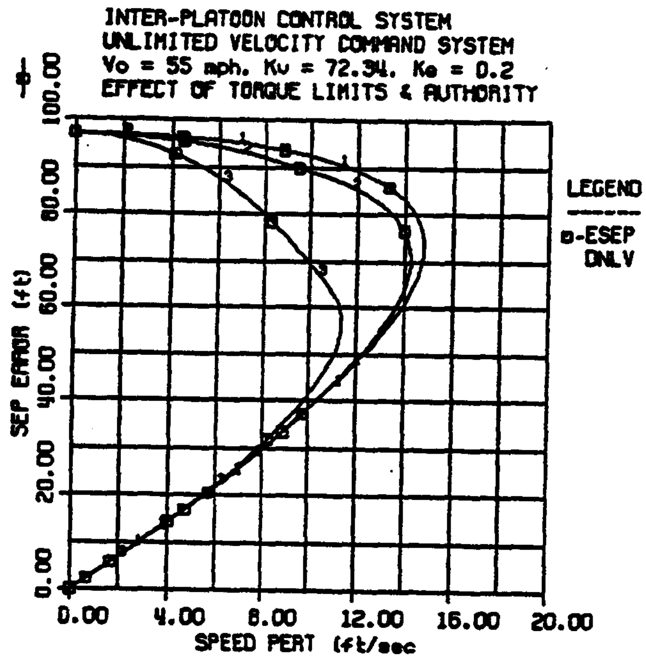
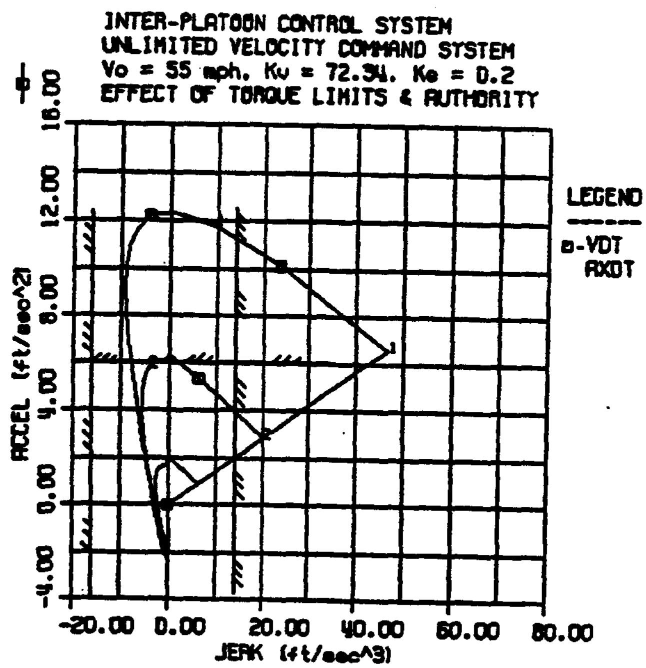


Figure 5-26a. Effect of Wheel Torque Limits and Authority on Merge Control System



b) SEPARATION ERROR VS SPEED



c) ACCELERATION VS JERK

Figure 5-26b & c. Effect of Wheel Torque Limits and Authority on Merge Control System

and jerk shown in Figure 5.26c shows that the desired limits are easily satisfied at 50% torque command authority.

5.2.4.3 Nonlinear Assessment with Velocity and Torque Command Limits

Figure 5.27a shows the merge maneuver time history with 50% torque command authority and three cases of velocity command limits: no limit, 110% of V_o, and 105% of V_o. As noted previously, it is desirable to minimize the velocity limit, because this will allow the nominal platoon speed to be close to the speed limit for traffic flow efficiency. The limit reduction from 110% to 105% has a greater effect than the original imposition of the (110%) velocity limit. At the low (105%) velocity limit the maneuver time is noticeably increased, but the time is still minimal compared to the time a platoon would have to remain in formation to provide the desired benefits.

Figure 5.27b shows that the speed limits have a clear impact on speed in the maneuver. There is also a significant impact on acceleration and jerk, but at any velocity limit or even without a limit, the desired acceleration and jerk limits are easily met.

5.3 Conclusion, Issues and Risks

Platoon Formation Task and Maneuver

There does not appear to be a compelling rationale for having the front platoon actively participate in the merge of two platoons. An active front platoon would imply system complexity beyond AICC with information simultaneously flowing both forward and rearward between the platoons. This would create two-way dynamic coupling that could be generally undesirable.

With a passive front platoon, merge involves only inter-platoon, not intra-platoon, dynamics. Consequently only the dynamics and control of the lead vehicle of the rear platoon need be treated explicitly.

It is important to distinguish between nominal merge conditions which would apply to the majority of platoon formations and special cases which will occur relatively rarely (emergency and failure cases). Platoon formation will always be an optional activity performed for traffic flow efficiency and not specifically to enhance safety. Thus aborting a platoon merge probably will be the correct strategy for many, if not most, off-nominal conditions. The nominal merge control design should not be compromised to allow platoon formation under off-nominal conditions where the maneuver could and should be aborted.

If the front platoon speed is much lower than the speed limit, or if it is decelerating rapidly, or if a third vehicle intrudes between the platoons, an off-nominal condition is indicated and platoon formation should not be initiated. This is particularly true without two-way inter-platoon communication. Further, the front platoon cannot accelerate significantly for long or the speed limit would be exceeded. Thus merging with an accelerating (or decelerating) front platoon should not be a system design issue.

Acceleration and jerk limits for platoon merges will be imposed for passenger comfort rather than safety and traffic flow. Thus these limits will likely be set by manufacturers (rather than the Government).

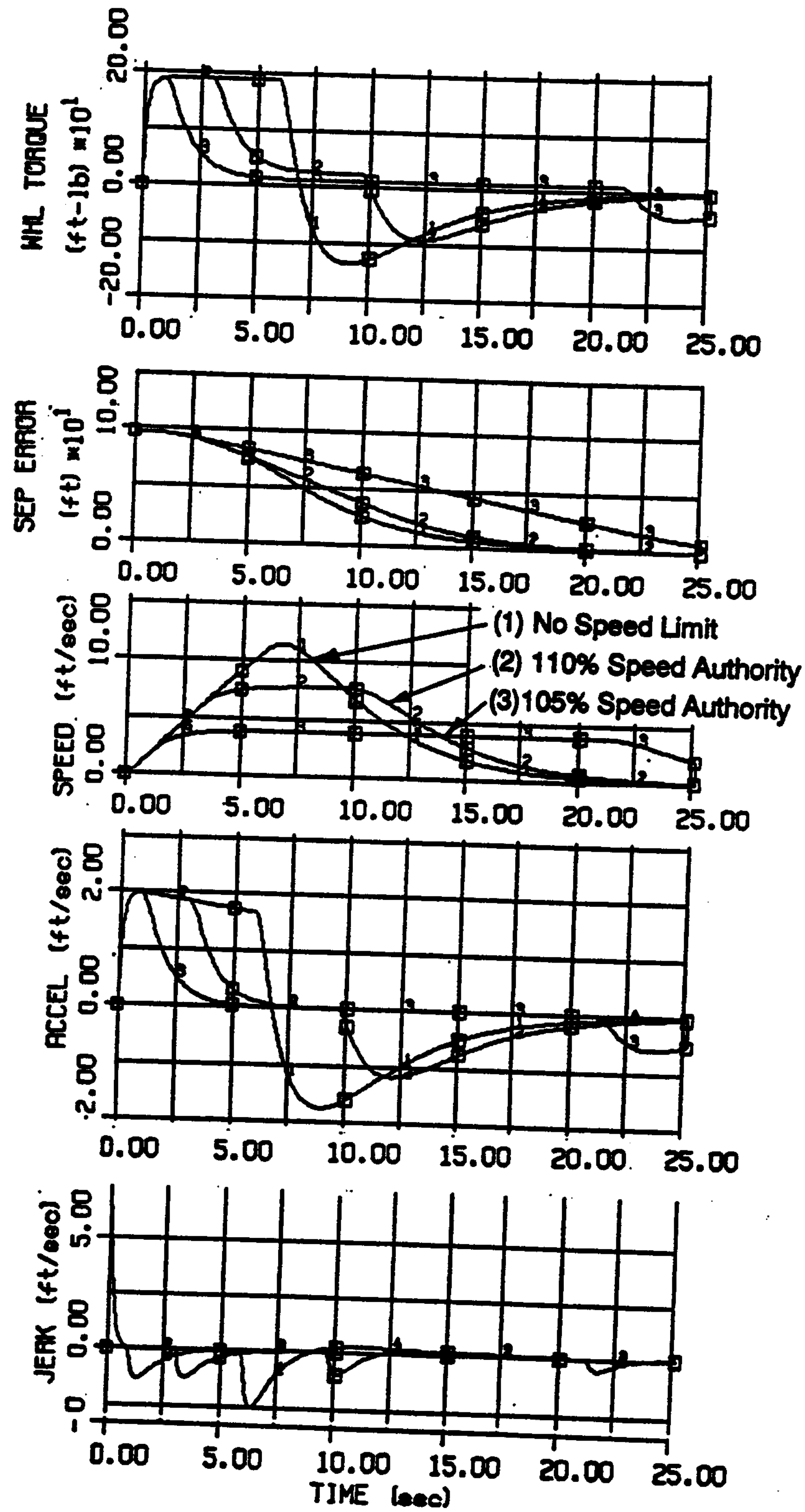
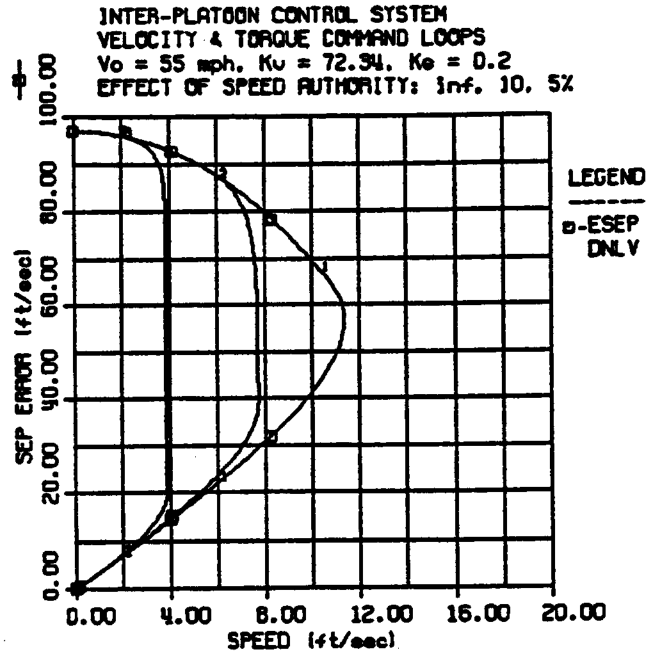
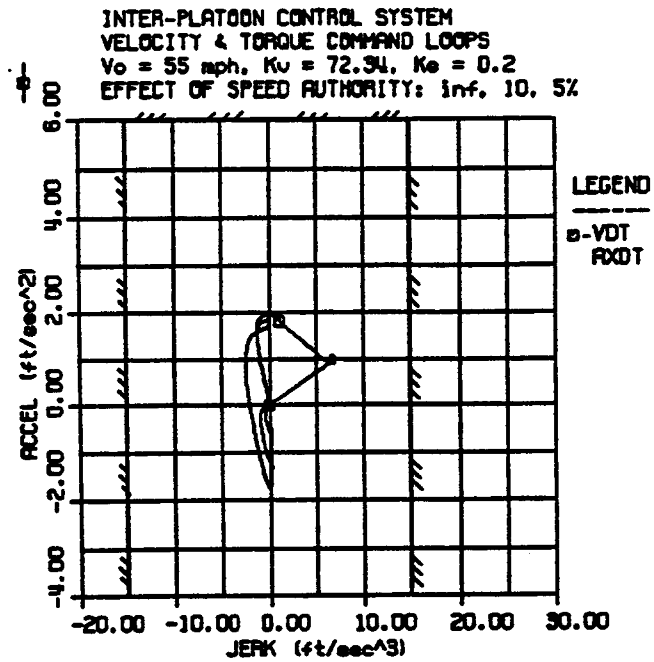


Figure 5-27a. Effect of Velocity Command Authority on Merge Control System



b) SEP ERROR VS SPEED



c) ACCELERATION VS JERK

Figure 5-27b & c. Effect of Velocity Command Authority on Merge Control System

The nominal merge maneuver could be addressed as a constrained trajectory optimization problem, if a relevant cost function could be identified. A minimum time maneuver is a possibility, but not a compelling one since elapsed times for merge maneuvers will be much shorter than useful platoon "half-lives". Thus minimum time maneuvers are primarily of interest as reference maneuvers. Maximizing safety and passenger comfort is much more important.

Idealized Merge Control System

Basic Architecture

Formulation of a platoon formation (merge) control system can be based on a single controlled variable, the separation error e_i, defined as the difference between the actual separation, d_i, and the desired separation, D_i, of the i^{th} and $i\text{-}1^{st}$ platoons (Fig. 5.5).

The basic merge control law can be based on feeding back the separation error to an appropriate control point on the vehicle (Fig. 5.9). This structure assumes only a sensor on the rear leader capable of ranging the rear of the front platoon. Direct range rate measurements do not appear to be required.

A key implied requirement for a system based on a single, outer separation error loop is an inner loop to provide equalization for the outer loop. The effective vehicle response type, with only the inner loop closed, should be "k/s-like". This implies a velocity command response-type for the inner loop (Fig. 5.9). The velocity command system has a low-pass characteristic with unity low frequency gain.

In the Figure 5.9 merge control system, the reference speed, V_o, is injected ahead of the velocity command, V_c, to insure that the nominal speed will be maintained even when the separation error returns to zero at the conclusion of a merge. More capable alternatives could include "follow-up trim" integrators and feedforward loops from the error command to the velocity command. However if the merge is to be aborted when there is significant maneuvering by the lead platoon, the simple V_o injection (Fig. 5.9) might be adequate for a minimal system.

The nominal speed dependence of the desired separation function, D_i (Eqn. 5-9) does not need to be explicitly incorporated into the merge feedback structure. Instead this can be treated with speed scheduling using a low sample rate and/or low pass filtered speed measurement. If the speed dependence is incorporated explicitly into the control law (Figure 5.2, Ref. 20) the control law is considerably complicated without benefit. Such a design would effectively apply the D_i speed dependence to infinite bandwidth although there is no empirical or theoretical basis for this.

Infinite Bandwidth Assessment

The basic design elements of the outer separation error loop for a merge control system can and should be initially synthesized and assessed assuming an infinite-bandwidth inner velocity command loop. This leads to a very simple linear model (Fig. 5.10a) which reveals fundamental characteristics that hold even in more complete mechanizations.

With the velocity command inner loop closed and the outer separation error loop open, the effective vehicle has the ideal k/s form (90^o phase margin and no gain margin constraint) such that no compensation is required and the merge controller G_e can take the form of a pure gain K_e (Fig. 5.10b). The closed loop bandwidth (also the crossover frequency) is K_e which is the only control parameter.

The closed loop separation error (Fig. 5.10c) has zero steady state gain implying zero steady state error for a step separation command of interest. If the lead platoon was accelerating or decelerating, there would be a steady state error. But this is not a significant problem because the task definition calls for abort of the merge when the lead platoon maneuvers significantly.

The system response in a merge maneuver (Fig. 5.11) has a characteristic exponential decay of separation error. This is desirable because it avoids overshoot that could lead to a collision. This characteristic is distinctly different from that of the minimum time solution (Fig. 5.5), but the increased maneuver time in the exponential response is negligible compared to practical platoon half-lives

Maneuver time can be reduced by increasing the system bandwidth by increasing the gain K_e. This will also adversely increase the peak velocity, but this problem may be readily dealt with using command limiters.

Acceleration and jerk can be maintained within reasonable limits (Fig. 5.11) except at $t = 0$ where the infinite bandwidth approximation is not valid. The peak (for $t > 0$) acceleration and jerk increase with, respectively, the square and cube of the outer loop bandwidth. Further peak acceleration and jerk will both increase roughly with the nominal speed V_o due to the D_{io} speed dependence. However the detailed initial jerk and acceleration response are quite sensitive to real vehicle effects.

Velocity Command System

<u>Linear Analysis and Design</u>

A velocity command system designed to provide equalization for the outer separation error loop can and should be initially synthesized and assessed as a linear system based on the speed-throttle transfer function (Fig. 5.12) .

The essence of the longitudinal vehicle dynamics is characterized by the speed mode (first order pole at x_v, Fig. 5.12). Whatever nonlinearities or uncertainties exist in the vehicle dynamics can be viewed, to a first approximation, as movement in the speed mode pole. In general the speed mode will be well below the engine mode frequency and well below the speed loop crossover frequency. The first order effect of the drag nonlinearities is to increase the speed mode frequency as the nominal speed increases (Fig. 5.13).

There will generally be a broad region of k/s between the speed and engine modes in the speed to throttle transfer function (Fig. 5.14) such that a pure gain speed loop closure is a possibility. The required closed loop bandwidth for the velocity loop is a key AHS design requirement. Bandwidths somewhat below 1 rad/sec should be adequate.

Bandwidths up to 1 rad/sec can be supported with negligible coupling between the speed and engine modes (Fig. 5.14). Higher bandwidths could be achieved, but the speed and engine modes would couple to form a second order mode. Significant high frequency lags could reduce the phase margin enough to create an undesirable low damping ratio for the dominant closed loop mode. This sets an implied requirement on any inner engine/powertrain control loops. A minimum effective engine mode frequency of 5 rad/sec engine appears acceptable.

A pure gain velocity command loop will have a "shelf" in $|G(j\quad)|$ below the speed mode indicating a potential command following problem. This can be resolved routinely by use of a PI controller instead of the pure gain K_v. The lead in the PI should be roughly scheduled with nominal speed based on the literal speed mode expression (Fig. 5.12).

In the closed loop time response of a pure gain velocity command system (Fig. 5.15) the rise time will be roughly the inverse of the bandwidth. Steady state "droop" will due to finite low frequency gain margin (Fig. 5.14) will result in less than perfect, but possibly acceptable, speed command following. This problem can be routinely eliminated by using a PI controller in the speed loop.

Inner Loops for the Velocity Command System

Currently available powertrain control subsystems (i.e., anti-lock braking systems (ABS), active traction control (Acceleration Slip Regulation, ASR) and a variety of engine management systems) significantly impact vehicle dynamics relevant to platoon control. These systems are currently designed for manually controlled vehicles; their design for dual mode vehicles (manual and automatic control) is a key AHS consideration.

