Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Lateral and Longitudinal Control Analysis

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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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and Development

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VOLUME IV — AHS SYSTEMS ANALYSIS

CHAPTER 3: LATERAL AND LONGITUDINAL CONTROL ANALYSIS (TASK D)

1.0 EXECUTIVE SUMMARY

The main emphasis of the Lateral and Longitudinal Control analysis was directed toward (1) a detailed review and study of the various technologies that may be utilized to provide sensors for lateral position measurement and longitudinal headway, and (2) a rather detailed digital simulation of a longitudinal control loop including the vehicle, engine, braking system, and control algorithms. To a lesser degree, consideration was given to communications associated with lateral and longitudinal control, obstacle detection, and a preliminary study of the cost trades between a system that employs an autonomous vehicle-follower longitudinal control and a point-follower system using an infrastructure base headway measurement system. Automatic lateral and longitudinal control is, of course, the heart of any AHS system. The studies conducted on this program barely scratch the surface of the automatic control problem. We do hope, however, that we have focused our efforts at some of the key design issues.

1.1 APPROACH

The following discussions briefly describe the various tasks performed.

Suggested Maneuvers

We very briefly looked at the various maneuvers that a vehicle will perform during travel on the AHS. These maneuvers include lane changing, closing a gap, and creating a gap. We defined some time/acceleration profiles for these maneuvers based upon ride comfort. This study was performed to give an insight into the time lines to perform these maneuvers. For instance, to close a gap of 60 ft. requires approximately 12 to 13 sec, if control is performed with throttle only (no braking).

Sensor Technology for Lateral and Longitudinal Control

A major effort was directed at the study of the sensor technology that might be applied to the problems of locating the lateral positions of a vehicle in a driving lane and the measurement of the headway between vehicles. For each of the technology areas, a review of the sensor technology was made along with a review of the work performed by other researchers.

Communication Considerations

Some preliminary communication studies were performed to address requirements , available technology, and possible communication structures. Because of the sheer numbers of vehicles in a given area, communication among vehicles, as well as with the infrastructure, require special techniques. One may want to consider operating frequencies in the absorption frequency bands (60 GHz) to limit the interference in other nearby regions. Some of the data to be passed between vehicles will require fairly high data rates, such as 20 Hertz to avoid data latency. The study examines transmitter power requirements, choice of frequencies, and network and link structures as well as multipath considerations.

Sensor Technology for Obstacle Detection

A brief study was performed into the various sensor technologies that may be employed to detect obstacles located on the AHS roadway, such as, mufflers, tail pipes, pieces of truck tires, and animals. Reliable detection of these obstacles with a low false alarm rate is extremely difficult. The most promising approach is to utilize two sensors, a passive optical system coupled with an active microwave radar. By comparing the data from the two sensors, one can eliminate shadow and flat items. The technology is by no means straightforward and may require a high resolution microwave radar.

Some Preliminary System Requirements for Lateral and Longitudinal Sensors

We have collected some preliminary requirements for the lateral and longitudinal sensors and control systems. It is too early in the AHS development to identify very many requirements or specifications; however, there are some general and a few specific values to suggest to AHS researchers.

We believe the automatic lateral and longitudinal control loops must be able to function in rather severe adverse weather, such as dense fog, heavy rain, and blizzard-like snow storms. Since the technology exists to provide an all weather operation, it makes little sense to pursue technology that exhibits the same limitations as the human. Lateral position sensor errors should be limited to approximately 5 to 7 cm (two to three in) (1 sigma value) in order to hold lane tracking deviations to less than 15 cm (6 in). We also believe that a measure of the coefficient of friction between the tire and the road surface will be required for both the lateral and longitudinal control loops. Headway gap, speed, and control loop gains must be adapted to the roadway conditions. Control loops that are designed for dry pavement will be completely unstable on an icy road.

Longitudinal Control Loop Digital Simulations

A rather detailed digital simulation of the longitudinal control loop was developed. This model included the vehicle, engine model, throttle control loop and a braking model. Provisions were made to allow a string of vehicles to operate in car-following mode. Tests were conducted with lead vehicle transients such as step accelerations and decelerations (including emergency braking). The simulation included modeling of headway radar sensor errors, both the headway gap distance and rate of change of the gap (differential velocity). Tradeoffs were made between loop bandwidths or gains vs. radar sensor errors. No effort was made to develop a lateral steering control loop. Because of limited program resources we focused on the longitudinal control loop, which is far more complex.

Recommended Sensor Technology

From a rather detailed study of the various sensor technologies, we have identified techniques that we judge as most promising and should be given special consideration.

Lateral guidance, in our view, can best be accomplished with magnetic markers such as the "nails" developed by the PATH program. The markers are low cost and very economical to install. Their greatest feature, however, is the ability to operate in all weather with very high reliability. The only drawbacks are that lane changing must be performed by dead reckoning between lanes. Also the range of control is limited to two feet or less from center line. Overhead induction wires can also be employed for lateral guidance, which will allow for lane change and a wider range of lateral control. The induction system is also all weather.

It appears that the measurement of headway gap can best be obtained from a millimeter wave radar which would allow for operation in fog, rain, and falling snow. Data link ranging using cooperative transceivers on the front and rear of each vehicle provides an all-weather approach but would only function if the vehicle ahead is also equipped. Since all vehicles must be AHS equipped, the system would not function on mixed traffic roadway that might be an early version of AHS.

Cost Trades Between a Vehicle Mounted Car-Follower Longitudinal Control System and an Infrastructure Based Point-Follower System

A preliminary cost trade study was made between a longitudinal control system that uses a vehicle-mounted headway measurement device operating in a vehicle-following mode as opposed to a system that uses roadway based sensors to measure the headway gaps between all vehicles. Each vehicle would be commanded to travel at a given speed, with periodic updates to each vehicle longitudinal control loop to maintain a given headway. For the assumptions made during the study (mainly that the roadway is located in a high population density where there is a very large number of vehicles per freeway mile), there are some total cost advantages to the infrastructure-based system, if the headway radar system costs more than $200 per vehicle.

1.2 CONCLUSIONS/KEY FINDINGS

During the course of the studies, several results became apparent. Because these results will have significant impact on further studies and research, we have referred to them as key findings. Each of these findings is discussed below:

- Sensors for lateral and longitudinal control must be capable of performing under severe adverse weather conditions

  An AHS system should be capable of operation during adverse weather such as very heavy rain, dense fog, and heavy falling snow. Many researchers are pursuing technologies that clearly will not function in severe weather. The argument that it is acceptable if it performs as well as a human does not make much sense to us. If, during severe weather, the lateral sensor can no longer locate the lateral position of the vehicle, or the headway sensor can no longer measure the headway, a serious safety condition exists. This is particularly true of lateral control. If a rain storm limits the performance of a headway sensor, other action can be taken, such as slowing (or stopping) all traffic. However, lateral guidance is required even if it is only used to steer the vehicle while a stopping maneuver is performed. During periods of severe weather, such as heavy rain or fog, the highway speed may be significantly reduced, provided that the sensors can continue to operate. To accommodate increased sensor errors, the gap spacing may be increased. Loss of lateral position information cannot be allowed to occur.

We must currently accept the limitations of the human sensors to function in severe weather, but we need not accept them for an AHS because sensor technology exists to provide for continued AHS operation in very dense fog, heavy rain storms, and blizzard conditions.

- Most promising lateral control technology involves magnetic markers or overhead wires

Of the many techniques that various researchers have explored to provide lateral position information, the magnetic markers or "nails" appear to be the most attractive. They are inexpensive and of low cost to install in a roadway. They are passive (requiring no power), extremely durable, and will provide control in all weather conditions. Component failure will occur gracefully; i.e., if a given magnet should fail, vehicle operation can continue because one missing magnet will not affect performance.

Lateral control based upon overhead wires that radiate signals, while more costly to install, also operates in all weather conditions. The wires can also be used to provide a moving reference for point-follower type longitudinal control.

Radio ranging techniques can also be employed to provide longitudinal, and possibly lateral, control. These techniques are more complex but will provide all-weather capability. Because of limited time and program funding, it was not possible to examine in detail those technologies during this study.

The accuracy required for lateral control is expected to be in the few centimeters category which is very difficult to obtain with ranging techniques unless very large bandwidth signals are employed.

- Headway radars will be required to provide high azimuth angle resolution

Headway radars used on an autonomous vehicle will be required to measure and locate the position of vehicles to determine the driving lane they occupy over ranges of approximately a few meters (feet) to 60 or 90 m (200 or 300 ft). Azimuth look or scan angles of ±45_ are likely to be required to confirm slots for lane change or merge/demerge. Because of the need to locate the vehicle in the azimuth plane, the headway radar will be required to have a beam width of one to two degrees, thus the radar sensor beam will need to scan in azimuth, either mechanically or electronically.

- Infrastructure-based systems may be cost effective

An AHS system configuration which is based on the use of infrastructure-mounted sensors to obtain vehicle longitudinal position and to provide a portion of the longitudinal guidance signals and vehicle malfunction detection functions may have cost advantages over a system containing vehicle-based sensors which perform these functions. The component reliability of the infrastructure equipment can be made sufficiently high through redundancy so that component failure does not contribute significantly to the reliability of the overall system.

- Communication between vehicles may not be required for vehicles following at gaps of 0.5 sec, even during emergency maneuvers

Results of simulations show that communication of the acceleration of the lead vehicle(s) is not necessary for braking maneuvers. The simulated design separated the brake controller from the throttle or accelerator controller. The accelerator controller is designed to maintain vehicle headway during normal maneuvers, while the brake controller is designed to avoid collisions. Simulation shows that no collisions occurred even with the lead vehicle braking up to 1 g. The conditions were 0.5 sec plus 1.5 m (5 ft) nominal gap, 97 kph (60 mph) speed, up to 15 following cars, and all cars had the capability of 1 g maximum braking. The reduction in headway as speed decreased to zero was more than enough to make up for distance lost because of sensing and braking dynamics. The acceleration of the preceding vehicle was estimated from the rate of change of the differential velocity. Up to 30 cm/sec (1 ft/sec) noise like errors on the speed measurements did not degrade the safety of the brake system. Speed and distance measurements were made at a 20 Hz rate, using an independent noise sample for each measurement. The minimum value for the gap to maintain safe braking has not been explored, but we expect it to be less than 3 m (10 ft). This finding is significant. Most researchers, ourselves included, have felt that each vehicle will need to pass its acceleration to following vehicles to prevent a collision during hard, emergency braking.

- There is a tradeoff between longitudinal maneuver errors and noise immunity

In the design of a longitudinal controller for an AHS, there exists a classical tradeoff between tolerable maneuver errors and noise immunity. Typically, a longitudinal controller is designed to maintain a certain headway from the preceding vehicle. When the preceding vehicle changes speed, the following vehicle's control system will generate an acceleration command to maintain the headway. During the speed change, the headway error could range from a few centimeters to meters (inches to feet) depending on the maneuver. In our simulations, an increase in speed from 80 kmph (50 mph) (73.3 ft/sec) to 97 kph (60 mph) (88 ft/sec) at 0.1 g generated a 2 m (7 ft) distance error. The headway error gradually diminished to near zero ft/in about 25 sec. after the maneuver. If the bandwidth of the control system is increased, the headway errors can be reduced to less than 0.6 m (2 ft) with total recovery in less than 10 sec. Although the tighter control seems more desirable, the effects of sensor errors in the system make a high bandwidth control system impractical. We believe that typical sensor errors for ranging and doppler devices are likely to be 0.3 m and 0.3 m/sec (1 ft and 1 ft/sec), respectively. When these errors are used in a high bandwidth simulation, throttle displacement is larger, causing accelerations of 0.6 m/sec/sec (±2 ft/sec/sec) during steady state cruising. The net result is an uncomfortable ride for the AHS user, not to mention reduced fuel economy. As the bandwidth of the control system is reduced, the ride may be more tolerable with accelerations for steady state cruising at 0.15 m (±0.5 ft/sec/sec). The net result is a tradeoff as shown below.

Control System	Steady State Accelerations	Max Error	Recovery
High Bandwidth	±0.6 m/sec/sec	±0.6 m	10 seconds
Low Bandwidth	±0.15 m/sec/sec	±2 m	25 seconds

In order to provide a high bandwidth control system providing rider comfort, improvements in the control system could be made. Improved decisions using Kalman filters or a different controller may provide lower errors and lower accelerations, but for each design a tradeoff between noise immunity and maneuver error must be made.

It should be recognized that the simulation used on this program did not assume that lead vehicles would communicate with following vehicles. The control system derived the lead vehicle acceleration from the differential velocity measurement which contains noise-like errors. If the leading vehicle passed its acceleration data to the following vehicle, a "cleaner" acceleration signal would be available. Thus, a high gain loop could have been used with better performance.

1.3 AREAS FOR FUTURE RESEARCH

The studies performed under this task have barely scratched the surface of the total problem of lateral and longitudinal control. Control of the steering, throttle, and brakes is, of course, the heart of an automatic highway system. From our studies, we have concluded that several areas need immediate study. These areas are discussed below.

- The longitudinal simulation effort begun on this task should be continued and expanded to include lateral control. Studies should be made with multiple vehicles in a car-follower mode to develop tradeoff data between sensor accuracy, performance, and ride comfort so that preliminary specifications can be developed for sensors and to evaluate various concepts for lane change, merge and demerge maneuvers.

- Promising sensor techniques for lateral position measurements and headway measurement should be developed and tested. Prototypes should be built and tested. In particular, the magnetic markers or nails developed on PATH program should be further developed and refined. The advantages of all weather, low cost, and high reliability make it a forerunner technique that should receive serious consideration.

- A detailed study, including simulations, should be made of the potential mutual interference problem of headway radars or lidars. These studies should consider the expected density of radars one would experience on a multiple lane, high density AHS roadway. Can the mutual interference be managed or is it a "show stopper"?

- Communication system concepts need to be defined and studied. These systems should consider the vehicle-to-vehicle and vehicle-to-roadway needs for lateral and longitudinal control, including lane-changing merge and demerge for an autonomous vehicle system, as well as for general information flow.

- Considerable effort should be given to an evolution plan. The various technologies employed in IVHS equipment, such as intelligent cruise control, need to be evaluated from a perspective of how these technologies/systems can evolve into an AHS — can they? Or must new technologies be introduced. A road map is needed to determine how AHS can evolve and be implemented considering market penetration and minimal impact on existing traffic flow. While this study is not a lateral/longitudinal control issue by itself, it may heavily impact on the technology chosen for lateral and longitudinal control.

- Tests should be conducted with an instrumented vehicle to collect data on maneuver parameters such as longitudinal accelerations. The relationship between lateral and longitudinal accelerations and ride comfort need to be developed. Tests should be made with a closed-loop longitudinal control system. Noise-like errors should be introduced to cause various levels of vehicle accelerations that would be used to develop a relationship between accelerations and ride comfort.

- Tests should be conducted with a vehicle-mounted differential GPS system that employs carrier phase tracking and pseudolites to evaluate the potential for using GPS combined with stored map data to provide lateral and longitudinal control. These tests should be conducted in urban areas and in tunnels.

2.0 INTRODUCTION

The area of lateral and longitudinal control for an automated highway system is multifaceted. Because of the limited resources, both funding and time we had to confine our studies to the areas that we felt presented the major problems, or issues. These areas include technology, to sense the vehicle's lateral position and to measure the gap between a vehicle and the preceding vehicle. There are numerous techniques that could be employed. We then reviewed the work of other researchers and experimenters. Finally, we attempted to highlight the most promising techniques.

Our main emphasis in the longitudinal control area was directed towards on-vehicle sensors to implement a vehicle-follower type system. Our primary assumption is that an AHS system should be able to at least operate in environmental conditions that today's manual traffic can accommodate. It is highly desirable that an all weather capability be pursued.

The second area of study includes the communication needs and a discussion of the types of technology that can be employed. Communications between vehicles and between a vehicle and the roadside infrastructure are considered.

A detailed simulation was developed of the longitudinal control system to study the interactions between a string of vehicles operating in a vehicle follower mode. Tests were made with a step acceleration and deceleration of the lead vehicle. Studies were also made with headway sensor errors and with emergency braking of the lead vehicle. Calspan developed the longitudinal control loop using an acceleration inner loop with velocity and position control wrapped around the inner loop. A braking model was also developed that provided up to 1 g braking. The throttle control and braking control loops were integrated into one longitudinal control loop.

The simulation was directed towards the longitudinal control loop. Calspan feels that the lateral control is rather straight forward. The longitudinal control is affected by the actions of the leading vehicles. It also must handle changes in velocity and acceleration and emergency braking. Since we were limited in resources, we chose to focus on the control loop that was more complex and exhibited major control issues.

A brief study of the obstacle detection problem was conducted by Princeton University. A wide variety of sensor technologies were examined. While the problem of obstacle detection is very difficult, it appears that the use of multiple sensors may prove effective.

A preliminary cost/trade study was performed between a longitudinal control system that utilizes headway sensors in a vehicle follower mode and a point follower system that employs infrastructure-based sensors to measure headways.

3.0 TECHNICAL DISCUSSIONS

The work performed on Lateral and Longitudinal Control analysis task consisted of eight sub tasks. The largest tasks by far, are the Sensor Technology studies (Sub-section 3.2) and the Simulation of the Longitudinal Control system (Sub-section 3.6). Sub-section 3.1 addresses the time/acceleration profiles for AHS maneuvers. Communication issues are addressed in Sub-section 3.3. A study of the Sensor Technology for Obstacle Detection, performed by Princeton University, is reported in Sub-section 3.4. Some key requirements of the lateral and longitudinal system are discussed in Sub-section 3.5. In Sub-section 3.7, we present our recommendations for the most promising sensor technology. Finally, a discussion of the cost trades between a vehicle mounted headway sensor and an infrastructure based headway sensor is presented in Sub-section 3.8. This last study was performed by Dunn Engineering Associates.

3.1 SUGGESTED LATERAL/LONGITUDINAL MANEUVERS

Operation on an AHS roadway will require the execution of several maneuvers. Lane keeping is a tracking function as is the normal longitudinal headway maintenance and therefore is not considered a maneuver. There are special maneuvers associated with lane changing, closing a gap and opening a gap. In this section we examine the acceleration/velocity time lines to execute those maneuvers based upon typical vehicle limits and ride comfort. While these profiles are based merely on kinematics they do serve to point out the time lines that are involved in these maneuvers. Each of the three cases is discussed below in the following sections.

3.1.1 Close a Gap

The process of closing a gap involves accelerating to some increased velocity, maintaining that velocity and decelerating to reduce the speed to the original speed. From digital simulations of the vehicle and engine (see Section 3.6) it was determined that the maximum acceleration that can be obtained at 97 kph (60 mph), without resulting in a transmission down, shift, is approximately 0.1g. Our simulation was based upon a low powered vehicle that would accelerate from a stop to 97 mph (60 mph) in 14 sec. It was also determined that the maximum deceleration that can be obtained by retarding the throttle to idle is 0.36 m/sec/sec (1.2 ft/sec/sec) at 97 kph (60 mph). Our current thinking is that brakes would not be applied during these maneuvers. Based upon accelerating at 0.1 g (3.2 ft/sec/sec) and decelerating at 0.36 m/sec (1.2 ft/sec/sec) a gap of 18.3 m (60 ft) could be closed in approximately 12 sec. Assume the vehicle accelerated for 2.5 sec. It would gain 2.44 m/sec (8 ft/sec) in speed and would close ~3 m (~10 ft) during the acceleration. The 2.44 m/sec (8 ft/sec) represents a little over 8 kph (5 mph) increase in speed. After 3 sec at this new speed the vehicle would close an additional 7.3 m (24 ft). A deceleration for 6.5 sec at 2.44 m/sec (1.2 ft/sec/sec) returns the vehicle to 97 kph (60 mph) and closes an additional 7.9 m (26 ft). Thus, a gap of 18.3 m (60 ft) is closed in 12 sec. If one eliminated the constant speed portion and accelerated to a point where the deceleration would begin only a few tenths of a second would be saved.

3.1.2 Create a Gap

To create a gap of 18.3 m (60 ft) assumes the vehicle decelerates at 0.36 m/sec/sec (1.2 ft/sec/sec) for 8.5 sec and then accelerates to recover the original 97 kph (60 mph). During the deceleration the vehicle slows by 3.11 m/sec (11.2 kph) (10.2 ft/sec, 7 mph) and creates a gap of 13.22 m (43.4 ft). The vehicle would then accelerate at 1 m/sec/sec (3.2 ft/sec/sec) to recover the 3.11 m/sec (10.2 ft/sec) speed decrease which would require 3.19 sec, further increasing the gap 5 m (16.3 ft). Thus, a total gap of 18.2 m (59.7 ft) would be created in 11.7 sec.

3.1.3 Lateral Lane Change

The lateral lane change maneuver involves a lateral acceleration to establish a lateral component of the velocity, a drift period at a constant lateral velocity and finally a lateral acceleration in the opposite direction to reduce the lateral velocity to zero. It appears that lateral accelerations during lane change should be limited to between 0.05g and 0.1g from a ride comfort standpoint. We also observed the process of lane change that human drivers execute. Drivers tend to complete the maneuver between 5 to 10 sec. As a starting point we assumed that the lateral acceleration would be 0.07g with a duration of 1 sec. Under these assumptions, a lateral velocity of 0.68 m/sec (2.25 ft/sec) would be established. The complete maneuver would require 6.33 sec. One second each for the acceleration periods and 4.33 sec drift time to transverse a 3.66 m (12 ft) lane. This maneuver has been roughly tested with manual driving and was found to be typical and acceptable.

3.2 REVIEW OF SENSOR TECHNOLOGY FOR LATERAL AND LONGITUDINAL CONTROL

The human driver depends on vision, hearing and kinesthetics - the feel of the wheel, the seat of the pants - as sensors to direct driving and steering activities. These senses, in the form of machine vision, feel and inertial sensors, as well as additional technologies are available for lateral and longitudinal (lat/long) control in an automated highway system. Lateral guidance by purely mechanical means, e.g. rails, slots or trolleys, was deliberately ruled out in this work. The following discussions explore the various sensor technologies that could be applied to the lateral and longitudinal control problem. Accuracy, range of operation, sensitivity to interference and inclement environments, perceived cost, reliability and maturity of a variety of sensors are addressed in the following sub-sections. In sub-sections 3.2.1 through 3.2.9 of this chapter we describe the characteristics of available technology and existing lateral and longitudinal guidance concepts. A summary in Section 3.2.9 presents the most promising technology.

3.2.1 Machine Vision

Observation of the scene in front and to the sides of the vehicle by means of one or more video cameras and subsequent computer interpretation of the video are obvious candidates. With proper choice of optics, accuracy can be comparable, if not better, than that of the human eye. All machine vision systems could offer an improvement in attention over human drivers. Sensors, including standard video cameras also work in regions of the near infrared and ultraviolet that may provide additional information. Special sensors can be provided in the mid and thermal infrared, as well. In the far infrared (50µm to 1mm) the atmosphere is substantially opaque and this spectral region separates optical from radio and radar sensors.

3.2.1.1 Machine Vision Technology

Current Machine vision systems are limited by their inability to adapt to various seeing conditions and visual cues. Machine vision systems often rely on visual cues, i.e. targets, which are added to the highway infrastructure. Sections 3.2.1.1.1 through 3.2.1.1.6 discuss concerns, infrastructure based cues and technologies of vision based systems.

3.2.1.1.1 Seeing Conditions

One concern about vision-based systems, whether machine or human, is the variability of seeing conditions. Almost everyone is familiar with the difficulty of driving at night, toward the Sun when it is near the horizon, in fog, heavy rain or drifting snow. Human drivers adapt to such conditions in a variety of ways that are not always without risk. Following a lead car, for example, can lead to several vehicles leaving the road. If this tactic is accepted in an automated system it could lead to an unacceptable legal burden on the lead vehicle.

3.2.1.1.2 Machine vs. Human Vision

Machine vision in its present state is perceived as inferior to human vision in its adaptability to the variety of visual cues. These include lane markings that may be worn or obscured by snow, side rails that cannot be used as guides at exits that are not taken, and other vehicles. Additionally there is a need to adapt to the problem of curves; a car that is straight ahead is not necessarily in one's lane if the roadway curves.

3.2.1.1.3 Facilities in the Infrastructure

Special targets can be added to the highway to provide reliable cues for machine vision. These may take the form of stripes or spot targets and could be retroflective, such as reflectors. With reflective targets, it becomes possible to illuminate the target area during one frame scan and subtract the (un-illuminated) video of the next frame. This attenuates all objects that are not retroflectors and with suitable non-linear processing permits their removal from the scene. It is not practical to use this technique when there is a significant scene change in successive frames, i.e. when angular velocity is high. At 97 kph (60 mph), for example, a car moves about 0.45 m (18 in) in the 1/60th of a sec. that elapses between frames. Only objects that are substantially in front of or behind the vehicle will not be moved by several pixels.

3.2.1.1.4 Lane Following

Lighting conditions can be controlled by placing a downward-looking camera under the car and compensating for the shade of the vehicle by illuminating the road in the field of view. In the simplest case, a contrasting or retroflective stripe is painted down the center of the lane. Its location in the field of view gives an indication of lateral error and its orientation indicates angular error (β). Longitudinal information could be added to the stripe. As an example, one could widen and shrink the stripe to indicate mile marks or upcoming turns. It is apparent that a simple line sensor scanning left and right under the car can extract all data except angular error .

3.2.1.1.5 Line Scanning

Line scanners can be used to sense angular width of a target of known size and therefore distance to another vehicle. Some processing is required to discriminate between the relatively constant video pattern of the back of a vehicle and the constantly changing scene on either side. Special processes would have to save data during stops when relative motion cannot be used to discriminate between vehicles and stationary background.

Sidelooking, horizontal line scanners can be used to measure angular rate of optical features on a barrier. This information, together with vehicle speed, permits accurate estimation of distance to the barrier. Barriers occasionally jut out to make space for a bridge pillar or the like. To avoid drastic lateral maneuvers in response to such protrusions, optical bar codes could be read by the line scanner. These could convey correction commands.

Any system that relies on the presence of a barrier to measure its position with respect to the barrier, whether optical, acoustic, laser or radar, requires that the barrier is observable by the sensor. If there are several lanes of traffic that are not each separated by barriers the problem exists of "looking through" other traffic, including vehicles in breakdown lanes, to "see" the barrier. The blockage, particularly if trucks are present, all but precludes these techniques.

Angular rate alone can be sensed by much simpler optics, the so-called V/H sensors used in aerial photography. These measure the dominant frequency in the difference between the outputs of two photosensors that view the scene through complimentary Ronchi gratings at the focus of a lens (Figure 3-1).

3.2.1.1.6 Beam Interruption

A (modulated) light source aimed at one (or two) optical receiver(s) in a traffic lane can sense the passage of (and speed of) a vehicle. Similar sensors utilizing conduction between rails as a train passes are used for longitudinal control by railroads. It is possible that longitudinal control based on beam interruption may be effective in controlling traffic at merges.

3.2.1.2 State-of-the-Art in Machine Vision

Vision based approaches to vehicle guidance have received attention throughout the world. In Germany, under the PROMETHEUS project, Manigel and Leonhard, 1991, have experimented with a vision based lateral guidance system which follows white guidelines on a flat road. The vision system comprises two CCD

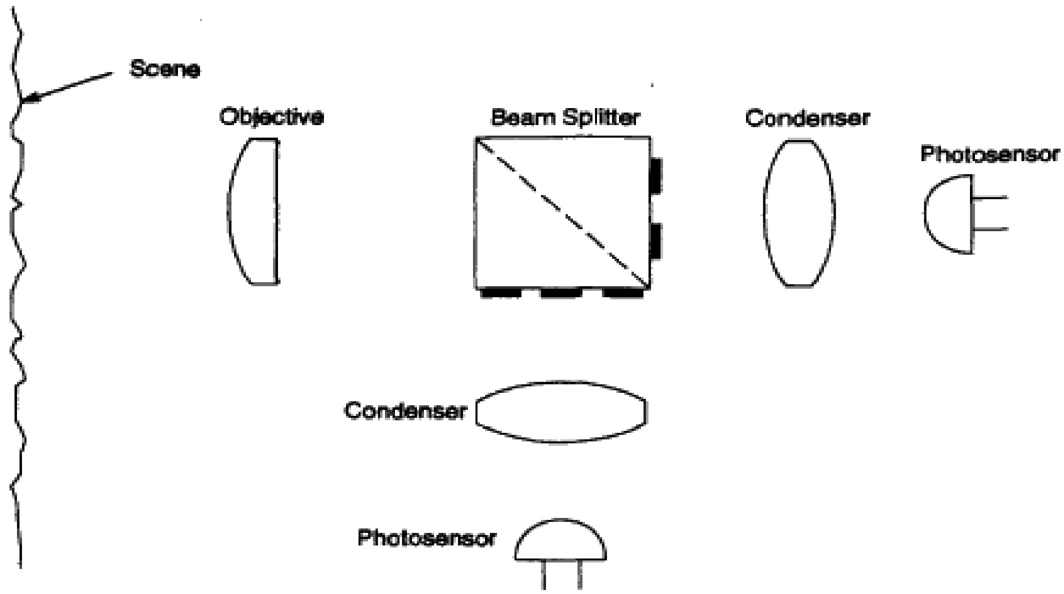

Figure 3-1. V/H Sensor

cameras, two image processors (based on T800 transputers), and a transputer network. The image processors scan the image for obstacles and road borderlines. Geometric coordinate transformation and a dynamic model (Kalman filter) are used to identify road curvature ahead and relative vehicle position. This method has been tested by simulation and with a VW Bus Caravell on typical autobahn scenes at velocities up to 120 kph. Data were recorded as a human driver and an autonomous driver traveled a left hand curve with a radius of 300 m. The steering angle of the computer operated vehicle resulted in higher frequency of correction. This is an indication of lateral displacement and, therefore, passenger discomfort. Some of the control loop may alleviate this characteristic. The peak position error of the autonomous vehicle, at a velocity of 55 kph during constant curvature, was approximately 0.1m. Predictive control could minimize a transient condition occurring at the beginning of the curve.

Daimler-Benz, Stuttgart Research Center, has developed a vision based system which tracks lane marking and ignores dirt. The system looks in the forward direction for edge and symmetry characteristics typical of a leading vehicle and slows to a stop behind a halted vehicle. Lane changes are ordered manually, by voice. Detection of people, by their characteristic gait, is planned for next year. Practical tests have demonstrated speeds up to 113 kph (70 mph); however, the vehicle displayed an unexpected drifting tendency. In addition to drifting, a notable problem existed while approaching an exit region. The vehicle exited the roadway.

Many vision based techniques can be classified according to two categories feature tracking and statistical classification methods (SCM). The feature tracking method, which as the name implies, locates the road by searching for a particular feature of interest. The location of the feature may be constrained by the location of the feature in the previous image. A periodically updated geometric road model generally facilitates tracking. Variations of the feature tracking method stem from how the feature is detected, how the road is modeled, and how the road model is updated.

Edge extraction techniques, for locating road boundaries or lane markers, incorporate predictions from the previous frame. Predictions may include such characteristics as lane width, gray levels, or gradient magnitude at borders.

In Japan, Taniguchi, Hosaka, and Oshige, 1992 of the Nissan Motor Company has reported on a vision based system which detects lane markers on the road surface using video cameras. However, an intermediate path inference mode, and an ultrasonic sensor are available to be used in the absence of vision information. The image processing algorithm relies on edge extraction. Tests conducted under various driving environments, including rainy weather, nighttime operation, and driving on an ordinary road, have confirmed the basic feasibility of autonomous vehicle operation. The highest rate of missing vision information, on 11 point spaces, over a distance 5 to 15 meters in front of the vehicle, during rainy weather operation was around 10% (Tests were conducted with rainfall intensities of 0.3, 3.2 and 7.6 mm/h). However, the results of nighttime operation, using both headlamps and auxiliary lamps, displayed an increase of missing vision information at points 11 meters beyond the vehicle. Missing vision information exceeded 90% beyond a forward distance of 13 meters. Measurements of the steering wheel angle during autonomous operation, at a speed of 10 kilometers per hour (kph), were recorded. The level of unsteadiness increased in the order of fine weather, nighttime and rainy weather. The path inference mode of operation converts previous vision information into numerical values. These values, which are stored in memory, are used to infer the upcoming path. This technique has been tested and found reliable for a distance up to 3 m (ten ft) after the loss of vision information. When vision cannot be restored and path inference modes are inoperable, the ultrasonic sensor mode is activated. It measures distance from the guide rail. Change from one operating mode, i.e. vision, to another, i.e. path inference, was accomplished without any problem.

Juberts-Nist and Raviv, 1993, describing the latest work at the National Institute of Standards and Technology (NIST) and Florida Atlantic University (FAU), discuss a vision system which tracks lane markings. Again, the edge extraction technique is implemented. During image processing, a window of interest, applied to road scene, shifts in order to keep it centered on the center of the road. The shape of the window changes as a function of the predicted road curvature. Testing at speeds up to 90 kph on curved and straight sections of a test track were successful. Weather conditions during testing varied from ideal to heavy rain; lighting varied from outdoor light to nighttime. Juberts and Raviv also report on autonomous vision based car following using both the “visual looming effect” approach developed at FAU, and a target tracking approach developed at NIST. The looming effect algorithm tracks the rate of expansion of the projections of 3-d objects in the image. The target method tracks a target secured to the back of a lead vehicle. Vehicle tracking for separations up to 30 meters has been demonstrated. A situation may occur in which the lead vehicle leaves the road, intentionally or unintentionally. This raises the question of how to prevent the tracking vehicle from following the lead vehicle off the road.