It can be reasonably expected that current powertrain control subsystems will evolve into an "active powertrain torque command system" that will integrate ABS, ASR, and engine management functions as well as support AHS by providing ideal (k/s-like) inner loop equalization for a velocity command system. The ideal equalization results because vehicle speed is the integral of powertrain torque to a first approximation. An AHS powertrain torque command system will almost certainly require integration with the ABS/ASR and engine control functions to be cost effective.

A key advantage of a torque command system is that it would deal with the key uncertainties, variations and nonlinearities in the vehicle dynamics in the inner most loops making the outer loop (velocity and separation error) design problem relatively simple and straightforward. This is consistent with long established good practice in vehicle control system design.

Because ABS/ASR systems are essentially limiters, they are distinctly different from the AHS powertrain torque command concept. The powertrain command system will determine the torque response over the entire range of the command whereas the ABS/ASR acts only at the control limit. However the control effectors, and, to a lessor extent, the sensors required to mechanize ABS/ASR should be very similar to those required for the AHS application.

While ABS and ASR are designed to modify vehicle dynamics, current engine management systems are designed primarily for emission control and fuel economy requirements. An new engine torque command function can be anticipated as a key element of an overall powertrain torque command system

The engine torque control element would be based on feedback of engine net torque to the throttle control point and perhaps to fuel and ignition control points as well. A model-based torque estimator would be require. Most likely this would use currently available engine management (engine speed, manifold pressure, throttle position, vehicle speed, and transmission gear) measurements augmented with specialized measurements such as longitudinal acceleration and engine mount loads.

Nonlinear Assessment of the Velocity Command System

The only nonlinear dynamic elements that significantly affect the velocity command system or the overall platoon merge system are the control system limiters, specifically the torque command limiter and the velocity command limiter (Fig. 5.17). Limits on available engine and brake torque would produce similar nonlinear effects, except that practical control systems will require that the torque limiters be set within the engine/brake torque.

The nonlinear variation of aerodynamic drag and rolling resistance with speed (Fig. 5.13) has negligible effect on the control system dynamics (Fig. 5.18 through 5.20). More importantly there are no qualitative differences indicating a characteristic nonlinear phenomena such as a limit cycle. The complex control system mechanizations that have been proposed in some other studies (e.g., Ref. 13) to compensate for the aerodynamic drag nonlinearity are not necessary and should not be used in practical designs. The primary effect of the drag nonlinearity with speed is the quasi-steady effect on the speed mode frequency (Fig. 5.12). This can be routinely treated by scheduling gains with dynamic pressure as has been done with aircraft flight control systems for many decades.

Although the torque command limiter nonlinearity will have a much more significant nonlinear effect than the drag nonlinearities, the limiter will also not produce any nonlinear pathologies such as limit cycles (Fig. 5.22) This is consistent with general experience with (statically stable) vehicle control systems that the usual problem, if any, with effector limiting is reduced performance. The torque command limiter will produce the additional benefit of reducing the transient peak acceleration and jerk levels (Fig. 5.21 vs 5.22c).

Merge Controller with Inner Loop Speed Command

The linearized dynamics of the overall merge control system with a finite bandwidth speed command system (Fig. 5.23) is somewhat more complex than those for with an idealized infinite bandwidth speed command system (Fig. 5.10). There is a minimum bandwidth requirement for the speed command loop, somewhat above 1 rad/sec, ultimately set by the coupling of the first order separation error and speed modes (Fig. 5.23). Finite but adequate speed command bandwidth has little adverse effect on the error response and the time for the maneuver (Fig. 5.24).

In the platoon merge control system, the velocity command limiter will normally be inserted between the merge controller element and the torque command limiter in the velocity command inner loop (Fig. 5.25).

Reduction in the torque command limit has the beneficial effect of reducing the peak transient acceleration and jerk in a merge maneuver without significant increase in maneuver time (Fig. 5.26).

The velocity command limit should be minimized to maintain the nominal platoon speed close to the speed limit (for traffic flow efficiency). Low velocity command limits, combined with the torque command limits, should generally reduce the acceleration and jerk transient peaks in a merge maneuver to acceptable levels (Fig. 5.27). Some increase in the maneuver time will result, but the time will be minimal compared to a useful platoon "half-life".

6. ANALYSIS OF OBSTACLE AVOIDANCE MANEUVERS

6.1 Objectives

The objectives of this section are to (1) analyze the two basic obstacle avoidance maneuvers, remaining in the current lane and brake, and maneuvering around the object, and (2) identify issues and risks. Detailed treatment of this problem requires data, in particular data about the population of objects that might appear as obstacles on highways, which are not readily available at the required level of detail. Thus the analysis presented here is not definitive, but rather is a very simplified sensitivity analysis performed to help understand the key elements of the problem.

6.2 Analysis of Obstacle Avoidance Maneuvers

The analyses of this study are confined to obstacles in the form of objects which appear accidentally and randomly on major highways. Thus detours and barriers erected intentionally for road repair are excluded. Further disabled vehicles are also excluded since this problem has been treated more generally in AHS and other studies (Ref. 43 and 44). With these exclusions, the key problem for this analysis is definition of the population of objects of interest. There does not appear to be a significant scientific literature on the subject of things that fall on highways, but omphaloskepsis leads to the following list:

- Cargo from vehicles
- Vehicle parts (wheels, tire treads, mufflers)
- Animals (living or recently deceased)
- Highway parts (broken signs)
- Snow drifts, ice patches
- Tumbleweeds, tree branches
- Blue ice" from airplanes

The above list is in estimated order of decreasing frequency of appearance and the first two or three categories probably account for the objects of primary concern.

At the most fundamental level there are two basic obstacle avoidance maneuvers, more appropriately two avoidance strategies: (1) remain in the current lane and brake, (2) maneuver around the object with the likelihood of an excursion into an adjacent lane. The first strategy is preferable when the object can be detected at a range which allows the vehicle to stop before impact. Otherwise the expected cost of these two strategies must be estimated and compared (in a matter of seconds) to decide between them. For either maneuver, the vehicle must also remain stable and controllable at limit lateral acceleration and/or limit braking. However these vehicle characteristics are required for either manual or AHS operation and are not special AHS requirements. Development of coordinated longitudinal and lateral AHS control laws will be required to execute either option. However, the basic features of these control laws are known from comparable work in manual control (Ref. 45 and 46). More importantly here, these continuous control laws, in particular the coordination of lateral and longitudinal control, cannot not be developed properly until the basic discrete control problem (the lane change decision) is basically understood. Thus the limited resources for this work was devoted to the discrete control problem.

Even if there is not sufficient time to stop before hitting the obstacle, a reduced speed impact with the obstacle might be less dangerous than a sudden lane change which results in a collision with a vehicle in the adjacent lane. While there is an extensive literature on vehicle-vehicle accidents and a smaller literature on vehicle collisions with fixed objects (e.g., bridge abutments), there is little published work on vehicle collisions with random objects in the roadway. For vehicle-vehicle collisions, relative velocity has been demonstrated to be a reasonably good correlate for accident severity. This is not true for highway obstacle collisions. If a car hits a large cardboard box at 55 mph, the results will be very different between an empty box and one containing a cast iron safe filled with gold bullion.

Thus even if a sensor complex can be devised to detect, range, and size an object in the lane ahead, this information is not enough to definitively estimate the probable cost of impact. However human drivers often must perform this detection, estimation and decision-making process and it is useful to consider how they do it. Humans apparently use some rather subtle clues, at least in daylight, to predict what the object might be. These probably include color, texture, motion (if it moves when other cars pass its not very dense), and pattern recognition (if its a black oval with a lighter center its probably a tire). For AHS, more than sophisticated sensors will be required; it will very likely be necessary to mimic some of the subtle pattern recognition of humans[4]. Further this processing must be done in timeframes on the order of a second.

However, even if the human pattern recognition/expert system functions can be mimicked or even improved upon (e.g., for night driving), the AHS obstacle avoidance problem will have non-technical difficulties beyond the current manual control situation. If a human driver swerves into an adjacent lane to avoid a suddenly-appearing obstacle and collides with an adjacent car, the likelihood of a lawsuit is probably low. However if the same maneuver was made under automatic (AHS) control and results in a similar collision with a second vehicle, legal action is likely simply because the system manufacturer provides a "deep pocket".

Even if a human or machine system can distinguish various objects (e.g., distinguish a cardboard box from a steel drum), this often would not be enough to even roughly estimate the danger of impact (i.e., is the box or drum empty ?). Thus in analyses, as in real-time decision-making, some statistical distribution of object density must be assumed. Such distributions are not readily available. Empirical distributions for aircargo densities provide a very rough reference point (Fig. 6.1, Ref. 47). Further some estimate of volume is needed as well. However, either a human or machine object detector can probably define little more than a single dimension in the viewing plane. Object width as a fraction of lane width is probably the most reliable measure and it does not require range information. Estimating object height may often be complicated by the difficulty in defining the object-road boundary. This the cube of one average dimension would have to serve as the "apparent" volume even though some objects (e.g, canoes and carpet

4 Techniques such as "object-oriented fuzzy logic" may be useful. If the object is fuzzy, there's a reasonable chance its a poodle; otherwise there is a greater chance that the object is a cast iron safe.

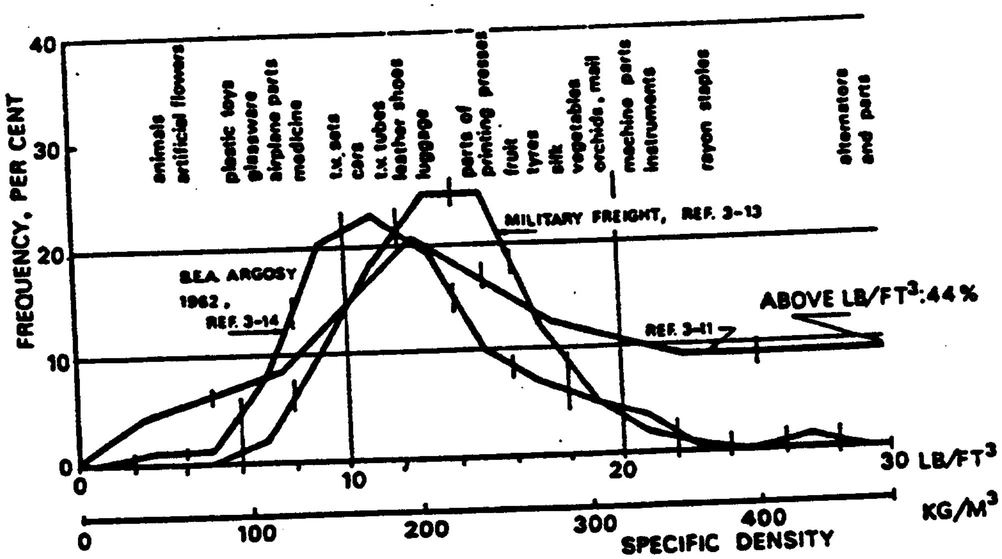


Figure 6-1. Distribution of Aircargo Density

rolls) will be quite sensitive to orientation. Table 6-1 and the corresponding plot in Figure 6.2 indicate that such a volume estimate may be adequate. While Figure 6.2 does not provide a distribution of density, it does suggest a range for the mean to be used in analyses below.

6.2.1 Collision Model

It is assumed that objects can be represented with the same collision model form as that used for vehicles, but with different model parameter values. The basic elements of the model are shown in Figure 6.3. The spring-mass on the left (subscript 1) represents the maneuvering vehicle; that on the right represents the object (which could be a second vehicle). The parts of the car and of the object which are crushed are represented by the (modified) spring characteristic. Point 3 represents the interface between the vehicle and the object. A final key point is that collisions (in which $\dot{x}_1 > \dot{x}_i$ and $\dot{x}_i > \dot{x}_2$) are assumed to be essentially inelastic leading to a modified spring characteristic as represented in Figure 6.4. In the initial part of the collision, up to the point of maximum relative displacement, the spring acts as an elastic element absorbing energy. However the spring "latches" at that point such that the relative displacement is not reversed except for a relatively small recovery.

Thus the "crush" of the vehicle or object can be found by computing the maximum relative displacement between vehicle and object using standard linear system models; the inelastic behavior does not actually have to be calculated in detail. For the "no lane change" case, the crush of the car is taken as the collision severity metric, i.e., the "cost" of the accident. The crush of the object is ignored, because the value of a random object falling on the freeway is assumed to become zero upon contact with the road. For the lane change case, the cost is the sum of the crush for both vehicles which by symmetry is twice the crush of each vehicle. This analytical process begins with the equations of motion of the Figure 6.4 dynamic system. Since the springs are massless

$$m_1 \ddot{x}_1 = (x_i - x_1)k_1 = -F(t) \tag{6-1}$$

$$m_2 \ddot{x}_2 = (x_i - x_2)k_2 = F(t) \tag{6-2}$$

From the right hand equality of Equations 6-1 and 6-2, a "static" expression for x_i can found

$$x_i = \frac{x_1 k_1 + x_2 k_2}{k_1 + k_2} \tag{6-3}$$

and used to eliminate x_i in Equations 1 and 2. This leads to the linear system

$$\ddot{x} = Ax \tag{6-4}$$

where

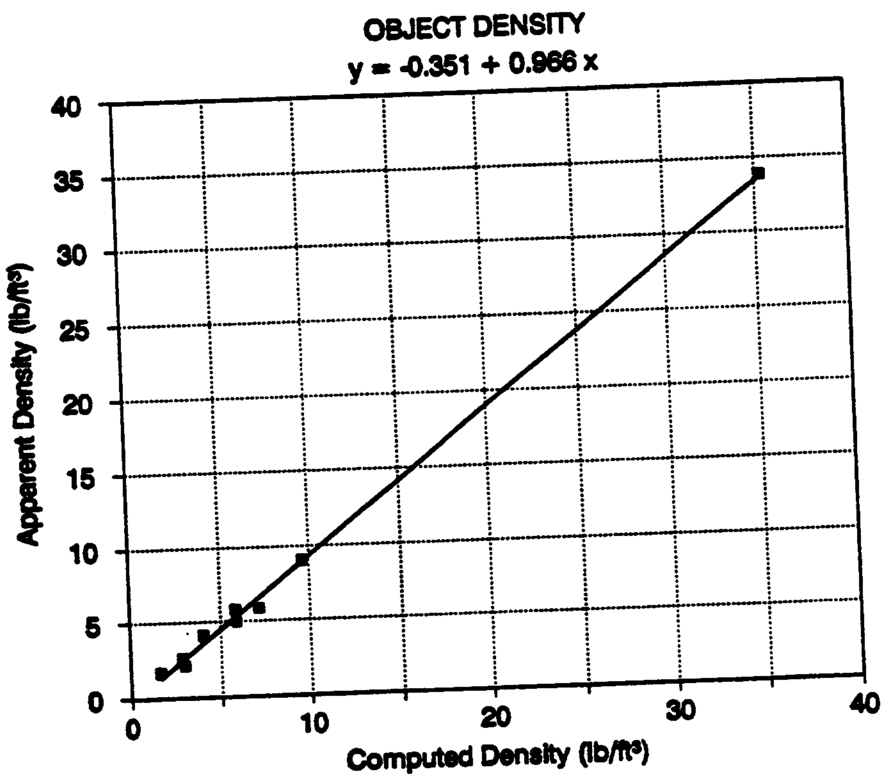


Figure 6-2. Computed and Apparent Densities of Common Objects

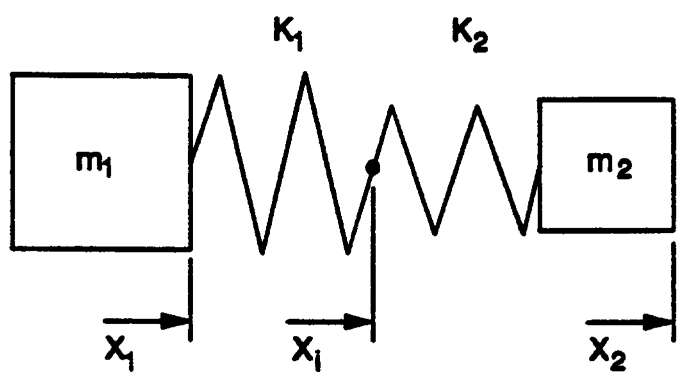


Figure 6-3. Elastic Elements of Collision Model

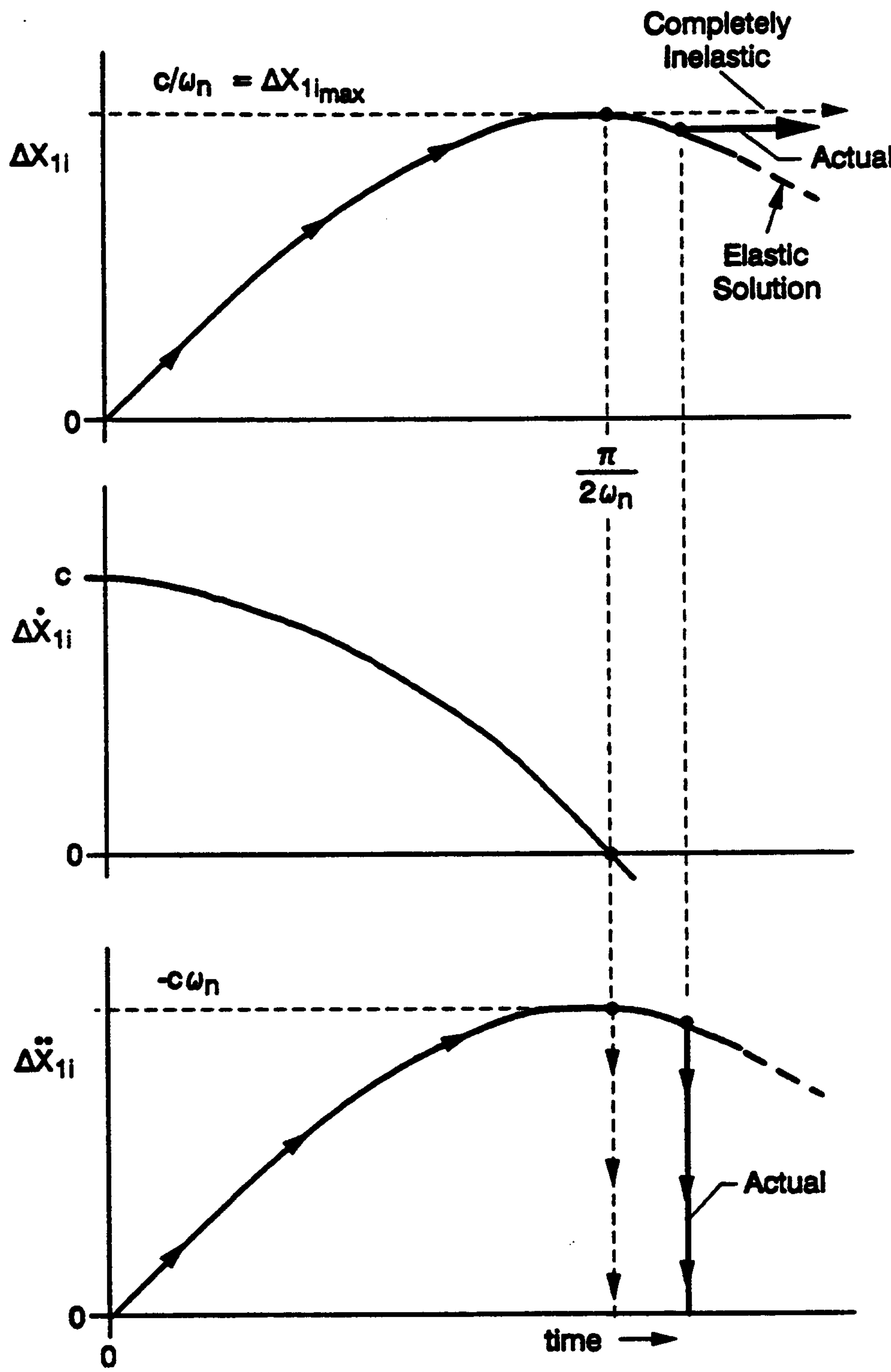


Figure 6-4. Crush Time Histories

$$x = (x_1 ,\ x_2)^T \qquad (6\text{-}5)$$

$$A = k_{eff} \begin{bmatrix} -\frac{1}{m_1} & \frac{1}{m_1} \\ \frac{1}{m_2} & -\frac{1}{m_2} \end{bmatrix} \qquad (6\text{-}6)$$

$$k_{eff} = \frac{k_1 k_2}{k_1 + k_2} \qquad (6\text{-}7)$$

LaPlace transforming Equation 6-4 and accounting for the non-zero initial conditions on velocity gives the frequency domain solution

$$x(s) = (I\, s^2 - A)^{-1}\, \dot{x}(0) \qquad (6\text{-}8)$$

where

$$\dot{x}(0) = (v_{10} , v_{20})^T \qquad (6\text{-}9)$$

and v_{10} and v_{20} are the initial velocities at the instant of collision.

The (elastic) crush $\Delta x_{1i} = x_1 - x_i$ of the vehicle is

$$\Delta x_{1i}(s) = \frac{c}{(s^2 + {}^{2}_{n})} \qquad (6\text{-}10)$$

where

$$c = \frac{v_{10}\, k_2}{k_1 + k_2} \qquad (6\text{-}11)$$

and the natural frequency $_n$ is

$$_n = \sqrt{\frac{k_{eff}}{m_{eff}}} \qquad (6\text{-}12)$$

with

$$m_{eff} = \frac{m_1 m_2}{m_1 + m_2} \qquad (6\text{-}13)$$

The (elastic) vehicle crush, crush speed, and crush acceleration can be obtained in the time domain by inverse LaPlace transforming Equation 6-10.

$$\Delta x_{1i}(t) = \frac{c}{\omega_n} \sin \omega_n t \qquad (6\text{-}14)$$

$$\Delta \dot{x}_{1i}(t) = c \sin \omega_n t \qquad (6\text{-}15)$$

$$\Delta \ddot{x}_{1i}(t) = -c\,\omega_n \sin \omega_n t \qquad (6\text{-}16)$$

Equations 6-14 through 6-16 define the elastic portion (first quarter cycle) of the idealized collision response and, most importantly, determine the maximum crush as

$$\Delta x_{1i_{max}} = \frac{c}{\omega_n} = \frac{v_{10} k_2 / (k_1 + k_2)}{\sqrt{k_{eff} / m_{eff}}} \qquad (6\text{-}17)$$

Similar relations follow for the object, however these are only of interest when the object is a second vehicle in which case the formulas are identical under the assumption of identical vehicles used here.

It should be noted that the vehicle parameters are taken to be deterministic; but the object parameters (k_2 and m_2) are viewed as random variables. Since adequate statistical distributions of object properties are not currently available, the best that can be done is to treat k_2 and m_2 as expected (mean) values to be varied in sensitivity analyses. Under this assumption, the crush $\Delta x_{1i_{max}} = x_1 - x_i$ from Equation 6-17 is interpreted as an expected value. If reasonable estimates of the variances of k_2 and m_2 for the object population could be obtained, then the variances of the accident costs (crushes) could be obtained by a straightforward extension of the present development. This would provide a more complete picture of the decision-making problem.

Following Ref. 48, Equations 6-14 through 6-16 can be interpreted in the deceleration-deflection plane as shown in Figure 6.5. If the collision were perfectly elastic the deflection would move along line AB and then reverse back on this line from B to A. Extensive experimental data reviewed in Reference 48

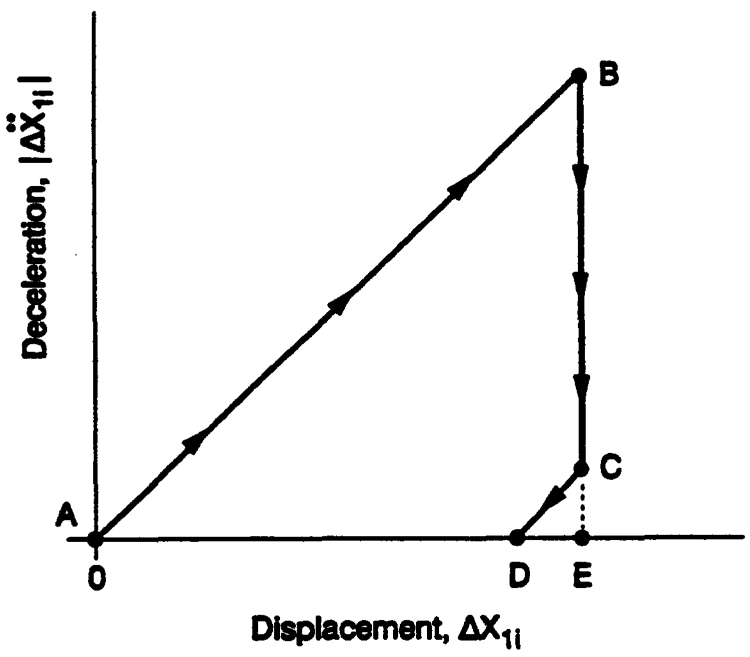


Figure 6-5. Variation of Deceleration with Displacement During a Collision

shows that actual vehicle collisions are nearly completely inelastic such that the deformation characteristics can be represented, to a first approximation, by ABCD. A perfectly inelastic collision would be represented by ABCE.

Equation 6-17 does indicate that, with comparable stiffness and mass, the severity (crush) of a vehicle-vehicle collision is proportional to relative velocity. This follows from the notion that the kinetic energy (proportional to v2) is converted (initially) to strain energy (proportional to x2) in a collision.

Reference 48 provides an effective value of k_1 based on analysis of crash data.

$$k_1 = K_1 m_1 \tag{6-18}$$

where the "unit" stiffness K_1 has the constant value of 12.5 g/ft for all cars in a head-on collision. This value was obtained from crash tests conducted on 1950 and early 1960 vintage cars which predate the advanced energy-absorbing bumper/front end designs of modern cars. However it is felt that the gross unit stiffness has not changed greatly due to these refinements. Further the absolute stiffness level is not as critical as its consistent use in both maneuver scenarios being compared. The greater problem is that the effective unit stiffness of the population of random highway objects is even more difficult to characterize than the density. While the unit stiffness of a runaway loveseat can be expected to be considerably less than 12.5 g/ft, no attempt was made to establish values. Rather sensitivities were examined over a range of conceivable values.

6.2.2 Maneuver Model: No Lane Change

For the "no lane change" case, the object mass and unit stiffness will be represented by the their ratios to the corresponding vehicle parameters.

$$m_2 = \left(\frac{m_2 g}{W_1}\right) m_1 \tag{6-19}$$

where W_1 is the vehicle weight and

$$k_2 = \left(\frac{K_2}{K_1}\right) K_1 m_2 \tag{6-20}$$

The final parameter to be determined is the vehicle velocity at its initial contact with the object, v_{10}. This can be obtained as indicated in Figure 6.6 where it is assumed that the vehicle decelerates at its maximum deceleration rate a_{min}. A time delay τ is assumed between the initial detection of the object at range l_d and the establishment steady deceleration. The time delay accounts not only for sensing and actuation, but also for any complex pattern recognition processing which might be the dominant delay. The time t_f at which the vehicle hits the object is given by

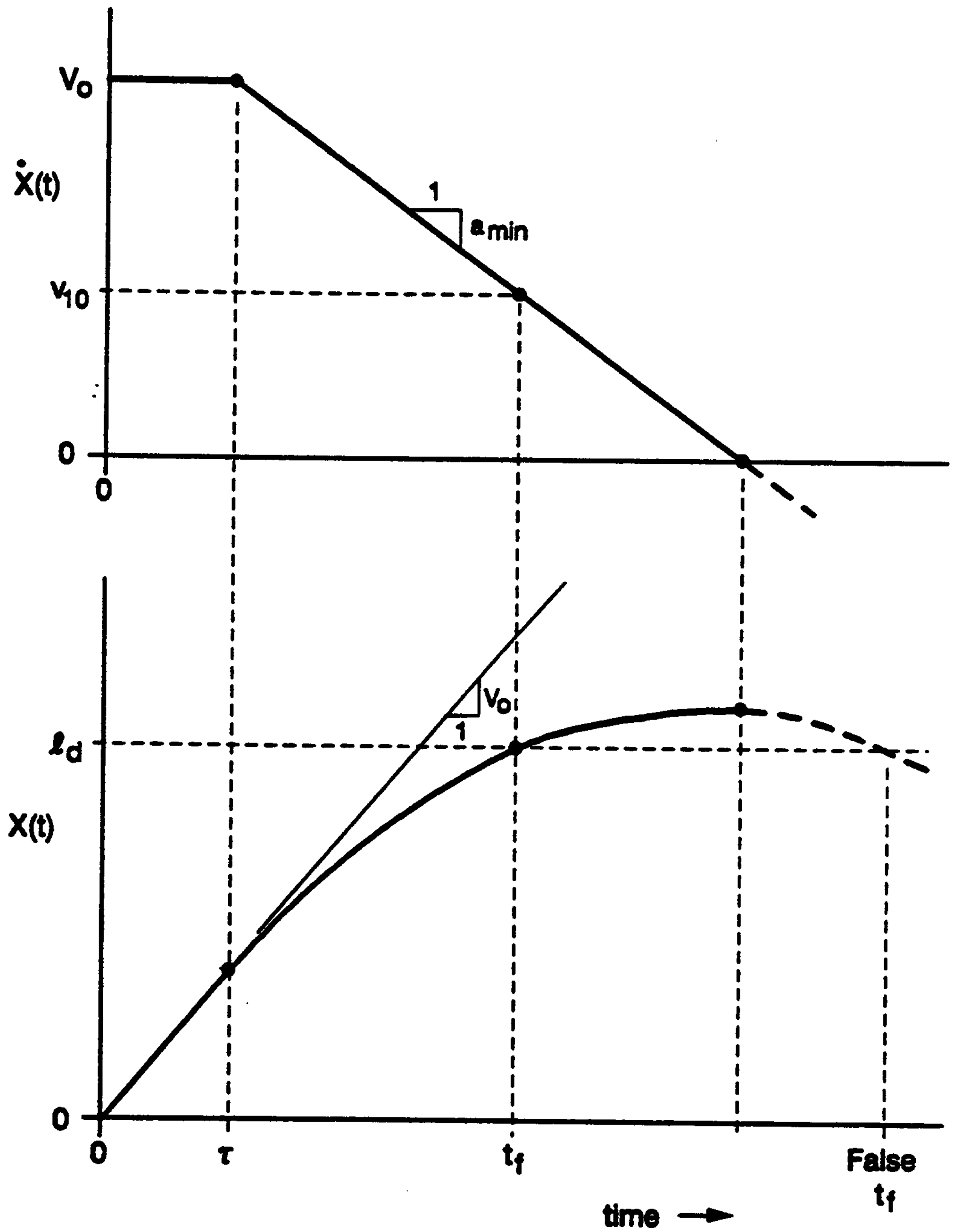


Figure 6-6. Determination of Impact Velocity v_{10}

$$t_f = -\frac{b_{t_f}}{2} - \frac{\sqrt{b_{t_f}^{\,2} - 4c_{t_f}}}{2} \quad (6\text{-}21)$$

where

$$b_{t_f} = 2\left(\frac{V_0}{a_{min}} - \quad\right) \quad (6\text{-}22)$$

$$c_{t_f} = \;^{2} - \frac{2 l_d}{a_{min}} \quad (6\text{-}23)$$

The minus sign is taken on the second term in Eqation 6-21 to avoid the false t_f shown in Figure 6.6. Equation 6-21 has a (real) solution when the discriminant $(b_{t_f}^{\,2} - 4c_{t_f})$ is positive. A negative discriminant implies that the vehicle will stop before impact so that no crush occurs and thus no costs are incurred. Costs of traffic disruptions other than collisions are neglected here.

Thus the impact velocity v_{10} is

$$v_{10} = \begin{cases} V_0 + a_{min}(t_f - \quad) & \text{if } b_{t_f}^{\,2} - 4c_{t_f} > \\ 0 & \text{if } b_{t_f}^{\,2} - 4c_{t_f} \le 0 \end{cases} \quad (6\text{-}24)$$

This value of impact velocity is applied to Equation 6-17 to compute the expected value of collision cost for the "no lane change" case.

6.2.3 Maneuver Model: Lane Change

The lane change maneuver is much more complex because it involves extreme lateral maneuvering, possibly with braking. Further there is awide (conceptually infinite) range of possible types of collisions between the maneuvering vehicle and vehicles in the adjacent lane. However the vehicle dynamic aspects of these maneuvers and collisions are essentially the same as for AHS and for manual control which has been studied extensively. Nonlinear simulations of vehicles with candidate maneuvering control systems should ultimately be performed. Adequate simulation software is available (Ref. 50), however, until the characteristics of the random object population are better defined, such elaborate simulations are probably not warranted.

Here a much simplified model of the lane change maneuver has been formulated which is only intended as a rough estimate of the probability of vehicle-vehicle collisions in a lane change. The primary emphasis is on accommodation of the key parameters and their first order influences on the decision between lane change and no lane change.

The possible outcomes of a lane change can be partitioned in four basic categories.

(1) No vehicle in slot, no collision

(2) No vehicle in slot, hit vehicle in front

(3) No vehicle in slot, hit by vehicle from rear

(4) Vehicle in adjacent slot

The "slot" referred to is the space in the adjacent lane where the maneuvering vehicle would ideally move into at least temporarily. Category 2 and 3 events will likely occur only if there is a significant difference in the nominal speeds between adjacent lanes. For AHS operation, it is reasonable to assume that the differences in mean lane speeds will be low. Thus Category 2 and 3 events will not be considered here.

The category 4 event is basically a double side impact vehicle-vehicle collision which is approximated as symmetric here. Given that such a collision occurs, the basic crush relationship can be developed from Equation 6-17 as

$$\Delta x_{max} = \frac{\Delta V_{13}}{\sqrt{k_3 / m_1}} \tag{6-25}$$

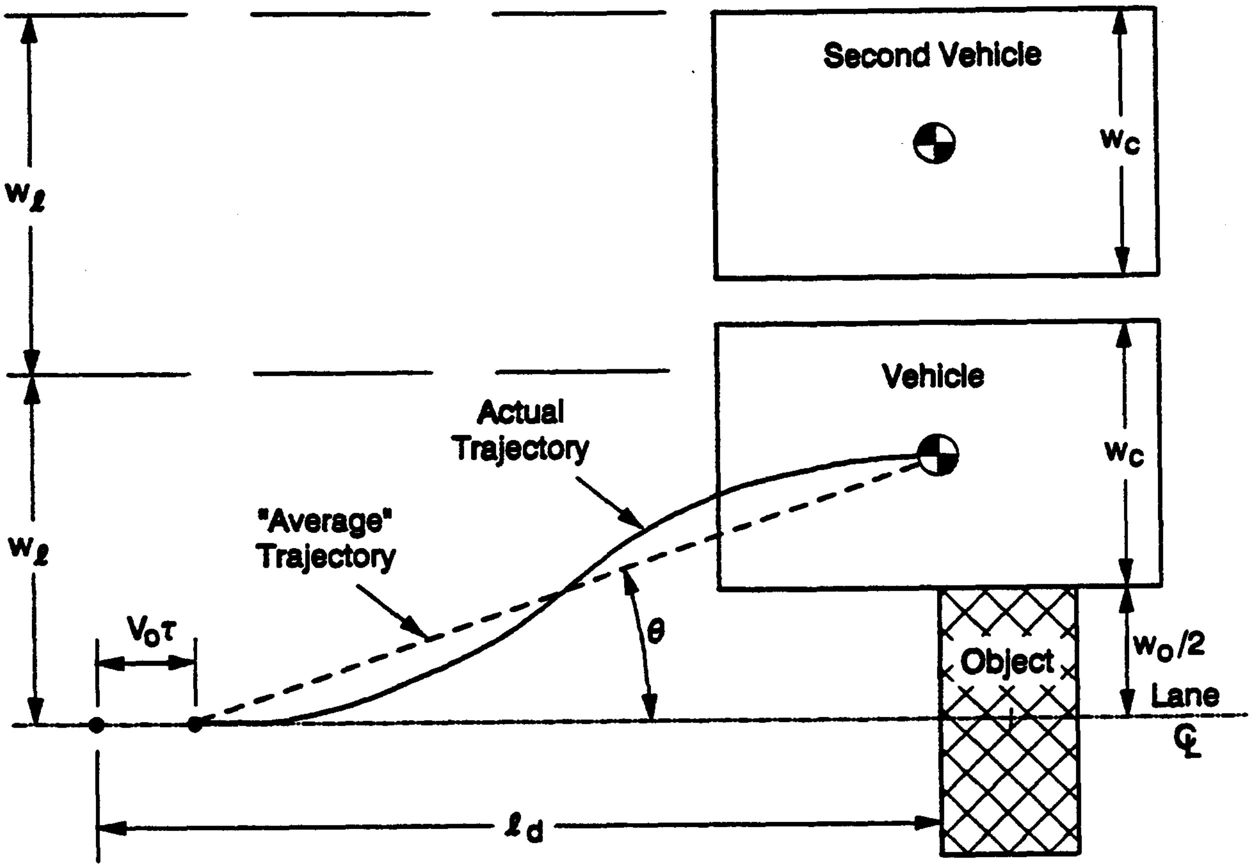
where ΔV_{13} is the relative velocity between the maneuvering and adjacent vehicles and is approximately normal to the sides of the two vehicles. The component of the relative speed tangential to the vehicle sides is considered negligible under the above assumption that the mean lane speeds are the same. It is assumed that the masses of the two vehicles are the same (m_1) as are their stiffnesses. However allowance is made for the possibility that the side stiffness (k_3) will probably be different from (lower than) the frontal coefficient. In the analyses to follow this is accounted for with a side/front unit stiffness ratio (K_3/K_1) such that:

$$k_3 = \left(\frac{K_3}{K_1}\right) k_1 \tag{6-26}$$

This relation applies as long as the two vehicle masses are the same.