The feature tracking system of Dickmanns and Grafe, 1990, has demonstrated autonomous road following at speeds up to 100 kph and continuous driving at up to 20 kph on the German autobahn. Road boundaries and lane markers are detected in the image using edge extraction. The image is correlated with edge masks in a range of orientations about the predicted edge orientation. If the extracted edges have low curvature and are almost parallel to the viewing direction, they are considered to belong to the desired roadway feature.

An additional vision based system which utilizes the feature tracking approach is mentioned by Thorpe, C., et. al., of Carnegie Mellon University, 1991. In particular, the “yet another road follower (YARF) system, which tracks lane markers and shoulders, has demonstrated autonomous driving capabilities at speeds up to 25 kph on public roads. Feature detection relies on known geometry, known color, and edges. The road is modeled as a flat plane and all feature points are used to find a second order polynomial that best describe the road path. Research has also been conducted on feature tracking techniques, specifically, using an edge extraction approach, at the University of Maryland and the University of Bristol (Schneiderman and Albus, 1993).

Komoda, et. al., 1992, of the Toyota Motor Corporation in Japan, have developed a prototype system which accomplishes lane line detection using a high speed vision system and lateral control based on locating the line between lanes. Road information such as road surface conditions, direction of the wind, etc., is transmitted to the vehicle by a roadside beacon. A Sobel operator converts input images into boundary line images thus allowing lane recognition using road model information. Longitudinal control is dependent on distance sensing using a laser radar. The prototype vehicle system has succeeded in tests running along the lane at 50 kph on a limited access roadway. The lateral deviation of the automated vehicle showed better stability than that of a manual operated vehicle running the same track. The lane sensing system performed satisfactorily except during severe conditions (i.e.. sunrise, sunset).

Two other detection approaches developed for detection under non-ideal conditions , include, but are not restricted to, template correlation and texture analysis. Template correlation can be used to locate the line and make initial predictions. The correlation of a strip-like template in the region of interest is analyzed. Texture analysis can be used as a method of line detection or as an alternative to detection of white lines or road signs. The texture technique relies on image differences between the road, the ground beside the road, and the shoulder. A white line may or may not be included in the field of image differentiation. deMiguel, Pastor and Rodriguez, Reference, 1992, discuss and compare edge detection, and texture analysis. In France, Fernandex-Maloigne also documents experiments with texture analysis for road detection. Fixture analysis experiments resulted in correct detection of the road in 92% of the cases. However, it is understood that much further work is necessary for practical applications. Texture analysis methods which classify pixels as either road or non-road, actually fall under the second category of vision techniques.

Statistical classification methods (SCM) constitute the second category of vision techniques . Statistical classification methods group pixels as either road or non-road. The region with the highest density of road pixels, where pixels are classified according to color, is deemed the road. Supervised SCM, where the statistics of each class are known prior to classification, and unsupervised SCM, where no prior categories exist, may be used. Statistical classification techniques are advantageous with respect to infrastructure., (i.e.. they require no additional infrastructure enhancement.) However, continuity in road appearance is desirable between successive images. Environmental, and other, factors often make this impractical. For instance, the sun hiding behind a cloud degrades system performance. Another problem to be addressed is the inability of the system to recover once an image is misinterpreted. This is attributable to a co-dependency between road statistics and segmentation. In addition, a large amount of computation tends to make image processing slow. Computational time and delays appears to be of concern for many image processing techniques. According to Zhang and Parsons “Computer and image processing techniques have demonstrated some limitations in accessing 3-D images in real time using a practical size computer.”

Statistical classification techniques have led to the development of approaches such as Supervised Classification Applied to Road (SCARF) (developed by Carnegie Mellon University, Ref. Thorpe, C., et. al., 1991), FMC developed by the FMC Corporation, Ref. Schneiderman and Albush, 1993), and Vision Task Sequencer (VITS) (developed by Martin Marietta , Ref. Turk, M. et. al., 1990).

SCARF, which uses adaptive color classification, implements simple models of road color and geometry. Few assumptions are made about the road during model formation. This allows the vehicle to run on unstructured roads. Tests have been conducted on a variety of unstructured roads including a bicycle path, a dirt road, a gravel road, and a suburban street. (FMC has also demonstrated road following on dirt, gravel, and pavement at speeds up to 19 kph.) Success has been reported in locating roads obscured by heavy shadows.

VTS performs road following by fast segmenting the image into road and non-road regions. The road edges are then traced and transformed from 2-D road edge-points to 3-D coordinates. Speeds up to 20 kph have been demonstrated.

Finally, Mecklenburg, et. al., 1992, discuss an experimental vision based autonomous road vehicle. Lateral control by a neutral network is presented. Simulations and practical testing at speeds up to 80 kph. have been demonstrated.

3.2.1.3 Summary

Summaries of machine vision based systems are shown in Table 3-1. The majority of vision based approaches track the lane markers or find/extract some natural boundary intrinsic to the roadway itself (i.e., road, road edges). Drive tests have demonstrated speeds up to 120 kph and accuracies of .075 m under ideal conditions. However, vision approaches are subject to limitations set by environmental factors. In particular, these systems appear inherently susceptible to failures in the presence of contrast and illumination variations caused by heavy rain, fog, snow, weak road marking, obscured or intermittent road or lane markers, patchy roads, puddles or shadowed areas, changes in illumination, and seasonal variations. Limited success of practical testing in "non-ideal" conditions has shown some accomplishments and defined failures. Some success has been reported overcoming the negative influences of rain, shadows and weak road markings.

Table 3-1. Machine Vision Based Systems

AUTHOR	REFERENCE	CONTRAST	ILLUMINATION	REQUIRED INFRA STRUCTURE	TESTS PERFORMED	BACK-UP SYSTEMS	COMMENTS
	Calspan AHS ,File No.	(snow. rain, fog)	(sun. night)	(lines. targets)	(drive test)	(type)	
de Miguel, P., Pastor, L., a n d Rodriguez, A. (1992)	204a "ARGOS" Project Madrid, Spain			;Painted line	Tested on prerecorded images		ledge detection technique used
de Miguel, P., Pastor, L, and Rodriguez, A. (1992)	204b "ARGOS" Project Madrid, Spain				Tested on prerecorded images		Ternplate correlation technique used
de Miguel, P., Pastor, L., and Rodriguez, A. (1992)	204c "ARCK)S" Project Madrid, Spain			Painted line	Tested on prerecorded images		Texture analysis technique used
Dickmanna, E. D., Mysliwetz, B., and Christians, T. (1990)	396 (University of the German Army)	Tested successfully in light rain	Tested successfully during day/night lighting, shadows	Lane markings	Tested up to 100 kph		Edge based feature[extraction ,technique used,
Fernandez Maloigne, C., Laugier, D., Bekkhoucha, A. (date not avaiblable)	199 France						Road detection by texture analysis, discriminates other vehicles on road

Table 3-1. Machine Vision Based Systems (continued)

AUTHOR	REFERENCE	CONTRAST	ILLUMINATION	REQUIRED INFRA STRUCTURE	TESTS PERFORMED	BACK-UP SYSTEMS	COMMENTS
	Calspan AHS ,File No.	(snow. rain, fog)	(sun. night)	(lines. targets)	(drive test)	(type)	
de Miguel, P., Pastor, L., a n d Rodriguez, A. (1992)	204a "ARGOS" Project Madrid, Spain			;Painted line	Tested on prerecorded images		ledge detection technique used
de Miguel, P., Pastor, L, and Rodriguez, A. (1992)	204b "ARGOS" Project Madrid, Spain				Tested on prerecorded images		Ternplate correlation technique used
de Miguel, P., Pastor, L., and Rodriguez, A. (1992)	204c "ARCK)S" Project Madrid, Spain			Painted line	Tested on prerecorded images		Texture analysis technique used
Dickmanna, E. D., Mysliwetz, B., and Christians, T. the German Army) (1990)	396 (University of	Tested successfully in light rain	Tested successfully during day/night lighting, shadows	Lane markings	Tested up to 100 kph		Edge based feature[extraction ,technique used,
Fernandez Maloigne, C., Laugier, D., Bekkhoucha, A. (date not avaiblable)	199 France						Road detection by texture analysis, discriminates other vehicles on road

Table 3-1. Machine Vision Based Systems (continued)

AUTHOR	REFERENCE	CONTRAST	ILLUMINATION	REQUIRED INFRA STRUCTURE	TESTS PERFORMED	BACK-UP SYSTEMS	COMMENTS
	Calspan AHS ,File No.	(snow. rain, fog)	(sun. night)	(lines. targets)	(drive test)	(type)	
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de Miguel, P., Pastor, L, and Rodriguez, A. (1992)	204b "ARGOS" Project Madrid, Spain				Tested on prerecorded images		Ternplate correlation technique used
de Miguel, P., Pastor, L., and Rodriguez, A. (1992)	204c "ARCK)S" Project Madrid, Spain			Painted line	Tested on prerecorded images		Texture analysis technique used
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Table 3-1. Machine Vision Based Systems (continued)

AUTHOR	REFERENCE	CONTRAST	ILLUMINATION	REQUIRED INFRA STRUCTURE	TESTS PERFORMED	BACK-UP SYSTEMS	COMMENTS
	Calspan AHS ,File No.	(snow. rain, fog)	(sun. night)	(lines. targets)	(drive test)	(type)	
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de Miguel, P., Pastor, L, and Rodriguez, A. (1992)	204b "ARGOS" Project Madrid, Spain				Tested on prerecorded images		Ternplate correlation technique used
de Miguel, P., Pastor, L., and Rodriguez, A. (1992)	204c "ARCK)S" Project Madrid, Spain			Painted line	Tested on prerecorded images		Texture analysis technique used
Dickmanna, E. D., Mysliwetz, B., and Christians, T. the German Army) (1990)	396 (University of	Tested successfully in light rain	Tested successfully during day/night lighting, shadows	Lane markings	Tested up to 100 kph		Edge based feature[extraction ,technique used,
Fernandez Maloigne, C., Laugier, D., Bekkhoucha, A. (date not avaiblable)	199 France						Road detection by texture analysis, discriminates other vehicles on road

3.2.2 Radar

Radio detection and ranging (Radar) is the process of transmitting electromagnetic signals and receiving the radio echo from objects of interest within its volume of coverage. Presence of, range and/or speed for stationary and/or moving objects may be extracted from the received echo. The information available from the received signal depends on the waveform of the transmitted energy. The oldest form of radar utilized transmission of short pulses of radio waves. Echo pulses are received at a later time, after reflection from the target, when the transmitter is off. Bandwidth of the pulse, (pulsewidth) determines range resolution. A bandwidth of about one Gigahertz (GHz) is required for 0.3 m resolution.

Continuous Wave (CW) energy, transmitted at one frequency, allows determination of vehicle speed via the Doppler shift associated with the echo (as shown in Figure 3-2). However, transmission of a CW signal does not allow detection of vehicles not moving with respect to the radar.

The frequency modulated continuous wave (FMCW) waveform allows detection of presence, measurement of range and of speed for vehicles that are stationary or moving with respect to the radar (Figure 3-3). The part of the waveform where frequency changes with time is used for presence detection and ranging. Speed may be measured in a manner similar to CW radar by providing a segment of constant frequency or by certain manipulations on an FM waveform. Variations of the FMCW waveform include different rates of change of frequency, time durations of each segment of the waveform, and types and sequencing of the segments of the waveform.

3.2.2.1 Sensor Technology

The process of determining range to and speed, with respect to vehicles and obstacles, and the field of coverage of radar sensors are of considerable interest in the AHS environment. In the following sub-sections, discuss ways of making targets more detectable and reduction of mutual interference in a fully deployed AHS using radar.

Although radar is historically associated with microwaves, AHS applications may dictate use of millimeter waves. The high frequencies of millimeter waves permit use of a less crowded portion of the electromagnetic spectrum, making a larger bandwidth, a limited commodity, available. Europe has already allocated a band of 76-77 GHz for automotive radar in the DRIVE and PROMETHEUS programs.

Radar technology evaluated for IVHS applications includes millimeter wave detectors. Recent developments of millimeter wave devices have initiated investigation into the use of millimeter wave technology for automotive radar. The attractiveness of millimeter wave technology stems from a promise of high electronic performance, very small size components, and low cost fabrication made possible by advances in microwave monolithic integrated circuits, and flat or active millimeter wave antennas. Millimeter wave radar tends to be more robust in terms of weather than laser techniques. It is also preferable with respect to penetration of adhered dust on the antenna and reduced risk of radiation hazards to human and animal eyes. Experiments (Takimoto, Kotaki, 1992) show rain and snow do not significantly

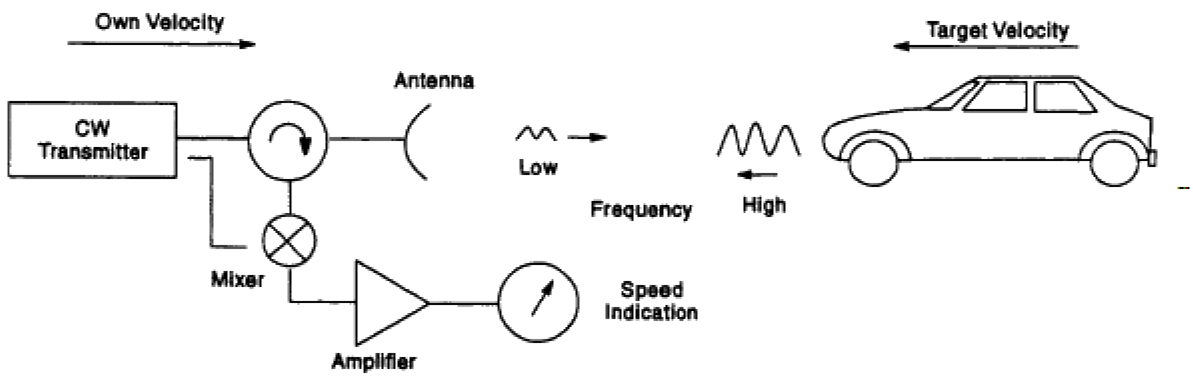


Figure 3-2. CW Doppler Radar

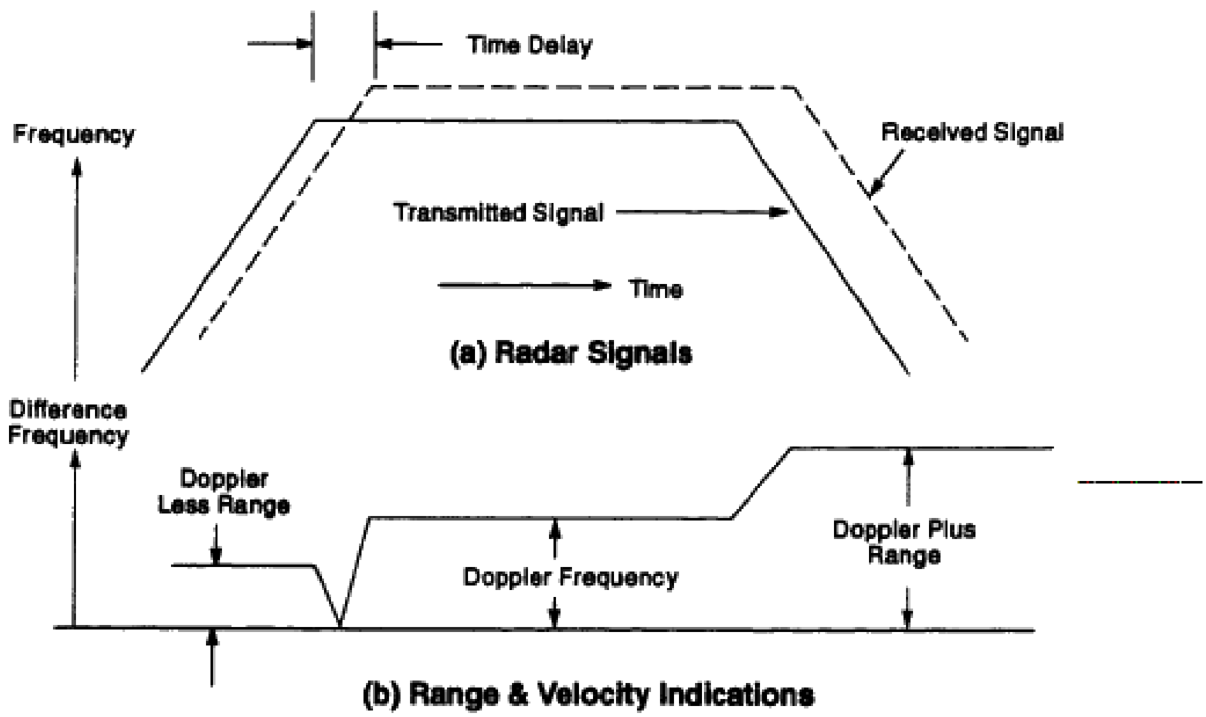


Figure 3-3. Fm/Cw Radar Waveforms

deteriorate performance even when sensors were covered with thick snow. Another attractive feature of millimeter wave radar is the ease with which accurate and narrow beam patterns can be formed.

There are two well known concerns in the application of millimeter waves. The first is the atmospheric propagation loss due to absorption resulting from water vapor and oxygen. The attenuation caused by water vapor and oxygen (Figure 3-4), often thought of as a problem, may in fact provide limits to mutual interference in large scale radar usage. Transmitted power should be limited to that necessary to receive echoes at the maximum desired range. Signals from other radars, especially those that are pointing their directive antennas at one's own radar, are detectable at a much greater range and can cause interference. Operation in high-absorption bands reduces the range over which such interference is a problem (Section 3.2.2.1.4).

The second potential problem is scattering due to rain and fog. The susceptibility of millimeter waves to scattering was investigated in (Takimoto, Kotaki, 1992). Keeping in mind that sensor range need only cover about 100 m ahead of the vehicle, for anticollision radar, millimeter wave radar was found to be "very effective even in rain as heavy as 10 mm/hr (0.4 in/hr)." However, problems were reported from raindrops on the antenna surface which distorted the radar antenna's beam.

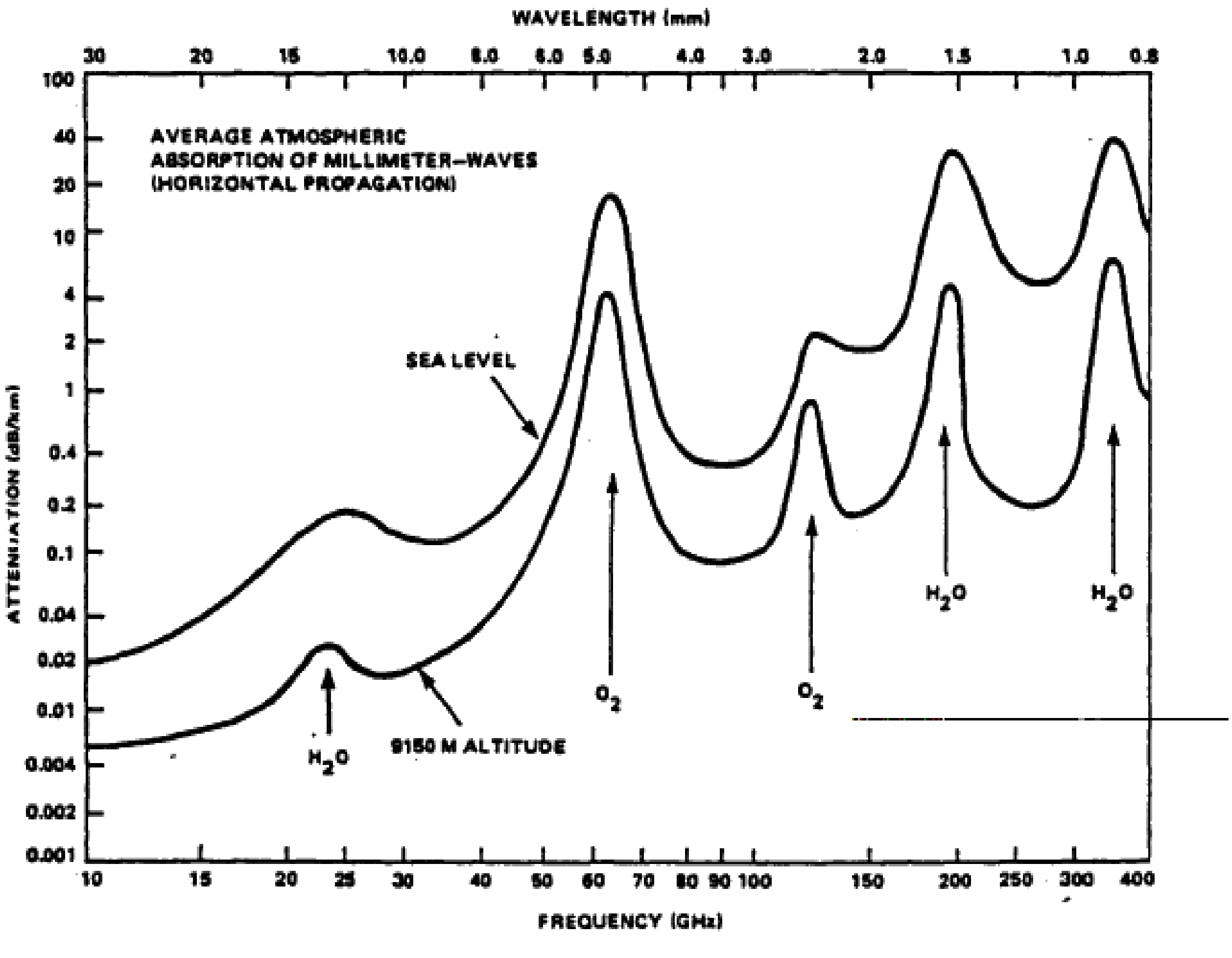


Figure 3-4. Atmospheric Absorption of Millimeter Waves

Resonant raindrops, i.e., ones with a circumference of about one wavelength occur at the higher millimeter frequencies and produce enhanced backscatter. This may be misinterpreted as a target for which the vehicle has to slow down.

3.2.2.1.1 Ranging

Radar appears to offer promise of detection capability suitable for longitudinal guidance, lateral guidance, and obstacle avoidance. Integral to all radar ranging techniques is the relationship between time delay and range. For pulse radars the time delay (Æt) from transmission to reception is related to range (R) by the equation

$$\Delta t = 2\ R/c$$

where (c) is the speed of light. Relative speed is determined by either tracking the rate of change of range or by pulse Doppler processing.

For an FMCW radar, range and speed are determined as follows: Consider a continuous waveform of uniformly increasing frequency transmitted at some time t_1 with frequency F_1. The echo of this signal, received at time t_2, is still of frequency F_1. However, the reference or transmitter signal is now at a frequency F_1'. The frequency difference between F_1 and F_1', which is dependent on the time delay, and, therefore, the range, is given by:

$$f_R=(2/c) \cdot R \cdot dF/dt,$$

where dF/dt is the rate of change of frequency with time.

Motion of either the transmitter/receiver apparatus or target results in a deformation of the waveform with respect to wavelength (for instance, if the wave source moves toward the target, the radiated wavelength is compressed). Known as the Doppler effect, the dependence of wavelength on motion ultimately means a variation of frequency. The overall effect of speed (S) and range is gauged by the beat note frequency (fb), resulting from a combination of the transmitted and received signal at time t_2, where,

$$f_b=(2/c) \cdot dF/dt \cdot R-(2/c) \cdot F_1 \cdot S.$$

Although both effects of speed and range are included in the aforementioned formula, the method described, continuously and uniformly increasing the transmitted signal frequency, does not allow easy access to both characteristics. Periodic variation of the waveform remedies this difficulty. A triangular waveform offers a suitable example (Figure 3-5a).

A stationary target simply delays the received signal in time relative to the transmitted signal (Figure 3-5b). Figure 3-5c singles out the effect of a moving target on the signal. The contribution of range to the received signal has been ignored, which, although impossible, is illustrative. Finally, Figure 3-5d exemplifies the combined result of range and speed.

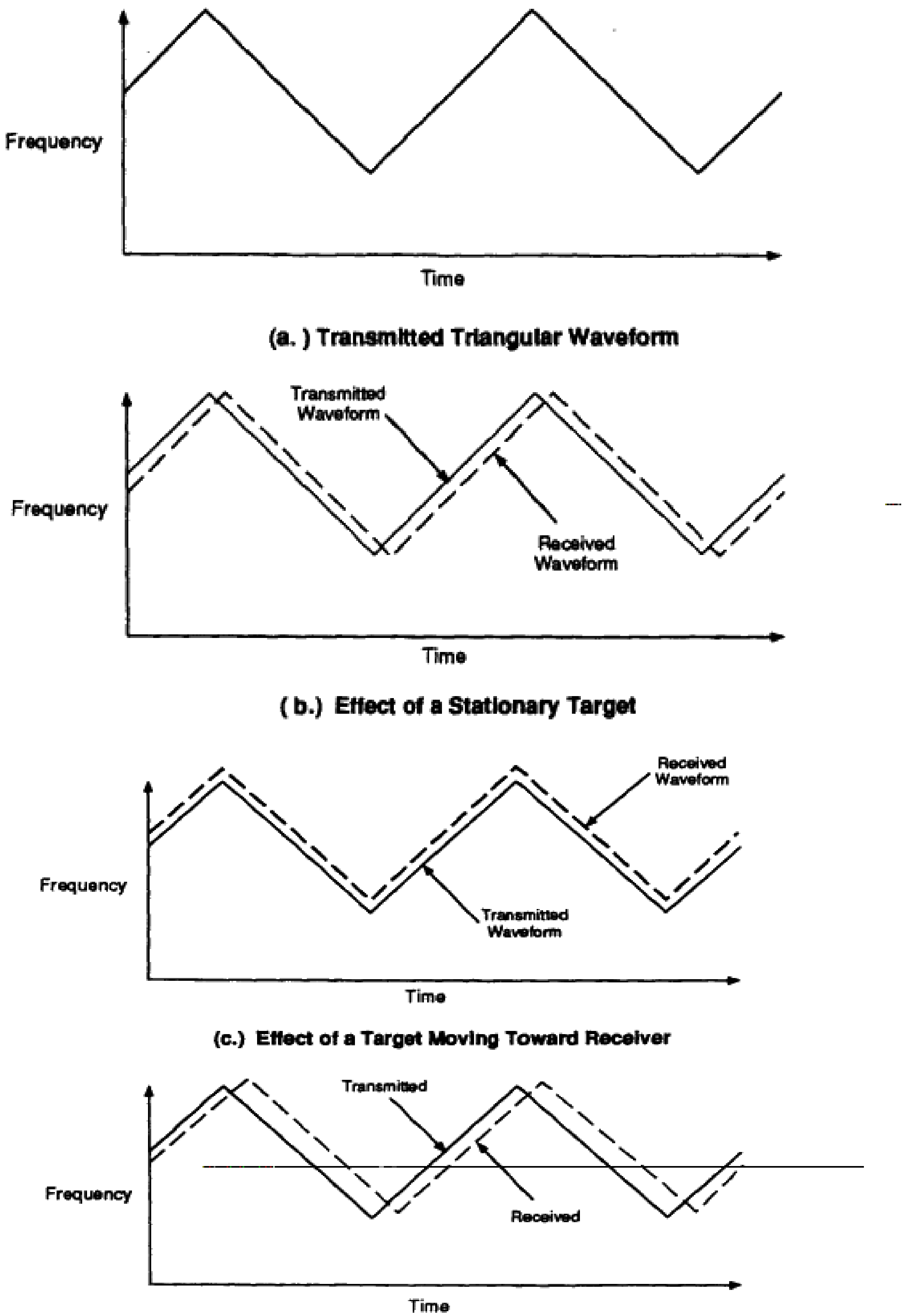


Figure 3-5. FMCW Waveforms

During the upsweep and downsweep of triangular modulation, the frequency rate is +|dF/dt|| and -|dF/dt|, respectively. The upsweep frequency and downsweep frequency of the beat may be obtained by substituting these values in the above beat note frequency equation. Only the absolute magnitude of the beat note frequencies need be considered. The range frequency and speed frequency may be determined from,

$f_r = 1/2 \cdot (|f_d| + |f_{u)}|,$

and

$f_s = 1/2 \cdot (|f_d| - |f_u|),$

when range frequency exceeds speed frequency. These are simply interchanged if speed frequency exceeds range frequency. It is apparent that several cycles of the beatnote should occur during the up and downsweeps. This is easily arranged at higher microwave frequencies with typical inter-vehicle ranges and closing velocities. For a target at constant range, it may happen that the beatnote during the upsweep has the opposite phase from the beatnote during the downsweep. In some FMCW implementations this results in cancellation of the echo from that target and indication of false targets at slightly smaller and greater range (range sidelobes).

3.2.2.1.2 Coverage

The volume of coverage of a radar is defined by the angular dimensions of a radar beam and the range coverage of the radar (Figure 3-6). Radar beams are generated by antennas that are several wavelengths wide. Beamwidth (B), in radians

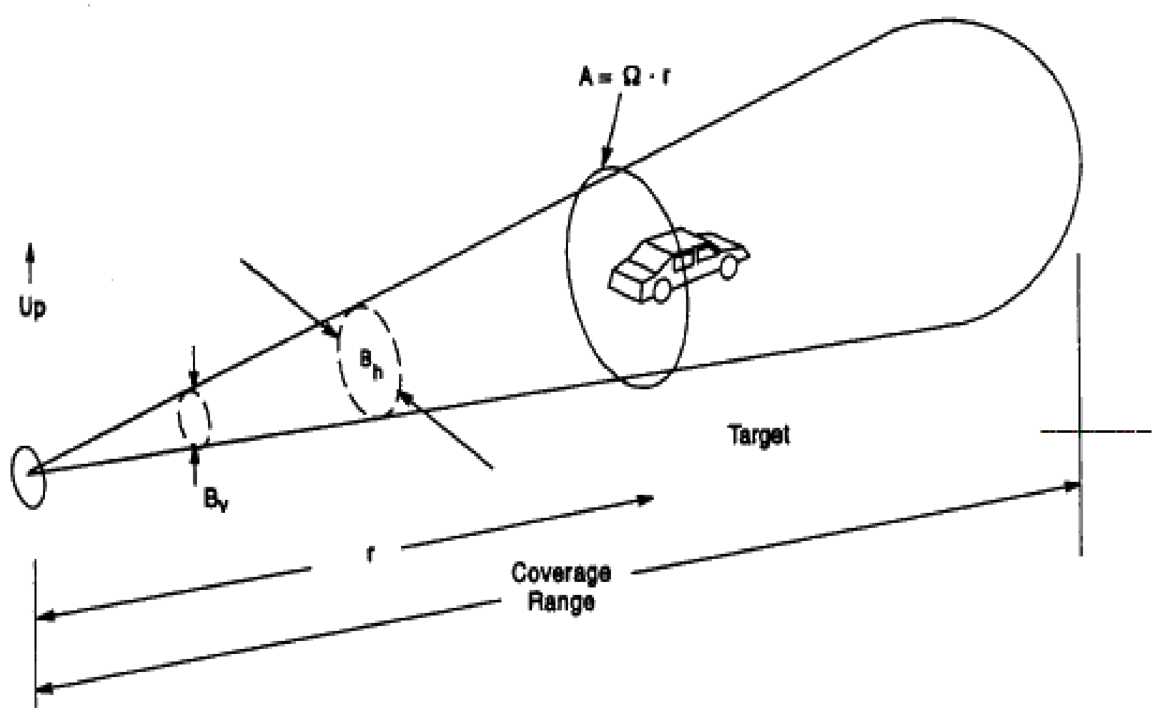


Figure 3-6. Coverage Volume of a Radar

(1 radian approximates 57.3 degrees), is approximately equal to wavelength (λ) divided by the antenna diameter (D), with these two dimensions in the same units.

B (rad.) = λ / D or B (degrees) = $57.3 \cdot \lambda / D$

If the vertical and horizontal diameters of the antenna are identical, the beam tends to be symmetric about the direction of propagation. It can be visualized as a baseball bat, with the antenna at the grip. If those two dimensions differ, one gets something like a beaver tail, with the narrower angular dimension along the widest diameter of the antenna.

Radar beams concentrate transmitter power in the direction of the beam. The power gain (G) that is achieved is approximately;

$G = 4 \,.\, ^1 / [\, B_V \text{ (rad.)} \cdot B_h \text{ (rad.)} \,]$

The factor ($4 \, ^1$) derives from the fact that without directionality the beam would be isotropic. It could spread out into all directions, i.e., into a solid angle of $4 \, ^1$ steradians (sr). The product of vertical beamwidth (B_V) and horizontal beamwidth (B_h) is an approximation to the solid angle (½, sr) that is illuminated by the beam.

In addition to the main beam that was described in the preceding paragraphs there are sidelobes. Sidelobes are one of the reasons that the word "approximately" has been used so often. They typically form a pattern of lesser beams at an angle to the main beam, detract from its power and can lead to errors in angular measurement. The aperture of antennas is usually not used completely. One tapers illumination, the power emitted by each part of the aperture, toward the edge in order to reduce the strength of sidelobes. This means that the effective diameters of antennas are less than the geometric dimensions. This effect is ascribed to an efficiency factor which is approximately 0.55 for well-designed antennas. Figure 3-7 shows amplitude (vertically) of the beam and side lobes of a square, uniformly illuminated antenna as a function of horizontal and vertical (receding) angle. The graph is the theoretical prediction; measured antenna patterns are usually not as perfectly symmetric because of various imperfections.