The relative velocity ΔV_{13} will vary in a complex way during the maneuver depending on the control laws under which both vehicles operate. This level of complexity is beyond the scope of this analysis and only an estimate of the expected value of ΔV_{13} will be made. This is developed as shown in Figure 6.7 as

$$\Delta V_{13} \simeq V_0 \simeq \frac{V_0 (w_c + w_0)}{2(1_d - V_0)} \tag{6-27}$$



$$\theta \approx \frac{w_c + w_o}{2(\ell_d - \tau v_o)}$$

$$\Delta v_{13} \approx \theta V_o$$

Figure 6-7. Lane Change Geometry

where the angle Θ is assumed small.

However a collision may or may not occur depending on the traffic density in the adjacent lane. Thus the expected cost (expected crush, $\Delta x_{13_{max}}$) for the lane change is obtained by applying an appropriate probability of collision to Equation 6-25.

$$\Delta x_{13_{max}} = \left(\frac{l_v}{d_v + l_v} \right) P_w \frac{\Delta V_{13}}{\sqrt{k_3 / m_1}} \tag{6-28}$$

where

$$P_w = \begin{cases} p \text{ if } 0 \le p \le 1 \\ 0 \text{ if } p < 0 \\ 1 \text{ if } p > 0 \end{cases} \tag{6-29}$$

and

$$p = \frac{w_0 + 2 w_c - w_l}{2(w_l - w_c)} \tag{6-30}$$

The first term in parentheses accounts for the local longitudinal traffic density in the adjacent lane. The probability P_w accounts for the effect of the relative widths of the object, the vehicles, and the lanes. While the maneuvering vehicle remains in its original lane, P_w is zero. P_w increases linearly to unity as the left edge of the maneuvering vehicle reaches the right edge of the second vehicle when it (the second vehicle)is shifted as far as possible to the left side of the adjacent lane (Fig. 6.7).

6.2.4 Sensitivity Analyses

6.2.4.1 Sensitivity to Object Parameters

a. No Lane Change

The three object parameters are width (w_o = wo), density (μ_o = densityo), and unit stiffness ratio (K_2/K_1 = RUK2UK1). The effect of variation of these independent variables (with all others held at the Table 6-2 values) are shown in Figures 6.8 through 6.15. The cost (vehicle crush, Fig. 6.8) of a collision with an object increases rapidly with object size, as well as with object density and unit stiffness ratio. Object stiffness is probably the most uncertain factor. However, it can be seen that stiffness is the least sensitive of the three parameters. An order of magnitude increase in stiffness typically produces only about a factor of two in increased vehicle crush. By way of comparison, the crush is doubled by density increases in the range of 2 to 5 with the higher sensitivity at low density levels. Finally object size (apparent width) is the most sensitive factor; crush actually increases faster than size. This follows because object mass increases with the cube of size. However, it should be noted that a 6 foot object weighs more than a half ton at a relatively low density of 5 lbs/ft3; objects this heavy are surely rare on highways.

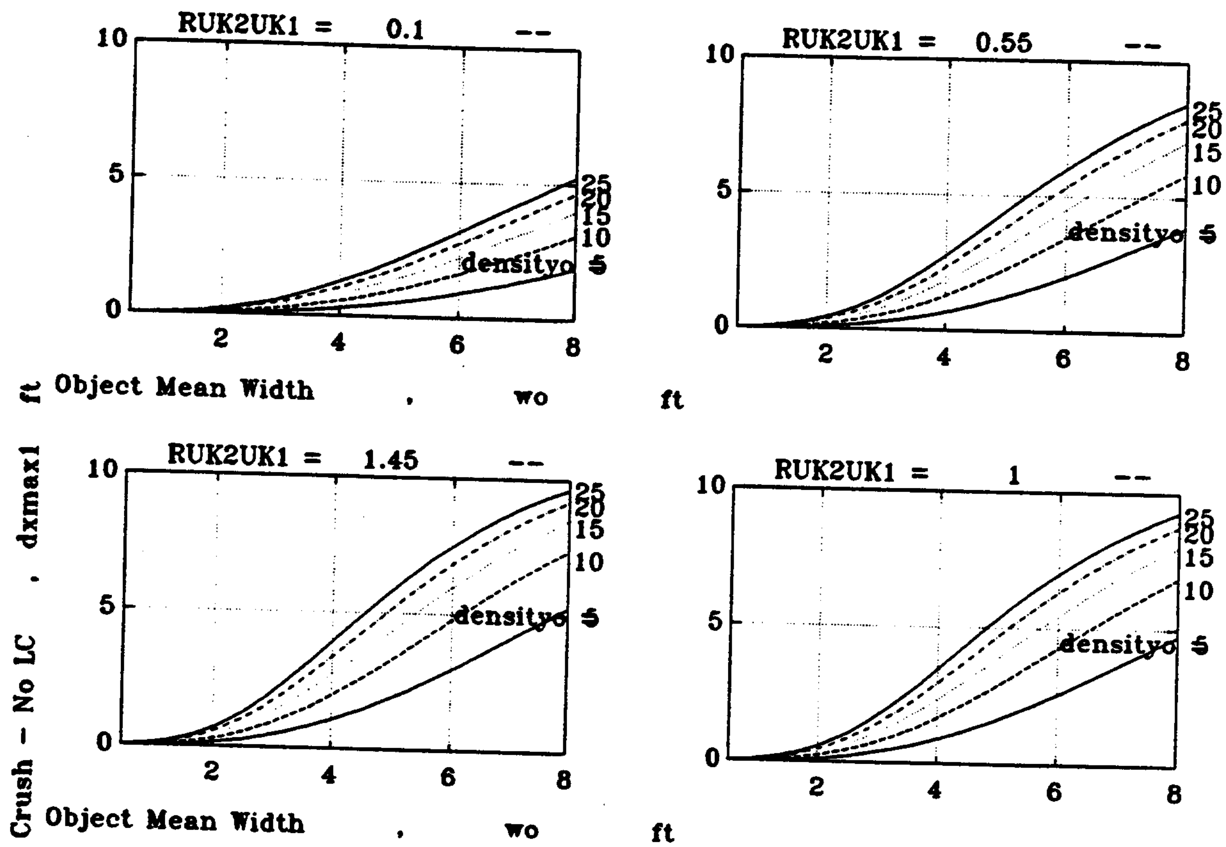


Figure 6-8. Vehicle Crush, No Lane Change

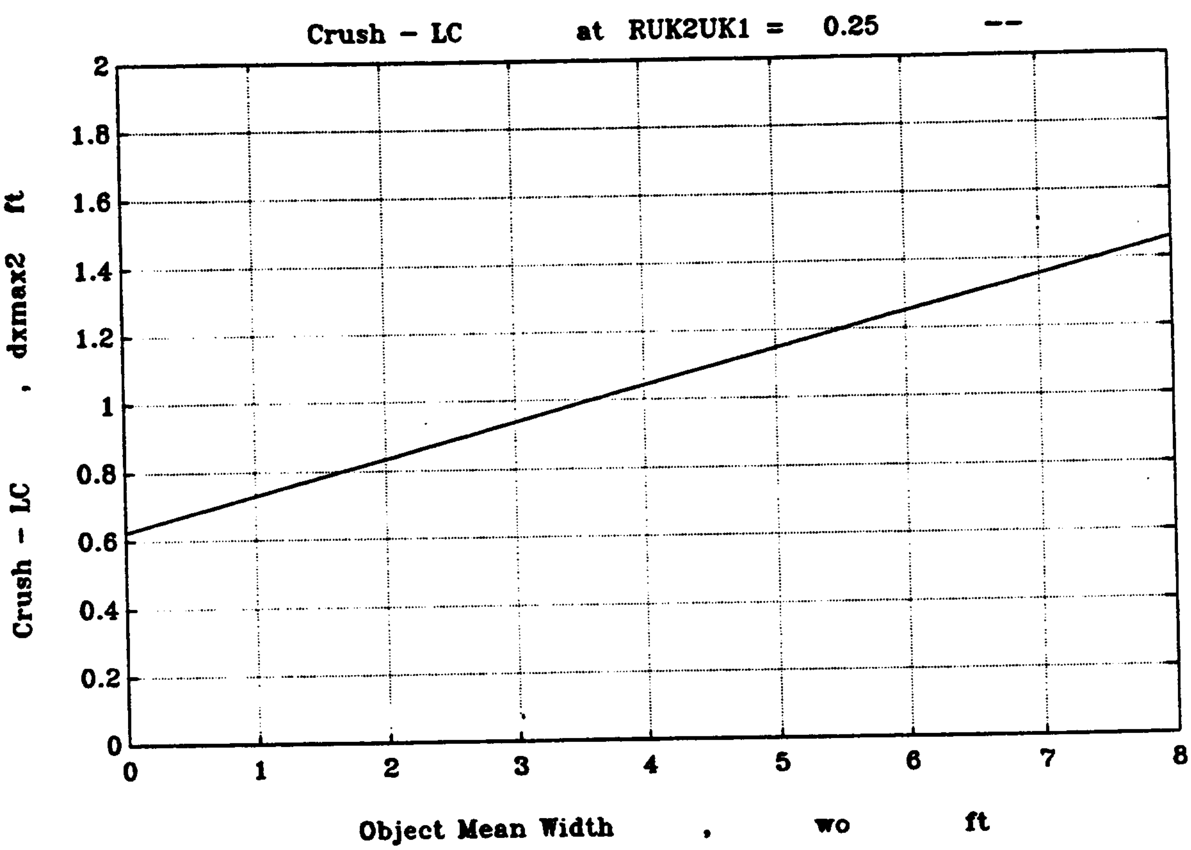


Figure 6-9. Two Vehicle Crush with Lane Change

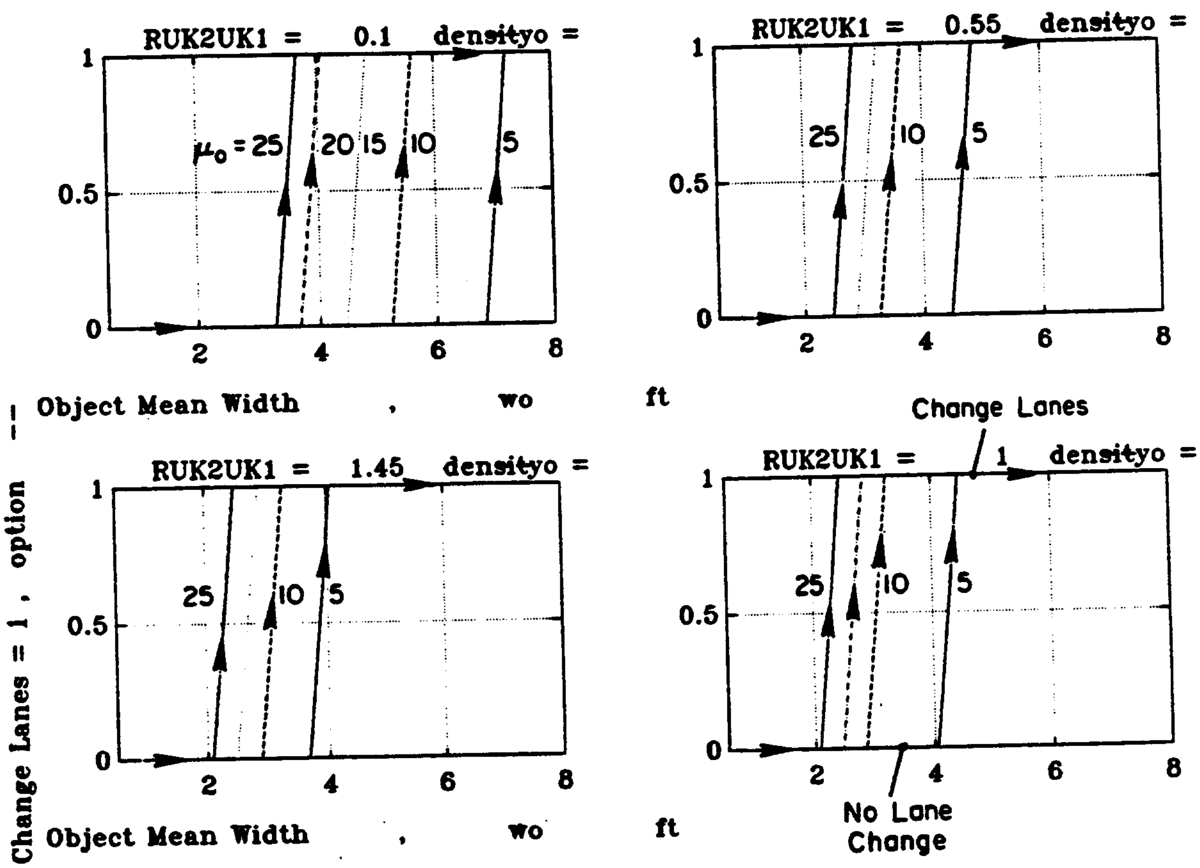


Figure 6-10. Lane Change Rule

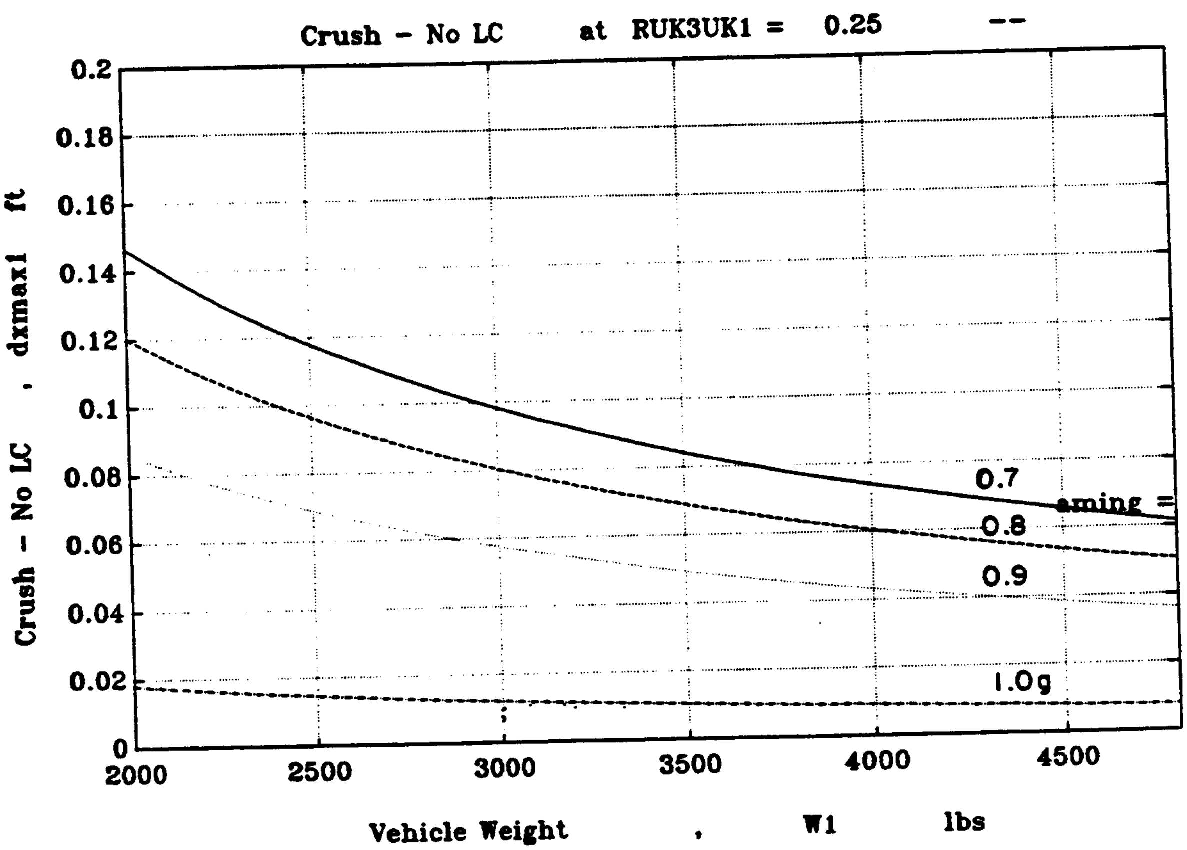


Figure 6-11. Vehicle Crush, No Lane Change

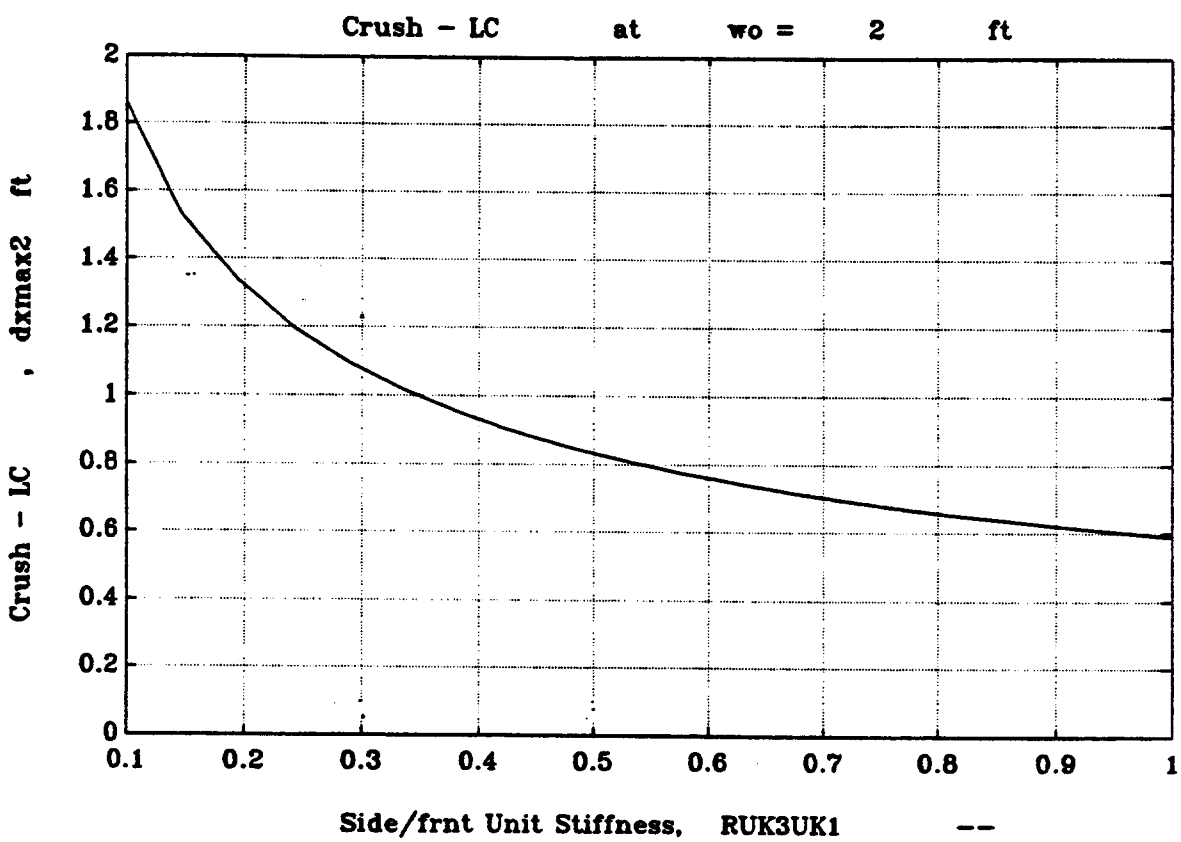


Figure 6-12. Two Vehicle Crush, with Lane Change

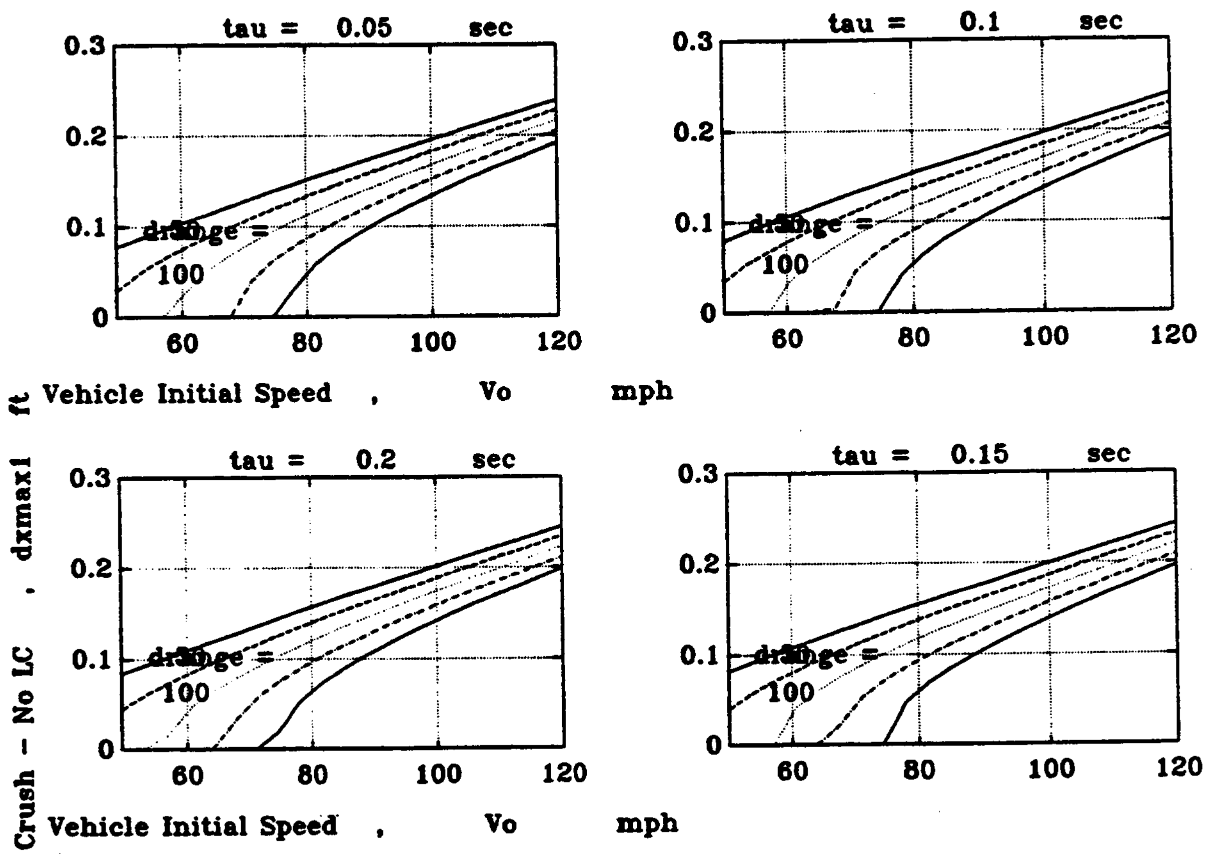


Figure 6-13. Vehicle Crush, No Lane Change

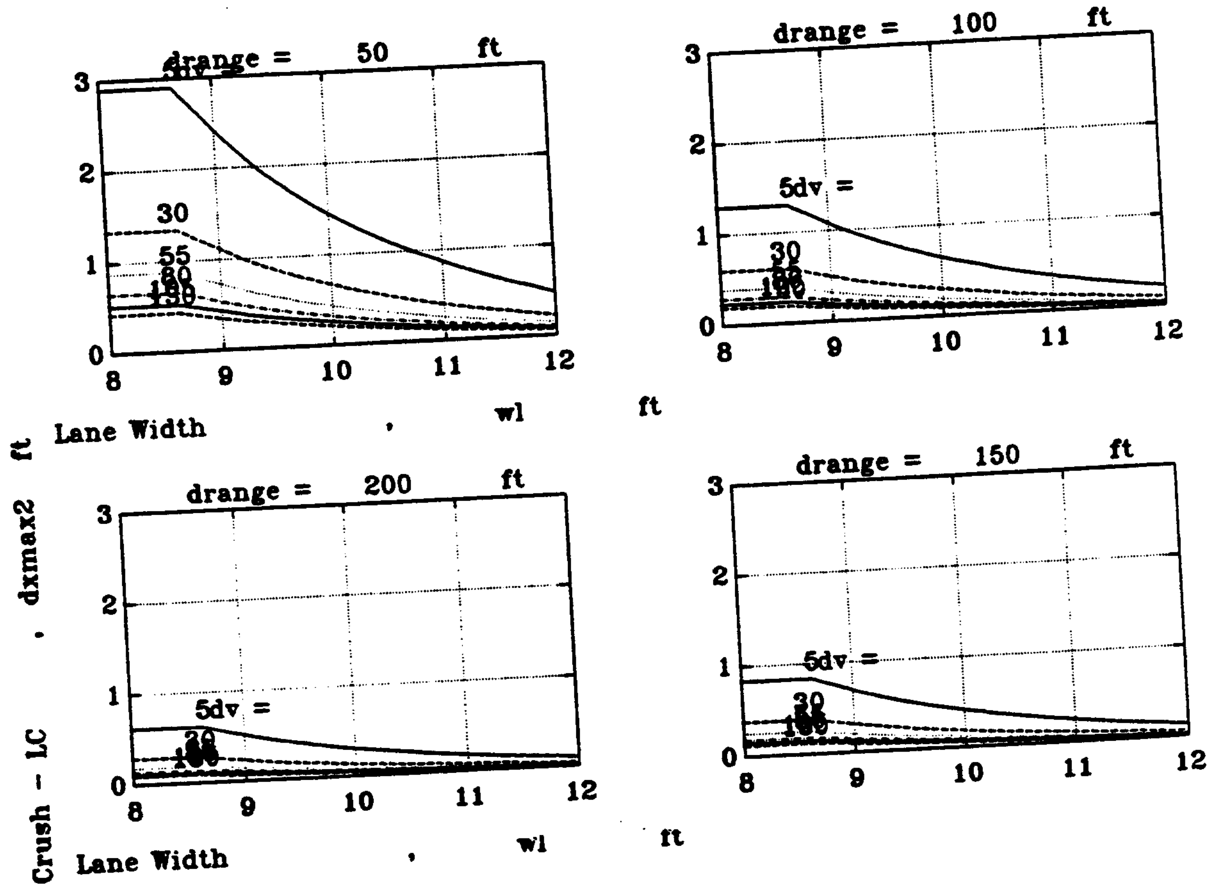


Figure 6-14. Two Vehicle Crush, with Lane Change

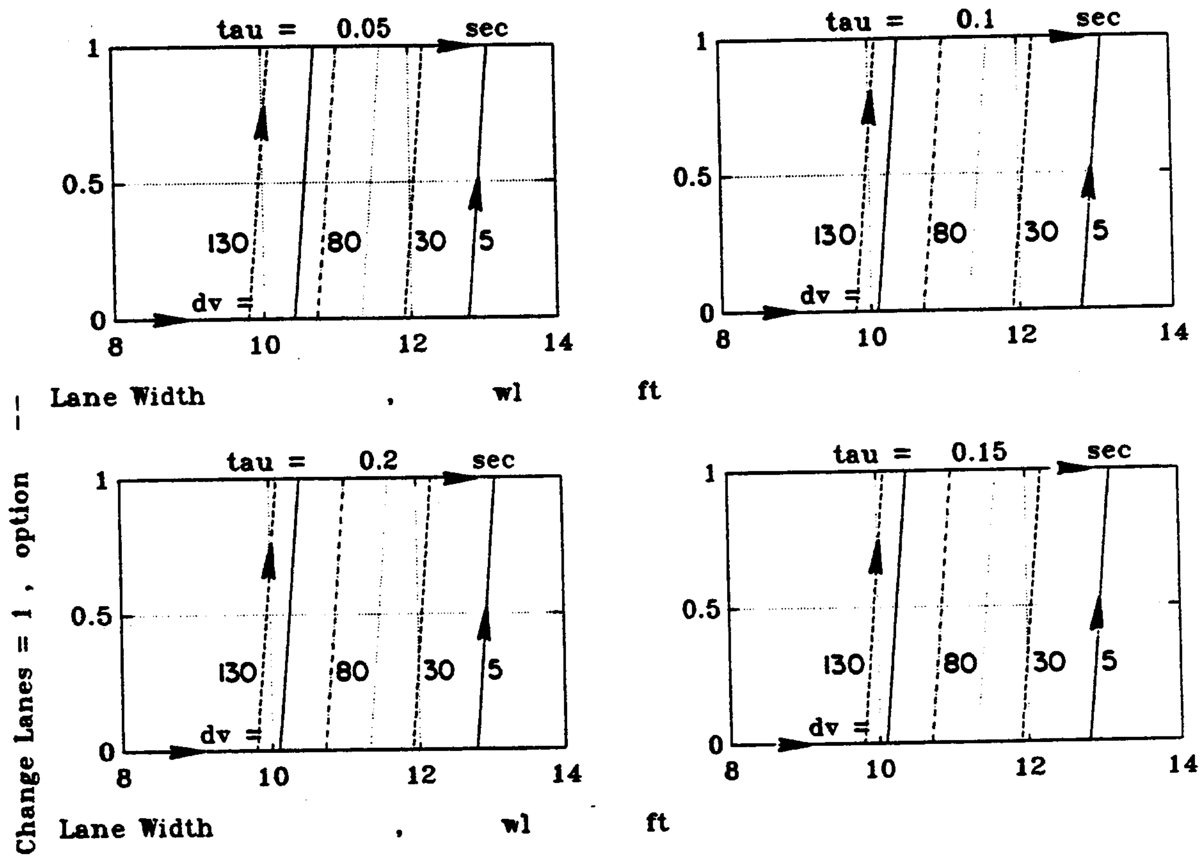


Figure 6-15. Lane Change Rule

While the absolute levels of vehicle crush must be considered quite unreliable, values above a few feet probably do indicate serious accident potential.

b. Lane Change

Figure 6.9 shows the effect of object size on the expected cost of a lane change. In this case increased object size simply requires the maneuvering vehicle to penetrate further into the adjacent lane to avoid the obstacle. This increases both the probability of a collision with a second vehicle and the relative velocity between vehicles. The object density and stiffness have no effect in the lane change case. Comparison with Figure 6.8 indicates that it is best to change lanes for objects larger than a few feet in size. This is shown more clearly in the lange change logical variable (Figure 6.10) for which 0 indicates "no change" and 1 indicates "change lane".

6.2.4.2 Sensitivity to Vehicle Parameters

As noted above, the maneuvering vehicle and the "second" vehicle in the adjacent lane are assumed identical. This was done because the mean differences among vehicles are relatively small compared to the differences between vehicles and random objects. Thus variations between vehicles is a second order effect that would only have obscured the primary issues of this preliminary study. The vehicle parameters are weight (W_1 = W1), maximum deceleration (a_{min} = aming), side/front unit stiffness ratio (K_3/K_1 = UK3/UK1), vehicle frontal unit stiffness (K_1 = UK1), width (w_c = wc), and length (l_v = lv). The variation of the first three are considered most important and only these are examined here.

a. No Lane Change

Figure 6.11 shows the effects of weight and deceleration limit for the "no lane change" case. The side/frontal stiffness ratio has no influence in this case. The absolute levels of crush here are much less than the extremes seen in Figure 6.8, primarily because the nominal object is small (2 ft and 40 lbs). On can see that larger cars generally suffer less damage for a given object. The deceleration limit has a more pronounced effect, because higher deceleration significantly reduces the impact velocity. If the stop could be made at 1g (a very high decel level) the impact velocity would only be about 4 mph for this situation.

b. Lane Change

If a lane change is made, the deceleration limit has no influence because, under the assumed scenario of common mean lane speeds, there is no reason for significant speed changes. Weight ($W_1 = m_1 g$) also has no effect because of the assumption here that the two vehicles are identical. This, perhaps counter-intuitive, effect can be understood by noting that the factor k_3/m_1 in Equation 6-28, which can be rewritten as

$$\frac{k_3}{m_1} = K_3 = \left(\frac{K_3}{K_1}\right)K_1 \tag{6-31}$$

is independent of weight. The remaining effect is the expected reduction in crush as the vehicle side stiffness increases (Fig. 6.12).

For this range of variables and the relatively small nominal object, no lane change is indicated.

6.2.4.3 Sensitivity to AHS System Parameters

The final assessments address the effects of AHS system parameters. These include mean lane speed (V_o = Vo), front-to- rear distance between vehicles (d_v = dv), lane width (w_l = wl), range at object detection (l_d = drange), and effective system time delay (τ = tau). Lane speed is considered an AHS system parameter because a possible long-term benefit of AHS could be increased lane capacity (vehicles per hour) from operation at higher (than current) speed. The critical assumption (which is outside the scope of this study) being that AHS would allow operation at higher speeds than manual control for a given level of safety.

a. No Lane Change

The effects on accident cost of the system parameters that are of most importance in the "no lane change" case -- mean lane speed, detection range, and system time delay are shown in Figure 6.13. As would be expected, reducing lane speed and increasing detection range reduce accident severity by ultimately reducing impact speeds. Increasing time delay up to 200 msec produces only a negligible increase in accident severity, but complex object identification schemes could create even longer delays.

b. Lane Change

Figure 6.14 shows the effect on accident cost of the parameters that are most significant in lane changes -- lane width, vehicle longitudinal separation, and detection range. The vehicle-vehicle crush is quite sensitive to lane width. As lane width is reduced, the second vehicle has less lateral room to move away from the vehicle maneuvering around the obstacle. This in turn raises the probability factor P_w (Eqn. 29) that a collision will occur. As can be seen from Figure 6.7, P_w goes to 1 for lanes narrower than about 8ft-8in. This effect is quite important since one proposed benefit of AHS is reduction of lane width (to as low as 8 ft) to increase the number of lanes available in a fixed highway corridor.

The probability of an accident decreases rapidly with increasing longitudinal vehicle separation l_v leading to high expected cost. The sensitivity is highest at low separations. Thus AHS platooning, particularly with very small intra-platoon spacings (a few feet), will be adverse from the standpoint of the obstacle avoidance problem. Increasing object detection range reduces expected crush in lane changes by reducing the expected value of relative velocity (see Equation 6-28 and Figure 6.7).

The effect of lane width and longitudinal vehicle separation are seen in the lane change rule diagram of Figure 6.15. Both the narrow lanes and small vehicle separations, that have been suggested for AHS, result in reductions in lane changes. But this may actually result in a higher accident cost than if lane changes were under the current (manual control) operational situation.

6.3 Conclusions, Issues and Risks

6.3.1 Conclusions

Currently the most important question concerning AHS obstacle avoidance is the discrete control strategy for determining if a vehicle should maneuver around an obstacle or simply remain in its current lane and brake.

The basic discrete lane change decision algorithm can be based on comparison of estimates of the expected costs of: (1) remaining in the lane and possibly impacting the object or, (2) maneuvering around the obstacle and possibly colliding with a vehicle in an adjacent lane.

The key uncertainties in the lane change decision problem, both for analysis and real-time systems, are the statistical distributions of the properties of the population of random objects that can be expected to appear on highways. The object properties of interest, in order of decreasing importance, are size, density, and effective structural stiffness. Relevant statistical data is not readily available.

The lane change decision problem for an automatic system is fundamentally the same as that for a human driver. However, in addition to simply detecting an object in the roadway, human drivers apparently apply, with various degrees of competence, subtle identification schemes to predict the danger of impacting the object. These probably involve cues from size, shape, color, and motion compared to a "knowledge-base" of likely highway objects. Achieving this capability in sensor processing for an automatic system can be expected to be a major challenge and a critical path in AHS development.

Even if an automated lane change decision capability can be developed and shown to equal or exceed human capability in tests, accidents with an automated system are probably more likely to result in lawsuits. This follows simply because of the "deeper pockets" of a system manufacturer compared to those of an individual driver.

The most sensitive object factor is size. Increased object size increases collision severity in the "no lane change" case by increasing object mass. It increases severity in the "lane change" case by increasing the expected relative velocity with respect to adjacent vehicles.

The most sensitive vehicle factor is the limit deceleration capability, but it effects only the "no lane change" case to a first approximation. Increasing the limit reduces the severity of "no lane change" accidents by decreasing the object impact speed. In lane changes some reduction in accident severity is achieved by increasing the effective side stiffness of the vehicle.

All of the AHS system parameters (lane speed, longitudinal vehicle separation, lane width, object detection range, and system effective time delay) are potentially significant. Reduction in longitudinal vehicle spacing and reduction in lane width from current nominals, possibilities that have been proposed as benefits from AHS and vehicle platooning, could have serious adverse impacts on the obstacle avoidance problem.