3.2.2.1.3 The Radar Equation

A target on the beam axis at range (r) is exposed to a power density (Φ, in W/m^2), called flux by designers of optical systems, given by

$\Phi = P_T \cdot G / (4 \cdot \, ^1 \cdot r^2)$

Here, the factor ($1 / 4 \, ^1 \, r^2$) is sometimes called the spreading loss.

The target cross section (σ, in m^2) is defined in such a fashion that the correct result is obtained from the following expressions if we assume that the target re-radiates equally in all directions. For a sphere of radius (R) it is the cross-sectional area ($^1 \cdot R^2$). A flat plate, large in units of wave length, with that area, oriented exactly

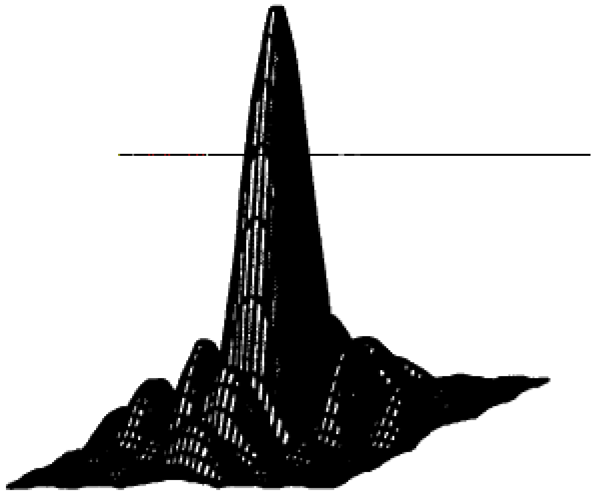


Figure 3-7. Theoretical Amplitude Pattern of a Large Uniformally Illuminated, Square Antenna Showing Sidelobes

perpendicular to the beam axis - which is appropriately called the Poynting vector (J. H. Poynting 1852 - 1914), will have a much larger target cross section (by a factor of $4 \cdot 1^2 \cdot R^2 / \lambda^2$), but will become invisible if tilted very little. This happens because it becomes a new antenna with its narrow beam not pointed back at the radar. This fact is exploited in stealth technology. Very large cross sections can be obtained with a corner reflector. This has the shape of a corner of a cube and its three adjacent facets.

After reflection from the target, the signal suffers another spreading loss in returning to the radar, where it is intercepted by the effective antenna area. The result is that power (P_R) received from the echo is

$$P_R = P_T \cdot G^2 \cdot \lambda^2 \cdot \sigma / ((4 \cdot \pi)^3 \cdot r^4)$$

This power must exceed the noise-plus-interference power at the radar receiver by some factor if the radar is to serve a useful purpose. Note that signal depends inversely on the fourth power of range.

3.2.2.1.4 Mutual Interference

Two radars facing each other can interfere with each other over a very long path. Time, frequency and code division multiple access (Section 3.3.1) may limit problems from mutual interference, but other techniques should be investigated, as well. One of these is operation at frequencies where the atmosphere is a good absorber (Figure 3-4). The lowest and most reliable of these is the oxygen band at 60 GHz where absorption is approximately 12 decibels (dB) per kilometer.

A hypothetical radar at that frequency was postulated in order to assess this effect. Its required transmitter power was then calculated with two assumptions on the radar cross section, one corresponding to a small car or large motorcycle ($2m^2$) and the other assumption corresponding to vehicles equipped with a 0.2 m corner reflector (σ=$268m^2$). In addition, it was assumed that there was no absorption in one case and 12 dB/km absorption in the other, for both cross sections. An interference range was calculated which is that range at which two radars, pointed at each other, receive as much signal from each other as the level of receiver noise.

Other parameters were kept the same over the resulting four cases. Operating range with a signal-to-noise ratio of 20 dB was 200 m. Receiver noise figure was 10 dB and RF bandwidth was 2 GHz for a range resolution of 0.3 m. Results of these calculations are presented in Table 3-2.

Table 3-2. Radar Performance with Atmospheric Absorption

Target Cross Section (m^2)	Transmitter Power (W)	Interference Range (km)	Atmosphere Absorption
2	83	1000	No
2	251	4.34	Yes
268	0.62	86	No
268	1.88	2.87	Yes

The results indicate that cross section is a strong factor in determining both transmitter power and interference range. For radar-based longitudinal control systems, this may suggest that the installation of corner reflectors on the back of all vehicles should be mandated a few years in advance of the phase-in of AHS. The benefits of operating in an absorption band, by reduction in interference range, are apparent. It should be noted that the water vapor absorption band at 22.24 GHz is subject to humidity fluctuations and not reliable.

3.2.2.2 State-of-the-Art in Radar

Millimeter wave monolithic technology has been under development in defense programs for over ten years. Advances have enabled the development of chips that are already applicable to the automotive industry. Raffaelli and Stewart, 1992, present mm wave monolithic components for automotive applications. Several MMIC chips developed for the military are either directly, or with minor modification, usable for collision avoidance radars.

In England, Lowbridge, Briggshaw and Kumar have worked with a 77GHz system for automotive cruise control. The system uses an FMCW radar transceiver, based on thin film micro-strip technology, with a switched beam quasi-optical antenna. The basic transceiver, in a hermetic housing is expected to have a production cost of less than $150 U.S., depending on the requirements. A production vehicle fitted with the FMCW radar system has successfully used intelligent cruise control (ICC) in closed loop mode.

In Japan, Takimoto and Kotaki, 1992, have conducted experiments on three mmwave radar automotive sensing systems for collision warning/obstacle avoidance. The three systems studied include a 50 GHz FMCW radar system, using slant 45° polarization so that opposing vehicles will have orthogonal polarizations, with a 60 GHz pulse doppler radar system with a single two dimensional scanning (mechanical) antennas, and a 70 GHz FMCW radar system with a multi-horn/beam one dimensional scanning antenna system. The 50 GHz radar system experiences a low interference signal from similarly equipped vehicles approaching in the opposite direction. The transmitting polarization of the two vehicles are plus and minus 45 degrees to the ground, which, ideally isolates the two vehicles. The false alarm rate on the freeway, downtown areas, and rural areas were 1.5%, 7.1%, and 10.2%, respectively. The 60 GHz system showed good image data. Target detection was sufficient in snow and fog conditions.

In Italy, under the EUREKA-PROMETHEUS projects, Cugiani, et. al., 1993, describes a 35 GHz FMCW radar system for acquiring real-time lateral position data. Lateral scenery is searched within a bounded region for a guard rail. The guard rail, which runs parallel to the road, is affixed with a double reflection reference target ,(e.g. a 90 degree corner reflector). Circular polarization, used to illuminate the corner reflector, helps discriminate between target and non-target reflections.

Research conducted in the United States include efforts by Heller and Huie, 1993, concentrating on the development of a 24 GHz radar system for lateral control of an automobile. The reflection of an AM modulated signal, transmitted from the vehicle to a reflector in the center of the roadway, is sensed by a receiving antenna. A 3M aluminum backed strip was implemented for the reflector. The received signal is split into two parts to reconstruct phase and amplitude. The phase shift of the return signal relative to the transmitted signal, along with the amplitude of the return signal, provide the information to determine the direction and lateral displacement of the vehicle relative to the reference. The effects of various weather conditions, including rain, sleet, and snow, were tested. Future investigations into the effects of water beading on striping materials and saline surfaces on the reflected signal are suggested.

In 1990, Lucas Advanced Engineering Center, conducted experiments with a 94 GHz FMCW microwave radar intelligent cruise control fitted to a SAAB 9000 (Tribe, 1993). The results were so encouraging that, after some modification, the system was fitted to a Jaguar car. Multiple beams enabled determination of angle, greater field of view and improved tracking of objects around bends. The addition of a video camera and image processing enabled detection of bends and lane markings, allowing false alarms to be filtered out. Current activities are concentrating on improving operation in heavy traffic and on bends.

Work carried out by Philips Research Labs, Redhill, Surrey, on car obstacle avoidance radar is described by Mallinson and Stove, 1989. This realizable radar system relies on FMCW techniques at 94 GHz. The technology is based on that developed for terminal guidance in Smart Weapons. The system radiates approximately 10 mW of RF power in an FMCW waveform which is transformed into range information using a Fast Fourier Transform based processor.

Cohn, 1993, describes a millimeter wave retrodirective transponder (RDT) for collision/obstacle avoidance and navigation /location. The principle of operation is based on the Van Atta array. The Van Atta array receives an incident RF wave, modulates it, and re-radiates the wave back in the direction from which it came. The advantages of such a system include the need for no other RF sources or receivers. RDTs have potential applications in the automotive industry as a cooperative collision avoidance system. Differing the modulation codes of front and rear mounted RDTs would enable an interrogating vehicle to distinguish oncoming vehicles from those traveling in the same direction. This may help minimize false alarms typical of radar collision avoidance systems. The speed of the interrogated vehicle may be modulated on the return signal. This makes the RDT capable of acting, at least, as a part of an intelligent cruise control or vehicle following system.

IVHS technologies are a precursor to future AHS applications. Integration of IVHS technologies is already underway. In 1992 Greyhound lines, Inc. began equipping its 2400 bus fleet with a vehicle detection and driver alert system manufactured by Vorad Safety Systems Inc. of San Diego (Tomsho, Robert, 1992). The Vehicle on-board radar, or Vorad, system tracks vehicle movement within a range of 300 ft., by transmitting and receiving low power microwave energy at 24 GHz. The processed signals appear to the driver as a vehicle light (yellow) or a collision warning light (red) and an audible tone. Vorad also offers an optional side looking radar for blind-spot detection which although of interest to AHS applications, is rarely addressed in the literature.

3.2.2.3 Summary

Radar is perceived as beneficial for longitudinal control, initially in intelligent cruise control (ICC) systems and ultimately for AHS. Only two of the 17 radar experimenters listed in Table 3-3 addressed radar-based lateral control. One used a two-sided corner reflector mounted on the guard rail as a target, while the other used a conductive strip cemented to the lane center.

Fairly good performance has been reported for longitudinal warning radar. Over a thousand Greyhound buses have been equipped with Vorad radars. These give visible and audible warning to the driver when the bus is closing on a leading vehicle at an excessive rate and have been credited with reducing the rate of accidents by twenty percent.

Certain issues need further study. Mutual interference has been addressed by some experiments. Linear polarization at an angle of 45 degrees to the vertical was found to be effective in reducing interference to oncoming vehicles (Kotaki, 1992). An other investigator (Stove, 1992) points out that intentional scan jitter will make it

Table 3-3. Radar Based Systems

AUTHOR	REFERENCE	LATERAL CONTROL,. LONGITUDINAL CONTROL, OR OBSTACLE DEFECt!ON	FREQ (GHZ), LEVEL OF ABSORPTION	ADDRESSES TURNS?	ADDRESSES INTERFERENCE	TESTS PERFORMED	COMMENTS
	Calspan AHS File No,					(Drive TcsO	
Chang, K., et.al. (1991)	9 (University of CA, Berkley, and VORAD Systems, Inc.)	Longitudinal	24.125	No	No	Yes, Tested at 90 kph with a longitudinal accuracy of 0.5 m	
Cohn, M. (1993)	! 92 (Wearing house Electric Corp.))	Longitudinal			Yes		Utilizes rctrodirectivc transpondcr based on thc Van Atta array
Cugiani, C., et. al. (1992, 1993)	191, 217 (EUREKA Prometheus Proiect~ Italy	Lateral	35, low	No	No		Guardrail corner reflector
Hodrick, J., eL al. (1992)	26 (University of CA, Berkley)	Longitudinal		No	No	Yes, Tested at speeds up to 122 kph	
Heller, M., and Huie, M. (1993)	i 88 (CA State University)	Lateral	2.4, Medium	No	No		Roadway stripe
Kotaki, M., et. aJ. (1992)	3 7 (Toyota, Fujitsu-Ten Ltd., Honda, Nissan, Communicati ons Res. lab, Advanced Millimeter Wave Technologies Co_1 Ltd.	Obstacle Detection	50, 60, 70	No	Yes, 45° polarization	Yes	

Table 3-3. Radar Based Systems (continued)

AUTHOR	REFERENCE	LATERAL CONTROL,: LONGITUDINAL CONTROL, OR OBSTACLE DETECTION	FREQ (GHZ), LEVEL OF ABSORPTION	ADDRESSES TURNS?	ADDRESSES INTERFERENCE	TESTS PERFORMED	COMMENTS
	Cadspan AHS Fade No,					(Drive Test)	
Lowbridge, P., Brigginshaw, P, and Kumar B. (date not available)	183, 207, 228 (GEC PiesMy Seeniconductors: GEC Hirst Rsrch Center)	Longitudinal	77, Medium	Yes, Scanning	No		
Mallinson, P., and Stove, A. (! 989)	206 (Philips Rsrch Labs)	Longitudinal	94, Medium	No	No		
Stove, A. (1991, 1992)	227, 208 (Philips Research LIbs, England)	Longitudinal, Obstacle Detection	8.0	No	Yes	Yes, scan jitter	
Takimoto, Y., and Kotaki M. (1992)	190a (Advnc'd Mm Wave Tech. Co., HOIkk~!do Tokai Univ.~	Longitudinal	60, High	Yes, Scanning/ Innaging	No		
Takimoto, Y., and Kotaki M. (1992)	190b (Advnc'd Men Wave Tech. Co., Hokkaido Tokai Univ.)	Longitudinal	50, Medium	No	Yes, 45° polarization	Yes, Tested at 95 kph over 1000 km of roadway ..	Mill's Cross antenna
Takimoto, Y., and Kotaki M. (1992)	190c (Advnc'd Mm Wave Tech. Co., Hokk~ido Tokai Univ.)	Longitudinal	70, Medium	Yes, Multibeam antenna	No		
Taniguchi, M., et. ad. (1992)	196, 200 (Nissan)	Obstacle detection		No	No	Yes	
Thorpe, C., et. al. (1991)	347, 393 (Carnegie Mellon University)	Obstacle Detection (& Terrain Modeling)				Yes	Acquisition rate too slow for high speed driving

Table 3-3. Radar Based Systems (continued)

AUTHOR	REFERENCE	LATERAL CONTROL,. LONGITUDINAL CONTROL, OR OBSTACLE DETECTION	FREQ (GHZ), LEVEL OF ABSORPTION	ADDRESSES TURNS?	ADDRESSES INTERFT, RENCE	TESTS PERFORMED	COMMENTS
	Cadspan AHS File No.					(Drive Test)	
Tribe, R. (no date available)	210 ~Lucas Advnc'd Ena.)	Longitudinal	94, Medium	No	No	Yes	
Turk, M., et. al. (1988)	394 (Martin Marietta)	Obstacle Detection				Yes	

extremely improbable that one FMCW radar will interfere with another for any significant duration. Another issue is false alarms which have been evaluated for a longitudinal warning radar in over 1,000 km of testing (Takimoto and Kotaki, 1992). False alarms were caused by guard rails on sharp curves, on-coming cars on a curve, opposing concrete walls at intersections and metal structures in the roadway at the start of an upgrade or at the end of a downgrade. Cars ahead were not detected at sudden changes in slope. Most of these problem conditions are not present on freeways eligible for AHS and this is reflected in the observed statistics. In rural areas 10.2 percent of alarms were false, in downtown driving this fraction was 7.1 percent while in freeway driving over 378 km only 2 out of 135 alarms (1.5%) were false.

On the whole, radar is a strong candidate for longitudinal vehicle following,and may, in combination with some infrastructure, become useful for lateral control. Radar may be used for more than simple longitudinal and lateral guidance. Coverage of blind spots (next to and behind the vehicle), as provided for example by Vorad's bus radars, improves safe performance of lateral maneuvers. Completely autonomous lane changing during AHS entry and exit, would require tracking of all vehicles around one's own. This is not a serious computational challenge but would require greater radar sensor coverage than has been explored so far.

3.2.3 Acoustics

There have been proposals to sense headway and vehicles in the blind spots acoustically. Acoustic transducers could become a source of annoyance unless they operated at a frequency that is not audible. Infrasonics are limited in range resolution, yielding approximately 20 m accuracy, and propagate very well and very far, which could lead to mutual interference. This suggests the use of ultrasonic frequencies. Short pulses at frequencies as low as 13 KHz are almost inaudible, but one should probably operate above 16 KHz. Calspan tested a battery-powered air sonar operating at 13 KHz, with a beam width of 10 degrees at ranges up to 50 m i.e. with a round-trip distance of 100 m, with satisfactory results. Greater range, up to 300 m, could undoubtedly be obtained with one-way communications, even without increasing output power.

3.2.3.1 Sensor Technology

Polaroid uses an acoustic range finder in an automatic focus system. That subsystem is offered for sale separately, as is a ranging module developed by Massa Products Corporation. Calspan developed two acoustic distance sensors in connection with environmental and robotics work. The acoustic robotics sensor served a particularly important function. It was designed to detect and avoid humans that strayed into the path of an autonomous (free-roving) robot forklift. The fact that it made a clearly audible clicking noise despite the fact that most of its acoustic power was at a frequency of about 50 KHz was actually beneficial since it warned the human involved in the encounter.

A hybrid radio/acoustic system may be useful for ranging to a cooperative vehicle. An acoustic source and radio transmitter are placed on each car. Both systems emit pulses simultaneously. The RF pulse, traveling outward at the speed of light, roughly one foot per nanosecond, arrives at any nearby vehicle in less than a microsecond. The acoustic pulse travels about 340 m per sec. An RF receiver and a microphone on the vehicle will receive the acoustic pulse some time after the RF pulse. To a good approximation, the delay between arrival of the two pulses is proportional to distance from the other vehicle, with one millisecond of delay corresponding to approximately one foot of distance or range.

The distance-delay calibration constant for acoustical systems is a function of temperature , varying as the square root of absolute temperature. Over the extreme temperature range from -40 to +50 degrees Celsius (-40 to +122F) this factor varies by plus or minus nine percent and this may be tolerable and certainly correctable with a temperature sensor. Wind blowing along the road changes the constant as well. A 97 kph (60 mph) wind will add eight percent error in one direction and subtract the same amount in the opposite direction.

Ultrasonic air transducers having significant output power tend to be several wavelengths in diameter and therefore quite directional. This is a benefit in that the acoustic signal can be concentrated in the desired direction but also a nuisance because alignment of the beams becomes critical. A second disadvantage arises when the beam is too narrow and there is a strong cross wind. The pulse packet, a pressure wave in the air mass, is blown sideways with the air mass and may be blown past the receiver. With 97 kph (60 mph) cross wind the beam is deflected by 4.7 degrees. This becomes a problem when ranging to the side of the vehicle.

Narrow beams appear to present a problem near the transducer where there appears to be inadequate angular coverage. This problem also occurs with radar, where a narrow beam, useful for finding the exact angular position of a target, seems incompatible with having sufficiently wide angular coverage. Fortunately these "blind" regions are near the radar where little power is needed. If one "steals" a little power from the directional beam and redirects it, in a pattern referred to as a cosecant squared pattern, one can obtain excellent coverage everywhere. Calspan utilized specially shaped beams for the personnel-avoidance sonar of the free-roving robot.

Noise generated by the car, its interaction with the wind and from other causes requires further analysis and experimentation. The robotic sensor required considerable development before it ceased responding to jangling key chains and arc welders.

3.2.3.2 State-of-the-Art in Acoustics for AHS

Taniguchi, et al, 1992 used an acoustic sensor as a second backup to a machine vision system backed up by dead reckoning. Acoustic transceivers mounted on the four corners of a van were used to range on guardrails in order to provide lateral guidance. The reference suggests that acoustic control was not smooth, but it is not known whether this was due to sensor noise or an inappropriate control algorithm.

Acoustic transceivers mounted on the four corners of a van were used to range on guardrails in order to provide lateral guidance. The reference suggests that acoustic control was not smooth, but it is not known whether this was due to sensor noise or an inappropriate control algorithm.

3.2.3.3 Acoustics Summary

Acoustics may be of utility in certain specialized applications in AHS. Experimentation in using acoustics for lateral guidance had limited success. Table 3-4 shows the one experiment that was conducted.

3.2.4 Optical Ranging

3.2.4.1 Sensor Technology

Laser radar introduces technology which offers more resistance to weather than vision based approaches, yet, less than microwave radar. It lends itself as an obvious candidate for car following and obstacle detection. However, techniques have also been developed which use a laser radar as a means of lateral guidance.

Light detection and ranging (Lidar) typically uses a pulsed (or otherwise modulated) laser and measures the round trip time of the pulse that is reflected from the ranging target. It has the advantage (and occasional curse) of excellent angular resolution. Because optics are typically many wavelengths across, there are few problems from sidelobes and multipath. Interference from systems on other cars can pose a problem. Since only a small spot on the target is illuminated, the target spot may be missed entirely if it has low reflectivity. If a more divergent beam is generated, signal strength is reduced. These problems may be manageable and Lidar designs should be explored. Very short pulses are needed to obtain good range resolution with a Lidar. One nanosecond, associated with a bandwidth of one Gigahertz, is needed to obtain one foot resolution.

Optical ranging can be accomplished in a much simpler fashion and with an accuracy that is very high at short ranges but less at long ranges, where it may not be important. The process (shown in top view in Figure 3-8) is another application of a line scanner. The line scanner views the scene at a slight angle to the sensing direction, e.g. forward, such that its left-most element stares in the sensing direction. The lens should be slightly astigmatic to spread light in the vertical plane and guarantee a point of good reflectivity in the field of view. The scene is now illuminated by a light source focused to provide a spot on a target in the sensing direction. If the reflection occurs at very large distances, the left-most cell of the line scanner detects it. If it occurs at a very short range (R_n in the figure), the right-most cell detects it. Range
cells, i.e., the segments in range that correspond to a sensor cell, are distributed as the cotangent of the angle labeled Θ in the figure, or approximately as 1/R where R is the range. As an example, consider a 256 cell line scanner with optics selected to make the closest detectable range one meter (m), with a baseline (b in the figure) of 0.1 m. At its minimum range it has a resolution of about 4 millimeters (mm). At maximum range it cannot distinguish an object at 257 m from one that is further away; the next-closest range cell extends from 128 m to 256 m.

Table 3-4. Acoustic Based Systems

AUTHOR	REFERENCE	ALTERNATE SYSTEMS	TESTS PERFORMED	COMMENTS
-	Calspan AHS File No.	-	Drive Test	-
Taniguchi, et. al. (1992)	196, 200 (Nissan)	Machine Vision, Dead Reckoning	Yes- Lacked Stability	Used as a backup for machine vision

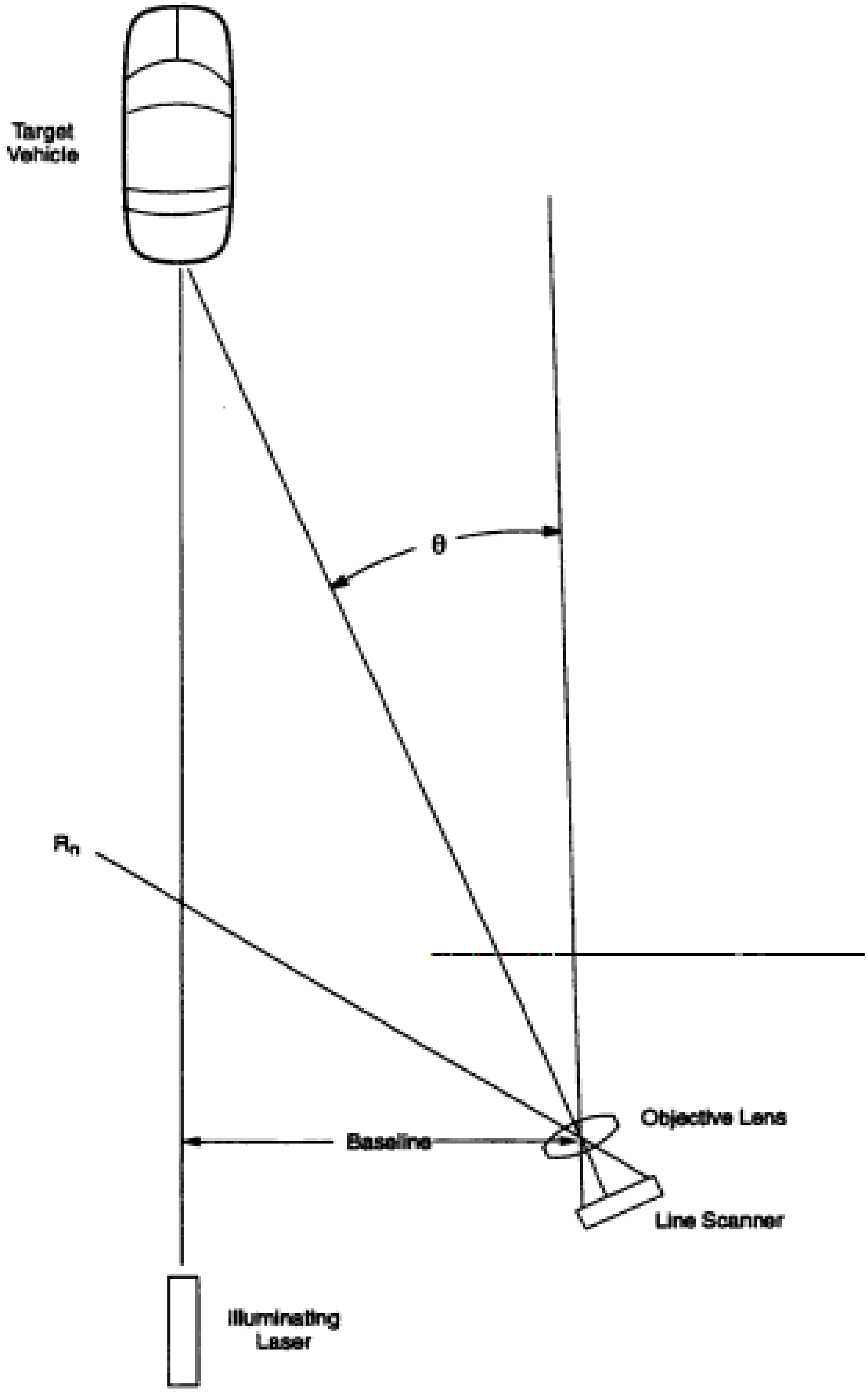


Figure 3-8. Line Scanner Optical Ranging

If the size of an object in the field-of-view (FOV) of a camera or line scanner is known, it is possible to estimate its range from its angular extent. This process is called estimation by looming and may be quite effective as a backup longitudinal control sensor. It certainly works for humans who tend to slam on the brakes when the tail lights of the car ahead suddenly develop a large "outward" angular velocity.

3.2.4.2 State-of-the-Art

Komoda, et. al., 1992, have developed a prototype to investigate and evaluate technology and system architecture. In addition to an on-board high speed vision system, as discussed previously, a laser radar system is incorporated. Mounted on the front of the vehicle, the radar facilitates detection of vehicles and motorcycles, between 5 and 100 meters ahead. The laser is scanned to provide detection in turns. Severe vehicle pitching or vertical road curvature still pose misdetection problems.

Both Hirano, 1993, and Taniguchi, et al, 1992 employed laser radar, for collision avoidance and obstacle detection, respectively. Installed on the front grill, Taniguchi's system detects obstacles in the vehicle's path during operation under ultrasonic sensor (lateral control) mode. The vehicle maneuvers to avoid the object if sufficient room is available to pass the object and remain between the white lines; otherwise, the vehicle stops.

Hirano uses a three-beam laser radar installed on the front end of the vehicle to sense vehicle-following distance. The laser beams are directed forward and reflected off the rear of the vehicle ahead. Warnings are issued by a lamp and buzzer.

A method has been proposed, (Tsumura, Okubu and Komatsu, 1993), to measure the position and heading of a vehicle on the roadway using laser transceivers and retro-reflective corner cubes on the roadside. Three fan shaped laser beams are emitted from the transceivers in an attempt to detect three corner cubes each, of previously known position. Time data from the returned beam are used to determine position and attitude. Time measurement error was 1mm/20 kph.

Tsumura, again, with Hashimoto and Fujiwara, 1988, present a method for obtaining position and heading using four laser transceivers and two corner cubes. Experimental results show that this method is capable of acting in a compensatory mode for errors caused by the dead reckoning method.

A lateral control approach using laser beams and retro-reflective lane definition markers is reported by Nakamura, et. al., 1993. The laser sends out a train of thirty-two 15 ns wide pulses with a peak power of 60 W. Up to three consecutive markers are illuminated. An avalanche photo diode is used to measure the returns and target distance is calculated based upon the time delay of the returned light. Distance resolution is less than 30 cm. A 128 element linear CCD array detects the reflected light and allows determination of the angle between the lane marker and the vehicle’s direction. Testing at speeds between 40 kph and 60 kph showed that tracking error remained within ± 10 cm for most of the track. However, at the end of the track, a maximum deviation of 20 cm occurred. All tests were conducted under ideal weather and lighting conditions along an asphalt track.

Acoustics Summary

3.2.4.3 Optical Ranging Summary

Optical ranging, summarized in Table 3-5, is sufficiently accurate to serve for both lateral and longitudinal control. Infrastructure equipment should be provided in the form of retroflection at known locations with respect to the roadway. Such are already emplaced on many freeways. The main drawback of optical systems is interference from other light sources, e.g. the sun, and meteorological effects, e.g. rain, fog and snow.

3.2.5 Magnetostatics

Static magnetic and possibly electrical fields, man-made or generated by the Earth, that do not vary significantly over time are addressed here. These are to be distinguished from alternating magnetic fields used in induction systems and electromagnetic fields used in radio and radar. Only Magnetostatics is of significant interest to AHS applications.

3.2.5.1 Magnetostatic Sensor Technology

The Earth's magnetic field as sensed by a compass, can serve as a directional reference of moderate accuracy. Natural magnetic disturbances can introduce offsets of as much as 45 degrees over a region of more than a mile (Kingston, Ontario, Canada). The variation is the angle between magnetic north and geographic north. In the lower 48 United States it ranges from 24 degrees east (i.e. the magnetic compass points east of true north) to more than 22 degrees west in northern Maine. It rises to over 30 degrees east on the Alaska north slope but there are no automatable roads there. Variation can be corrected to an accuracy of about one degree by a relatively simple geographic model if one knows one's position to an accuracy of about 30 miles. Variation can change by two or less degrees at a fixed place over the ten year life of an automobile.

The Earth's magnetic field induces a magnetic field in ferromagnetic materials (e.g. iron, steel and nickel) that changes the direction of the measurable magnetic field near objects, notably cars, engines, bridges and even reinforced concrete, made of such materials. It is possible to correct somewhat for the magnetism induced in the vehicle by "swinging" the compass, i.e. pointing the vehicle to magnetic north, east, south and west and adjusting a compensating magnet to make the compass read correctly. A compensating magnet is really a pair of equally strong magnets aligned opposite each other near the compass. One pair points east-west and is used to correct north and south alignment. By changing a perfectly opposite alignment of the pair one can generate a small east-west field to counter the vehicle's induced field. The other pair points north-south and is used to correct the east and west indications.

Induced fields vary somewhat non-linearly (the so-called soft iron component) and hysterically (The hard iron component; hysteresis is a behavior of some process that means that you have to know the entire past history of the process to estimate the current situation) with applied field which, in turn, varies by more than two to one

Table 3-5. Optical Based Systems

AUTHOR	REFERENCE	LATERAL CONTROL LONGITUDINAL CONTROL, OR OBSTACLE DETECTION	ADDRESSES TURNS?	ADDRESSES INTERFERENCE	TESTS PERFORMED	COMMENTS
	Cadspan AHS Ric No.		.		(Drive Test)	
Himno, M. (! 993)	221 (Mitsubishi Motors Co.)	Longitudinal	Yes	No	Yes	Laser radar employed for co!!sion avoidance
Komoda, N., et. al. (i 992)	187 (Toyota Motor Co.)	Obstacle Detection	Yes, Scanning	False alarms in rain, Turns	Yes, Tested at 50 kph	
Nakamura, M., et. ad. (1993)	186, Aisin Seiki Co., Ltd, IMRA America, Inc., and Toyota	Lateral	Yes	No	Yes, Tested at speeds of 40 to 60 kph	
Taniguchi, M., et. ad. (1992)	196, 200 (Nissan)	Obstacle Detection	No	No	Yes	
Tsumura, T., et. al. (1988,1993)	184, 185 (University of Osaka Prefecture, Japan:)	Lateral	No	No	Yes, Tested at 10 and 15 kph	Used to compensate for errors caused by dead reckoning positiontag method

between Minnesota and Texas. The conventional wisdom suggests that a compass is reliable, on a fiberglass boat not under a steel bridge, to a few degrees and, on a car, worse by up to an order of magnitude.

The geological record indicates that there have been complete reversals of the Earth's magnetic field in a few years or less. If they had lasted longer there might have been mass exterminations from the effects mentioned in the following paragraph, but such mass exterminations have not yet been observed, except after astronomical collisions.

The Earth's magnetic field, while weak (at the surface of the Earth it is of the order of a gauss or one-ten thousands of a Tesla, while man-made fields range up to ten Teslas), is very extensive, ranging out to several Earth diameters. This makes it possible for the field to deflect protons, ionized and energetic hydrogen atoms emitted by the sun, around the Earth and its magnetosphere, which is not a sphere at all but shaped more like a viscous drop with a long tail facing away from the sun. Occasionally the sun generates an excessive number of protons, a solar flare. These "overload" the Earth's protective field, posing a danger to astronauts and cosmonauts, but also change the local magnetic field perceptibly. Because of the aforementioned defects of magnetic compasses this does not contribute significantly to the error in direction finding. It could be a noticeable cause of noise in tracking "magnetic rails", however (see below).