6.3.2 Issues and Risks

The primary need for future research in this area is better characterization of the population of random objects that can be expected to appear on highways (AHS highways in particular). Statistical distributions of (in order of decreasing importance) size, density, and effective stiffness should be obtained. Reasonable empirical data could probably be obtained from state highway departments and highway patrols.

When improved object statistics are available, the analytical procedure reported here should be refined to predict the variances of accident severity as well as expected severity. The lane change accident probabilities should also be refined. Ultimately the lane change model should be based on a vehicle dynamic simulation (which are currently available). However this step should be postponed, until a refined version of the closed form probabilistic model reported here has been thoroughly examined.

The problem of detecting and characterizing random roadway objects with machine systems should be studied as a distinct problem This should begin with a study of human driver behavior and technique for object detection and classification. This could be done with integrated driver-in-the-loop simulation and field experiments. This effort can build on relevant technology developments for similar applications. New technologies in the area of artificial intelligence, machine vision, etc. should be examined. Developments could find application in collision warning systems (especially for night and foul weather) before AHS is operational.

Table 6-1. Reference Object Density Data

	Actual Parameters						Apparent Parameters		
Parameter	w	h	l	Wt	Vol	Dnsty	Size	Volume	Density
Units	in	in	in	lbs	ft3	pcf	ft	ft3	pcf
25" Color Television	30	27	24	66	11.3	5.87	2.25	11.4	5.79
48" Round Table	48	36	48	82	48.0	1.71	3.67	49.3	1.66
Microwave Oven	25	15	20	42	4.3	9.68	1.67	4.6	9.07
Wooden Desk	72	36	36	320	54.0	5.93	4.00	64.0	5.00
Sofa	79	29	29	118	38.4	3.07	3.81	55.1	2.14
Loveseat	54	29	29	78	26.3	2.97	3.11	30.1	2.59
Upholstered Chair	29	29	29	58	14.1	4.11	2.42	14.1	4.11
Executive Office Chair	18	40	20	60	8.3	7.20	2.17	10.2	5.90
Office Safe	18	26	26	249	7.0	35.36	1.94	7.4	33.87

Table 6-2. Independent Variables and Nominal Values

Symbol		Independent Variable	Nominal Value	Units
Eqn	Plot			
W_1	W1	Vehicle weight	4000.	lbs
K_1	UK1	Vehicle front unit stiffness	12.5	g/ft
K_2/K_1	RUK2UK1	Object/vehicle unit stiffness ratio	0.25	--
V_o	Vo	Mean lane speed	65.0	mph
a_{min}	aming	Maximum deceleration	0.8	g's
l_d	drange	Range at object detection	150.	ft
τ	tau	System time delay	0.1	sec
w_c	wc	Vehicle width	6.0	ft
d_v	dv	Distance between vehicles, front to rear	5.	ft
l_v	lv	Vehicle length	16.5	ft
w_l	wl	Lane width	8.0	ft
w_o	wo	Object mean width	2.0	ft
μ_o	densityo	Object mean weight density	5.	lb/ft^3
K_3/K_1	RUK3UK1	Side/front vehicle unit stiffness ratio	0.5	--

Table 6-3. Dependent Variables

Symbols		Dependent Variable	Units
Equation	Plots		
t_f	tf	Time at Object Contact	sec
v_{10}	v10	Initial Speed ar Object Contact	fps
$\Delta x_{1i_{max}}$	dxmax1	Crush - No Lane Change	ft
$\Delta v_{13_{max}}$	delv	Relative Velocity Between Vehicles	fps
$\Delta v_{13_{max}}$	dxmax2	Crush - Lane Change	ft
option	option	Lane Change Logical Variable	0 = no 1 = yes

7. ASSESSMENT OF THE STREAM STABILITY PROBLEM

7.1 Objectives

The objectives of this section are to (1) examine the instability arising in ag gregate flows of the AHS and (2) identify the potential issues and risks. In particular, the introduction of automation may generate couplings among much larger numbers of vehicles covering a large spatial extent (compared to today's manually driven freeways), such that a small perturbation by one vehicle may instigate a widespread reaction in the traffic flows. Whether this is the case and whether this can lead to inefficient or dangerous situations is a primary subject in this investigation.

7.2 Analyses of Stream Stability

This study's approach consists of three components: a review of the open literature, a short mathematical analysis, and a simulation-based investigation.

7.2.1 Literature Review

The literature review is divided between two areas: (i) research in the potential for perturbation amplification in a contiguous string of vehicles employing longitudinal control, using fairly conventional mathematical tools in control theory, and (ii) recent results from researchers using cellular automata models that are directed at discovering phenomena characterisic of complex systems.

7.2.1.1 Perturbation amplification in strings of automated vehicles

There have been a number of researchers that have analyzed the following stream stability problem: If a string of consecutive vehicles follow one another using longitudinal control, will instabilities arise through an amplification of longitudinal disturbances in the lead vehicle? This has been referred to as the "slinky" effect, and can arise in the context of a platoon of closely spaced vehicles, as well as all vehicles simply employing Automatic Intelligent Cruise Control (AICC) and relatively conventional spacings.

Control laws have been developed that require knowledge of the velocity and acceleration of the lead vehicle for the group, and have been shown to result in stable performance (Ref. 51, 52). This implies that a communications system is available to continuously provide the lead vehicle information to all the following vehicles. As stated in Ref. 53, "At present system designers are inclined to view the communication system within the platoon to be indispensible for safety, entrainment, and detrainment maneuvers."

More recent studies have focused on systems that do not require knowledge of the group lead vehicle's motion, but only that of the immediately preceding vehicle. Such information may be acquired through on-board sensors, precluding the necessity of a communication link between vehicles. This can make the system more reliable and most likely less expensive to implement. However, the stream stability ("slinky") effect is of much greater concern. In addition, it is generally agreed that the performance, in terms of throughput (flow) capacity, will be impacted relative to the system with lead vehicle motion information available to the controller. There is a fairly wide spectrum of opinions on the degree of this relative degradation. For example, in Ref. 54 it was concluded that "AICC may not be able to significantly increase highway capacity over current levels. The major benefits of AICC may appear to lie in enhancing driver comfort." The controller of Ref.53 that does not require communication is such that "deviations in vehicle spacings from their assigned positions increase from one vehicle to the next as one goes down the platoon", implying that a maximum platoon size will have to be enforced. This paper proposes its use as a backup mode, with normal operation utilizing communications; if this communication capability is lost, then performance is degraded "but is not catastrophic." Other researchers have presented a longitudinal controller [Ref. 55] that does not require information exchange between vehicles and yet yields "faster and better transient response that leads to much smoother and faster traffic flow" compared to human driven vehicles.

7.2.1.2 Impact of Entering and Exiting on Stream Stability

An issue that has been investigated is the effect on the traffic flow of vehicles entering and exiting the AHS. We review two investigations here.

In the work on the spontaneous platooning concept [Ref. 56], the entering vehicles were controlled so that an appropriately chosen vehicle in the mainstream flow would decelerate (if required) just enough to allow the vehicle to safely enter (in nonplatooned mode). The algorithm selected the mainstream vehicle as the first upstream vehicle that could "comfortably" (at some prescribed deceleration value) allow the process, however, another constraint was that the mainstream vehicle would not decelerate below a minimum velocity (i.e., mainstream vehilces had priority in this sense). The on-ramp vehicle would enter as soon as the gap was opened enough. It was found that this merge procedure, which was analyzed using a simulation model, resulted in quite smooth entrance behavior.

In the same work, vehicle exiting was modeled as follows. Each exiting vehicle must not be in a platoon; this assumption has been stated in various PATH studies and appears to be reasonable if not somewhat conservative. (The possibility of a platoon of vehicles all exiting at the same location raises the possibility of deplatooning after the off-ramp has been reached, and could yield performance improvements depending on the probability of such platoons.) The procedure for exiting analyzed in [Ref. 56] was as follows. When a vehicle became within a certain distance (which was a function of its speed as well as absolute distance) of its intended destination, it would begin a deplatoon maneuver. The control did not directly use any information such as the prevailing load on the roadway or any exit information for vehicles in its neighborhood. Simulation of this control mechanism found that the exiting behavior had a significant impact on the stream stability, much more so than the merge process.

The study [Ref. 57] also investigated these issues, using the SmartPath simulation model. They found that "entrance and egress of vehicles will be the primary cause of traffic stream disturbance and that ultimately this will dictate the flow rates which can be sustained reliably." In this paper, different strategies were developed for how platoons were constructed (through merging and lane changing), including techniques in which they are sorted according to exit (destination) information. This latter method was found to significantly improve the stream stability impacts of egress. (Of course, it also requires communication of the destination information among the vehicles.)

7.2.1.3 Complexity of Vehicle Interactions

A variety of mathematical models have been offered by researchers for use in studying the behavior of uninterrupted flow of traffic. For example, in addition to analyses based on vehicle-following laws such as those indicated in the previous section, investigations have used continuum hydrodynamics models of a compressible fluid, as well as approaches using the kinetic theory of gases. A full review of these various methods of analyses to stream stability is beyond the scop of this report. Instead, we focus on a relatively new approach to traffic flow analysis: cellular automata.

Cellular automata can be used to model single lane flow of traffic as follows. The road is constructed as a one-dimensional lattice of cells, where each cell has a finite number of states: either no vehicle is present in that cell, or a single vehicle is present with an integer velocity $v = 0, \ldots, v_{max}$. Time is modeled as a sequence of unit steps. All cells use the same simple set of rules that dictate the evolution of the traffic process, where the rules are evaluated each time step. There is a notion of direction in the lattice, such that the rules depend only on the state of the cells "downstream" (as well as its present state). This is therefore an asymmetric (downstream dependence) exclusion (at most one vehicle per cell) cellular automata model. The rules typically say that [Ref. 58] if the cell is occupied, then (1) if the velocity of the vehicle is less than v_{max}., then increment v by 1; (2) if the distance d (number of cells) to the next downstream vehicle is less than the current speed v, then reduce the velocity to d-1, and (3) with probability p, reduce the velocity v by 1 provided it remains nonnegative. Once the rule is evaluated, motion is determined by advancing each vehicle by v cells. There are a number of variations of the model possible, including cases with lane changing [Ref. 60] and two-dimensional models for networks [Ref. 61]. In this stream stability study, only single-lane models were considered.

The cellular automata model of single-lane traffic flow is "microscopic" in its treatment of traffic at the level of individual particles (vehicles), as opposed to (say) continuous-time continuous-state fluid dynamics models. The cellular automata model described above is too simple to accurately capture the details of a realistic AHS, however, it may shed light on the qualitative phenomena that can arise in complex systems of many entities interacting according to nonlinear dynamics. Cellular automata have been used to analyze the phase transition (criticality) from laminar flow to turbulent flow [Ref. 59, 60]. Furthermore, Traffic Managment Systems often attempt to drive the system near this critical point, since this also corresponds to the maximum flow capacity (see [Ref 65, p. 1-6]). In [Ref. 62], a cellular automata model is used to demonstrate that the maximum travel time variation occurs at this critical point as well.

Cellular automata are representative systems th at are under scrutiny within the new science of complexity. A major component in this newly emerging science is Artificial Life, which (in part) is identifying aspects of biological systems that can be applied to the engineering of man-made systems that are inherently complex adaptive systems. A concept that has been offered in the context of ethology (the study of the behavior of animals) is that randomness may play a positive role in the welfare of an animal species, specifically in that of a species that has characteristics of societal behavior. For example, when one views an insect society such as an ant colony, at the individual level there appears to be a large amount of randomness. The initial thought might be that this randomness causes great inefficiencies in achieving the goal of the society (moving the nest, for example). However, recently, it has been proposed that in fact this randomness aids the adaptibility of the society, yielding a greater survivability of the species [Ref. 63, 64]. By many metrics (e.g., total biomass) the ant species are the most successful on the planet, and certainly demonstrate incredible survivability. In the case of AHS stream stability, it may very well be prudent to intentionally incorporate some randomness in the behavior of the vehicles, sacrificing (so to be speak) some degradation from an ideal optimum, in order to ensure a more robust and adaptable system.

7.2.2 Simulation-Based Study of Behavior in Incidents

An issue of concern is whether the introdu ction of automation into highway system by means of longitudinal control will inherently cause a much wider coupling among vehicles both in their number and the spatial extent. We initiated a simulation study, using the microscopic simulation model described in [Ref. 56], to investigate the relative performance of manual and automated systems in response to a short incident. To concentrate on longitudinal effects, we used a simple single lane model with no on- or off-ramps (only mainstream vehicles arriving from a single source).

While the model in [Ref. 56] has been used to study the concept of spontaneous platooning, this aspect was "turned off" for the purposes of this study. The difference between a manual system and an AHS was modeled as follows.

Straightforward deterministic second order equations for basic speed-density-flow relationships (e.g., [Ref. 65]) can be derived for equilibrium uninterrupted flow, based on of vehicle following behavior, that are a function of the reaction time, minimum vehicle spacing (at jam density), velocity, the follower deceleration rate a_F, and the leader deceleration rate a_L. Adjustment of the parameters of reaction time and the two deceleration rates a_F and a_L allows a reasonable fit to empirically derived data over a range of velocity values for manually driven vehicles. Values that may be considered as providing a reasonable fit were taken in this study as reaction time = .75 second, a_F = -.6g and a_L = -1g, where g = force of gravity = 980 cm/s^2. We also took the minimum vehicle spacing as 5.5 m throughout. With these values, one can derive that a determinstic model has a maximum flow of 2228 veh/h (for the single lane) when the vehicles travel at velocity 45.6 km/h. We instead simulated a flow of 2011 veh/h, with corresponding velocities 85 km/h. That is, we imposed a load of about 90.3% of maximum flow in the manual case.

When automation is applied, certainly the reaction times are lowered, and so in this case we took reaction time = .2 seconds. The impact of automation on the parameters a_F and a_L is less clear. However, we left a_F = -.6g, since we assume the mechanics of the vehicle are essentially unchanged regarding braking capability. However, since the AHS is better managed and controlled, the likelihood of a very large sudden deceleration is decreased, so we assumed that the lead vehicle deceleration used for the vehicle following law can be relaxed to a_L = -.75g. This results in a maximum flow of 4427 veh/h for velocities of 64.6 km/h. We instead used a flow rate of 3991 veh/hr, corresponding to a velocity value of 110 km/h, so that we have the system load at about 90.1% of maxmum capacity.

Summarizing, the manual and automated cases use different parameter values for reaction time and a_L so that the automated case has twice the capacity of the manual case. Also, the offered loads used were 90% of the respective maximum capacities. While operating speeds for the cases differ, the factor of 2 difference in flow rates provides a useful and convenient basis for comparison.

The simulations were made in which, after a settling time for transients in the intitialization to die out, an incident is created for a short period. This incident consisted of a single vehicle suddenly decelerating at aF = -.6g to zero speed, until one minute passed, and then accelerating normally to the speed limit. In both cases the speed limit in both cases was set to 112.7 km/h (70 mi/h). The purpose of the simulation was to investigate the duration and spatial extent of the resulting traffic jams, and compare the manual and automated cases. The freeway segment modeled was 17.7 km in length, with the incident occuring at the 3.2 km point. While such a long stretch without on- and off-ramps is idealistic, this allows concentration on a single phenomenon with a model that is large enough to prevent anomolies caused by edge effects.

Figures 7.1 and 7.2 correspond to the manual case. Figure 7.1 shows, for each point in time, the number of vehicles whose velocities fell below a given velocity V, where V is parameterized (4 curves) as 16 km/h, 32 km/h, 48 km/h, and 64 km/h. The incident was initiated at time 600 seconds, and persisted until time 660 seconds. Since the nominal flow is 2011 veh/h, approximately 33.5 vehicles will be stopped after 60 seconds. The duration of the jam, measured in terms of when all vehicles are again traveling at at least 64 km/h is just over 11 minutes from when the incident was removed.

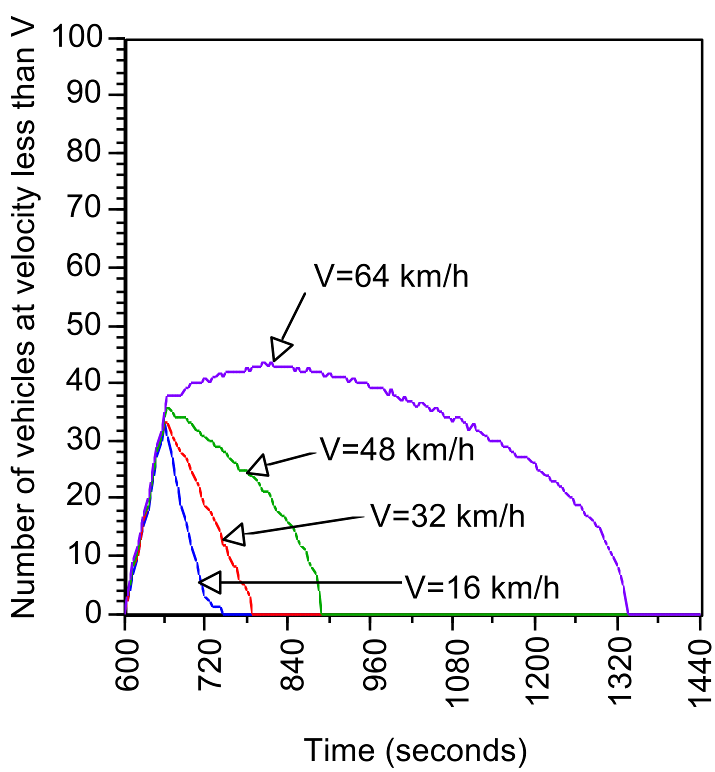


Figure 7.1. Number in jam versus time, manual case

Figure 7.2 shows the spatial extent of the jam versus time for the same (manual traffic) case. Here, extent is measured in feet (due to the units used in the simulation program). The extent of the 64 km/h jam rises to more than 1 km (3281 feet) some 4 minutes after the incident is removed.

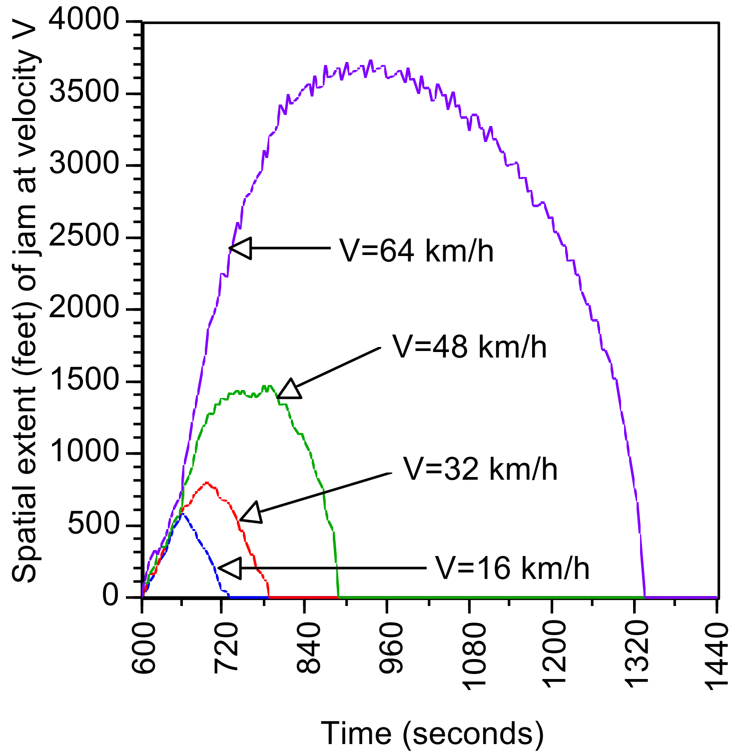


Figure 7.2. Spatial extent of jam versus time, manual case

Figures 7.3 and 7.4 similarly present statistics for the automated case. Again, the incident was initiated at time 600 seconds and removed at 660 seconds. . Since the nominal flow is 3991 veh/h, approximately 66.5 vehicles will be stopped after 60 seconds. It is seen that the jam at velocities less than 64 km/h appears to dissipate about 6.5 minutes from the removal of the incident, which is conisderably sooner than the previous manual case. That is, even though twice the flow is being offered, the jams appear to clear in just over half the time. However, note that approximately twice as manner vehicles are involved in the jam.

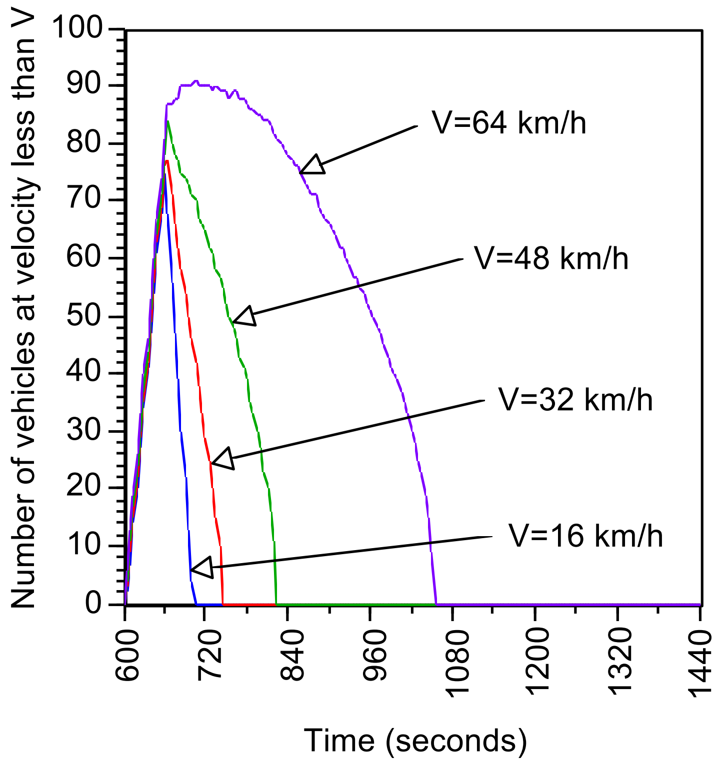


Figure 7.3. Number in jam versus time, automated case.

Figure 7.4 shows that the spatial extent of the jam becomes about the same size as in the compared manual case, however, it dissipates in just over half the time.

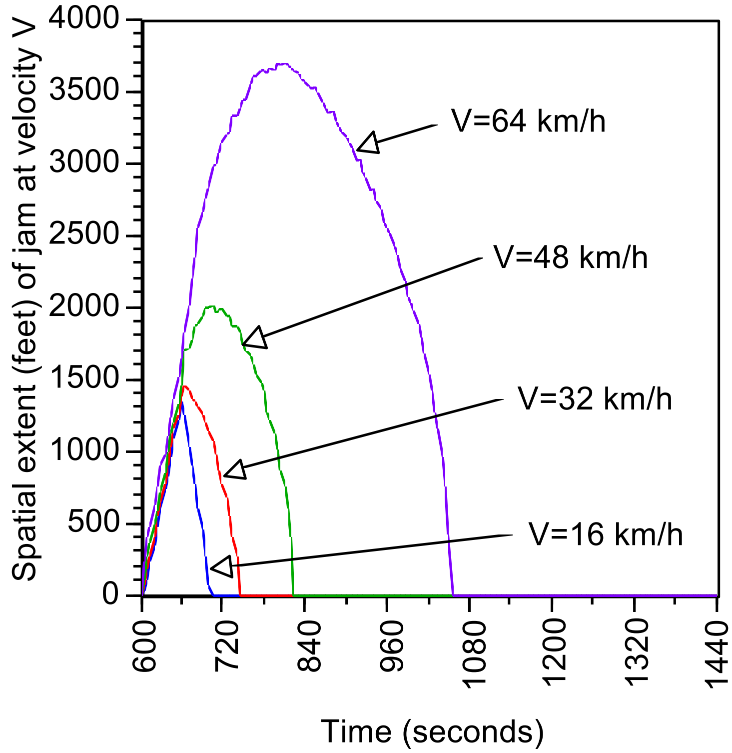


Figure 7.4. Spatial extent of jam versus time, automated case.

Summarizing the results of the simulation analysis, there are many more vehicles affected by the incident in the automated case simply because of the higher flow. However, because of the shorter reaction times, the incident clears earlier in the automated case. The total additional vehicle-delays (very roughly, the area under the curve for Figures 7.1 and 7.3) are not too dissimilar; it appears that the automated case is slightly worse. However, the nominal operating speed for the automated case is higher, so that aside from the transient caused by the incident, individual vehicle mobility is better in the automated case. We point out, however, that this represents a very limited study, and further investigation is warranted to investigate a wider range of parameters and scenarios (on- and off-ramp effects, etc.).

7.3 Issues and Risks

<u>Perturbation amplification in strings of automated vehicles.</u> There is a general consensus that if communications links are provided so that each vehicle in a platoon obtains continuous information regarding the motion of the lead vehicle, then stability of the platoon can be sustained indefinitely. There is an issue of the safety of the platoon in the event of sudden failure of the communications system, however, this does not appear to be insurmountable and back-up control algorithms have been designed. There is an issue of the cost of the communications system, including the use of the spectral bandwidth needed. It is not generally agreed that a longitudinal control system can be designed without the aid of communications that will both provide major benefits in flow capacity as well as provide guaranteed stable performance. However, some benefits are realizable, and it may be possible to impose constraints on the maximum platoon size (via a less expensive communications link from traffic management) that provides the necessary limits for safe and stable operation.

Impact of Entering and Exiting on Stream Stability. It has been found that the effect on the traffic flow of vehicles entering and exiting the AHS effects must be accounted for in deriving the potential flow capacity increase benefits of an AHS, as well as used in any on-ramp flow control (to ensure the system is not overloaded). However, these effects do not appear to impose an obstacle to implementation of the AHS. There are some approaches that have been investigated that indicate substantial mitigation of these detrimental effects by communicating information regarding exit destination and utilizing this in the behavior of the vehicles (viz., platoon formation and dissolution). However, these will bring issues both of cost of implementation such communications links and algorithms as well as the problem of privacy.

Complexity of Vehicle Interactions. The AHS, like any road traffic system, is representative of a complex dynamic system, in which many entities interact asychronously based on local information and nonlinear rules of operation. Analysis and prediction in such systems is generally intractable, much like predicting the weather (which can be chaotic in the sense of sensitive dependence on initial conditions). Newly emerging concepts in the field of complex systems theory will need to be applied to bound the problem of performance evaluation, and ensure stable conditions will prevail.

Effect of Automation on Vehicle Neighborhoods. It seems clear that in the AHS, the coupling among vehicles will necessarily be increased. Thus, when an incident occurs, the effects will be much more widespread both in the number affected and the spatial extent. While one approach is to emphasize the rapid removal of problems, we feel that at least concurrent with this must be a careful design that ensures that the AHS is not too brittle, wherein every small disturbance is felt by every vehicle in a large region.

8. CONCLUSIONS AND RECOMMENDATIONS

Rockwell has performed precursor analyses in the area of AHS lat/long control analyses in terms of primarily four maneuvers (headway maintenance, lane change, platoon formation and obstacle avoidance), and stream stability. As stated earlier in Section 1, the purpose of this effort is to identify issues and risks for future AHS researchers. In lieu of that, the most important conclusion resulting from these analyses is that there are no show stoppers at this stage of the program. However, there are many issues that remain unresolved and which necessitate further investigation. The major conclusions and recommendations are summarized below:

Headway Maintenance

Safety distance between two vehicles depends upon many deterministic as well as random factors, e.g., vehicle velocities, brake capabilities, road condition, tires, and weather. Safety distance may be able to be established adaptively in real time, if we know what constitutes safety apriori.

Safety distance can be defined according to two basic principles: no impact and limited impact. No impact principle states that the safety distance is the minimum distance required at which the rear vehicle will not impact the front vehicle when it decelerates suddenly. The limited impact principle states that the safety distance is the maximum distance required at which the impact energy is under a certain threshold when the front vehicle decelerates suddenly.

Lane Change Maneuver

An intuitively robust, but inefficient, lane change maneuver process seems to be possible if gap making in the receiving lane and speed matching are both done by slowing down the pertinent vehicles.

While the efficiency of a lane change maneuver can be optimized, given a particular traffic condition, the optimization is often accomplished at the expense of system robustness. The trade off between efficiency and robustness requires careful analysis, tuning, and tests in the future.

A transition lane between automated and manual lanes seems to be necessary to warrant a fully automated lane change maneuver from auto to manual, assuming only automated vehicles are allowed in the transition lane.

Platoon Formation

There does not appear to be a compelling rationale for having the front platoon actively participate in the merging of two platoons. An active front platoon would imply system complexity beyond AICC with information simultaneously flowing both forward and backward between the platoons. This would create two-way dynamic coupling that could be generally undesirable.

It is important to distinguish between nominal merge conditions, which would apply to the majority of platoon formations, and special cases, which will occur relatively rarely (emergency and failure cases). Platoon formation will always be an optional activity performed for traffic flow efficiency and not specifically to enhance safety. Thus, aborting a platoon merge probably will be the correct strategy for many, if not most, off-nominal conditions. The nominal merge control design should not be compromised to allow platoon formation under off-nominal conditions where the maneuver could and should be aborted.

The nominal merge maneuver should be addressed as a constrained trajectory optimization problem, if a relevant cost function is identified. A minimum time maneuver is a possibility, but not a compelling one, since elapsed times for merge maneuvers will be much shorter than useful platoon "half-lives". Thus, minimum time maneuvers are primarily of interest as reference maneuvers. Maximizing safety and passenger comfort is much more important.

Obstacle Avoidance

Currently the most important question concerning AHS obstacle avoidance is the discrete control strategy for determining if a vehicle should maneuver around an obstacle or simply remain in its current lane and brake.

The basic discrete lane change decision algorithm can be based on comparison of estimates of the expected costs of: (1) remaining in the lane and possibly impacting the object or, (2) maneuvering around the obstacle and possibly colliding with a vehicle in an adjacent lane.

The key uncertainties in the lane change decision problem, both for analysis and real-time systems, are the statistical distributions of the properties of the population of random objects that can be expected to appear on highways. The object properties of interest, in order of decreasing importance, are size, density, and effective structural stiffness. Relevant statistical data is not readily available.

The lane change decision problem for an automatic system is fundamentally the same as that for a human driver. However, in addition to simply detecting an object in the roadway, human drivers apparently apply, with various degrees of competence, subtle identification schemes to predict the danger of impacting the object. These probably involve cues from size, shape, color, and motion compared to a "knowledge-base" of likely highway objects. Achieving this capability in sensor processing for an automatic system can be expected to be a major challenge and a critical path in AHS development.

The primary need for future research in this area is better characterization of the population of random objects that can be expected to appear on highways (AHS highways in particular). Statistical distributions of (in order of decreasing importance) size, density, and effective stiffness should be obtained. Reasonable empirical data could probably be obtained from state highway departments and highway patrols.

Stream Stability

There is a general consensus that if communications links are provided so that each vehicle in a platoon obtains continuous information regarding the motion of the lead vehicle, then stability of the platoon can be sustained indefinitely. The issue is the impact on the safety of the platoon in the event of sudden failure of the communications system.

It has been found that the effect on the traffic flow of vehicles entering and exiting the AHS effects must be accounted for in deriving the potential flow capacity increase benefits of an AHS, as well as used in any on-ramp flow control (to ensure the system is not overloaded).

The AHS, like any road traffic system, is representative of a complex dynamic system, in which many entities interact asynchronously based on local information and nonlinear rules of operation. Analysis and prediction in such systems is generally intractable, much like predicting the weather (which can be chaotic in the sense of sensitive dependence on initial conditions). Newly emerging concepts in the field of complex systems theory will need to be applied to bound the problem of performance evaluation, and ensure stable conditions will prevail.

It seems clear that in the AHS, the coupling among vehicles will necessarily be increased. Thus, when an incident occurs, the effects will be much more widespread both in the number affected and the spatial extent. While one approach is to emphasize the rapid removal of problems, we feel that at least concurrent with this must be a careful design that ensures that the AHS is not too brittle, wherein every small disturbance is felt by every vehicle in a large region.

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APPENDIX A

LONGITUDINAL VEHICLE MODEL

A1. Introduction and Overview

This Appendix documents the development of the vehicle model used for platoon dynamic assessments. This model is simpler than the complete nonlinear simulation models (e.g., STI's VDANL, Ref. 40-42) sometimes used for vehicle dynamics studies. However, it is tailored to this application and generally consistent with models presented in PATH REPORTS.

Safety analyses of platoon operation suggest that the *differences* in parameter values among vehicles may be more important than the mean parameter values. The view here is that complex simulation models, with large numbers of parameters that are complicated to estimate, would not be appropriate for addressing this issue, at least in the initial stages. Thus the strategy used was to develop a simple, deterministic model form that will be the same for all vehicles in the platoon-capable population. Numerical values of the vehicle parameters will differ among the vehicles and the parameter values for the platoon as a whole woud be (conceptually) a statistical distribution.

Table 1 summarizes the generic vehicle model form. The model development begins with the freebody diagrams in Figure A1. This initial model is restricted to purely longitudinal motion; each vehicle has one DOF and does not roll, pitch, or yaw and has no heave or sideslip velocity. These and other simplifications and approximations are essential to achieving the objectives noted above, however there is a risk of violating the model assumptions when using such simplified models in analyses unless the assumptions are clearly understood. Thus the derivation is detailed below to clarify the assumptions even though the final result will be quite simple.

A2. Model Development

The basic longitudinal equation of motion can be developed from three freebody diagrams (Fig. A1) for the unsprung mass, the front pair of wheels and the rear pair of wheels. Figure A1 implies a two axle automobile, however simplifications to follow will lead to a model general enough to encompass trucks and buses as well. The forces and moments shown on the wheels are the totals for both wheels in a pair. Since no lateral motion is allowed at this point, the wheel pairs can be treated as if connected by a rigid axle. The aerodynamic force F_A would not actually pass through the unsprung cg in general, but this is a convenient approximation to which the dynamics should be insensitive. Note that the braking torques T_{bf} and T_{br} are reacted by the body as pitching moments, but the driving torques T_{df} and T_{dr} are not. This is because it is assumed that the engine and transmission are mounted longitudinally so that the torque reaction (at the engine mounts) produces a roll moment. For a front wheel drive car with a transverse engine there would be a pitching moment reaction T_{df} at the front of the body but not at the rear. However, these differences should be negligible for the initial studies.

The forces at the tire-road interface include the shear forces F_{sf} and F_{sr} that are the traction (or braking forces when negative). Note that there is no physical "rolling resistance force", instead rolling resistance results from the moment about the hub produced by the normal forces N_f and N_r. Due to compression of the tire near the leading edge of the contact patch, the lines of action of the normal forces are forward of the hub by the distances ε_f and ε_r. The resulting moments produce the rolling resistance, however, following standard practice, this moment will be represented below by use of a fictitious force.

The equilibrium force and moment equations (Eqn. A1 - A9) for the three freebodies (sprung mass, front wheels, and rear wheels) of Figure A1 are summarized below.