Electronic readout of compass heading is facilitated by the use of a fluxgate compass. This has a ring of a magnetic material that has very high permeability. (I.e. a small applied magnetic field, like that of the Earth, can induce a large magnetic field in the material.) The ring is wound with a toroidal wire winding (Figure 3-9), connected to an electronic oscillator, that switches the circumferential magnetic field at a rate of a few Kilohertz. The circumferential field is aided by the Earth's field on one side of the circumference and opposed on the other side. Orthogonal sensing coils wound around the outside of the ring core (Figure 3-9) detect the rate of change of flux in the core as pulses at the switching rate whose magnitude is related to the fore-aft and left-right components of magnetic field.

A fluxgate "engine" (Figure 3-10) is a computerized fluxgate compass that can be calibrated by driving the vehicle carrying it in a circle, starting at an arbitrary angle and stopping every 45 degrees around the circle. After pushing a calibration button, the computer memorizes the correction needed at that heading and thereafter interpolates between these corrections. Even a fluxgate compass must be mounted as far away from magnetic materials as possible. In aircraft that is usually high in the tail.

Magnetic nails is a term for a sequence of permanent magnets imbedded in a roadway along the centerline of an AHS lane with a spacing of about five feet. Vehicles traveling along this lane would receive lateral guidance as they pass each nail by measurement of the vector ratio of horizontal to vertical magnetic field strength, using a pair of fluxgate magnetometers mounted in a vertical plane perpendicular to the direction of motion. This ratio would be equal and opposite if the pair of sensors accurately straddled the nail (Figure 3-11). As one sensor gets closer to the nail, and the other further away, the former will have less horizontal component and the latter

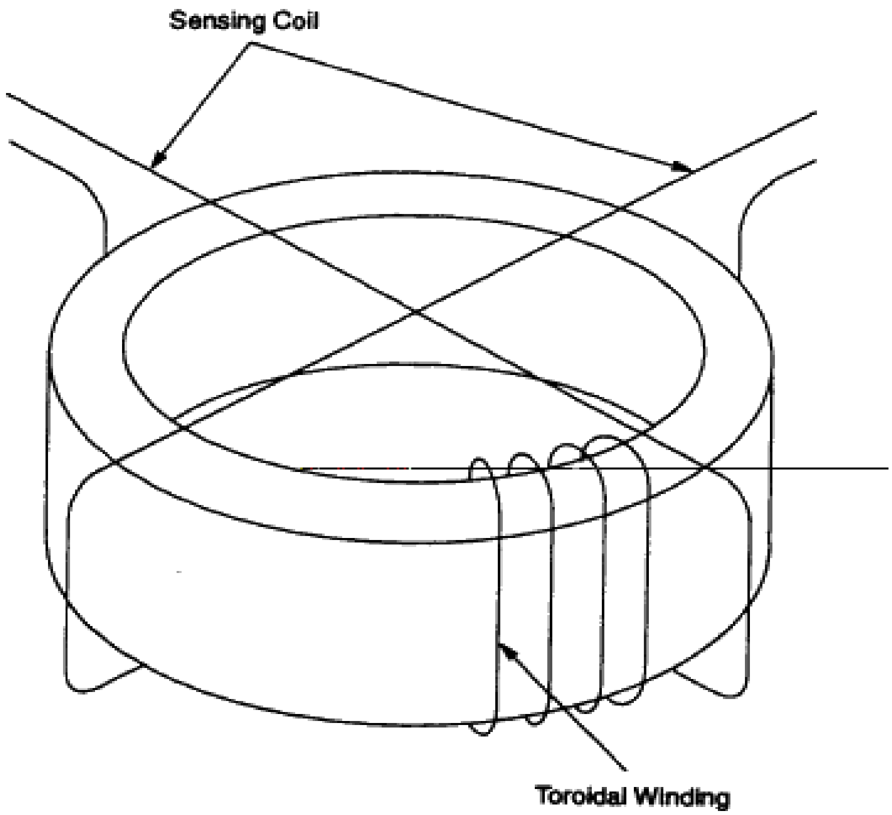


Figure 3-9. Fluxgate Compass

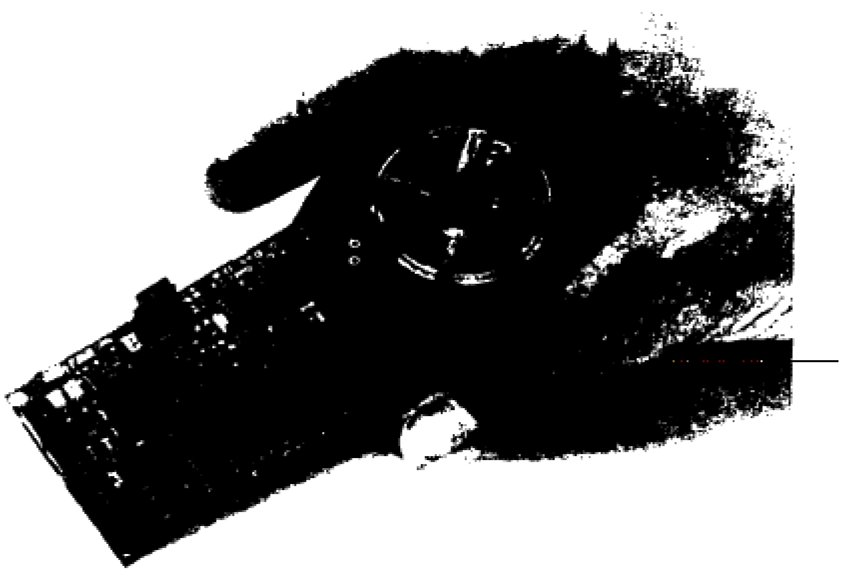


Photo Courtesy of KVH Industries

Figure 3-10. Fluxgate Engine

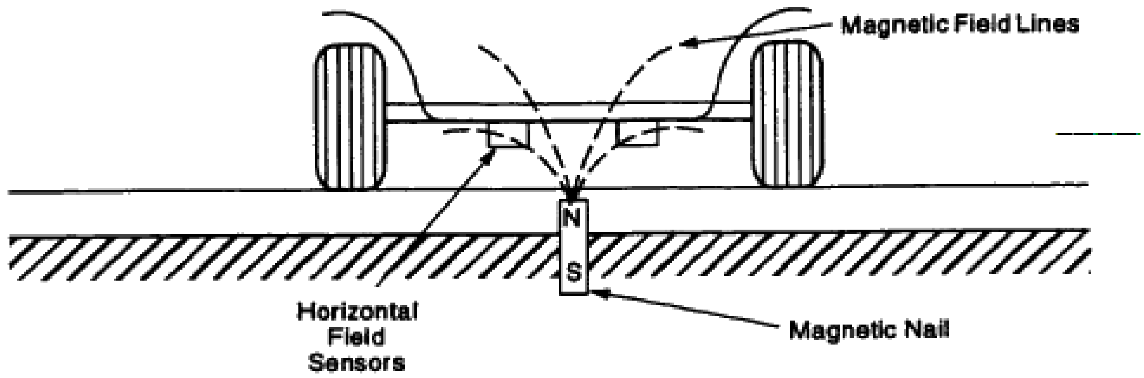


Figure 3-11. Magnetic Nail Guidance

more. The difference has been demonstrated as being effective in lateral vehicle control at medium speeds.

To date there has been no demonstration of a magnetic monopole, although observational physicists believe that such may exist. Each magnetic pole is found to be accompanied by another pole of opposite polarity, usually not too for away, near a physical body. A pair of opposite and equal magnetic poles is called a dipole and produces a magnetic field. The largest familiar one is the magnetic field of the Earth which extends a few dozen Megameters beyond Earth. Beyond that, as mentioned earlier, the feeble flux of solar protons which, as a current of electricity, is associated with its own minute magnetic field, can usually cancel the Earth's dipole field.

Similarly, the Earth's magnetic field cancels the field of a magnetic nail at a fairly short distance. Magnitude of a dipole magnetic field increases as the cube root of the size of a dipole and decreases as the inverse cube of range from a dipole. For realistic permanent magnets (e.g. 13 cm (5 in) long), the distance at which the Earth's field is equal to that of the magnet is of the order of 45 to 50 cm (18 to 20 in). Several magnetometers, spaced perhaps 40 cm (16 in) apart, should be mounted under an AHS car to assure continued operation in case of a swerve. One of the standard tests of magnetic nail guidance is control with a missing nail. This is a useful criterion in view of the pothole problem of northern states.

Electrostatic fields exist in the atmosphere due to charge separation by precipitation which, in the extreme case, results in lightning. Lines of equal potential generally follow ground contour near the Earth's surface. Because of this, model airplane control systems have been designed that keep the airplane at a constant potential or altitude above ground (rather than at constant atmospheric pressure), a primitive form of terrain following. These systems use ionizing, radioactive devices on the wingtips and tail to sense deviations from an equipotential plane.

In principle, similar systems could be used for lateral AHS guidance if a horizontal electrostatic field was placed across a roadway. There are severe problems with mutual interference between passing vehicles because electric fields are short-circuited by any conductor, unlike static magnetic fields that are only disturbed noticeably by ferromagnetic materials like iron.

3.2.5.2 State-of-the-Art in Magnetostatics

California's Partners for Advanced Transit and Highways (PATH) has carried out extensive research on the use of permanent magnetic markers for lateral guidance. The reference system developed by PATH consists of a series of ceramic permanent magnets, 2.5cm in diameter and 10 cm long, buried vertically in the lane center at 1 meter intervals.(Dynamic testing on the system is being conducted to determine the effects of spacing on performance.) On-vehicle magnetic sensors acquire both vertical and horizontal components of the magnetic field created by the markers. However, the markers cannot be used for guidance when the vehicle is more than 50 cm from lane center (i.e.. during lane change maneuvers).

A necessary characteristic of any lateral guidance system for automated vehicles is weather resistance. Magnetic nails offer a comparably robust alternative under conditions which render many of the other reference systems, at best, inoperable. Additionally, a reference system utilizing discrete magnetic markers is inherently equipped to code information. Studies indicate that lateral guidance systems which measure lateral deviation can only operate in a compensatory mode. "Even approaches such as Kalman filtering do not predict road geometry adequately when the radius of the road changes," (Zhang and Parsons). By using the magnets' polarities, preview information pertaining to road geometry, (i.e.. radius, curve start, superelevation), may be extracted through binary code.

Magnetic nails require little maintenance and may be incorporated into the existing highways without changing the rest of the infrastructure. Their life cycle, which is several decades, is similar to the life cycle of highways. Another key benefit is flexibility. For example, a damaged marker affects only it's immediate location. Again, the flexibility of magnetic markers allows relatively easy rerouting of traffic around construction, or other , areas.

Probing into the feasibility of a magnetic marker referencing system included investigation of interference problems and countermeasures. Interference with lateral position measurement, as analyzed, encompasses coexistence with the earth's magnetic field, high frequency magnetic noise generated by the vehicle's engine system, and spontaneous vertical movements of the vehicle. Subsequently, an algorithm designed for determining the vehicle's lateral position from the magnetic field of the permanent markers has been tested on both scaled and full size vehicles (Zhang and Parsons). The theoretical limit of lateral position estimation is about 1mm rms uncertainty for the current magnet/sensor configuration (Andrews, 1992).

Analysis indicates that the capabilities of the magnetic marker reference system are sufficient for storage of information such as absolute longitudinal vehicle position, lane recognition, speed limit, etc. The addition of a communication link and an inertial measurement unit (IMU) should enable more complex maneuvers (i.e. lane change, merging, etc.).

Peng, et. al., 1992, evaluated two control laws, PID and Optimal Preview. Key parameters which affect lateral dynamics are vehicle speed and cornering stiffness. To reduce sensitivity to these parameters, a sensitivity reduction algorithm was introduced to modify the optimal control law. The preview control design incorporates the Frequency Shaped Linear Quadratic design technique. This allows the frequency dependence of ride quality to be included in the performance.

Efforts in the PATH program have demonstrated the feasibility of using an intelligent roadway reference system of magnetic markers to achieve reliable lateral position measurements and road geometry information. The approach has been tested on a track imbedded with magnetic nails, using a vehicle with four magnetic sensors coupled to an automatic steering system. While traveling around a 90-degree curve at speeds up to 48 kph (30 mph), corresponding to a lateral acceleration of 0.27g, it remained within 5 cm (2 in) of the lane center under normal conditions. Even under deteriorating conditions, tracking remained within a range of 15 cm (6 in) of center. Ride quality, as perceived by driver and passengers, remained smooth. Documentation of principal technical findings may be found in reference A. Andrews, 1992. An overview of PATH experimentation is presented by Chira Chavala, et al., 1992.

3.2.5.3 Summary

Magnetostatic based systems are insensitive to weather conditions which severely impair or disable operation of alternative systems. Drive tests at speeds up to 135 kph have been demonstrated. Preview control enables accuracies of ± 1 cm when lateral displacement is within ± 25 cm and ± 25 cm when lateral displacement is ± 40 cm. Table 3-6 lists a number of magnetic rail guidance systems.

Lateral range, that range at which the earth's magnetic field cancels that of the magnetic nails, appears to be on the order of 0.5 m and may dictate use of additional sensors. Future work should address the issue of lane changes.

3.2.6 Induction Techniques

Induction can be used to transfer electric power to a vehicle as well as to sense lateral and longitudinal position. It differs from the familiar electromagnetic phenomena, radio, radar and light, not so much in the way it is produced but in its effective range. Like the field of a magnetic dipole, the effect of induction drops off as the third power of distance while radio and light fields drop off, at worst, as the inverse of range and radar fields drop off as the inverse square of range only because radar involves a reflection, i.e. a two-way path. (Since some electrical engineers may bristle at the previous sentence we should reemphasize the word "field". Power drops off as the inverse sixth, second and fourth power of range for induction, radio/light and radar, respectively. The "at worst" precaution refers to "near field" systems at very high frequencies for which field strength and power is more or less independent of distance e.g. a microwave system for powering a remotely piloted aircraft that has been tested in Canada.)

Rapid drop-off of an effect reduces interference between nearby guidance activities. On the other hand, it may make them impossible or at least difficult to utilize. This was illustrated by the capability of magnetic nails to provide control over only a very limited range. Guidance into a merge may be one of the most challenging AHS issues. Compatibility of two guide ways as they approach each other may become of great

Table 3-6. Magnetostetics Based Systems

AUTHOR	REFERENCE	LATERAL RANGE	FREQUENCY OF MARKERS	CONTROL LAW/ ACCURACY	TESTS PERFORMED	COMMENTS
	Calspan AHS File No.	(m)	(m)		(drive test)	
Chira Chavala, T., et. al. (1992)	120 (PATH)	±-0.5	I	Feedb'ack/Preview control laws, 4-9-0 cm	Tested at ' 10.8 kph on a scaled vehicle	
Hedrick, J. Karl, et. al. (1992)	26, 28, 81, 52 (Univ. of CA, Berkley)	±-0.8	1	Preview-FSLQ, Preview-PID control laws- 4-1cm accuracy, when lateral displacement is within :1:25cm, :1:25cm accuracy when lateral displacement is 4-40cm.		Steady'state feedforward control law is inadequate for tracking 90° curve beyond 40 kph
Zhang, W., Parsons, R., and West, T. (date not available)	82 (Univ. of CA, Berkley and CADOT)			Preview control law	Tested at speeds up to 135 kph	2.5 cm diameter, 10 cm long ceratnic bar provides a 20 cm radius magnetic field.
Andrews, Angus (1992)	143 (Rockwell] International Science Center)		1 .. .	1mm theoretical accuracy at a height of 10cm, 50 to 150 mm accuracy observed	Tested at ~$8" kph	

interest. Induction systems, operating with alternating current (AC) can use frequency diversity as well as spacing to separate signals.

In addition it can be used for signaling, of possible interest in managing electromagnetic field leakage from inductive propulsion systems and for other longitudinal control purposes. Lateral guidance by induction has been demonstrated with buried wires but found wanting for numerous roadway (due to the nearby presence of steel) structures. Inductive guidance with overhead transmission lines remains a strong candidate because it permits lateral location anywhere on a multi-lane roadway, and it is affected by weather.

3.2.6.1 Potential AHS Applications for Induction Technique

There are three potential areas for induction techniques. They include power transfer, signaling, and guidance.

3.2.6.1.1 Continuous and Modulated Power Transfer

Power transfer from the road to a vehicle by induction involves the use of a transformer, the primary of which is built into the roadway and the secondary of which is on the car. The primary generates an alternating magnetic field which induces an AC voltage in the secondary that is proportional to the rate of change of the primary field. Voltage is related to distance between the primary and secondary. That distance may vary because of vertical or lateral motions of the vehicle with respect to the transformer primary. Since a motor reacting to a variable voltage could induce undesirable speed variations, a power conditioner and power storage facility is needed. At the present time batteries are touted as appropriate for storage but all available batteries exhibit very poor efficiency under rapidly varying charge-discharge conditions. Flywheels and compressed air systems are much better energy storage devices in this milieu.

The fact that coupling is strongly dependent on lateral position may be used as a lateral guidance scheme for inductively powered vehicles. Since an induction scheme may be used for other vehicles as well, detailed description of this approach is deferred to sub-section 3.2.6.1.3.

Induction is but a minimized form of radio. Marconi, one of the inventors of radio, succeeded in his enterprises partly because his radio outperformed a proposed system of coupling England and France inductively. A large-scale inductive system, such as might be deployed for multi-lane lateral guidance, will radiate, albeit at low power. A power coupling induction system will radiate a lot of power.

Wasteful radiation from induction power systems can be reduced greatly if induction power is provided to only those vehicles actually using it. These vehicles can then act as partial shields that prevent most radiation from escaping. Relatively simple communications schemes, including those described in the next section, could be used by the vehicle to request power transfer.

3.2.6.1.2 Induction Signaling

The induction communication system that Marconi supplanted was to consist of two windings, one approximately surrounding Kent, the south easternmost county of England, and another, wound around the northwestern French province of Artois, including Calais. Despite such prodigious dimensions, it was not at all sure that there would be adequate coupling for reliable inductive communications with technology available in the 1890s.

It may be remembered that magnetic dipole coupling depends on the cube root of dipole dimensions and the inverse cube of range. By comparing the diameter (30 Km) and center distance (100 Km) of the Anglo-French system and sensor length (20 cm) and measured range (100 m) of a modern induction system used to locate skiers buried in an avalanche, it appears that the modern induction systems are approximately ten million times more sensitive than the system that was proposed for trans-channel communications. Sensitivity, of course does not only depend on the parameters mentioned. Transmitter power is a major contributor, but induction transmitter power is frequently limited by the magnetic properties of known materials.

Inductive signaling over ranges of tens of meters with a few watts of power is a useful strategy that avoids mutual interference effects. It could be used in AHS for beacons to announce exits and the like. Inductive signaling from a vehicle to the road could be used for various purposes, including requests for induction power. Inductive signaling may also be possible along the highway and across all lanes, as further discussed in the next section.

3.2.6.1.3 Inductive Guidance

Induction fields exist in the vicinity of current carrying conductors. The word vicinity is here defined as a region within up to a wavelength of the conductor, and usually much closer than that. The wavelengths corresponding to frequencies useful for inductive communications range from about 100 to 30,000 meters and are therefore comparable to highway dimensions. The magnetic component of the induction field has a specific direction at each point. That direction can be sensed by suitable designed pickup coils and associated circuits.

For a long time it was thought that guidance with respect to the induction field of a wire buried in the roadway would be the best approach to lateral AHS guidance. Early experiments on a blacktop road at Ohio State University were actually quite successful. Later it was discovered that extensive, conducting metal structures associated with major highways made this approach unattractive. Such structures generate image fields that distort the shape of the induction field, actually canceling it in some places, i.e. very near the metal structures.

Overhead transmission lines (pairs of wires) generate induction fields that can be kept much further from conducting objects in the highway and can be configured to have a direction that varies in a predictable manner with lateral position on the highway. Experimental research on the robustness of this approach in the presence of larger vehicles, bridges and the like is desirable. Guidance based on this approach is one of a few candidates that provide lateral control during lane changes.

Overhead wires can also be used to provide longitudinal position along the roadway. A signal, such as a sinewave, can be made to move along a wire at a given speed. A receiver can sense the null of a this moving signal Therefore, a control loop can be used to control the throttle so the vehicle stays in step with the moving signal. Thus, a vehicle could be operated in a point-follower mode with the error sensing and control provided by the vehicle. The use of in a point-follower mode with the error sensing and control provided by the vehicle. The use of overhead wires should be pursued further as it can provide an all-weather lateral and longitudinal control. The lateral and longitudinal position sensing is performed on the vehicle and thus the control loops can be closed without including roadway infrastructure data links, computers and sensors.

3.2.6.2 State-of-the-Art for Induction

Fenton and Mayham 1991 describes Zworykin and Flory 1958, and Gardels 1960, at RCA and GM respectively as early experimenters in the field of inductive guidance. They used a single wire along the center of a lane at speeds up to 35 mph. Conductive materials in the roadway are quoted as shifting the electronically sensed centerline by about six in. with unpleasant effect on ride quality. After much effort at Ohio State University (OSU) an inductive guidance system was made workable with conventional steel-reinforced concrete roadways and standard steel bridges. Quoting Fenton and Mayham: "In 1977 FHWA decided, because of operations and maintenance considerations, that active reference systems should not be used either at wayside or under the road surface/" OSU then abandoned further work on this concept.

Heller and Huie, 1993, at California State University, Sacramento, tested a passive induction guidance system. Installed on a quarter-mile test track incorporating an 260 m (850 ft) radius turn, the guideway comprised a pair of wires, three feet apart, laid each side of the lane centerline. These are shorted by a cross wire every seven feet along the lane. The vehicle "radiates" one watt of 5 KHz excitation from a coil in the horizontal plane which induces an image field around the shorted turn of the guideway. This field is sensed by a receiver coil in the vertical plane containing the vehicle longitudinal axis. The received signal is zero when the vehicle is centered on the guideway and changes phase with respect to the transmitted signal in moving from left to right. Magnitude of the received signal is closely proportional to lateral displacement until the exciting (transmitter) coil approaches the edge of the guide loop. Signal-to-noise ration (SNR) was not as good as desired with the one watt transmitter, but tests at up to 48 kph (30 mph) showed a maximum lateral error of only ± 5 cm.

Heller and Hire, 1993, have also evaluated a machine vision system (105 kph (65 mph), ± 15 cm) and were about to test a radar system referenced to a an aluminum tape on the centerline.

Induction power systems for Roadway Powered Electric Vehicles, (RPEV) were tested on a 122 m (400 ft) test track at the Richmond Field Station of JC Berkeley (Caltrans, 1991, "Highway Electrification and Automation"). Power transfer up to 60 kw to an electric bus was achieved. Transfer efficiency was 60 percent at 60 kw and 50 percent at 27 kw but was further reduced by 50 percent for a 10 cm lateral offset. This offset is displayed to the driver as a steering assist. The receiver coil is detuned when power demand is reduced, e.g. during braking, as described in detail in Eghtesadi 1990.

When power was transferred at 400 Hz, magnetofriction of vehicle components caused an annoying 800 Hz whine at a 40 to 45 dBA level. A future project using a van as the test vehicle will operate at 8500 Hz to move the noise out of the audible spectrum.

Magnetic field at 30 cm above the roadway is 10 gauss (gs) comparable to that from an electric shaver (1 to 10 gs), but larger than 0.1 to 0.2 gs from an electric blanket or toaster.

Florida has a State Regulatory Standard of 0.150 to 0.250 gs at the fenced edge of electric utility operations.

Much of the previous material is reviewed in Chira-Chavala, et al, 1992. This feasibility study estimates capital and operating costs which suggest that RPEV buses would be more cost effective than small cars.

Fujioka et al, 1993, mentions inductive and leakage coaxial cables for lateral guidance in a case study of the Super Expressway for Automated Driving 21 (SEAD 21, a Japanese AHS concept) but provides no technical detail.

3.2.6.3 Summary

Inductive techniques applicable to AHS lateral guidance include both passive and active systems. Practical testing at speeds up to 30 mph demonstrated a maximum lateral displacement error of $\pm$ 0.05m. (Table 3-7). Experimentation with active laid wire techniques demonstrated phase sensing techniques that were able to overcome initial difficulties associated with ferrous materials in the roadway. Laid wire techniques support lateral control during lane changes and merging maneuvers. However, problems associates with conducting metal structures, maintenance of active systems, and roadway surface conditions remain. Overhead transmission lines offer some promise of overcoming these difficulties.

3.2.7 Radio-Frequency Position Location Systems

Induction coils and transmission lines, being much smaller than a wavelength, are inefficient radiators of electromagnetic waves. For example, the 1320 ft. towers of Omega stations that are about 1/80th of a wavelength high require 150 Kilowatts (KW) input to radiate 10 KW. Efficient antennas, i.e. ones that radiate electromagnetic or radio waves will have dimensions that range from a little less than a quarter wavelength to a few dozen wavelengths. At 30 Megahertz (MHz) wavelength is 10 meters; at 300 Gigahertz (GHz) it is 1 millimeter. Efficient antennas can be attached to road vehicles at these frequencies and anywhere between. Suitably designed antennas that are many wavelengths in size permit radiation in a narrow beam. Infrared, visible and ultraviolet radiation, as well as X-rays and gamma rays are also

Table 3-7. Induction Based Systems

AUTHOR	REFERENCE GROUND	CONDITION	POWER SUPPLY	TESTS PERFORMED (ACCURACY)
	Calspan AHS File No.			Drive Test
Eghtesadi, M. (1990)	14 (Systems Control Technology, Inc.)		Yes	No
Fenton, R., and Mayhan, R. (1991)	17 (Ohio State UniVersity)	Interfered	No	Yes
Heller, M., and Huie, M. .(1993)	188 (California State University)	May Interfere	No	48 kph (0.05 m)

electromagnetic waves. They are characterized by much higher frequencies. The lowest infrared frequency is 6 Terahertz (THz). The atmosphere is substantially opaque between 300 GHz and 6 THz and partially so in a number of absorption bands between 30 and 300 GHz.

3.2.7.1 Radio Sensor Technology

Radio and radar (Section 3.2.2) are two applications of electromagnetic waves. One-way radio, e.g. the familiar form of news and entertainment broadcasting, is the basis of the Global Positioning System (GPS), which is a candidate for lateral/longitudinal guidance. Broadcasting would also be involved in certain traveler information systems, including the transmission of GPS corrections. These corrections facilitate differential GPS (DGPS) which is much more accurate than GPS. Two-way radio, e.g. the type used by police and taxi dispatchers, is also used for data links which might be needed for negotiating merges, lane changes and exits. Properly configured, such datalinks can be used to measure distance, including longitudinal distance between cars.

3.2.7.1.1 GPS and DGPS Technology

The Global Positioning System (GPS) is a code division multiple access (CDMA), satellite broadcast, navigation system. An excellent overview article (J. Gallant, "System revolutionizes surveying and navigation:, EDN 7 January 1993, p. 31) is abstracted in the bibliography.

GPS uses a constellation of 24 satellites at an altitude of 17,540 km (10,900 nautical miles). Up to six and always four of these are visible above an elevation of five degrees at any one time, anywhere on Earth. They transmit signals on two frequencies, 1227.60 and 1575.42 MHz, that suffer slightly different delay and refraction when penetrating the ionosphere. This fact can be used to correct for ionospheric distortion. Modulation on the 1575 MHz signal is available to the public but can be distorted in case of war, in order to reduce accuracy of the system. Military users can access modulation on both frequencies that provides improved accuracy but this would be encrypted in case of war, in order to restrict access to users who are issued the encryption key.

Navigation is conducted as follows:

1. A local oscillator (LO), biphase modulated with the Gold code sequence of a satellite, preferably one that is in view, is used to down-convert the signal, usually into a Costas receiver. When correlation is detected, a delay lock loop is used to put the LO on frequency (Figure 3-12).

2. The 1500 bit data message of the satellite is received over a period of 30 sec. and used to calculate position and velocity of the satellite. Some receivers have to repeat this process for four different satellites but most have several, up to six, parallel channels that receive signals from different satellites.

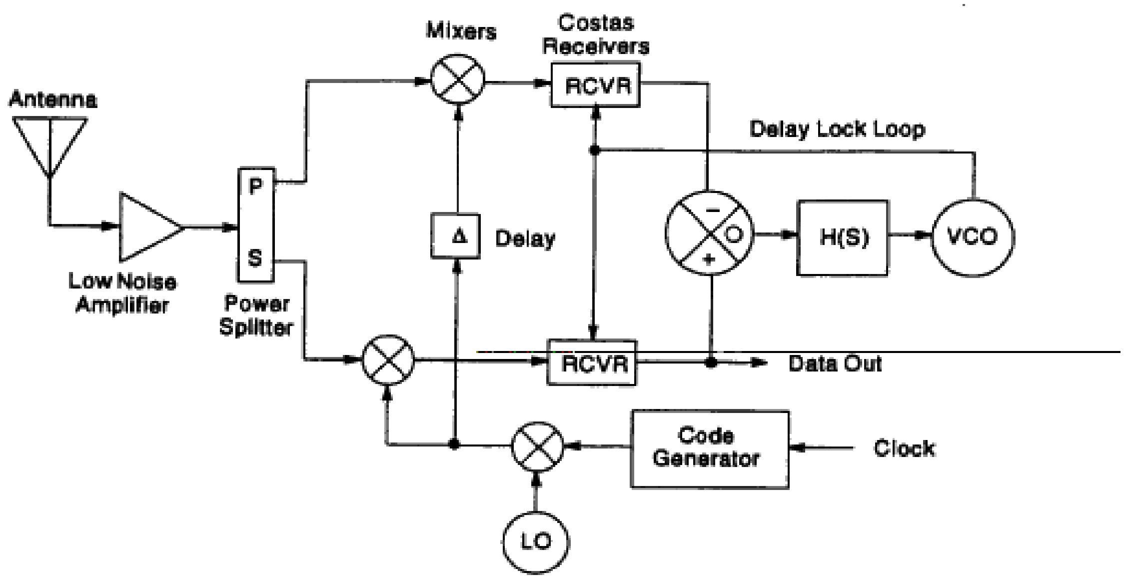


Figure 3-12. GPS Receiver

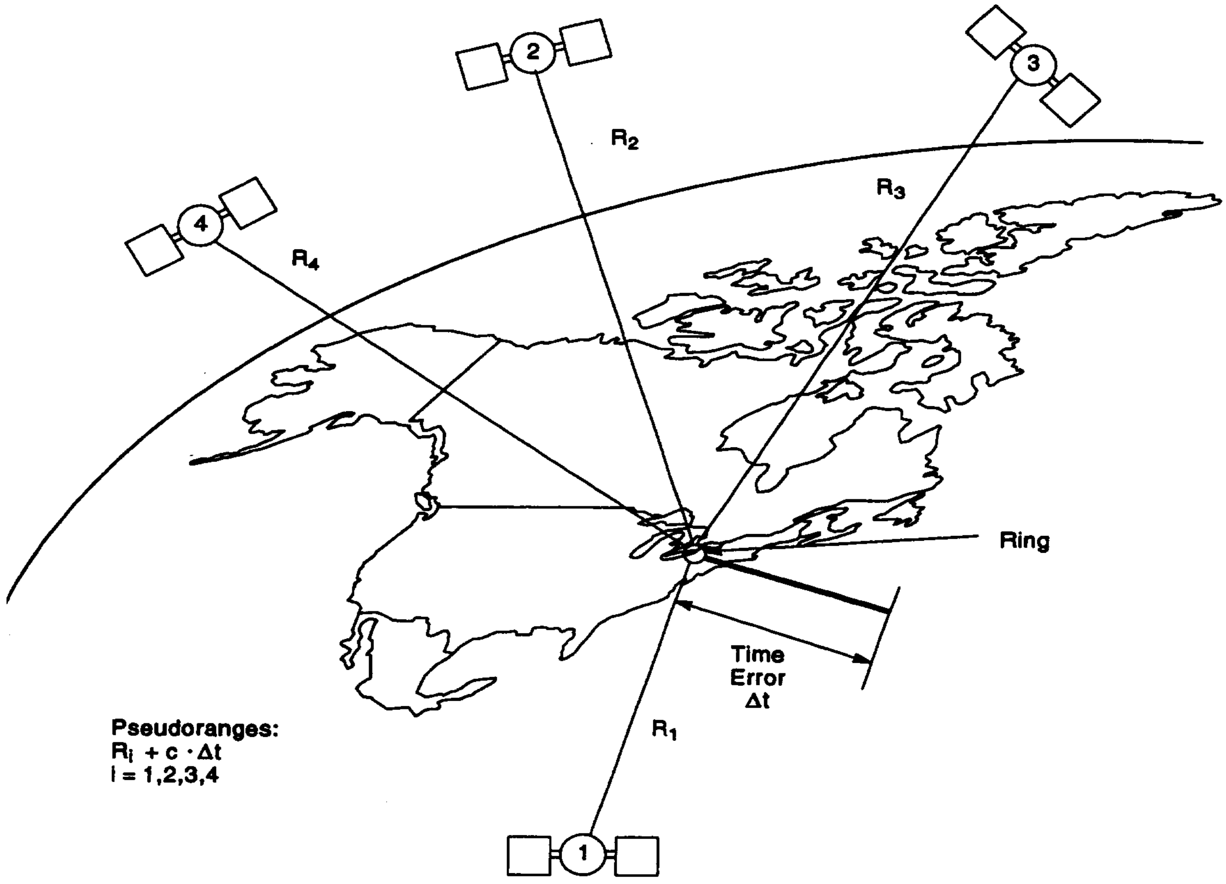


Figure 3-13. Reduction of Pseudoranges to Position and Time Error

3.Four satellites with desirable geometric dilution of position (GDOP) are selected. Good GDOP is observed for satellites that are spaced widely in angle, e.g. three at a reasonably low elevation, spaced 120 degrees in azimuth, with a fourth one above.

4.The processor then makes his best estimate of time and measures the time that the satellite signals, which are very accurately timed, take to reach him. Multiplying these times by the speed of light yields so-called pseudoranges.

5.It may be easiest to explain the next step of calculation, which is performed by iteration, by describing a thought experiment. Assume that a string as long as the pseudorange is attached to each satellite. The other ends are joined together. All four strings are passed through a small ring and joined together at their other end. One can now move the ring around until all four strings are taut (Figure 3-13). The resulting position of the ring is one's position. The length of string extending beyond the ring, divided by the speed of light, is one's clock error.

Additional features of the GPS signal may be exploited. A user who has access to the position error of another GPS set at a known position nearby can correct his own position in a process called differential GPS (DGPS) or navigate with respect to the known position (Relative Navigation). Attitude of a vehicle can be measured by interferometry using carrier phase, knowledge of satellite velocity and at least three antennas. Given an initial position, carrier phase can be integrated (Kinematic GPS) to achieve high accuracy. Initial position can be obtained using special receivers that can navigate in Transit Navigation Satellite fashion using a nearby, e.g. roadside, "pseudolite", a low-power emitter of a GPS-like signal.

Accuracy of the Standard Positioning Service (SPS), absent wartime distortion by Selective Availability (SA) which reduces it to 300 m, is normally 30 m but reduces to 2 to 5 m with DGPS. Long-term (> 2 to 3 minutes) averaging of DGPS provides better than one meter accuracy, which should also be achievable by Kalman filtering with data from an inertial navigation system (INS) that is good to better than a meter for a few minutes. Relative navigation, with updating of the satellite selection or pseudorange list every six seconds is predicted to yield 1.7 m vertical and 0.72 m horizontal error. (Vertical error tends to be larger because one cannot improve GDOP by using satellites below one's position.) SRI International is conducting research on Kinematic GPS (KGPS) that suggests accuracy of a few centimeters is possible. Cars are handicapped because KGPS fails when the vehicle passes through a tunnel or under a bridge, necessitating use of pseudolites at such places.

3.2.7.1.2 Data Link Ranging Technology

Two stations exchanging data, by radio, can determine the range between them by measuring travel time of two-way messages. The modulation carrying data can switch the carrier frequency in amplitude, frequency or phase, or in combinations thereof, at a clock rate that is the inverse of the data link's bandwidth. The switching time of the modulation can be measured with surprising accuracy, especially at short range, when a high signal-to-noise-and-interference ratio (SNIR) is available. When averaged over a message of several bits, often called a packet, the time of arrival of a message can be determined to a precision useful not only for longitudinal control but even for estimating turns of a leading vehicle.

A suitable protocol must be used to assure that the two stations can determine range. In the simplest case a station waits an exactly known, short time (called the guard interval or guard time) after it has received a packet of fixed length before it responds with a packet. The other station receives that packet and determines the time of arrival of the end of that message as explained in the previous paragraph. That time, less the known time of departure of its own (the other station's) last message, is equal to the sum of three packet durations, a guard time and two propagation delays (Figure 3-14). With the first two of these fixed, it is easy to calculate propagation delay, and therefore range at the other station. (If another transmission were to be made to the first station, that station could measure its range to the second station, as well).

The slight asymmetry in the status of the first and second transmitter's knowledge of range can be exploited for AHS. Figure 3-15 shows two scenarios for transmissions between a leading and trailing vehicle that are intended to convey the following information to a trailing vehicle:

1. Distance to the leading vehicle.

2. Relative bearing to the leading vehicle.

3. Changes in 1. and 2., by calculation.

4. Messages regarding the leading vehicle's, and perhaps that of more leading vehicles', intentions, e.g. velocities, accelerations and other variables that effect the trailing vehicle's best response to traffic.

In Figure 3-15a, the leading car (the apparently logical initiator of communications) transmits first (M_1) to two receivers near the trailing car's left and right head lights. Later the leading vehicle receives the return message (M_2) which provides it with range, which is not terribly useful at the leading car. Angle is available to the trailing vehicle by the difference in range to the two receivers. It would be possible to send the derived range information to the trailing car on the next packet but this just adds to the communications load.

In Figure 3-15b, the first message is sent by the trailing car, which has little to report and may send only a few bits. After receiving the return message, both range and bearing are available to the trailing car.

An alternative system (Figure 3-16) has transceivers on the left and right front and back corners of each vehicle. It can measure relative yaw attitude, i.e. the difference in heading between the leading and trailing vehicle, in addition to providing redundancy. Failure of any one data link still leaves several ways of communicating and measuring relative position.

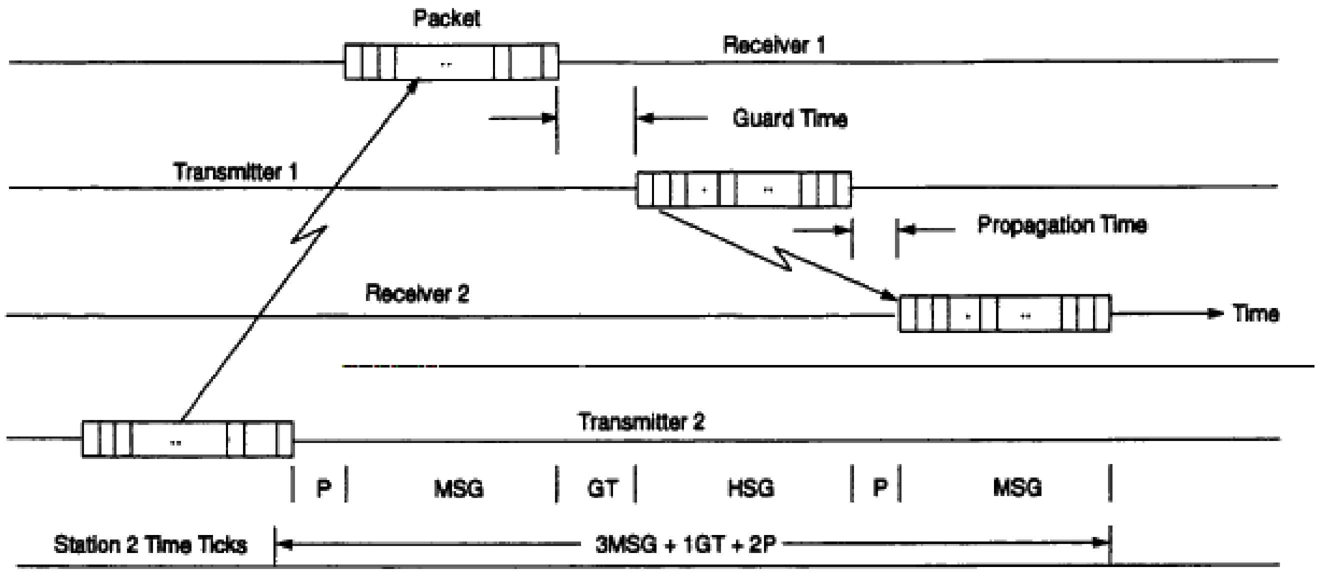


Figure 3-14. Data Link Ranging Protocol

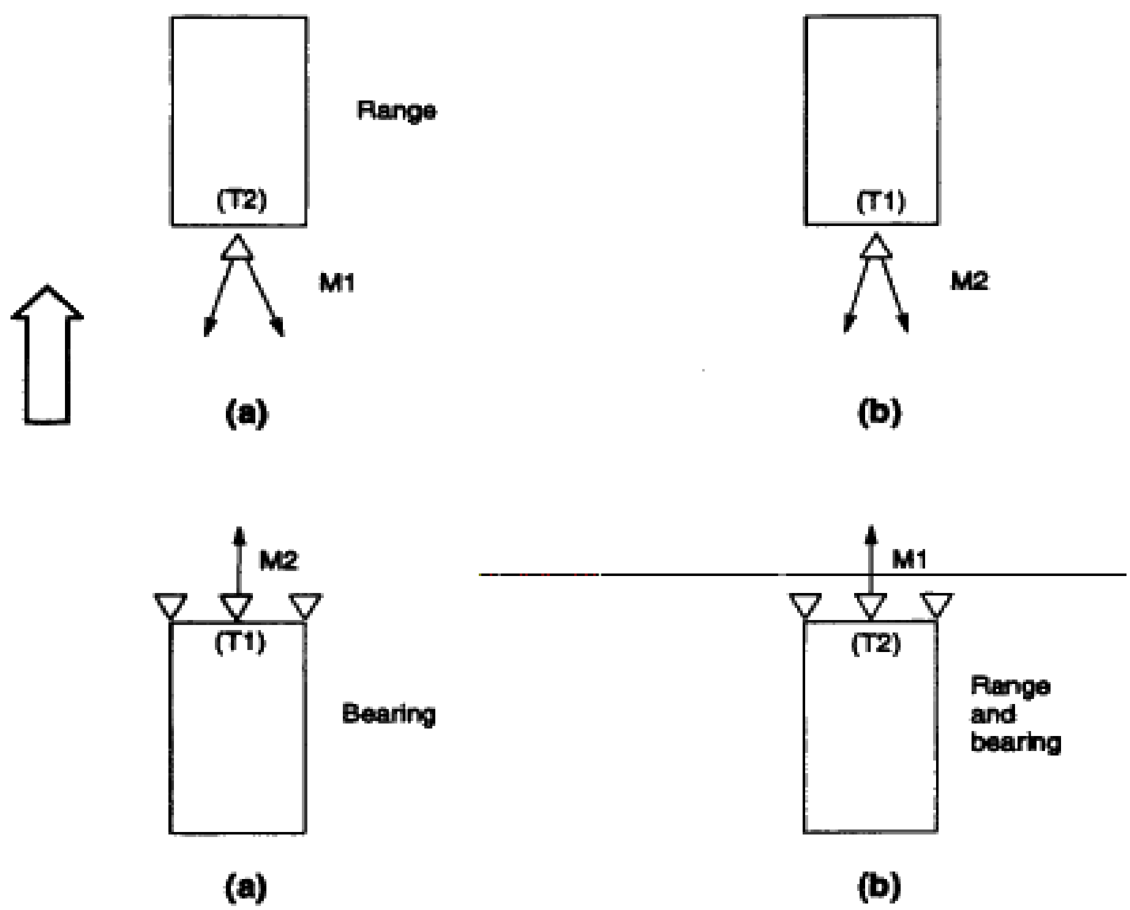


Figure 3-15. Range/Bearing Measurement Scenarios

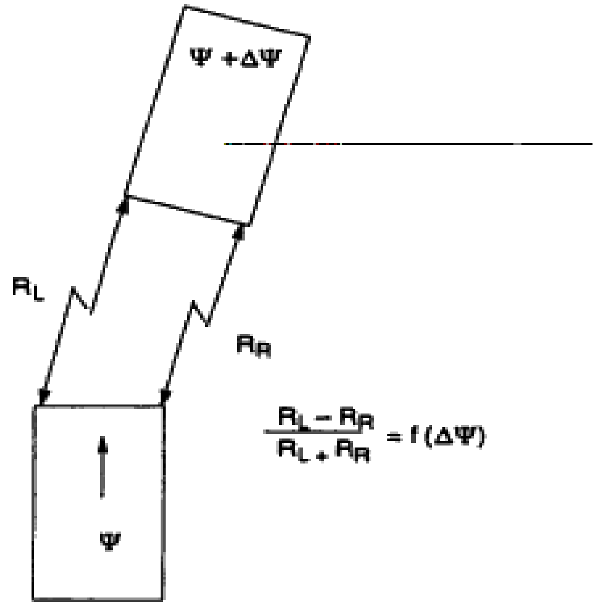


Figure 3-16. Relative Heading, or Yaw Attitude Measurement

Rudimentary lateral control is possible if bearing and relative heading of the leading vehicle is known. This may provide an emergency lateral control sensor if the primary system fails. Further research on the stability of long chains of vehicles following each other as a lateral control mechanism may identify new techniques that reduce demand on lateral guidance infrastructure. For example, it may prove possible to guide a group of cars by reference to the preceding car, with occasional fine corrections by reference to infrastructure-based guidance.

In the following a rather arbitrary, but possible, data link is postulated in order to determine its accuracy as a longitudinal and lateral position sensor. It is generally accepted that the rise time (τ_r) of a signal passed through a radio frequency (RF) channel at carrier frequency (F, Hz) and of bandwidth (B, Hz) is

$$\tau_r = 0.7 / B$$

From this and the definition of the SNIR given earlier, it is easy to prove that the timing error (Δt, sec) is

$$\Delta t = 0.875 / B \cdot SNIR$$

A typical link may be required to move 100 bits in 10 milliseconds (ms) over a range of 200 m. It was assumed that a 20 db SNIR was sufficient to carry the data. This requires a 10 KHz bandwidth. Given an easily achieved antenna gain of 11 dB at 2 GHz - more would be desired to avoid wet road multipath (Section 3.3) - it appears that a transmitter power of 75 nanowatts is required. This is very low and easily provided. Range uncertainty for the postulated link, at a range of 200 m, is some 30 m. At 20 m (60 ft), where longitudinal control becomes important, uncertainty is reduced to 0.3 m (1 ft), an error that may be acceptable, because the SNIR is higher (40 dB).

If power were raised to higher levels, miles of roadway would be polluted by stray signals. A calculation shows that receivers up to 2 kilometers (km) away, but in the beam, would suffer interference from the postulated link. A less powerful link was postulated to minimize interference, yet have sufficient range to manage braking behind a stopped vehicle in heavy rain (0.25 G deceleration). This link is still a source of interference for ranges of over 1.3 km.

Problems of mutual interference can be reduced significantly by using low-probability-of-intercept (LPI) technology developed for military communications. One LPI technique reduces power to the level needed at a given range. This would reduce interference range to 200 m for cars communicating over 20 m with the postulated data link. It would also reduce its utility as a ranging device because error at 20m would become $\pm$ 3 m, but that problem can be overcome by increasing bandwidth and reducing transmission time. Other LPI options involve atmospheric absorption (Section 3.3).

At 20 m range, with a vehicle 2 m wide, bearing and lead vehicle heading can only be measured by phase comparison. The difference produced by a one meter lateral offset is only about one-third of the uncertainty in the measurement of data propagation but it is most of a cycle in the measurement of carrier phase. Phase measurements of this nature are not difficult. They are similar to those used in determining aircraft attitude by GPS, with an accuracy of a fraction of a degree.

Data link ranging can be performed between a vehicle and fixed roadside stations. Consider a vehicle transmitting a pulse or burst of RF carrier. Several ground stations can then receive the pulse and measure the time of arrival. By comparing the various received time of arrivals, one can determine the location of the vehicle transmitting the pulse. Systems have been built using these principles to locate vehicles for fleet management. A company named Pinpoint offers vehicle fleet tracking using these techniques. The system commands a given vehicle to transmit at a given time. Thus it sequentially ranges on vehicles. The system can be quite acceptable for applications where 5-10 meters is acceptable accuracy and a ranging on a vehicle is required only every few minutes. For AHS applications where accuracies of approximately 30 cm are required for longitudinal control and a few cm for lateral control, one would be required to use a high bandwidth system (30 cm requires a bandwidth of nearly 1 GHz). For lateral control even greater bandwidth is required. Techniques can be employed to lock onto a given cycle of the carrier in a pulse much like what is used in LONAN-C navigation which reduces the bandwidth to a tens of megahertz. Its questionable if rapid ranging could be achieved because each receiver would be required to detect a carrier and track zero crossings. Another problem is the quantity of vehicles that must be handled in a given area and the update rates to each vehicle (several per sec). Multiple receivers must be employed to limit the coverage area of a given receiver to include a manageable number of vehicles.

One can also conceive of a system that employs a series of transmitting stations in the vicinity of the roadway. Pulses can be sent from each transmitter at different times. The vehicle-mounted receiver could measure the difference in times between the various received signals and locate the x-y position of the vehicle in a fashion similar to LONAN-C. Again, accuracies required for control, particularly for lateral control, will dictate large bandwidths. These bandwidths will dictate a carrier frequency at least in the VHF band, which will limit the coverage to line-of-sight . One has to devise a scheme to control multiple transmitters such that they do not interfere with each other.

While ranging techniques between the vehicles and the roadway infrastructure do present problems, we feel that serious consideration be given to examining in more detail the issues and solutions. Such a system is attractive in that it can operate in all weather. It appears that it will be very difficult to obtain the accuracies required for lateral lane following control, but could provide longitudinal position data for use with a point-follower system.

3.2.7.2 State-of-the-Art in AHS Applications of Radio Systems

In the following subsection we will describe existing experience with GPS/DGPS and data link ranging. Since GPS/DGPS is currently not quite ready for self sufficient lateral/longitudinal guidance, we also address GPS/DGPS navigation which might be used in conjunction with map matching and/or other guidance systems. GPS/DGPS is also used for altitude measurement. Means of distributing DGPS corrections are also addressed.

GPS has an error of 30 m 2DRMS in the C/A channel (L1). This error can be reduced to 1 to 5 m by using differential GPS (DGPS). DGPS transmissions will become available on a number of US Coast Guard beacons in the summer of 1994, e.g. on the 286 KHz beacon at Buffalo Harbor. DGPS accuracy is sufficient for harbor entry even in very poor visibility, if there is some form of longitudinal traffic management. DGPS accuracy is insufficient for automotive lateral guidance on standard 4 m wide roadway lanes, and marginally adequate for longitudinal guidance.

3.2.7.2.1 GPS Lateral/Longitudinal Guidance

Only one experiment with DGPS lat/long automotive guidance was discovered. Juhala and Karppinen, 1992, report on a modified Subaru Justy (named Justina) equipped with a black and white video camera, image processing to detect road markings and a steering/throttle/brake control system. Tests were conducted on a course of 140 m length. DGPS was included for guidance in off-road situations. (The writers' research interests concentrate on construction machinery and farm tractors.) 2DRMS errors of ± 3 m, were observed as expected, with extreme errors of ± 10 m on 7 percent of one of 6 test runs.

A joystick was included in these experiments for manual override of the computer that provides automatic guidance. It is of interest to the problem of the driver/AHS interface to note the writers' comment that: "In tests this (feature) has proven to be very practical and has saved Justina from many critical situations." Further study of the ability of a driver to take over during a guidance discrepancy seem in order .

Carrier phase tracking can provide sufficient accuracy for lat/long/vertical guidance of aircraft, as demonstrated by experiments primarily at Stanford Research Institute (SRI). Estimates of errors vary over the range of centimeters to decimeters but are certainly acceptable. A problem arises in AHS applications in the fact that roadways are occasionally covered by bridges or tunnels and that carrier phase tracking has to be re-acquired, with some delay (currently minutes), after loss of satellite access. Several ways for the solution of this problem have been suggested in Zanutta, 1993, who quotes Cohen 1993, Remondi, 1991 and 1993, and Hatch, 1989.

The carrier phase tracking acquisition problem may be stated as follows: A vehicle using DGPS can locate itself inside a sphere of, say 3 m radius. Within that sphere are a number of places where the measurable phase between the carriers of the signals from several satellites would be essentially identical (i.e. within the accuracy of phase measurement). One of these is correct. If the world were static, one could never discover the correct one.

There are many places of the type described above. For three satellites transmitting with a wavelength of 19 cm (L1) and ideal GDOP, there are 16,475 places to be monitored. As the satellite/vehicle configuration changes, one can eliminate certain places. If one were to get permission from the Department of Defense (DOD) to utilize the L2 channel, the difference frequency of which with L1 corresponds to a "wavelength" of 86 cm, one only needs to sort through 178 places, for a reduction of computing effort by a factor of 93. Zanutta shows a reduction factor of 125 but appears to consider combinations of 4 or 5 satellites which provide additional information.

The reason that it may take minutes to find the right place involves the glacial rate of change of angular velocity of the Navstar constellation. Even if a satellite were to move at 10 Km/s, at a range of 10 mm it would at most move at one milliradian, or 1/16th degree, per sec. Phase measurements across a six meter sphere would vary by six millimeters, or only 11 degrees per sec. Unfortunately all visible satellites move more or less parallel to each other, at lower velocities and longer ranges than suggested above. Angular motion is even less at the difference frequency. Thus its use, while it reduces the number of places significantly, may require better phase resolution. This might be attainable on the P code.

Large angular rates of change are available for ground-based pseudolites. These imitate Navstars but can be placed close enough to the road to give large angular rates, possibly usable in sorting out the correct "place" among the many candidates. Another way of viewing the pseudolites' utility is to compare them to the older TRANSIT navigation satellites. These worked on the principle that the Doppler shift of a transmission is zero when a moving receiver is abreast the transmitter and that the rate of change of Doppler shift is inversely proportional to the range between transmitter and receiver. At zero range, Doppler shift changes in a step-wise fashion, at infinite range there is no rate of change. In one way or another, a pseudolite can provide fairly exact two-dimensional position information.

Pseudolites have a ratio (near-far ratio), of the short range at which Navstar signals are buried in distortion, to the maximum range at which signal can still be detected, of about 10 to 1. Stansell, 1986, suggests that pseudolites have to be spaced by 50 to 100 Km apart, a condition that would render them useless in accommodating bridges every few miles. However, the quoted results refer to pseudolites designed for aeronautical location, with operating range of 50 Km and using the same code sequence. AHS pseudolites will need much lower power than aeronautical ones and may employ a few dozen more or less orthogonal codes. Radio Technical Committee Maritime (RTCM) Standard RTCM-SC104, Stansell, 1986, in addition to listing these codes, also suggests a transmission format for pseudolites that detracts only one dB from Navstar reception by using time division multiple access (TDMA), in addition to CDMA and greatly reduces the near-far problem, at some expense to pseudolite performance.

A sufficiently large group of pseudolites, e.g. 3 on a level road and 4 on an inclined road can provide GPS navigation on their own. This has been suggested (Galijan 1994) for traversing tunnels. Several minor problems face this approach:

1. A tunnel is a waveguide and propagation velocity is slightly different than the speed of light in vacuum. Another way of stating this problem is to suggest that there is a lot of multipath propagation in a tunnel.
2. GDOP is poor in the lateral (and unimportant vertical) dimensions unless a large number of very low-power pseudolites is deployed, i.e. one for approximately each tunnel diameter.
3. Acquisition of pseudolites and re-acquisition of Navstars and entrance and exit to the tunnel, respectively, require more time than is probably convenient. In the interest of advancing the development of AHS, it is suggested that one might be better off in controlling the vehicle manually or via a backup system in passing through tunnels. Those of us that live in cities without tunnels drive in a manual, yet mildly terrified mode, when forced to use them, in any case.

Really long tunnels, e.g. Eisenhower Tunnel or the Channel, if converted to AHS usage, may benefit from the technology adopted for the latter, i.e. electrified rail carriage (Newman, 1994,). In some cases this will be necessary to avoid carbon monoxide poisoning.

3.2.7.2.2 GPS Navigation

This topic is distinguished from GPS Lat/Long Guidance in that the 1 to 5 m accuracy of DGPS (and perhaps even the 30 to 100 m accuracy of corrupted GPS) may be useful in locating vehicles with respect to such features as turns in the road, entry points and exits and other features that may be used by another lat/long guidance system to improve AHS operation.

Krakiwsky, 1993, reviews over 100 IVHS applications of GPS navigation worldwide; this includes applications to fleet management, advisory and inventory control in addition to the autonomous use that would be of most use in lat/long control. El-Sheimy and Schwarz, 1993, describe a system that uses machine vision and inertial/GPS navigation to acquire coordinates of important features of a roadway. GPS is used to eliminate drift in the inertial navigation system (INS) as well as to provide timing for events in the machine vision system. Abousalem and Krakiwsky,, 1993, discuss the merits of distributed Kalman filtering. They describe their approach as a federated architecture that permits isolation of malfunctioning sensors. For example, consider a system of three sensors for the same variable that are combined pairwise in Kalman filters. If one pair shows a differing output from the others, it may be assumed that the sensor shared by the other two filters is defective. The approach appears to require the same ground rules as majority voting but may have utility in that Kalman filter outputs may have fewer errors, e.g. due to drift, than sensor outputs.

Kao, 1991, uses GPS to calibrate as well as "rescue" a dead reckoning system. The term "rescue" refers to recovery from accumulated drift errors, possibly in a step-wise fashion if dead reckoning carried the vehicle through a region, e.g. an urban canyon, of inadequate GPS coverage. GPS is combined with map matching and experimental evidence is presented. Koliadin 1993, as judged from the abstract of an unpublished paper, covers similar territory.

3.2.7.2.3 GPS Miscellany

Unclassified features of the Global Positioning System (GPS) are described in its Interface Control Document (ICD-GPS-200), Rockwell International, et al, 1986. This document also lists the documents that describe classified features.

Possible ways of implementing DGPS are reviewed in Blackwell 1985 which suggests the only robust method. This is broadcast of pseudorange corrections for each satellite available to a well-sited (e.g. hilltop) reference station. Individual users, in any number, can then correct the pseudoranges of such satellites as their navigation sets select, using the atmosphere/ionosphere model of their choice if sufficiently distant from the reference station.

Feijoo and Perez, 1993 describes one method for distributing DGPS data, Suchko, 1993, another. The latter is the Radio Broadcast Data Standard (RBDS) for the FM entertainment broadcast third subcarrier. This subcarrier can only support about 1000 bits per sec. and has to be shared with other IVHS traffic, e.g. traffic advisories. As a consequence, some accuracy-degrading latency may be introduced. A study of relative navigation (Anonymous, Av, Wk, & Sp. T'y Nv, 92) indicates that six sec. updating provides adequate performance. Alsip, et al, 1992, describes the US Coast Guard DGPS radio beacon system. This will be deployed at numerous port cities in 1994 and DGPS receivers and beacon receivers are commercially available for about $500 each at boating supply houses.

DeMeis, 1993, describes the limits of attitude measurement using GPS as being 5 mm plus one part per million of the baseline. If this is of the order of a meter, as it would be on a car, a resolution of 0.3 degree would be expected, in reasonable agreement with Cohen and Parkinson, no date, and Anonymous, Av. Wk & Sp T'y Nv, 92, who measure 0.1 degree and 1.4 mm, with a possibly larger array on an airplane.

One of the natural limits on the accuracy of GPS is time-varying propagation through the ionosphere. Military users can overcome this problem by using both L1 and L2 frequencies. Klobucher, 1991, describes the structure and magnitude of ionospheric variations and allows estimation of the area over which standard ionosphere models can be corrected. This area appears to be somewhat larger than the coverage area of VHF broadcast reference receivers. To obtain DGPS accuracy useful for ocean shipping, reference stations may be spaced several thousand kilometers. Corrections are relayed via Inmarsat geostationary communication satellites (GPS World Newsletter, February 1993).

3.2.7.3 State-of-the-Art in Data Link Ranging

Radio links appear to be fundamental to automated highway system (AHS) design. In terms of AHS communication strategies, inter-vehicle links enable the transmission of information from the lead vehicle to following vehicle(s), i.e., time clock, vehicle speed, acceleration, or, from following vehicle to lead vehicle. Beacon-vehicle links allow potentially beneficial, and possibly necessary, information exchange including upcoming road conditions and accident situations. Two way radio used for data links may be necessary for maneuvering strategies on AHS lanes. However, if configured properly, data links may be used for distance measurements, such as the longitudinal distance between two cars.

Chang and Georghiades, 1992, present a distance estimation algorithm for vehicle following on automated highways. Two transceivers are installed at the back of the leading vehicle and two transceivers at the front of the following vehicle. The travel time of the data is used to estimate the distance between the leading and following transceivers. The turn angle of the lead vehicle can be calculated from the estimated distances. The following vehicle may adjust it's speed and direction in accordance with the estimated distance and turn angle information.

The Tactical Air Navigation (TACAN) System Distance Measuring Equipment (DME) provides distance from an aircraft to a beacon by exchanging coded pulses. Amplitude modulation of these pulses has been used as a data link for air traffic control. This illustrates the opposite of data link ranging, namely use of navigation system as a data link.

3.2.7.4 Summary

Data link ranging appears a possible method of distance measurement. Although it received little attention in the literature investigated, Chang and Georghiades, 1992, (Table 3-8), point out that, theoretically, extremely accurate ranging is possible with data links. However, the costs of high bandwidth and mutual interference must be considered.

An improved accuracy (30 cm or better for a 3.66 m (12 ft) lane) DGPS, with pseudolites included as necessary , may be useful to AHS lateral control applications. Lanes narrower than the sometimes advocated 12 ft. width would require a corresponding improvement in system accuracy. Since DGPS only provides vehicle position on the Earth, some means of locating the road must be established, i.e., map matching.

3.2.8 Inertial and Force Measurements

The measures that correspond to kinesthesia include accelerations, including gravity, and angular rates as well as forces and torques. These are sensible without reference to features of the infrastructure, referring either to the inertial frame of reference, the Earth's gravitational field or being measured by reaction forces inside the vehicle. Being relatively independent of the environment, they may be used for feedback, built-in-test (BIT) and as backup systems in malfunction management. An example of the latter application is the notion that the application of brakes and continued steering is probably the best response to a failure of other major subsystems of AHS. Braking (deceleration) and continued steering (lack of yaw acceleration) can be sensed by strictly inertial sensors. On dry road there is a good correlation between mild lateral and longitudinal commands, i.e. steering, throttle and braking and the resulting accelerations. This fact can be exploited for BIT, especially at check-in but also at other times. Force and torque measurements can be used to measure brake and steering input in either manual or automated driving.

3.2.8.1 Inertial Sensor Technology

In normal AHS operation, it is important to estimate the coefficient of adhesion, a function of the environment (rain, ice, spills), since this determines available longitudinal acceleration. The same applies to steering stiffness, subject to the same factors, which controls available lateral acceleration. Direct measurement of these parameters is only practical under laboratory conditions. They have to be estimated from vehicle reaction to

Table 3-8. Radio Based Systems

AUTHOR	REFERENCE	DATA LINK	REQUIRED INFRA STRUCTURE	BACKUP SYSTEM	ACCURACY	USE
	Calspan AHS File No.				(m)	
Chang, K.; and Gcorghiades, C (1992)	8 (Texas A&M University)	Dual	None		= 1	AHS (Data Link Ranging)
El-She/my, N. and Schwarz, K.P. 41993)	198 (The University of Calgary)	Roadway/ Vehicle	Base Station	Inertial Navigation System	< 10 cm	Mapping Roads
Galijan, R. (1994)	446 (Stanford Research Institute)	Roadway/ Vehicle	Pseudolites	Inertial Navigation System	< 10 cm	AHS
Juhala, M. a n d Karppinen, A. (1992)	197 (Helsinki University of Technology)	Roadway/ Vehicle	Base Station	Dead Reckoning	= 3 m	Off-road Nay/gation

applied control effort, e.g. the amount of deceleration attendant upon a given brake input or the angular rate following a steering input. Estimation of adhesion coefficient and steering stiffness must be continuous in the presence of patches of slippery road, a task that even proves difficult for experienced human drivers.

3.2.8.1.1 Accelerometers

An accelerometer is a small test mass is attached to a vehicle by a restoring force, e.g. a spring, and provided with some sort of damping so that oscillations die out. As long as the vehicle moves at constant velocity - which may be zero, i.e. the vehicle is stopped - the test mass will remain at rest with respect to the vehicle. If the vehicle accelerates forward, the test mass, following Newton's First Law of Motion, will attempt to continue at the old velocity and will therefore appear to move backwards with respect to the vehicle. This motion can be sensed as a displacement of the test mass with respect to the vehicle. For a simple spring obeying Hook's Law the displacement is proportional to the magnitude of the acceleration. In some accelerometers the displacement is detected when it is still negligibly small and a force is applied that returns the test mass to the rest position (force feedback). This force is usually generated by passing a current through a coil in a magnetic field. The force, and therefore the measured acceleration, is accurately proportional to the current in the wire.

A mass-spring accelerometer measures acceleration along the line of action of the restoring force. It takes three accelerometers to measure all linear accelerations of a vehicle and they are usually arranged fore-aft, left-right and up-down to measure x, y and z accelerations respectively. The up-down accelerometer will measure downward acceleration of gravity. Accelerometers mounted horizontally in the vehicle will pick up a component of the acceleration of gravity if the vehicle is tilted, by uneven load distribution, when climbing a hill or on a road with a sideways tilt, e.g., superelevation.

It is often assumed that one can navigate by doubly integrating x, y and z accelerations. This is not true in a gravitational field because altitude and attitude must be known as well to permit subtraction of the gravitational acceleration. Even in an orbiting satellite where there is no "gravity", the wrong result would be obtained. If one integrated the non-existing measured accelerations one would predict that the satellite is moving in a straight line at its insertion velocity when it is actually moving along a circle or ellipse.

Angular acceleration can be measured by a pair of identical accelerometers, as the difference of their outputs. For example, if left-right accelerometers are mounted in the nose and tail of the vehicle, the difference of their outputs will indicate angular acceleration around the vertical yaw axis, a useful indication of a turn or swerving skid. The average of their outputs will represent the sideways acceleration of a point halfway between the accelerometers. If roll attitude is known, lateral (sway) acceleration and speed can be used to indicate turn radius. A turn would be indicated by a temporary yaw acceleration followed by an appropriate, i.e. calculable lateral acceleration. In a swerving skid the latter would be absent or at best very erratic.