Force equations - horizontal

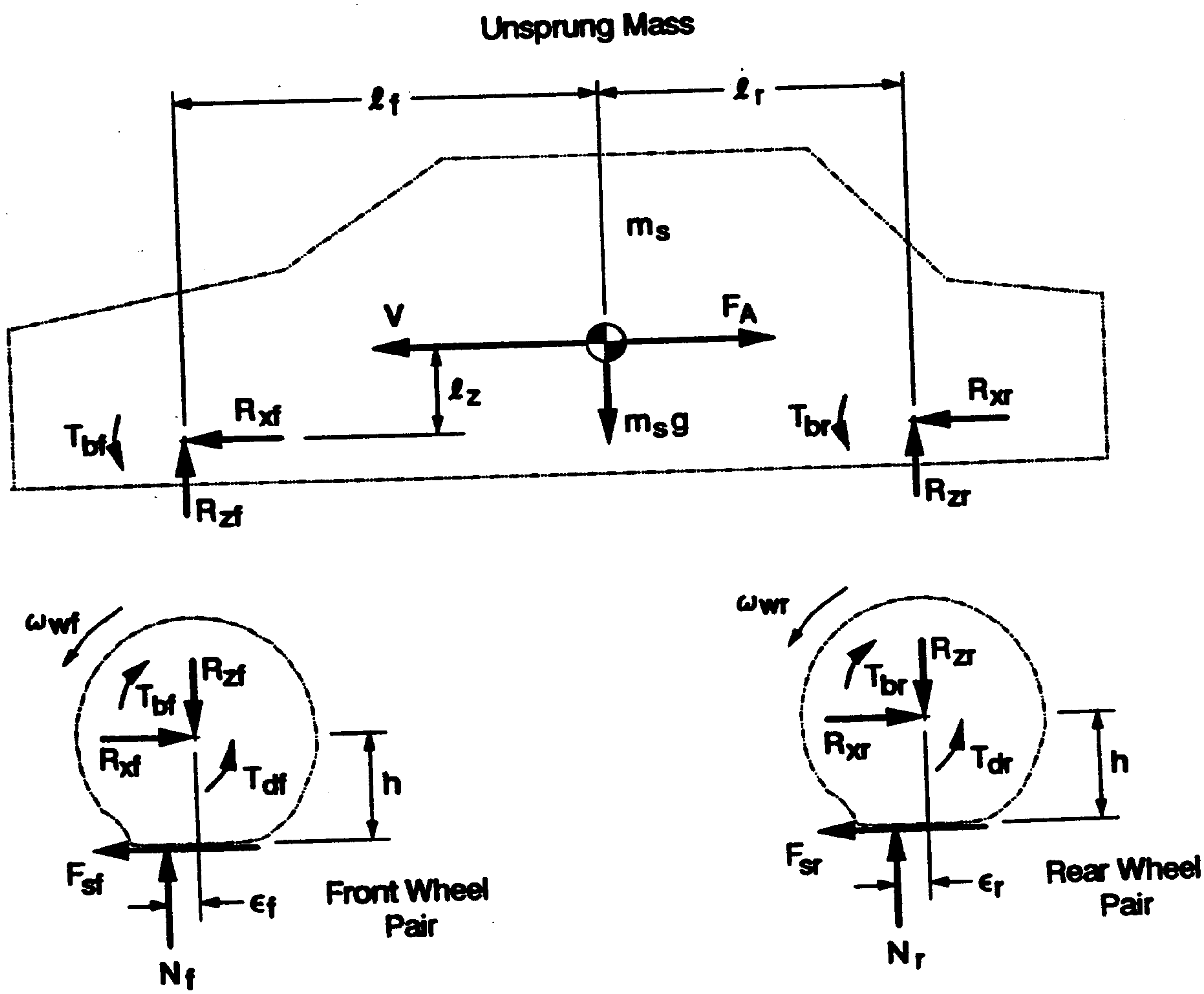

Figure A1. Vehicle Freebody Diagram

$$m_s\dot{V} = R_{x_f} + R_{x_r} - F_A \tag{A1}$$

$$m_{w_f}\dot{V} = -R_{x_f} + F_{s_f} \tag{A2}$$

$$m_{w_r}\dot{V} = -R_{x_r} + F_{s_r} \tag{A3}$$

Force equations - vertical (no vertical motion)

$$0 = R_{z_f} + R_{z_r} - m_s g \tag{A4}$$

$$0 = N_f - R_{zf} \tag{A5}$$

$$0 = N_r - R_{z_r} \tag{A6}$$

Moment Equations

$$0 = T_{b_f} + T_{b_r} - R_{z_f} l_f + R_{z_r} l_r - (R_{x_f} + R_{x_r}) l_z \tag{A7}$$

$$I_w \dot{\omega}_{w_f} = T_{d_f} - T_{b_f} - N_f \varepsilon_f - F_{s_f} h \tag{A8}$$

$$I_w \dot{\omega}_{w_r} = T_{d_r} - T_{b_r} - N_r \varepsilon_r - F_{s_r} h \tag{A9}$$

Note that four acceleration terms are zero due to the constraints on pitch and heave. This is equivalent to having infinitely stiff suspension; this would not be appropriate in a ride study but will be adequate for initial platoon studies. This follows because longitudinal load transfer is captured by these equations. This can be seen by solving Equation A2-7 for the wheel normal forces in terms of the horizontal axle reactions R_{xf} and R_{xr} (Eqn. A10 and B11).

$$R_{z_f} = N_f = \frac{l_r m_s g - T_{b_f} - T_{b_r} - (R_{x_f} + R_{x_r}) l_z}{(l_f + l_r)} \tag{A10}$$

$$R_{z_r} = N_r = \frac{l_f m_s g - T_{b_f} - T_{b_r} + (R_{x_f} + R_{x_r}) l_z}{(l_f + l_r)} \tag{A11}$$

When the vehicle accelerates there is positive increase in both R_{xf} and R_{xr} and Equations A10 and A11 show that this will result in load transfer -- a reduction in the front normal force and an increase in the rear normal force -- as expected for l_z positive as shown. However, the model will ultimately be simplified to dependence on only the total normal force N

$$N = N_f + N_r = m_s g \tag{A12}$$

so that load transfer will not affect normal platoon maneuvering to a first approximation (load transfer becomes more important in lateral stability analyses).

The required traction/braking forces can be found from Eqn A8 and A9 as shown in Equation A13 and A14

$$F_{s_f} = (T_{d_f} - T_{b_f} - N_f \varepsilon_f - I_w \dot{\omega}_{w_f})/h \tag{A13}$$

$$F_{s_r} = (T_{d_r} - T_{b_r} - N_r \varepsilon_r - I_w \dot{\omega}_{w_r})/h \tag{A14}$$

However the magnitude of the tractive force a tire can actually develop (i.e., the tire force available as opposed to the tire force required) is limited and varies with slip, normal force, and the road surface conditions. (This will be discussed further below). If limit performance maneuvers (e.g., emergency braking) are to be considered, a detailed model (e.g., STI tire model) which accounts for complex, nonlinear interactions is required. However, the normal platoon maneuvers of interest here can be assumed not to reach the highly nonlinear, limit performance region so that the tire models can be considerably simplified. This follows because:

- Operation at limit performance would greatly accentuate the differences among vehicles in the platoon which, as noted previously, will adversely affect safety.
- Operation near limit performance would be unpleasant and alarming to passengers.
- The AHS system will have to maintain safety margin in normal maneuvering for inevitable emergencies.

Thus it will be assumed here that each tire is can and does generate traction/braking forces equal to those required by Equation A13 and A14 up to a limit. As will be discussed further below, this is consistent with assuming that the longitudinal slip ratio (traction) and the skid ratio (braking) remain low. As discussed in Section 5, for modern automobiles and certainly for AHS vehicles, anti-lock braking systems (ABS) and active traction control systems (ASR) will effectively gaurantee that these assumptions hold. Going one step further it will be assumed that the tire slip is approximately zero so

$$\omega_{w_f} = \omega_{w_r} = \omega_w = V/h \tag{A15}$$

Further it will be assumed that

$$\varepsilon_f = \varepsilon_r = f_R h \tag{A16}$$

where f_R is the tire rolling resistance coefficient (discussed further below). With this assumption, Equation A13 and 14 can be simplified and substituted into Equation A1 resulting in

$$m_e \dot{V} = (T_{d_f} + T_{d_r} - T_{b_f} - T_{b_r} - m_s g f_R h)/h - F_A \tag{A17}$$

where

$$m_e = m_s + m_{w_f} + m_{w_r} + 2I_w/h^2 \tag{A18}$$

The effective mass m_e includes a term involving wheel inertia. However the wheel radius of gyration should be less than h so that the inertia term will be less than the total wheel mass. Thus for convenience m_e and m_s will be approximated by the vehicle total mass m. It is also useful to combine the front and rear drive and braking torques into total values, T_d and T_b respectively. Then Equation A18 can be divided by total mass to obtain the basic longitudinal equation of motion.

$$\dot{V} = \frac{T_d - T_b}{mh} - g f_R - \frac{F_A}{m} \tag{A19}$$

Each term in Equation A19 is dimensionally an acceleration. This form is particularly useful for the platoon model becasue it should be easier to estimate data for vehicle populations in terms of maximum acceleration/maximum deceleration capabilities. In any case further definition of T_d, T_b, f_R, F_A is required and this is provided below.

a. Engine and Drivetrain

The drive torque T_d must now be related to engine power. For operation about some cruise condition it will be assumed that the torque converter is locked so that the engine speed ω_e is related to the wheel speed ω_w by the overall drivetrain gear ratio R_g as

$$\omega_e = R_g \omega_w \tag{A20}$$

The power delivered to the wheels will be equal to that at the engine flywheel less parasitic losses in the drivetrain thus

$$T_d = \eta R_g T_e \tag{A21}$$

where $0 \gg \eta < 1$ is the fraction of engine power transmitted to the wheels (note that at this level of approximation no distinction is made between rear-, front-, or four-wheel drive). For initial studies a very simple engine model will be used, later consideration of closed loop engine control may require refinements of this model along the lines suggested by Hedrick. Figure A2 shows typical full throttle torque, power, and specific fuel consumption curves traditionally used to characterize gasoline-fueled automotive engine performance. Generally both the torque and specific fuel consumption curves are roughly constant over a significant engine speed range.

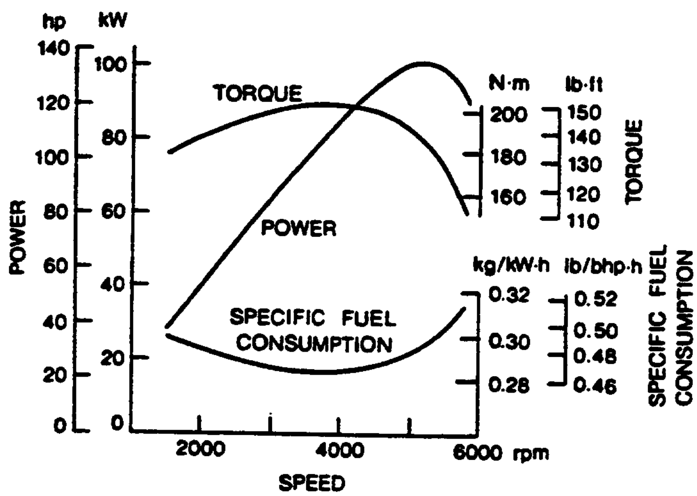

Figure A2. Performance characteristics of a Gasoline Engine

Here the engine model will be simplified by assuming that the torque is constant (i.e., does not vary at all with engine speed) over the engine speed range of interest and is proportional to a throttle variable δ_t. Thus

$$T_e = T_{e_{max}} \delta_t \tag{A22}$$

where

$$0 \leq \delta_t \leq 1 \tag{A23}$$

In the reference cruise condition at speed V_o, we assume that the overall gear ratio R_g is such that the engine speed is ω_e^* which is near the minimum specific fuel consumption speed thus

$$R_g = \omega_e^* / (V_o / h) \tag{A24}$$

That is we assume that AHS-compatible vehicles, like current vehicles, will evolve toward minimum fuel consumption in platooning. Computing the reference gear ratio from Equation A20, approximates the discrete levels of transmission gear ratios with a continuous variation, however this should be adequate here. Nominal platoon maneuvering should not require the transmission to shift routinely, thus R_g will normally remain constant during maneuvers and power will be modulated with the throttle.

As AHS-compatible vehicles evolve, engines should be sized (i.e., minimums set for T_{emax}) so that the vehicles can operate in platoons with the reference ("trim") throttle setting δ_{to} well below unity to provide a margin for maneuvering. Current automobiles have evolved in a similar way, the only consideration here is the possibility that platoons may operate at speeds well above current speed limits. This will increase the mean T_{emax} in the AHS vehicle population, however there still will be a distribution of T_{emax} (or more significantly maximum power-to-weight ratio). The first order impact on platoon operations will appear in the form of differences in the throttle margins among platoon members. The throttle margin in cruise will be $1 - \delta_{to}$ where the reference trim throttle is determined from Equation A10 multiplied by mV_o

$$m\dot{V} V_o = 0 = \frac{V_o}{h} \eta R_g T_{e_{max}} \delta_{t_o} - (W f_R + F_A) V_o \tag{A25}$$

but the first term on the right is the power *available* at the wheels

$$P_{avail} = P_{avail_{max}} \delta_{t_o} = \frac{V_o}{h} \eta R_g T_{e_{max}} \delta_{t_o} \tag{A26}$$

The second term is the power *required* to cruise at V_o

$$P_{req} = (W f_R + F_A) V_o \tag{A27}$$

Thus the trim throttle is

$$\delta_{t_o} = \frac{P_{req}}{P_{avail_{max}}} = \frac{(W f_R + F_A)}{\eta R_g T_{e_{max}}} \tag{A28}$$

and the throttle margin

$$1 - \delta_{t_o} = \frac{(P_{avail_{max}} - P_{req})}{P_{avail_{max}}} \tag{A29}$$

is proportional to the excess power. Thus, at this level of model, the nonlinear characteristics of the engine are entirely expressed in terms of the throttle margin or equivalently excess power.

Within a population of AHS-compatible cars, trim throttle will vary in part due to variations in maximum engine power. For reference trim throttle statistics for the current population could be estimated from a knowledge of the distribution of maximum engine power. However maximum engine power is dependent on vehicle weight, so the variance of the power-to-weight ratio is the meaningful parameter. The lower end of (flywheel) power-to-weight ratio of current cars is probably around 0.04 hp/lb but could be several times higher for some cars.

To this point only engine performance has been considered but, if feedback control loops are to be closed around the engine, engine dynamics must be considered. As a first approximation, this will be modeled with a first order lag transfer function between the throttle and throttle command δ_{tc}

$$\delta_t = \frac{\delta_{t_c}}{(\tau_t s + 1)} \tag{A30}$$

where s is the LaPlace variable and τ_t is the throttle time constant which includes not only the lag of the throttle servo but an effective lag of the engine. The time constant can be estimated, but it may be more appropriate to analyze the system sensitivity to τ_t to set requirements on its maximum value.

b. Traction and Braking Forces

In addition to the nonlinearity resulting from the limit on engine power, there are also limits on the traction and braking forces that affect vehicle dynamics. Both the tractive and braking forces are proportional to normal load on the tire. The tractive (braking) force F_s can thus be expressed in terms of the nondimensional tractive (braking) effort coefficient μ. The tractive coefficient is a function of "slip" $(1 - V/r_w\omega_w)$, whereas the braking coefficient is a function of "skid" $(1 - r_w\omega_w/V)$. As indicated in Figure A3, the variation of the coefficient is similar for each of these two independent variables. As noted previously it will be assumed that normal platoon maneuvers result in slip and/or skid values low enough (on the order of 10%) so that operation is in the roughly linear region below the peak coefficient. With this assumption, the tire nonlinearity can be simplified to limits on the tractive and braking coefficients.

However this μ limit will be considered to be implemented by a control system element (a limiter). This is consistent with standard practice in control system design to limit commands to avoid reaching physical system limits. (A similar situation would be a software limit on a servo command in an aircraft flight control system to avoid hitting the physical stops on a control surface actuator.) Thus in system studies the first order effects of the nonlinear tire limit will be addressed indirectly through their implication for control system command limiting. More specifically it is reasonable to assume that any AHS-compatible vehicle will have the equivalent of automatic traction control (acceleration slip regulation ASR) and an antilock braking system (ABS) as "inner-loops". These systems will mechanize the limits and effectively prevent the tires from operating in the nonlinear (high slip/skid) range of Figure A3. However the limit coefficient will still depend on the road surface conditions. Data is given by Wong in Figure A4 and shows that glare ice greatly reduces the peak coefficient value as should be expected.

The force coefficient is a gross indicator of the vehicle acceleration/deceleration in "g's" since

$$A = \frac{F_s}{m} = \frac{\mu W}{m} = \mu g \tag{A31}$$

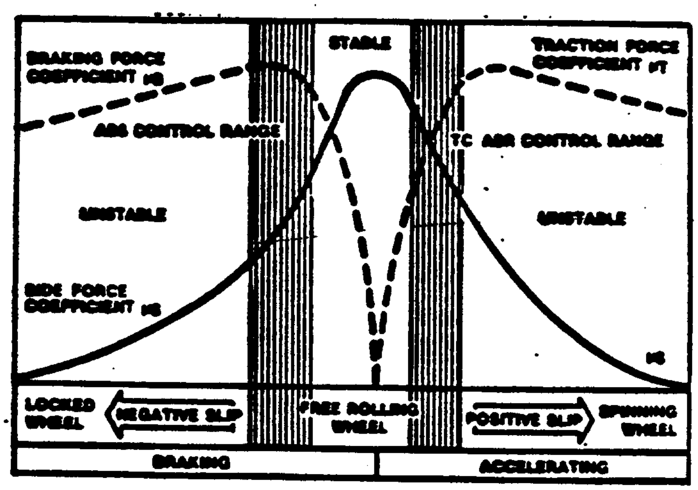

Figure A3. Traction and Braking Force Coefficients

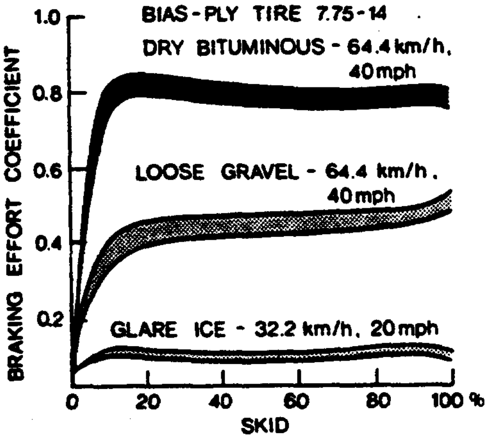

Figure A4. Variation of Braking Effort coefficient with Skid of a Tire of Various Surfaces

However, at highway speeds, the maximum drive torque at the wheels will be reached before the tire traction limit. That is, with the possible exception of certain race car types, it is only possible to "burn rubber" at low speeds. Brakes can produce higher torques, in part, because they act directly on the wheels and thus are not affected by transmission gearing. Therefore no physical brake torque limit need be included beyond the ABS limiters.

The brake system dynamics will also be represented by a first order lag between the brake torque and the commanded brake torque T_{bc}

$$T_b = \frac{T_{b_c}}{(\tau_b s + 1)} \tag{A32}$$

where τ_b is the brake system time constant for which requirements will be sought.

c. Drag Forces

The rolling resistance coefficient can be obtained from empirical correlations. A formula for the mean rolling resistance can be developed from that in Wong as

$$f_R = 0.010 + 0.005(\frac{V}{91.13})^{2.5} \tag{A33}$$

where V is in ft/sec.

The aerodynamic drag Fa is given by

$$F_A = \frac{1}{2}\rho V^2 A_f C_D \tag{A34}$$

Atmospheric density ρ can be taken as the standard (sea level) value of 0.00238 slug/ft^3. Cross sectional area A_f scales with vehicle size and the population mean can thus be expected to be proportional to the 2/3 power of weight. Typical values are on the order of 20 ft^2. The drag coefficient C_D should be independent of other parameters, but will decrease in platoons as separation distance decreases. Data on this latter effect is available from Frascaroli, but only for separation distances of up to about three car lengths. Extrapolation of this data implies that the reduction in C_D from the isolated vehicle value may be significant (on the order of 10%) for much larger separation distances. The reduction also increases with vehicle position behind the platoon leader. However the sensitivity of C_D to separation distance is highest in the 0 to 2 car length range. Some sensitivity analysis should be performed to determine how best to treat this nonlinear effect in analysis. Statistics on the isolated vehicle C_D of the current vehicle population could be developed as outlined herein. However gross ranges of this parameter (Wong) are

Passenger cars	0.3 -- 0.6
Buses	0.6 -- 0.7
Trucks	0.8 - 1.0

Continuing emphasis on fuel economy should bias these ranges toward the low end.