3.2.8.1.2 Gyros

A spinning mass has angular momentum, the product of its angular rate and moment of inertia. Angular momentum is subject to a conservation law, similar to Newton's First Law of Motion. If torque is applied around an axis at right angles to the spin axis, the direction of the spin axis changes at a rate proportional to the applied torque, a process called precession. The axis around which precession takes place is at right angles to the spin axis and that of the applied torque. Figure 3-17 shows the sense of precession induced by the torque due to gravity acting on a spinning disk suspended from a pivot on its axis. This is a special case that permits continued precession since the axis of the applied (gravity) torque continues to rotate at the same rate as the precession.

A spinning gyro (spin axis X) is generally mounted in at least one gymbal as shown in Figure 3-18. If such a gymbal is restrained from moving around one non-spin axis (Y), perhaps by a stiff spring, and then rotated around the other axis (Z), it will exert a torque proportional to rate of rotation around Z. This torque can be measured by the slight rotation around Y. As in the case of accelerometers with force feedback (Section 3.2.8.1.1), torque feedback may be used to keep the spin axis from rotating, with torquer current becoming the measure of rotation rate around Z. The device described in this paragraph is known as a rate gyro. Its output may be integrated to obtain an attitude angle. If the Z axis points down , the attitude that would result is the yaw angle or direction of travel in degrees east of north. This angle is generally not

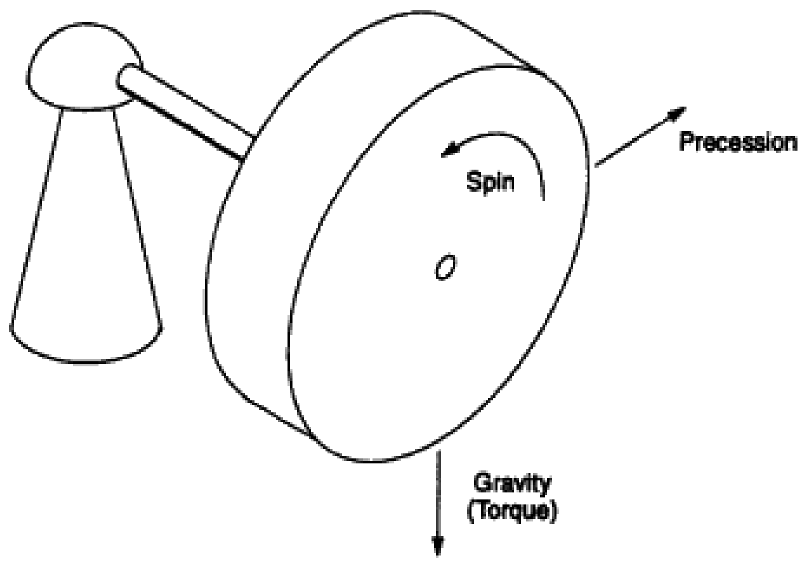


Figure 3-17. Precession of a Gyroscope

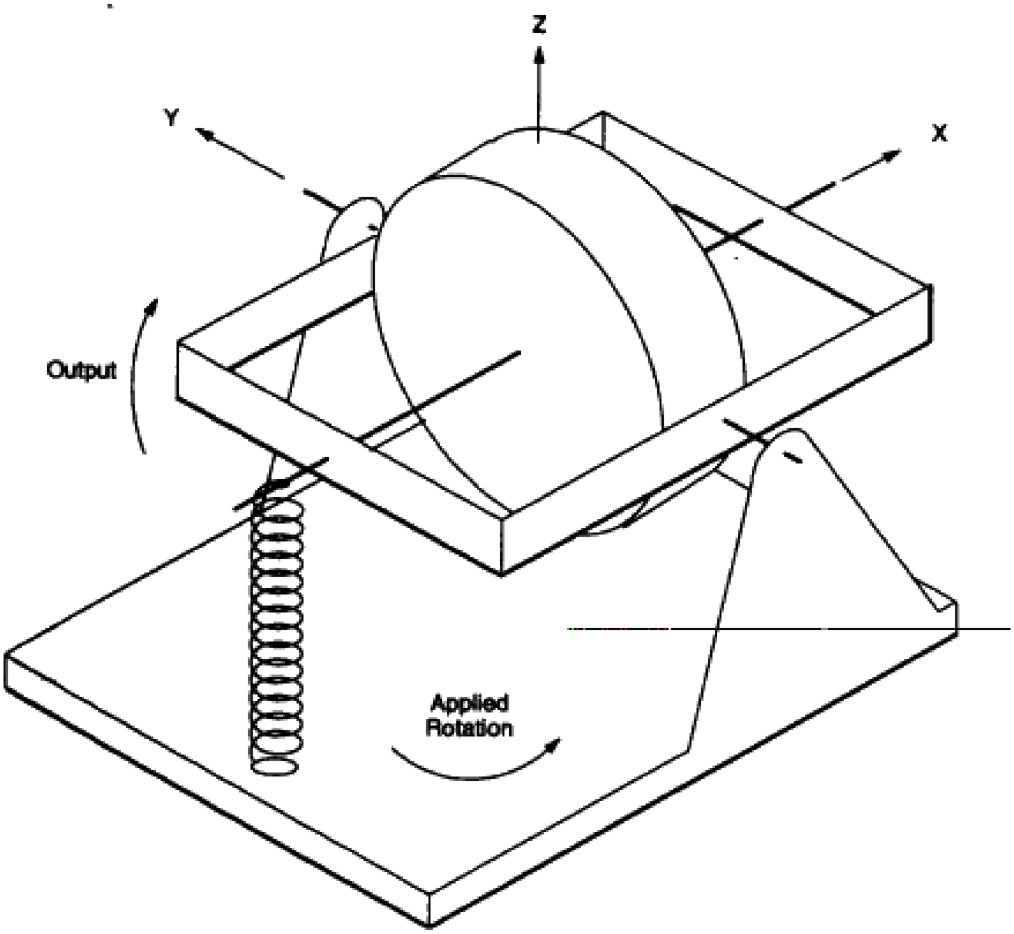


Figure 3-18. Rate Gyro

known when the device is turned on and another sensor must be used to initialize it. Integration usually produces a slowly growing error and other means must be found to compensate for that error.

All rate gyros should be viewed as sensors of rapid changes in attitude with a tendency to drift at least by a degree or so per hour. Another sensor, for example horizontal accelerometers for vertical attitude or a compass for direction, should be used as a slow, compensating sensor. These sensors are also full of errors, due to, for example, turns, banked roads or nearby iron objects. A long-term average of their readings usually is a reasonably good indication since left turns alternate with right turns, etc. Kalman filtering, the combination of signals after high, low, and bandpass filtering, is used to combine the best features and reject the worst features of each sensor output.

The term gyro is now applied to systems that use vibrating structures and hydrodynamics of jets to sense rate of rotation. The former system is based on the flight stabilization sensors of the order Diptera (two-winged flies, including the housefly). These have two club-like vestigial wings (halteres) that vibrate rapidly at right angles to their flight direction, making some of the buzzing noise that characterizes their flight. Biological studies of flies whose halteres had been removed indicated that they exhibited a spiral instability that can also occur in aircraft. Spiral instability is accompanied by yawing. It was hypothesized that the halteres, acting through nerves called the campaniform and ordotonal sensilla, provide neural yaw rate feedback that permits flies to avoid the spiral instability.

A vibratory rate gyro is shown in Figure 3-19. Motion of the tuning fork is sensed by a tine pickoff whose output is applied to a high-gain power amplifier (the fork drive amplifier) that powers driving coils that keep the tuning fork vibrating. The tuning fork is connected by a torsion bar to the vehicle whose rotation, again around a vertical axis, is to be sensed. Resonant frequency of the torsion pendulum formed by the moment of inertia of the tuning fork and the restoring torque of the torsion bar is made equal to resonant frequency of the tuning fork. The tines, which may be thought of as constantly reversing gyro rotors, exert constantly reversing torques on the torsion pendulum whenever the vehicle rotates. The alternating torque is amplified by the resonance, sensed by the torsion pickup and converted to a rate-proportional output by a phase-sensitive demodulator.

Figure 3-20 shows a jet rate gyro. A small fan circulates a gas through a pair of concentric chambers. A nozzle just downstream from the fan produces a jet that drifts through most of the inner chamber before entering the space between four heat exchange sensors. If the gyro is not rotating, the jet is centered and heat exchange is identical at all four sensors. If the gyro is turned around a vertical axis, the jet is turned in the horizontal plane during its trip from the nozzle to the sensors. The sensor toward which the jet is deflected experiences greater cooling than the one opposite. The remaining two sensors measure rotation around the horizontal axis perpendicularto the jet. Helium is the ideal fill gas since it has high thermal conductivity. Heated wires or thermistors may be used as heat exchange sensors.

Rotary and vibratory gyros must be very well balanced to avoid sensitivity to accelerations, including gravity. Sensitivity to acceleration is less of a problem in a jet

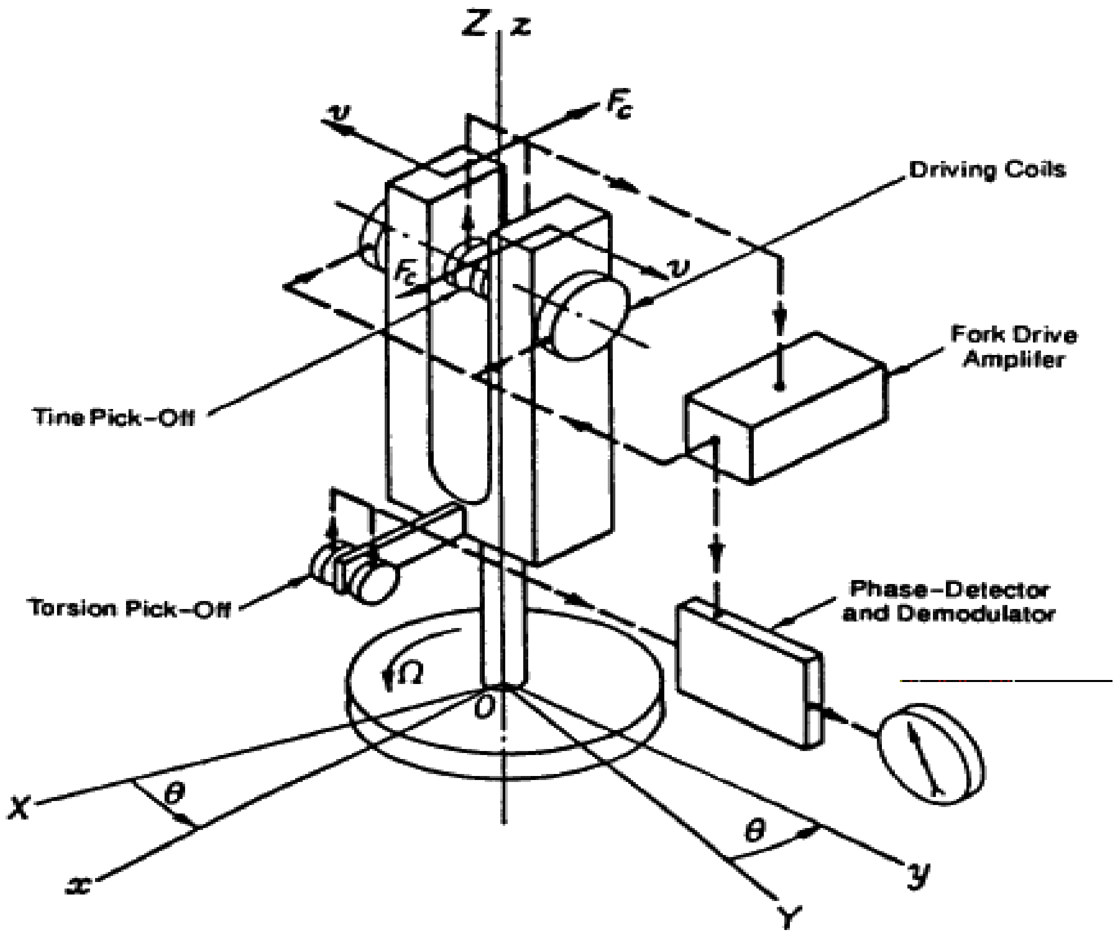


Figure 3-19. Vibratory Rate Gyroscope

gyro since the sensing element (the jet) is supported by buoyancy. Vibratory gyros could be constructed in quantity by micromachining if dimensional control is adequate. Balance in a micromachined vibratory gyro may be less of a problem than sensitivity because of the small masses that are involved.

There are many more types of gyros that are used in aircraft, missiles and spacecraft. They are much more accurate than the simple devices described above but also much more expensive and complex. One example is a light hollow sphere with colored markings whose position and attitude is sensed by photosensors. It is electrically charged and suspended inside a slightly larger evacuated sphere by electrostatic repulsion. It is then spun up by a rotating magnetic field and used as a gyro. The electrostatic forces that have to be applied to keep the sphere centered are a measure of acceleration.

One type of advanced gyro that may become sufficiently inexpensive to find use in AHS applications is the laser gyro. This is a rate gyro comprising a long fiberoptic

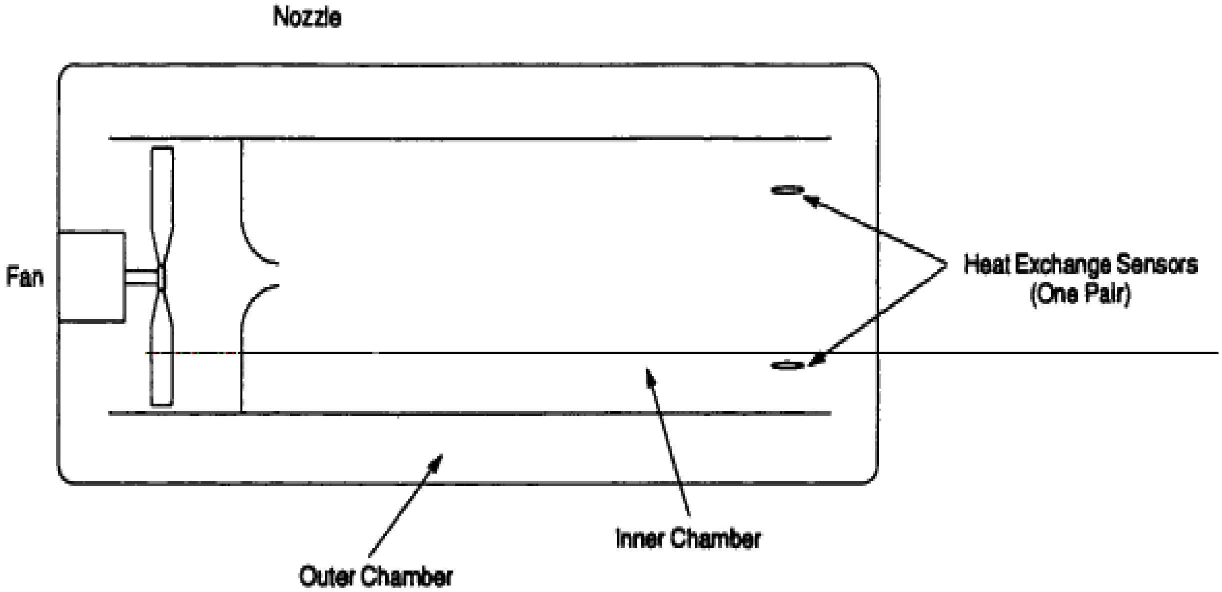


Figure 3-20. Jet Rate Gyro

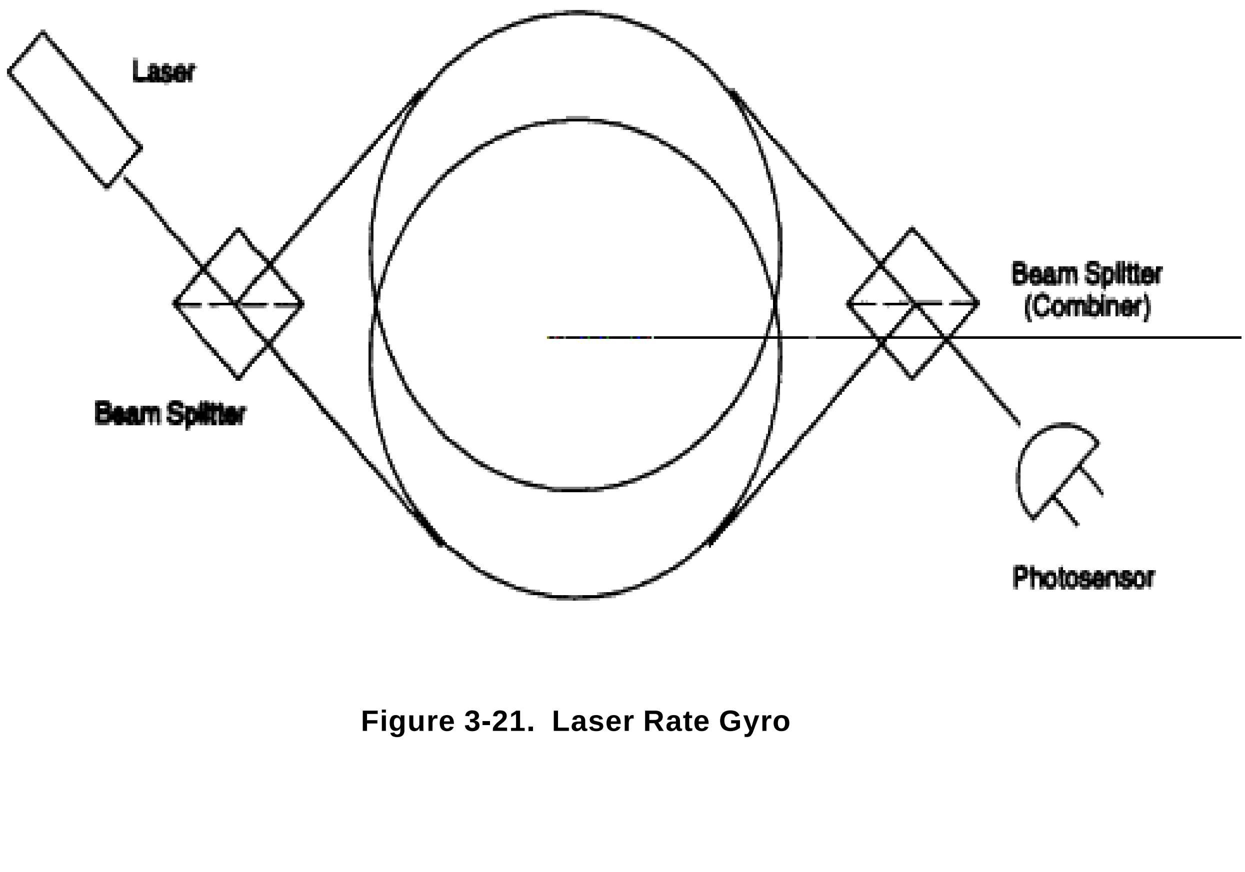


Figure 3-21. Laser Rate Gyro

cable wound on a spool. Laser light is passed through the loop of fiber in both directions (Figure 3-21). Halfway around the loop, where parts of the beam meet that are coherent with each other, a standing wave is formed. (Contrary to simple descriptions of lasers, their light is not coherent forever. Each laser has a specific coherence length.) When the spool rotates around its axis, one of the light beams has to travel a little further while the other travels a little less distance. This appears to shift the aforementioned standing wave pattern. The shift, which can be observed, is proportional to angular rate. By clever manipulations involving polarization and beam splitters, it is possible to use the whole length of the fiber rather than only half, as described here.

3.2.8.1.3 Force Sensor Technology

When a conductor or semiconductor is stretched it gets both thinner and longer. In combination, these effects increase its electrical resistance. This effect can be utilized in strain gauges to measure force. Since the measurement of very small resistances requires special procedures (e. g, a Kelvin bridge), conductor wires are usually made very thin and of an alloy whose temperature coefficient of resistance is very low. Semiconductors, having a larger inherent resistivity than conductors, can be made in thicker cross section and therefore can also exhibit a decrease in resistance under compression along the line of current flow. Semiconductors usually have a large temperature coefficient of resistivity.

A conductor strain gauge is usually immersed in a thin, fairly strong plastic and cemented to a stronger mechanical beam that will be deflected by an applied force. A good example is the control stick of a research airplane. As shown in Figure 3-22, one strain gauge is bonded on the front and one on the back side of the stick. (There might be ones on each side, as well.) The two strain gauges are connected in series, as a bridge, to which a voltage is applied, and at the center point (C) of which a voltage appears that is approximately half of the applied voltage. When the pilot pulls or pushes on the stick, variations of the voltage at the center point of the bridge formed by the two strain gauges indicate the force that he is applying. This force may be quitedifferent than the deflection angle of the stick because of changes in airspeed, longitudinal trim or other factors.

Torque can be measured by placing strain gauges on a radial element of a structure, for example the spokes of a steering wheel (Figure 3-23a). Since forces can lead to misleading indications, e.g. bending without attendant torqueing, it may be useful to instrument opposing radial members. Power carried on a shaft is proportional to rotational speed and torque in the shaft and can be measured as shown in Figure 3-23b. Optical markers are placed on the shaft at two places separated by some distance along its axis. Twist of the shaft, proportional to torque, is measured by a phase shift between the signals from two photoelectric sensors, while the rate of arrival of either signal provides a measure of rotations per minute.

The most common application of force and torque sensors is estimation of turning stiffness and coefficient of friction between the tire surface and the road. The latter is sometimes called adhesion coefficient to distinguish it from the coefficient of rolling friction which measures a part of the vehicle's resistance to forward motion.

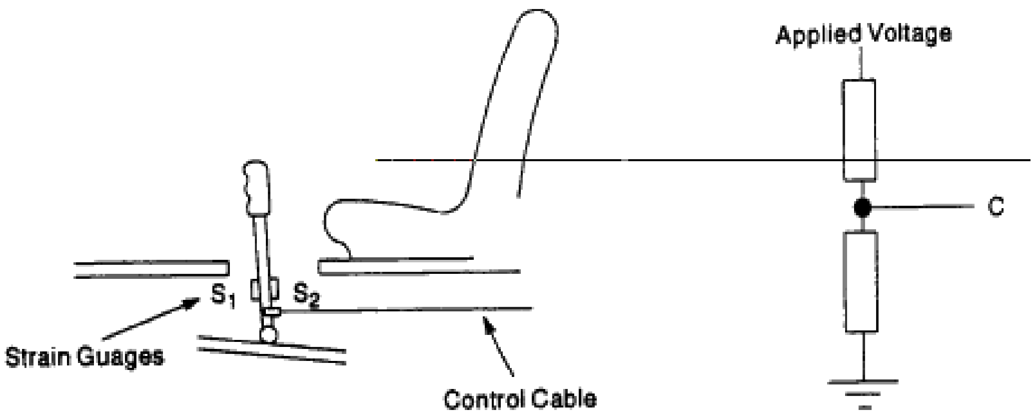


Figure 3-22. Strain Gauge Force Measurement

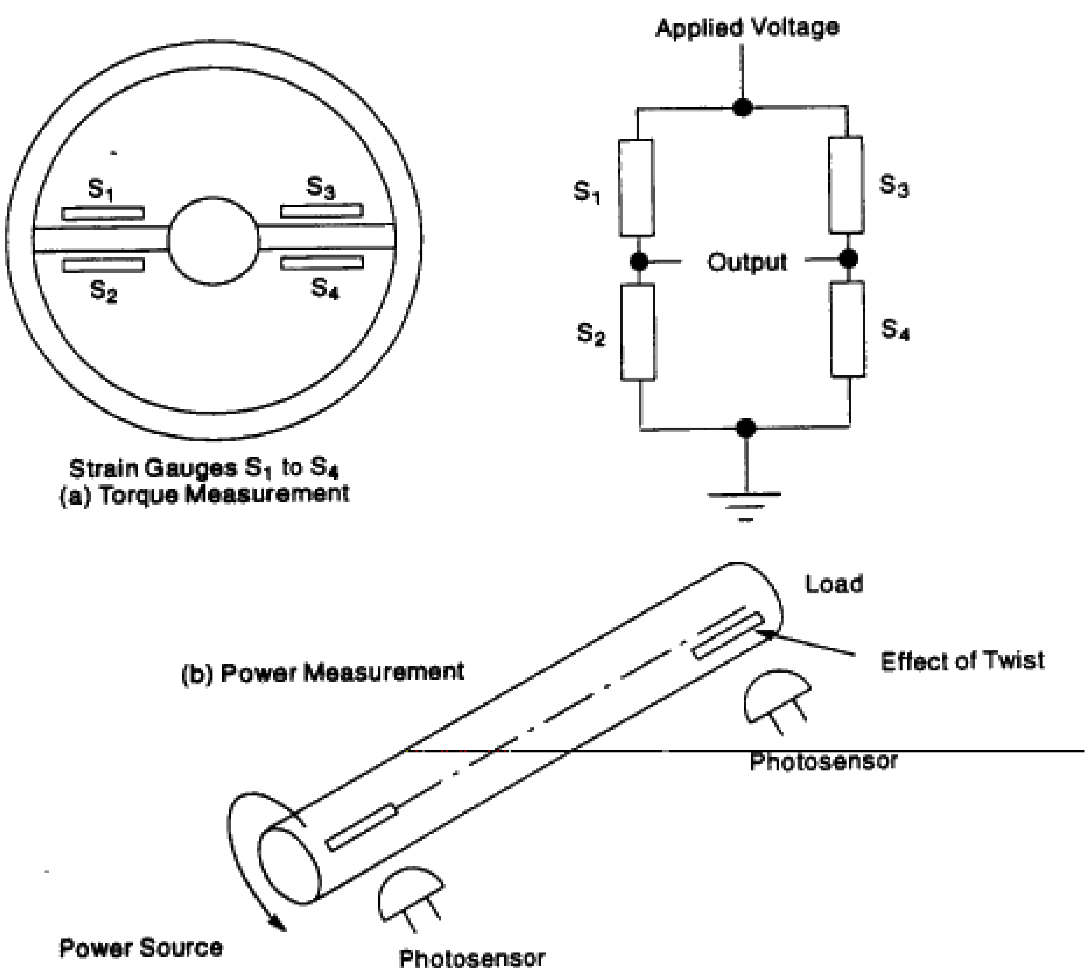


Figure 3-23. Static and Dynamic Torque Measurement

Adhesion coefficient can be estimated from brake line pressure and consequent deceleration. Maximum deceleration of a vehicle is normally observed during braking. Brake line pressure is a better braking force measure than force on the pedal. A small fifth wheel under the car, held against the road by a known force and braked intermittently with increasing torque, could also be used to estimate adhesion coefficient.

Pressure gauges now include relatively inexpensive semiconductor pressure sensors. Silicon has mechanical properties, other than a yield point, that are not dissimilar from those of steel. Silicon diaphragms covered with suitable strain gauges can be formed and placed between volumes at one selected pressure, including a vacuum, and another, to be measured. The inventory of such pressure sensors already includes tire pressure sensors that compensate for the dependence of tire pressure on temperature and permit on-line measurement of "tire pressure", actually air density, even when the temperature is varying.

In some representative system configurations of AHS, vehicles will follow each other closely and at very similar speeds e.g. platooning. Malfunctions of the longitudinal control system, leading to touching at very small relative velocity, might be detected by a bumper pressure switch acting as an inexpensive backup sensor.

3.2.8.2 State-of-the-Art in Dead Reckoning (DR)

In the traditional definition of dead reckoning, a vehicle measures its speed and direction in order to determine its motion, typically in a two-dimensional plane, by integration of vector velocity. Since the advent of the V-2 missile, which derived speed from the integration of forward acceleration and "knew" direction from a pre-programmed maneuver sequence tested against gyros, inertial navigation sources of speed and direction have become accepted as DR inputs.

Major sources of error in traditional DR are currents and winds, neither of which are a serious problem for road vehicles. Inertial navigation systems (INS) suffer from offsets and drift. All of these errors are magnified by the integration process over time. This means that error is typically specified as a percentage of distance traveled, e.g. two percent meaning that after 10 km of travel there is an uncertainty of 200 m. With INSs, there is the possibility of an offset error in acceleration that grows as the square of time or, typically, distance traveled.

Errors in current speed and of direction sensors and affordable INS components are such that one would not base a lateral/longitudinal AHS on DR alone. For one thing, DR gives no information on adjacent traffic at all. On the other hand there is no process better than DR when everything else fails. A car that has not suffered a blowout can be kept in a standard 4 m lane for some 100 to 150 m by simply holding the wheel steady. Neglecting high cross winds, ice or heavy rain, it may be possible to bring a vehicle to a halt without departing the lane. Although this process breaks down when road curvature changes, it is better than nothing.

Possibly because of the limitations of DR, only one reference was found (Necsulescu, Sasiadek, Green, 1993) that described lat/long guidance by an ingenious, Kalman-combinatorial filtering of INS and odometer/steering angle sensors for a three-wheeled robot. Calspan concluded that such guidance was useful for at most tens of meters in the presence of normal lateral load imbalances on solid polyurethane wheels of an industrial, free-roaming robot. There is not enough information to extrapolate these data to automobiles.

Interpolation between periodic fixes of other navigation sensors, e.g. GPS, is another application of DR. El-Sheimy and Schwarz, 1993, describe a system for surveying road features at 50 to 60 kph that uses CCD cameras to detect the features while a combination of inertial sensors and GPS provide Earth-referenced camera coordinates. Features are located to an accuracy of 30 cm within 50 m of the vehicle.

A number of navigation systems using map matching have been demonstrated. These have not been intended for lat/long guidance in the sense of lane keeping but rather for the general sort of navigation that is useful in following and directing delivery fleets or drivers unfamiliar with a region. Sweeney, et al, 1993, describe a system that uses wheel rotation sensors and a magnetic compass for DR between fixes from map matching, e.g. at stop signs or turns. The system, in use since 1985, was later augmented by inclinometers used for compass correction and a directional rate gyro. The system drives a heading-up, moving map display (HUMM). Kao, 1991, uses GPS to calibrate a DR system which then becomes accurate enough to interpolate between map-match fixes. Krakiwsky, 1993, mentions DR in an overview of IVHS navigation technology as a method used for navigation.

Taniguchi, et. al., 1992, backs up a machine vision system, with a DR-type system he calls path inference, for up to 10 m of travel. Path inference is backed up by a system using ultrasonic sensors ranging against a guard rail. Koliadin, 1993 (Abstract only), calibrates a DR system with GPS and uses it to interpolate between GPS fixes in poor coverage areas.

Vlcek, et. al., 1993, achieved two percent of distance traveled accuracy using the odometer and a yaw rate gyro, after calibration via GPS. Thereafter, jumps in GPS position occasioned by constellation switch or due to urban canyon multipath could be smoothed by proper Kalman complementary filtering. Accuracy with DGPS/DR were 0.1 city block (San Francisco, halfway between the southern end of the Golden Gate Bridge and Hunter's Point) versus 0.3 city blocks with GPS/DR. The most important aspect of this work is the filtering technique which allows DR extrapolation between intermittent GPS/DGPS fixes.

One should also consider the use of DR in vehicle control, particularly since it is likely to be the ultimate default option. Fujioka, 1993, describes use of kinaesthetic sensors in lat/long vehicle control by including speed, torque and steering sensors in systems based on cable guidance (100 km/h) and machine vision (30 km/h).

Hedrick, 1992, addresses one of the most important aspects of DR and INS: Are the data collected from these and an infrastructure guidance system consistent? If they are not, something is broken or the vehicle has lost contact with the road. Either possibility is likely and resolution of the conflict requires techniques described in Aboujelam and Krakiwski, 1993, or estimation of cornering stiffness and coefficient of adhesion. These variables have a strong influence on AHS throughput and capacity. Given correct measurement and application of these variables, excellent performance may be achieved, even in inclement conditions, as in heavy rain, on ice or in heavy snow. Hedrick's system, otherwise dependent on magnetic nails, has been tested in varying road conditions from 20 to 60 km/h.

Pikula and Caves, no date available, describe a variable-reluctance wheel odometer which operates at low, but not very low or creeping speeds. One would not be able to differentiate between stopped or creeping vehicle. Because of this, use of a Hall-Effect sensor should be considered.

Hitchcock, 1993, describes a representative system configuration (RSC) for AHS that uses longitudinal dead reckoning in "blocks" of an automated highway system. Distance traveled in the block is used to inform other vehicles of one's position along the road. Block length could be selected to assure that odometer errors cannot build up beyond allowable accuracy with this approach, since each odometer is electronically "reset" when entering a block.

3.2.8.3 Summary

Limitations of dead reckoning (DR) suggest its application to the AHS environment be in combination with, or as a back-up to another system (i.e., GPS). The useful range of dead reckoning is severely restricted due to offset and drift, usually specified as a percentage of the distance traveled. DR. has been implemented reliably for up to 10 m as a back-up system and may be practical as a default controller during a malfunction-induced stop or escape to the breakdown lane. (Table 3-9).

3.3 COMMUNICATIONS CONSIDERATIONS

"The communications needs for all automated highway system may be significantly different from those of other IVHS applications, including intense, high-volume short-range communications as well as overall system management communications." (TRB, 1993, P. 23). In the course of analyzing the techniques applicable to lateral and longitudinal control of vehicles on an automated highway, it has become apparent that communications play an integral role: Interactions between adjacent vehicles must be closely correlated if any improvement in traffic density to be achieved in a safe fashion.

At the same time, health and status of the system must be monitored and corrected in a more global fashion.

To continue the quotation: "AHS technology itself is early in development, making definition of such requirements difficult." (TRB, 1993, P. 23) The scope of an AHS communications subsystem can only be estimated at the present time. Experience in experimental systems at best points out problem areas. In the following discussion, we will attempt to suggest known requirements, available technology and possible communications structures.

In order to separate communication problems into orderly subsets, the International Organization for Standardization (ISO) Open Systems Interconnection (OSI) Reference Model (RM) will be utilized. ISO/OSI-RM distinguishes seven

Table 3-9. Inertial and Force Sensor Based Systems

AUTHOR	REFERENCE	RANGE/DURATION	TESTS PERFORMED	ADDITIONAL SYSTEMS	COMMENTS
	Calspan AHS File No.	(m, s)	(drive test)		
Necsulescu, D.,Kim, B. and Green, D. (1993)	47	10			Guidance for a three wheel robot
Taniguchi, M. Hosada, A., and Oshige, K. (1992)	196	Approx. 10 m	Tested at 10 kph	Machine vision, ultrasound	Used as an intermediate mode of operation when machine vision is disabled- If machine vision cannot be restored before the path inference mode becomes unreliable, ultrasonic mode assumes control.

organizational levels ranging from operations on data links or modems (Level 1 - Physical Layer), past Link, Network, Transport, Session, Presentation to the Application Layer. These are appropriate for the description of the digital data manipulations involved in communications but do not encompass other important aspects of communications including data flow requirements, the medium, e.g. sending and receiving equipment and the intermediate channel, and use, e.g. suitability and capacity inside a vehicular control loop.

3.3.1 Data Flow Requirements

Two major communications concepts have evolved for various representative systems configurations (RSCs). In one of these data flow is primarily inside a "pack" of vehicles that are currently near each other on the roadway. They inform each other about intended maneuvers, e.g. deceleration or lane change, on various time scales, "I wish to merge" or "create a gap for lane change" As a secondary activity of this first concept, there is an exchange of traffic management and vehicle status/health data with the infrastructure.

A second concept reverses the importance of inter-vehicle and vehicle-roadway communications. Decisions on traffic management, including vehicle spacing and lane utilization are made in the infrastructure and inter-vehicle communication is used only for purposes of assisting the lateral/longitudinal control loops.

Either concept requires packets of data transfer in the order of a few hundred bits between any two communications in some tens of milliseconds. It might be noted that this rate also was found to be necessary in modeling longitudinal control in the presence of some noise (Section 3.6). By analogy, the US Navy all-weather carrier landing system controls aircraft vertically and laterally with about one foot accuracy with 70 bits every 100 milliseconds.

Required data rate may be increased if several users must share a channel, a very real possibility in the AHS environment. When several stations, either one-way or two-way, share a channel they must arrange to have access to it. There are a number of ways of arranging this. In amplitude modulation (AM) and frequency modulation (FM) broadcasting, the channels (550 to 1600 kilohertz (KHz), and 88 to 108 MHz, respectively) are subdivided into 105 and 100 narrower frequency bands. A station is assigned one of these frequencies with stations in one coverage area being separated by several frequencies that are in use in other coverage areas. This is frequency division multiple access (FDMA).

Dispatchers and radio amateurs wait for the other users to stop talking before transmitting. This process is called time division multiple access (TDMA) and usually works unless a large number of amateurs want to contact one station that may be in an esoteric location or have unusual news. When TDMA-linked computers have this problem it is called a collision and may be corrected by waiting a random interval and repeating the attempt to communicate (e.g. Ethernet). Because of the obvious waste of time in the possibly unsuccessful wait and repetition by both parties, such systems can reach only some 38 percent of theoretical capacity. Military TDMA data links, when configured to maximum efficiency for a critical function, can approach 90 percent. This is achieved by assigning each user a specific time slot.

In a broadcast system, if all listeners are at approximately the same distance from the broadcasters who each transmit the same power and there is more bandwidth available in the channel than is needed for the broadcast, there is another method of separating links in the channel. This is code division multiple access (CDMA). Each sender biphase modulates its broadcast by a binary sequence, e.g. a Gold Code, that is substantially orthogonal to other stations' codes. Orthogonal here means that there is a method of listening for one code that doesn't respond to the others. Signals that have a high ratio of the code (chipping) rate to the signaling (data) rate can be made more accurately orthogonal.

Additional possibilities for limiting mutual interference between stations are presented by atmospheric absorption, the capture effect and induction signaling. Crowded conditions in the electromagnetic spectrum below 30 Gigahertz will likely force the more intense communications needs of IVHS into the millimeter (mm) band (30 to 300 GHz) where there are numerous atmospheric absorption bands (Section 3.2.2 Figure 3-4). Operations in these bands favors short range communications in the same way that it affects radar (Section 3.2.2.1.4, Table 3-2). This process, as it affects communications will be further addressed below in subsection 3.3.3.

Frequency (FM) and phase modulation (PM) exhibit a capture effect which causes the strongest signal to suppress weaker signals. Thus, the transmitter on the car ahead - and, unfortunately, the one next to us - are more likely to be heard than more distant ones. Signals from the car next to us can be suppressed by using directional antennas, which are almost dictated if one operates in the mm band. Some thought must be given to the problem of communicating between vehicles in adjacent lanes for lane changes.

Induction signalling (Section 3.2.6.1.2) provides a very limited coverage area. Induction signalling is not really directional. One can make a null along one axis, but this is probably insufficient in view of constantly changing relative alignment of vehicles in adjacent lanes.

Given that there are numerous ways of limiting mutual interference without demanding extreme bandwidth, the type of data stream postulated for data link ranging (Section 3.2.7.2.2) of 100 bits in 10 milliseconds (ms) or 10 kilobaud is probably realistic. A pack of four cars in sequence in a lane could complete a data exchange in 40 ms, a delay comparable to that used in longitudinal control modeling.

3.3.2 Media

Radio, light and infrared, induction signaling and, possibly, ultrasonics may be used for AHS communications. Shladover, et al, 1991 compared ultrasonics, radio and optical (IR) links and concluded that the latter were more suitable for carrying the communications needed for longitudinal vehicle control. Chang and Georghiades, 1992, discuss a longitudinal control system incorporating some lateral guidance features that uses two data links between a leading and following vehicle that would provide a redundant link (Section 3.2.7.2.2). For reasons discussed in detail in Section 3.2, radio, particularly in the millimeter band, appears as a strong candidate.

At frequencies below 1 GHz, it is not difficult to obtain substantially omnidirectional antenna patterns. This makes it possible to communicate with vehicles in all directions but also leads to the prospect of much mutual interference. Omnidirectional data links, in the 902-928 MHz spread spectrum band were used in experiments at University of California, Berkeley, by Chang et al, 1991, and Hendrick, et al, 1992. The latter used a 122 kilobaud synchronous radio link. Data links at these lower frequencies should be used infrequently but may be necessary, e.g. for lane changes. They are also useful for one-way broadcasting, e.g. of differential GPS data.

Above 1 GHz (30 cm wavelength) it is likely that antennas have some directionality since they tend to be as large or larger than a wavelength. Microwave antennas also are typically mounted on the front, back or side of the vehicle, and radiate in the corresponding direction. They provide some protection against mutual interference, and are eligible for vehicle-to-vehicle links.

Above 35 GHz, there are atmospheric absorption bands that further reduce mutual interference. These frequencies with the exception of a few gaps in the absorption bands, are not used much by the military and are more likely to be available for AHS users. Frequency assignments generally are more difficult to obtain at lower frequencies than at higher ones. AHS could require a significant bandwidth, as might be illustrated by a rather extreme example. If each of the approximately 100 million vehicles in the US were assigned an individual frequency channel of 10 KHz bandwidth, one would need one terahertz (THz), i.e., about three times as much radio spectrum as actually exists.

Because the atmosphere is highly attenuating above 300 GHz (1 mm wavelength) there has been little use of this region. Until recently there were no coherent RF sources available for these frequencies. It is not impossible that technology will expand into this spectrum and that the atmospheric absorption may prove beneficial in AHS.

The next atmospheric window starts at 20 THz (15 µm wavelength) in the far infrared (IR). Lasers (as transmitters) and detectors are available in the far (8 to 15 µm) and mid (2 to 8 µm) IR bands. IR communications are generally conducted in the 0.7 to 2µm band where semiconductor diode lasers and emitters are used as transmitters and semiconductor detectors serve as receivers. At the present, most IR links use fiber optics as a medium. In one instance, an IR link was used in an AHS-related test.

3.3.3 Link Budgets

The transmitted power (P_T, Watts) of a communications link, when received at a range (r, meters) would be spread over a surface of $4\pi r^2$ square meters, unless the transmitting antenna was directional, i.e. had a gain (G_T, dimensionless). Power density (Φ), the power received by one square meter (called the flux in optics), is then:

$$\Phi\ (\mathrm{W/m^2}) = P_T G_T / 4\pi r^2$$

The area (A_r) of the receiving antenna is related to its gain (G_r) by the following relation:

$$G_r = 4\pi A_r \eta / \lambda^2$$

Here η is a dimensionless effectiveness, typically 55 percent for a well-designed antenna, and λ (in meters) is the wavelength. The effective area of the receiving antenna (λA), when multiplied by the power density, yields the received power (P_r).

$$P_r = \frac{P_T G_T G_r \lambda^2}{(4\pi)^2 r^2}$$

For the common case that the receiving and transmitting antennas are identical

$(G_r = G_T = G)$

$$\frac{P_r}{P_T} = \frac{G^2\lambda^2}{(4\pi)^2 r^2}$$

which can also be expressed in terms of the effective antenna area as

$$\frac{P_r}{P_T} = \left(\frac{\eta A}{\lambda^2}\right)\left(\frac{\eta A}{r^2}\right)$$

In this last form it becomes apparent that the factors that favorably influence the performance of a communication link are effective antenna size, measured in terms of wavelength ($\eta A/\lambda^2$) and antenna size, measured in terms of range ($\eta A/r^2$).

These measures are both dimensionless. Incidentally, there is no way of getting more power at the receiver than was transmitted. If the right hand side of the equation exceeds 0.08, operation is in the so-called near field and P_r approaches P_T.

It may be useful to calculate required transmitter power for a few typical scenarios. It should be remembered that this power should be as low as possible to reduce mutual interference to other users of the frequency band that is assigned for AHS purposes. Three scenarios are considered here: In the first, it is assumed that the beam width of the communication antenna is kept small, covering only 4 m of a typical lane width at an intended maximum range of 100 m. In the second, the beam is spread over 34 m at 100 m, allowing for a road radius of 300 m or 1000 ft which is very tight on freeways. In the third, it is assumed that a dipole antenna (G=2) is mounted on top of the vehicle so that communications are possible in all directions.

The preceding expressions provide a ratio of received power (P_r) to transmitted power (P_T). Received power should exceed noise by a signal-to-noise-and-interference-ratio (SNIR) that assures reception of data with a low bit error rate (BER), while allowing for some losses. Noise in the receiver is somewhat larger, by a factor called the noise figure (NF), than the thermal noise given by the product (KTB) of Boltzmann's constant (k), the antenna temperature (T) which is normally 300_ Kelvin and receiver and receiver bandwidth (B). Noise power is therefore:

$$P_n = (NF)\cdot K\cdot T\cdot B$$

For these examples, a bandwidth of 10 KHz was assumed and the noise figure was 10. Both numbers are consistent with available technology and AHS data flow projections and suggest that noise power would be $4\cdot 10^{-16}$ Watts or -124 dBm. It is reasonable to aim for a SNIR of 100,or 20 dB, which makes the received power $4\cdot 10^{-14}$ Watts (or 104 dBm) if there are no interference signals. Table 3-10 shows required transmitter power and antenna dimensions for the narrow, intermediate and broad coverage communication links, if they were operated at 60GHz, in the center of the oxygen absorption band.

Table 3-10. Link Budgets

Coverage	Transmitter Power	Antenna Size (mm)
Narrow	$6.5 \cdot 10^{-11}$	125
Intermediate	$3.1 \cdot 10^{-7}$	15
Wide	$1.0 \cdot 10^{-3}$	2.5

An allowance was made for the oxygen absorption which, at 20 dB/Km, amounts to 2dB. If one were to operate at a frequency without absorption, and assure reception to 100 m range, all stations out to 1 km range would potentially produce interference above noise level. For both directions on a two-lane highway, with cars moving at 105 kph (65 mph) and one second headway almost 300 interferes could be present. By operating in the absorption band this number is reduced to 120. Assignment of 120 frequencies in a 1.2 MHz band is not impossible. Operation in more absorptive environments i.e., above 500 GHz may prove to be desirable.

Doppler shift presents another risk. At 60 GHz, vehicles approaching each other at 105 kph (65 mph) will observe 23 kHz of Doppler shift. This means that an oncoming car would be received more than two 10 kHz channels above the frequency it is transmitting, and, as it passes, ends up more than two channels lower. With 10 KHz channels, Doppler effect would make frequency assignment quite difficult. It might be managed with 100 KHz channels, where Doppler shift is only 23 percent of bandwidth, or by another approach, derived from civil aviation. At lower altitudes, between 915 m (3,000 ft) and 5,486 m (18,000 ft), aircraft flying under visual flight rules (VFR) in a generally easterly direction (0.179_ magnetic heading) fly at an altitude that is 152 m (500 ft) above an odd number of thousands of feet, e.g. at 1,676 m (5,500 ft), while aircraft flying generally west are at an altitude that is 500 ft. above an even kilofoot altitude (305 m), e.g. at 6,500 ft. Similarly, vehicles moving east on the I-90 might use a separate frequency band to keep away from the Doppler-shifted signals of those moving west. An issue is raised on sections of the freeways that occasionally run straight north-and-south while generally running substantially east and west. A four-quadrant frequency assignment with some angular overlap could resolve this problem. In an extreme case, each lane might receive its own sub-band in order to permit traffic shear.

Power calculations have so far been based on so-called free space propagation. The AHS environment will provide many opportunities for multipath propagation. The most obvious of these is reflection from the road surface which can be very strong, and can lead to nearly complete cancellation of the signal received at any particular antenna. When another antenna is properly located with respect to the first antenna one can frequently arrange to have coverage despite multipath. This procedure is referred to as space diversity. (Frequency diversity, which uses several frequency assignments to achieve the same purpose, wastes valuable spectrum.)

Figure 3-24 shows the signals received at two antennas, one 40 cm and another 50 cm above the road, from a transmitting antenna 40 cm above the road as a function of range. It is apparent that deep cancellation nulls at 63 and 80 m in each signal are compensated by maxima on the other channel. Near 16 m range, both channels have a coincident null that might require introduction of a third antenna. This would be desirable, in any case, to counter lateral multipath, e.g. from reflections in the sides of vehicles in adjacent lanes. At very short range multipath is less important: Not only is the signal much stronger, but the bounce path is significantly longer, causing it to suffer more attenuation and rendering it incapable of completely canceling the direct path. This effect manifests itself in the reduced depth of the coincident null at 16 m range.

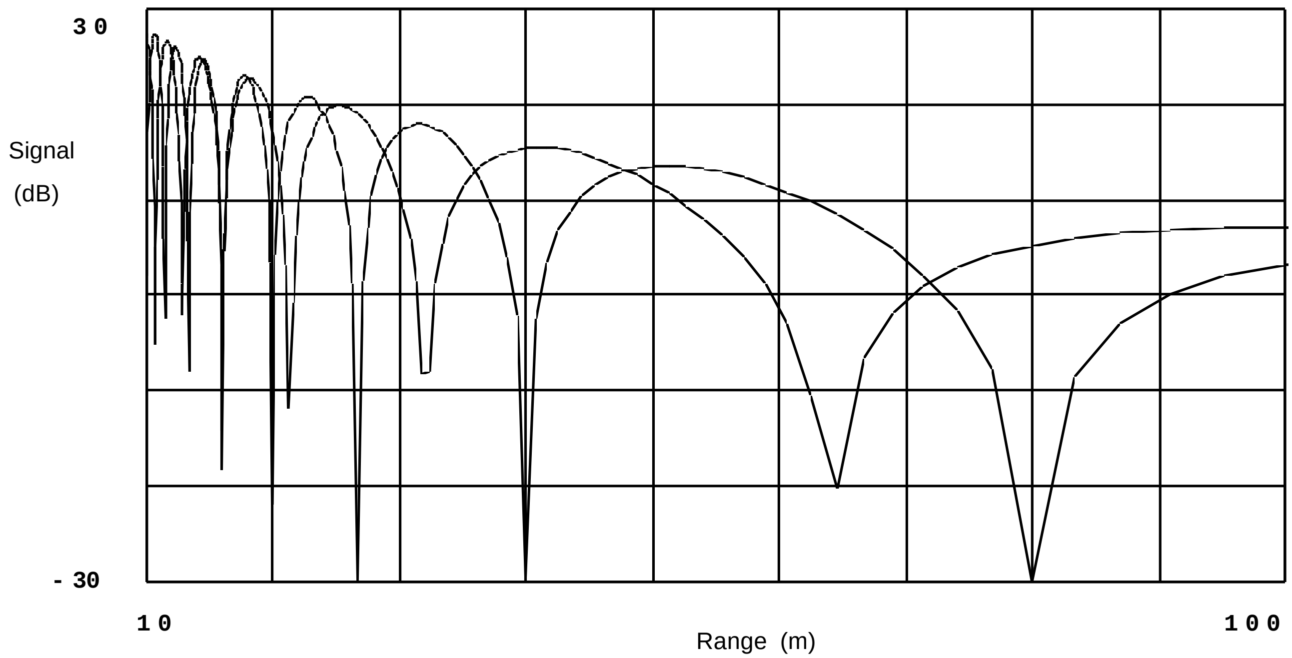


Figure 3-24. Effect of Space Diversity on Signal Strength

3.3.3.1 Link Budget Summary

While the material presented in Section 3.3.3 may seem to stray beyond the limits of identifying issues and risks for AHS communications, it is really necessary to present it. First of all, it suggests that one doesn't increase power to succeed. Less power in communications between millions of AHS users means less mutual interference. Next, one doesn't just communicate with one neighbor, like the car ahead. What if the car in the next lane wants to merge into this lane? What if your antenna cannot detect its emissions?

There is currently no standard for communication formats and protocols in AHS. This is as it should be. It is too early to get such standards. Even we shoot down our "sufficient" 10 KHz bandwidth standard in proposing 60 GHz as an interference-reducing band while noting its large Doppler shift problem.

Communications coverage is a real issue. Unless we know a little bit about the real intentions of those cars that are traveling in our "pack" we might collide, a rather serious consequence. How much exchange of information is needed for successful merges and such?

Yet there is no problem in finding solutions to each problem. It will take an exchange similar to the interservice discussions that brought us the Global Positioning System (GPS) if the issues posed by the communications needs of the Automated Highway System are to be resolved.

3.3.4 Link Structure

In was mentioned earlier that it is estimated that packets of the order of 100 bits will have to be exchanged in small "packs" of vehicles at the rate of 100 packets per sec. This implied a signaling rate of 10 Kilobaud, and a channel bandwidth of about 10 KHz. At the higher frequencies that may be assignable to AHS issues, Doppler effects suggest that a wider channel is more desirable. There are a number of ways to accommodate this interaction.

In a vehicle-based system, many more users than pack members have access to each channel - even though that access may be of poor quality. This is illustrated in Figure 3.3.3 where the signal level is almost always above the threshold (0 dB) for good BER, even though the system was designed for a free-space range of 100m. Ideally, the other users will be off the air - either off, on a different frequency, or waiting for a later time slot - when we want to use the channel. (Code division multiple is not a good solution for intervehicle communications because of the wide variation of inter-vehicle range.) One way of assuring this is to signal rapidly and for a short time (TDMA, Section 3.3.1). This raises bandwidth and reduces the depredations of the Doppler effect. Unfortunately it requires organization of timing which is further addressed in Section 3.3.5.

In infrastructure-based systems, the controller may be in a position to multiplex control transmissions, i.e. to send Vehicle Number 511 its instructions on Channel 511 in time-frequency-or, if the control transmitter is sufficiently distant to overcome near-far effect code division multiplex. This process is again hardened against Doppler effect if TDMA is used.

Infrastructure-based systems are usually attached to sections of road (Section 3.3.5). At the end of each road section, each car will have to be told it can keep its channel - what if my car, NY 3EG 573 can't keep Channel 573 because IL CH1 573 already is using it? This gets to be an accomplishable but critical task requiring redundancy in the assignment controller.

If a system can be developed that uses communicators at a relatively constant and therefore, fairly distant, range from the communicating AHS users, it is possible that CDMA (Section 3.3.1) or the wideband FM System used for television distribution by satellite may be employed in AHS. in the latter system, a number of channels - their content could be derived from transmissions from moderately, uniformly distant vehicles or infrastructure sensors - are transmitted as subcarriers. While the transmitter cost is high, signal-to-noise-plus-interference-ration (SNIR) need not be great to permit each user to extract data with good BER. Transmitter cost may be shared over many users and may be quite affordable. Because of urban canyons and rural valleys, the only realistic system of communicating in the fashion suggested in this paragraph involves numerous satellites. Satellites whose orbits don't decay are many hundred kilometers above the earth. This means that there are several milliseconds of latency in signals passed through such a system, in addition to the frequency and time-slot delays posed in its use.

3.3.5 Network Structure

The most difficult task in AHS communications appears to be that of forming useful networks between stations that should communicate. Some communications, e.g. electronic entry/exit signs, are attached to the infrastructure and others, e.g. data link ranging and merge/demerge, are attached to a group or pack of vehicles. A pack moves through different sections of roadway and different lanes of traffic may move at differing velocity, requiring networks to change membership in a smooth fashion. Simple TDMA ordering on a shared band is probably insufficient for the rapid changes taking place as packs move through sections. Frequency division multiple access (FDMA) may also be needed to separate infrastructure-based communications from vehicle-based ones.

A typical spectrum and time image is illustrated in Figure 3-25 One FDMA sub-band is used for road/vehicle communication. It has a number of channels that is dictated by the ration of reuse distance to inter-beacon distance. The reuse distance is determined by the coverage area of one station; a station's frequency cannot be used again until one has left its coverage area. The inter-beacon distance is the average distance between stations in one station's coverage area. It is apparent that the limited coverage attainable in absorption regions again makes them attractive. Each beacon would notify vehicles of the channel for the next beacon as they pass.

Another sub-band serves inter-vehicle communications. It's TDMA structure reduces mutual interference and Doppler problems but requires fairly frequent reorganization to make sure that users "stay out of each others' hair". The user of a

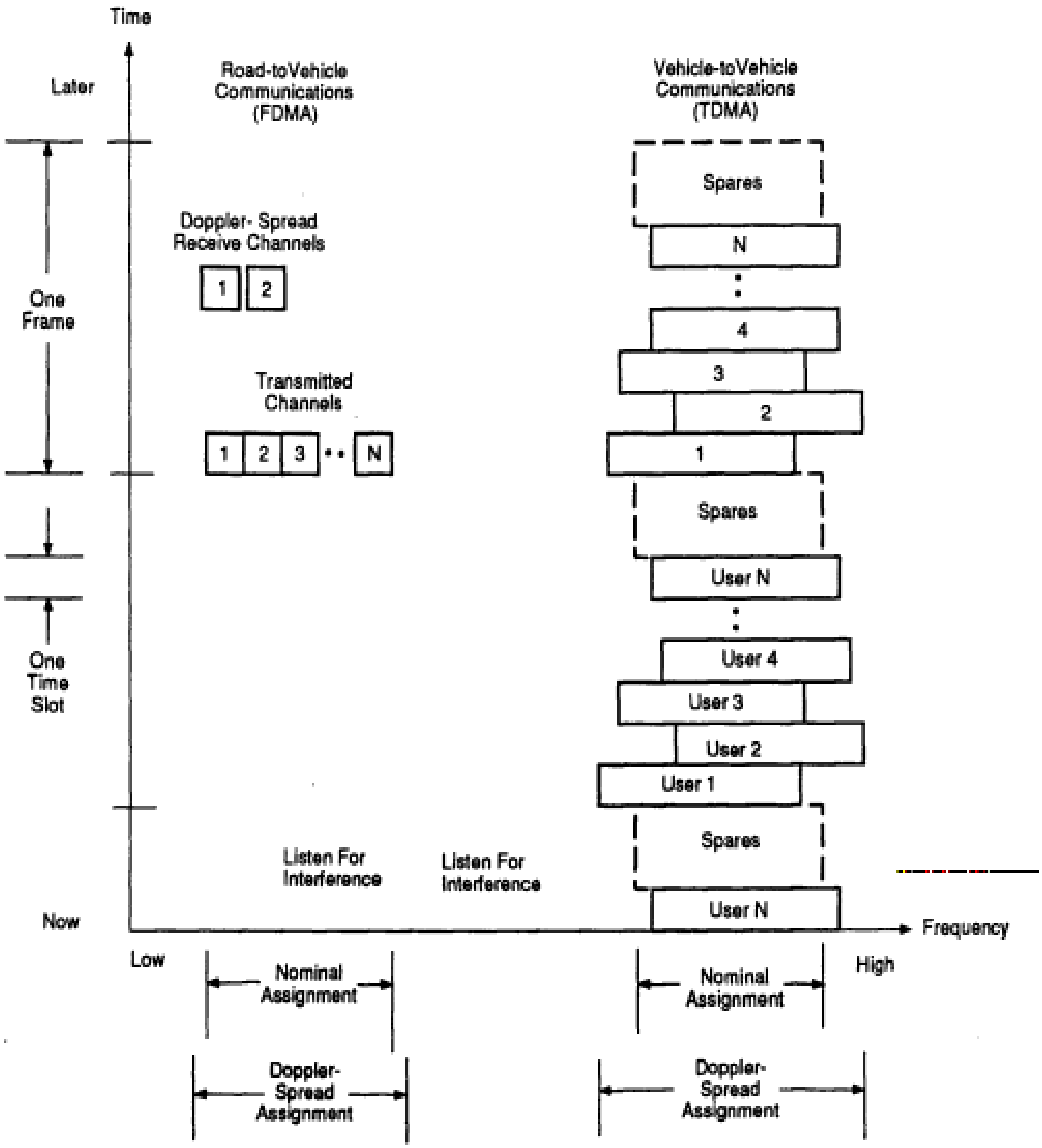


Figure 3-25. Spectrum and Frequency Usage for AHS Communications

transmitting time slot should occasionally listen on that slot to make sure that someone else who is using it has not drifted into interference range. If that happens, he should abandon the slot and move to a slot at the end of the time slot queue, after informing his pack of his new address.

We do not recommend Ethernet-like structures, but rather recommend one similar to the US Navy Link 4. It has fixed time slots, assigned users in quantities on the basis of need if that should change, e.g. because combat or a carrier landing requires higher data rate than usual. That might apply to merge/demerge activities and to data link ranging between vehicles following each other. Fixed time slots certainly sufficient in number to accommodate all uses capable of interfering with each other, have the advantage that one can gauge the approach of overload and consequent disaster. If few active slots are left at the end of the queue, even after users, who should always be looking for consistently open ones earlier in the list, have utilized the system to its fullest extent, it may be necessary to declare an overload malfunction. This could occur if spatial traffic density becomes excessive, due perhaps to a general slowdown. A responsive to this issue is possible but has not been pursued further. It should probably involve the infrastructure, by analogy to police work in clearing up the confusion after a serious accident.

3.3.6 Session Structure

The most important aspect of communication in AHS is latency. Every time one permits an instruction to a vehicle - about future actions, other vehicle intentions, whatever happens on the road - to escape the attention of an AHS vehicle controller, one creates a potential incident. Immediate response is important.

Latency is generally associated with desire to use a computing facility in concert with a communications capability with some physical latency, e.g. transmission or propagation time. If one can transmit several messages before listening, less waste occur because propagation time is shared by the messages. Since some users have to wait for others' messages to be sent, there is a delay called latency after addition of propagation delays and ones own delay in responding. There are control loops within control loops in AHS, as in any traffic. It would be nice to know if the third car ahead has slammed on the brakes.

Design of a low-latency session structure requires considerable thought. It is another issue in AHS communications.

3.4 SENSOR TRADEOFFS FOR OBSTACLE DETECTION FOR AUTONOMOUS VEHICLES

3.4.1 Introduction

There is a wide choice of sensors for autonomous vehicles that are needed to sense the location of road, road conditions, the location of other vehicles and to detect obstacles. Different sensors may be optimum for each task. Furthermore, a combination of sensors may be better than one alone for each of these sensing tasks. The purpose of this study is to outline the various tradeoffs for sensor systems used in obstacle detection for autonomous and semi-autonomous vehicles.

There are a number of factors to consider when choosing a sensor system configuration. Cost is certainly a primary factor. Computing costs to process information from the sensor system can also be a secondary factor that is as important as the cost of the sensors. Computing costs manifest themselves in the trade-off between the cost of onboard computing hardware and the processing speed dictated by time constraints of the control system design.

Angle and range resolution for various sensors are determined by wavelength and system configuration. Visual wavelength and infrared systems have good angular resolution and can be used for scene analysis. Scene analysis requires an image with at least 256x256 resolution elements. For visual or IR wavelengths this is implemented with an area detector, usually a CCD array. Active sensors such as lidar or radar are typically scanned to produce angular information. Sonar typically has only one resolution element though low resolution area scanning could be considered for AHS applications. Active sensors such as sonar and radar have the additional capacity of measuring relative velocity through doppler shift.

Different sensor systems have different penetration characteristics to find the road surface through precipitation, fog, ice and snow. Optical wavelengths do not penetrate well because of light scattering. Infra-red energy penetrate precipitation poorly because of the absorption of these wavelengths by water vapor Park, J. et. al., 1987. There is a window of transparency however at 3.3 microns wavelength which may be used for infra-red sensor purposes Park, J. et. al., 1987. Radar has the best precipitation penetration characteristics. However, location of the vehicle in the driving lane may best be performed with reflectors on the side of the road, rather than detecting the road surface itself.

The unexpected nature of obstacles complicated by the limited processing time encounters in automated highway system design. The discussion here is primarily for vehicle based detector systems, however, the principles presented here are useful in the design of centrally based road hazard detection systems. Vehicle based hazard detection would be used in RSC #1 through RSC #11. Infrastructure based detection might be used in RSC #12 and RSC #13.

3.4.2 Obstacles and System Configurations

There are a number of ways in which hazards can enter the road surface. Pieces of cargo or components of cars may fall off. This hazard can be much reduced compared to ordinary highway operation because one can regulate and inspect cars on an automated highway system so that they will be less likely to have loose components. Presumably there will be tight regulation on roof racks and other cargo carrying methods. Large animals, particularly deer may gain access to an automated lane and cause difficulty. Automated lanes will probably be fenced, but there is still the possibility that an animal can get gain access at entry exit point. In addition to objects that are genuine hazards, a major problem exists with objects that are really not a hazard but will trigger a reaction from an automated vehicle and cause emergency braking This may result in unnecessary injury or damage to vehicles. The difference between a brick or muffler on the road which is a potential danger, or a paper bag or shadow which is not, requires some analysis and processing. The aim of this section, is to discuss design tradeoffs for a system that is sensitive enough to avoid disastrous collisions with road hazards but will not stop a whole line of cars if a piece of paper blows across the road or the sun comes out from behind a cloud and a shadow of a telephone pole or fence suddenly appears in the field of view.

During high capacity operation, road hazards due to obstacles will probably not be a problem. When cars are tightly spaced there will be no room for hazards to lay on the road. When the distance between vehicles become large as on a low capacity highway, animals and debris can enter the roadway and create a hazardous situation. Also, hazard detection would be the responsibility of the lead car in any platooning configuration where the spacing to the end of the next platoon might be greater than between cars within a platoon.

3.4.3 SENSOR REQUIREMENTS

There are large differences in the physical properties of objects that are likely to appear in an image of the road environment. Table 3-11 shows some comparisons of the detectability of various obstacles. In this analysis objects are distinguished by their dielectric properties, density and presence of illumination at the wavelength of the detector. Dielectric properties influence the interaction with electromagnetic radiation. Mass density is the primary property influencing ultrasound reflection. Shadows, which can be mistaken for road hazards, are influenced by ambient illumination. The intensity of illumination is influenced by wavelength because the transparency of the atmosphere is a function of wavelength.

Table 3-11. Analysis of Obstacle Detectability

	Passive			Active		
Object	**Vis**	**IR**	**LIDAR**	**IR**	**Radar**	**Acoustic**
good dielectric						
opaque						
brick	+	+	+	+	–	+
paper	+	+	+	–	–	
tire	+	+	+	+	+	+
transparent						
glass	–	+/–	–	+/–	–	+
poor dielectric						
animal	+	+	+	+/–	+	
wood	+	+	+	+	–	+
Conductor						
metal-muffler etc.	+	+	+	+	+	+
Shadow	+	+/–	–	–	–	–

1) + or- indicates detectability either due to reflectivity or differences in absorption from background.
 + = easily detectable
 - = difficult to detect.
2) A tire is detectable at radar wavelengths because of steel belts
3) +/- for IR entries indicates strong wavelength dependence

For passive detection, objects must be distinguished from the background by differences in absorption and reflectivity at the wavelength of the image. The data in the table indicated that this is possible except for transparent objects which only rarely occur as road hazards. With passive detection, shadows present a problem because some scene analysis is required to distinguish a shadow from possible debris on the road surface. For active sensors, reflectivity is most important because detection is based upon receiving an echo from the object. Most solid objects absorb light at visible, UV and IR wavelengths. Solid objects also reflect some light at these wavelengths so they would be visible with active lidar. Not all solid objects reflect radar well. Good dielectrics such as plastic, dry wood and cardboard are relatively transparent at radar frequencies. Rather than being a disadvantage of radar this property allows us to use radar in combination with other sensors to rapidly distinguish among possible hazardous conditions. The same is true to a lesser extent with sonar operating at ultrasound frequencies. Objects reflect sound primarily because their mass density differs from that of air. However, very thin materials such as the paper in a paper bag will be much more transparent to ultrasound than a brick for example. We note that shadows caused by ambient illumination are not detected by active sensors and that this can be used to rapidly distinguish a shadow from a real object.

The presence of illumination either by sun or artificial light is required to cause a shadow. Solar illumination is not present at ultraviolet wavelengths shorter than approximately 300 nanometers because of absorption in the atmosphere, principally the ozone layer Park, J. et. al., 1987. Also, there is no illumination at some infra-red wavelengths because of atmospheric absorption, principally by water vapor Park, J. et. al., 1987. At night a similar situation results because of atmospheric absorption and the wavelength distribution of output from light sources. Further work is needed to determine if a wavelength range exists where shadows are diminished but sufficient ambient radiation can present a useable image. This may be possible at far infra-red wavelengths where objects are visible due to the radiation emitted.

Upon examining the data in the table, one can see that it is possible to use a combination of sensor systems to make rapid decisions about hazardous conditions. For example, a brick or a paper bag has differing reflectivity for different sensors and this fact alone can distinguish its presence. A piece of metal being a good conductor with a high density has a strong reflection for all sensors and can readily be perceived as a danger without further analysis provided its geometry in such that an echo is reflected back to the radar.

3.4.4 Active Vs. Passive Sensor Systems

Passive detection of road conditions usually requires analyzing images and identifying objects by pattern recognition. Many road hazards have irregular form and are difficult to identify. Furthermore, scenes of the road environment have considerable detail in the background. This requires that foreground objects be separated from background clutter. One can look for change in the image as an indicator of the presence of an obstacle entering the road area. However, this cannot be done on a pixel by pixel basis because there are many changes that do not represent hazards. For example, the preceding vehicle can change position in the lane. In order to detect changes that are threats, one needs to detect changes in the scene at the object level, which requires a great deal of computation. Also, the determination of the distance and closing speed of objects in a scene require a detailed analysis of many frames.

Active sensing depends upon echoes from objects in the field of view. It is possible to determine distance and closing speed directly, in a single time interval, with active sensing. This property makes it ideally suited to provide an initial determination of a possible hazardous condition. Furthermore, since this information is available directly there is no need to have either high range resolution or angular resolution. One only needs sufficient resolution to determine if an object is within a broad category of possible threats based upon distance and closing speed. This reduces the specifications of the capability of these sensors allowing less expensive equipment to be used. The optimum strategy to employ is to use active sensors in cooperation with passive imaging. Active sensors can do an initial determination of a possible hazard condition. If one exists, then braking should begin, but not necessarily at emergency levels. When precautionary braking has begun, a more thorough analysis of the image of the road environment can be analyzed. If a hazardous condition exists based upon this more complete analysis, then emergency braking should commence. Any system must exhibit a very low false alarm rate or the system will be unacceptable.

3.4.5 State-of-the-Art In Obstacle Detection

Komoda 1992 has an infrastructure TV camera at the Toyota test track that is intended to detect small obstacles over the range from 10 to 500 m. The camera is mounted atop an 8.8 m tall pole. It can detect objects 0.3 x 0.3 x 0.05 m at between 10 and 30 m and objects 2 x 2 x 0.3 m at 100 to 500 m. The algorithm for obstacle detection involves subtraction of the previous scene from the present. In the same paper the term obstacle detection is used in reference to the detection of "four-wheel vehicles and motorcycles" from an instrumented vehicle, however.

Komoda uses scene subtraction to indicate changes in the scene, not unusual structures. The rate at which the reference scene (the one that is subtracted from the current scene) is updated determines how long an obstacle is recognized. One cannot keep a reference scene forever because insolation, shadows and changing weather will alter the scene. Such alterations would produce false obstacle detections. If, on the other hand, one accepts each frame as the reference for the following frame, the only "obstacles" that are detected are ones that move a significant number of pixels in a sixtieth of a sec. These obstacles are furthermore "lost" once they stop moving.

Gradient analysis is fairly effective in discriminating roadway from shoulders and ground next to the road (De Miguel et al 1992). Gray level run length (GLRL) and gradient magnitude standard deviation over a patch of pixels were used successfully to identify the edge of the road, even in the presence of shadows. There is a suggestion that road continuity was assumed as a tracking aid. Fernandez-Maloigne et al (no date) present a pixel patch filtering algorithm that separates roadway from other objects (e.g. a passing truck) effectively.

Such texture analysis techniques should be effective in detecting obstacles but will not discriminate between harmless, e.g. flat markings, and potentially harmful obstacles. Even the relatively inexpensive technique used in image motion compensation (American Society of Photogrammetry 1980) could detect, but not localize obstacles in this fashion.

Mallinson 1989 describes the goals of his obstacle-detection vehicular radar: It is to detect a 0.1 m^2 (- 10 dBm^2) target at 300 m range in bad weather with a range resolution of 5 m at maximum ramge, one Hz update rate, +/- 15 degree coverage and one degree resolution in aximuth and elevation. Operating at 94 GHz, the radar shows a background of 5 to 25 dB in a sample of raw data covering 500 m of range with 128 range cells. A man at 80 m presents a

58 dB echo, a Ford Fiesta at 160 m is 62 dB, a fence at 240 m is 58 dB and trees at 200 m are 32 dB. The background is almost independent of range, suggesting processing in the nature of sensitivity-range-control. Radar cross sections at this frequency are quoted as 10 dBm^2 for a small car, 15 dBm^2 for a van, 0 dBm^2 for a man, -10 to + 10 dBm^2 for debris. A road, at an incidence angle of five degrees, is quoted as having a radar cross section of -40 dB/m^2. It is believed that this should read -40 dBm^2/m^2, referring to sigma zero, the clutter cross section of the road per unit area at the quoted incidence angle. In an older concept of radar back scattering which assumes that the apparent cross section varies as the cosine of elevation angle, as measured from the nadir, one could define the coefficient gamma as -29.4 dBm^2/m^2.

3.4.6 Summary

The problem of detecting obstacles that may appear on the road surface is extremely difficult. For early AHS systems we may be required to rely on the driver to intervene when an obstacle appears. Much of the obstacle problem can be legislated away. That is, do not allow vehicles with external cargo, require all trunks to be closed with no exposed loads, and inspect all AHS certified vehicles periodically so that mufflers, tail pipes, and piece of truck tires will not be thrown from the vehicles. AHS roadways should be fenced to limit animal access. High frequency acoustic radiators can be located at entry/exit ramps to discourage animal entry. If all these measures are employed, there should be a greatly reduced occurrence of obstacles on the roadway.

Some principal conclusions and recommendations are itemized below:

- Rejecting false determinations of hazards is as important as detecting genuine hazards.
- Solely analyzing images for road hazards is very computationally costly.
- A combination of active sensors offers an accurate instantaneous picture of the road hazard situation because distance and relative velocity are directly available.
- Active sensing would be considerably aided if the rear of each car provided a characteristic signature.
- Field tests are needed for active sensor systems, particularly high frequency radar, on typical road hazards such as large animals, cardboard boxes, tires, etc.

3.5 PRELIMINARY LATERAL AND LONGITUDINAL SYSTEM REQUIREMENTS

While it is very early in the studies and development of an AHS to be addressing detailed requirement specifications of sub systems, we feel it is useful to begin the process of postulating values based upon preliminary studies, simulation, and common sense. These requirements serve to provide some realism and to guide researchers.

The discussions presented below are very preliminary and certainly not complete. One might disagree with some of the requirements but hopefully it will generate additional thinking and discussion.

3.5.1 Headway Measurement System

The Calspan team feels that the AHS should be able to function in adverse weather such as fog, heavy rain, heavy falling snow, and icy and snow covered roads. One can argue that if an AHS performed as well as manually driven vehicles, that ought to be sufficient. While we currently live with the weather problems and human driving, we feel this is an opportunity to provide safe traffic flow in dense fog, heavy rain and blizzard conditions. The technology is available to provide an all weather, zero visibility, capability.

The headway sensor, whether it employs radar or laser techniques, must provide sufficient azimuth resolution to be able to locate vehicles ahead to a given driving lane. It is important that the longitudinal control system does not control on vehicles in adjacent lanes, or that it picks up adjacent lane vehicles on curves. If one were to postulate detection ranges of 91 m (300 ft) for a headway radar , a 2 degree azimuth beam width is required to limit the beam coverage to 3 m (10 ft) at 91 m (300 ft). Thus, it appears that azimuth resolution of about 1.5 to 2 degrees is required. This headway radar must also cover a fairly wide azimuth coverage to detect and locate vehicles in adjacent lanes for verifying that a space is available for lane change maneuvers. This situation is depicted in Figure 3-26. The coverage of the headway radar is shown as ± 45°. Thus, the headway radar will be required to have a narrow azimuth beam width and be scanned, in azimuth, whether mechanically or electronically. The figure also depicts the proximity radar coverage required to detect vehicles to the sides to verify empty slots for lane change maneuvers. The proximity radars will probably be separate radar from the headway sensor, although both functions could be provided by a single radar that scanned through 360_. Work is currently underway to develop and test proximity radars for lateral collision avoidance systems to assist human drivers. These systems should reduce the number of lateral collisions due to improper lane change and may well be available to the public before an AHS is developed.

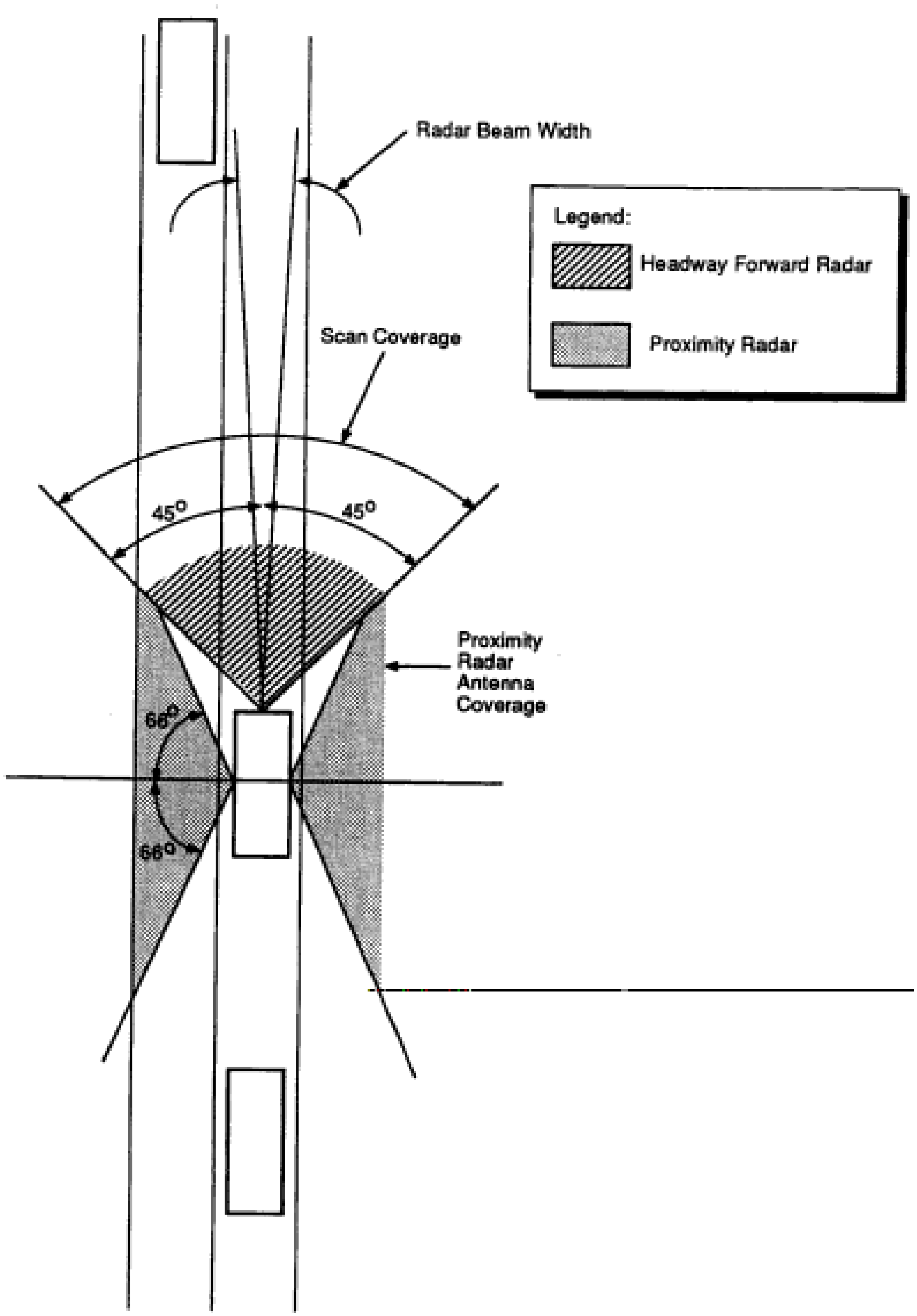


Figure 3-26. Radar Azimuth Antenna Coverage

The accuracy of the headway sensor system needs to be addressed. It is envisioned that a headway sensor will provide range and differentiated velocity measurement (ÆV) to the longitudinal control system. The time varying errors, such as noise, impact on the quality of the control. The reader is referred to in Section 3.6 of this chapter for a discussion of the effect of noise like errors upon the closed loop performance. The loop gains which controls the "tightness" of the control loop must be reduced to accommodate noisy sensor signals. It appears that reasonably good control can be obtained with range errors of 1 foot (1 sigma), and velocity errors of 1 ft/sec (1 sigma). These values also appear reasonable to obtain with a radar sensor. Greater errors could be tolerated if the acceleration of the preceding vehicle were known. Our simulation determined the acceleration from the differential velocity measurements. As a starting point, one could consider the 1 ft and 1 ft/sec values. Additional studies, including simulations, are required to further refine these values.

3.5.2 Lateral System Considerations

The lateral control systems that maintain lane tracking should be based upon an all weather sensor. The vehicles must never be denied lateral steering information. If the weather conditions are such that longitudinal control is no longer functioning, the whole highway can be shut down and all vehicles brought to a stop. To even bring vehicles to an orderly stop, the steering system must be functioning.

In addition to operation in all weather, the lateral sensor system must be highly reliable. As discussed in Chapter One of this volume the probability of a loss of steering control must be extremely low. Techniques that can be confused or generate large errors under unfavorable conditions such as low contrast, low sun angles etc. are not acceptable.

Lateral sensor errors will probably need to be restricted to 2.5 to 5 cm (1 to 2 in (1 sigma)) in order to restrict control errors to 15 cm (6 in) (3 sigma value). To examine effects of lateral sensor errors a high fidelity lateral control loop simulation is required. Until such simulations are performed, these values may be used as guidelines.

3.5.3 Road Conditions

The control loop parameters for both the lateral and longitudinal control loops will need to be optimized for some conditions. The lateral steering rates, longitudinal accelerations, and braking levels will need to change with road surface conditions. Under wet conditions, less aggressive accelerations, lateral maneuvers and braking levels will be required. For snow covered and icy road surfaces even less aggressive maneuvers are required. Both the lateral and longitudinal control loops will require a measurement of the coefficient of friction between the tire and road surface. This estimate of coefficient of friction could be supplied by roadside instrumentation or be measured onboard the vehicle. One method to measure the coefficient of friction is to employ a small wheel that is lowered to the road surface when measurements are required (wet or icy conditions). A given force would be applied to the wheel, possibly with a spring assembly. A brake on the wheel would be pulsed and the breaking force would be measured. For a given wheel load, and measured brake force a good estimate of the coefficient of friction can be derived. The wheel would only be lowered during wet or icy conditions and can be pulsed at a fairly high rate if needed. It is very important that measure of coefficient of friction be available. A control system optimized for dry conditions will be completely unsafe on icy roads. A human adapts to the aggressiveness of his/her maneuvers with weather conditions.

3.6 SIMULATION

Simulation of longitudinal control systems has provided results indicating the ability of a vehicle to work in an AHS. There has been a great deal of research by our peers in this area. Researchers have concentrated on developing controllers ideal for platoons. It is envisioned that a platoon will consist of a string of vehicles, ranging in number from 10-20, traveling at very close distances to each other on the order of a few feet. Some concerns arise from this situation dealing with safety due to the small headway. Proponents of this idea counter with the argument that if a collision occurs, small delta velocities will result yielding limited damage. Proponents have also shown that very tight control, on the order of inches is possible. The work performed in our simulations examines the ability of three different controllers to operate in an AHS environment. In particular, we have concentrated on the effects sensor noise will have on an AHS. Our results indicate that knowledge of the previous vehicle's acceleration is not required for the headways employed. In addition, sensor errors represented by with normal distributions of +/- .3048 m (1 ft, one sigma) for distance and +/- .3048 m/sec (1 ft/sec, one sigma) for velocity can be accommodated at a cost of maneuver error. Our results indicate that sensor errors of this magnitude will not jeopardize the safety of the vehicle due to a robust braking algorithm.

3.6.1 Simulation Tools

The only simulation tool used in the longitudinal simulations was Simulink, a program for simulating dynamic systems. Simulink contains all the necessary tools for both model definition and model analysis. Model definition takes place by a graphical prototyping method. All block diagrams in section 3.6 are direct outputs of Simulink. Simulations were run using Simulink's built in Runge Kutta integration algorithm. Other integration algorithm were available but Runge Kutta handles non-linearities and a mix of continuous and discrete signals.

3.6.2 Vehicle Model

A vehicle model with longitudinal, lateral, and yaw characteristics was designed to represent the characteristics of a lower powered mid-size car. The reason for selecting this car is to model the lowest performing automobile that would be driven on an AHS. In this way, operating characteristics can be developed that would ensure safe operation for all classes of vehicles. The vehicle model as shown in Figure 3-27 was developed from an engine model and a vehicle dynamics model. The engine model uses throttle angle as an input and provides torque as an output. The vehicle dynamic's model contains four inputs: torque from the engine model, torque from the brake, front wheel steering angle, and rear wheel steering angle. Outputs are the acceleration, velocity, and position for the longitudinal, lateral and yaw directions. The description of the engine model and vehicle dynamics model are described in detail in the following two subsections.

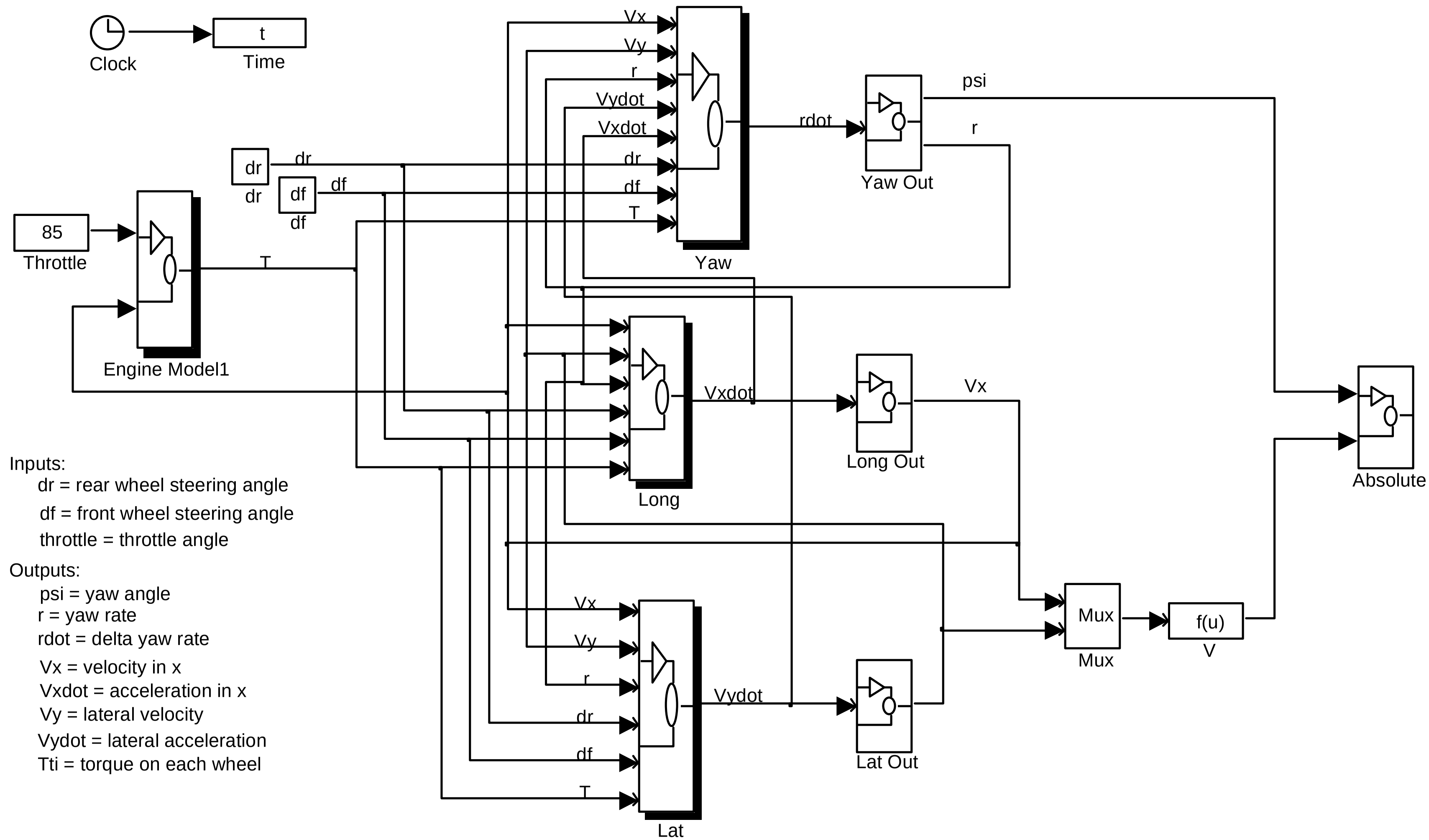


Figure 3-27 A vehicle model contains four components: Engine Model, and the Yaw, Longitudinal, and Lateral Dynamics

Performance of the vehicle model was measured in terms of 0 to 60 mph acceleration time at full throttle and the acceleration at 60 mph at full throttle. The model was optimized to provide a 0.0 to 26.82 m/sec (88.0 ft/sec or 60.0 mph) acceleration in 14 seconds and an acceleration of 0.98 m/sec/sec (0.1 g or 3.22 ft/sec/sec) at 26.82 m/sec. Figures 3-28 and 3-29 depict the acceleration and velocity profiles vs time for full throttle acceleration. Another vehicle characteristic of interest is the capability of the vehicle to slow down without braking, i.e. by coasting. By utilizing a vehicles capability to coast for reducing speed, fuel efficiency will be higher and rider comfort will increase. Brakes normally would not be used in an AHS except for emergency maneuvers. Figures 3-30 and 3-31 show the ability of a vehicle to reduce speed without using brakes. This vehicle model is used through out the remainder of the simulations.

3.6.2.1 Engine Model

The engine model is a modification to the engine model developed by Ioannou and Xu, 1994. A modification was made to change the characteristics of the vehicle from a premium-size car such as Lincoln-Town car to a low powered mid-size car. The reason for changing the performance of the vehicle is to model the lowest performing vehicle that would be driven on an AHS. In this way, operating characteristics can be developed that would ensure safe operation for all classes of vehicles. In addition to changing the performance of the vehicle, the units were changed from a miles-per-hour system to a feet-per-second system.

Figure 3-32 shows the engine model as implemented in Simulink. The engine model contains the engine, torque converter, and transmission. The throttle input is limited by the saturation function from 3 to 85 degrees. The engine speed, n (rpm), is an output from the engine and input to the torque converter. The gain on the turbine speed was reduced from 28.17 to 20.5 in the torque converter to lower the

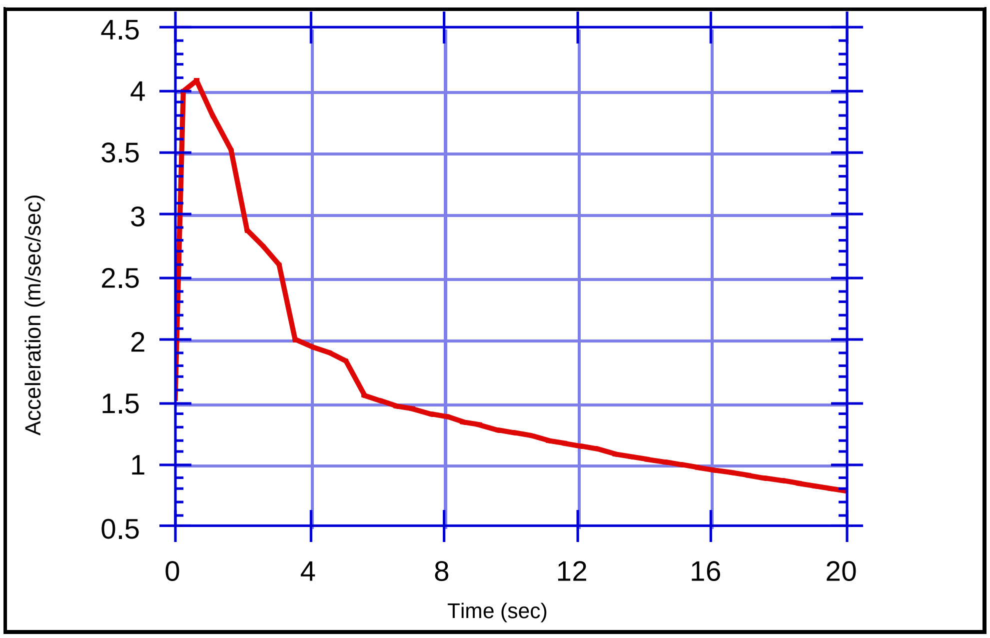


Figure 3-28. Acceleration for Full Throttle

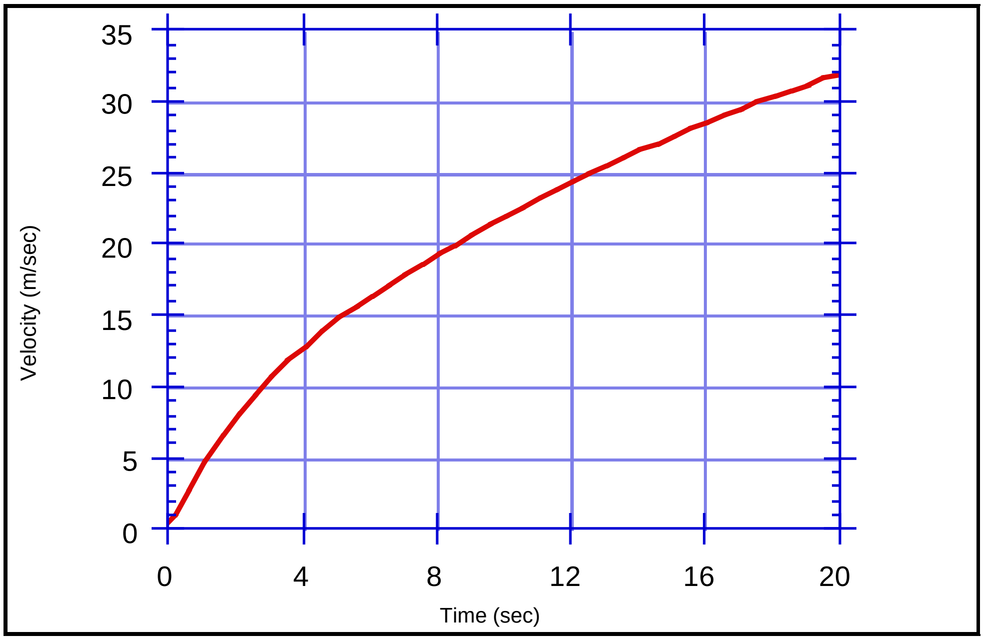


Figure 3-29. Velocity at Full Throttle

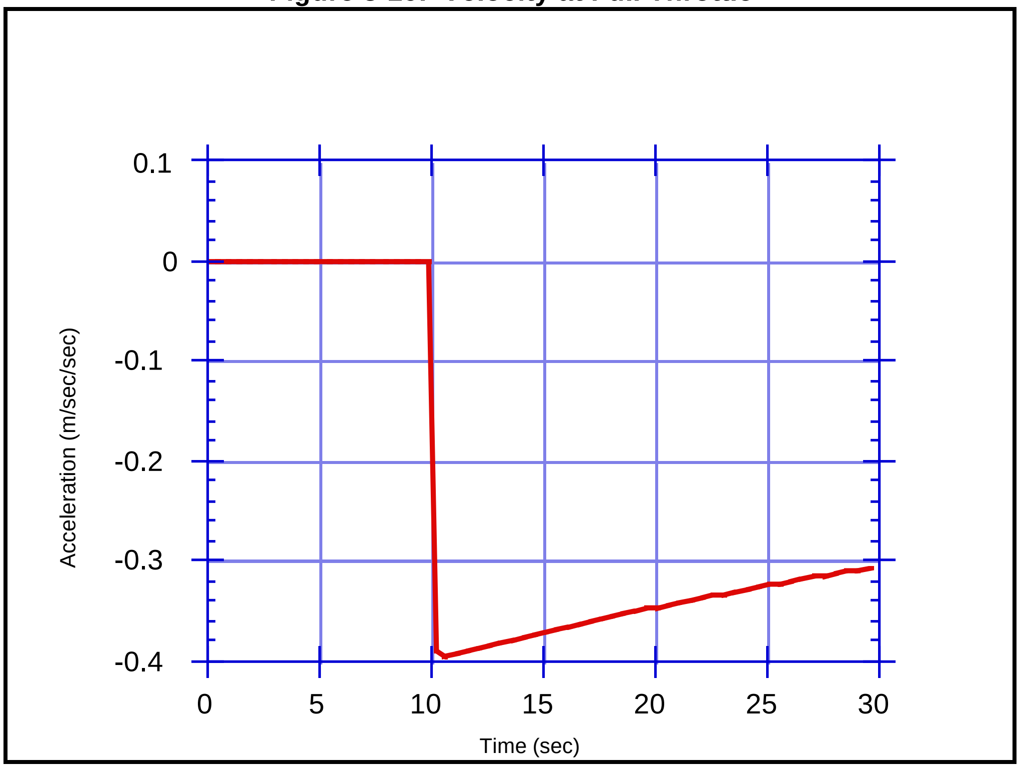


Figure 3-30. No Throttle Deceleration from 26.82 m/sec

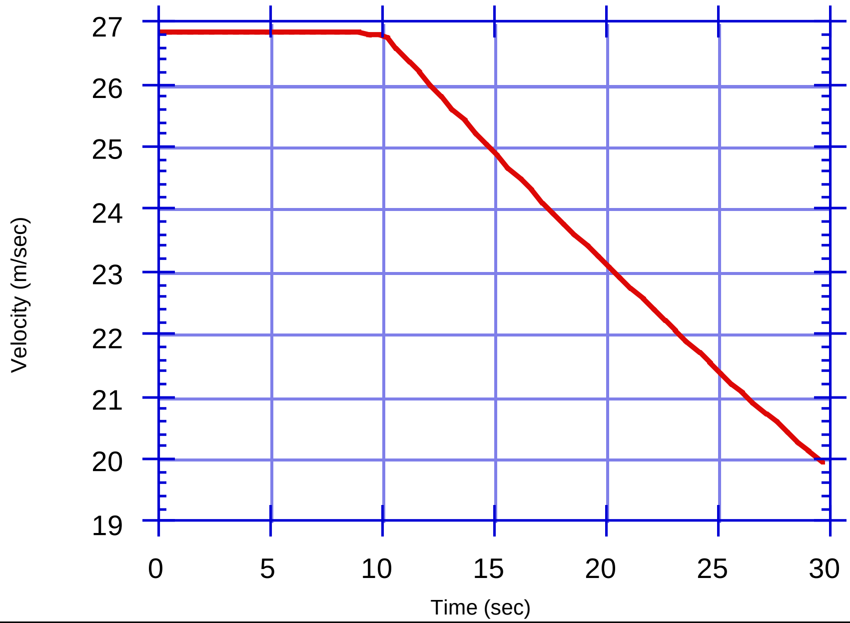


Figure 3-31. No Throttle Velocity Maneuver

3.6.2.2 Vehicle Dynamics

The vehicle dynamics model was modeled based on the work of Matsumoto and Tomizuka, 1992. In the vehicle dynamics model of Matsumoto and Tomizuka, an assumption was made that the velocity of the vehicle was approximately the velocity in the longitudinal direction. Although this is almost always the case, an equation of motion was added in the longitudinal direction giving three equations of motion:

longitudinal direction:

$$M(\dot{V}_x - V_y r) = X_1 + X_2 + X_3 + X_4 \qquad (1)$$

lateral direction:

$$M(\dot{V}_y + V_x r) = Y_1 + Y_2 + Y_3 + Y_4 \qquad (2)$$

yaw motion:

$$I\ddot{r} = l_f(Y_1 + Y_2) - l_r(Y_3 + Y_4) - d(X_1 + X_3) + d(X_2 + X_4) \qquad (3)$$

where X_i is the longitudinal force on each tire, Y_i is the lateral force on each tire, l_f , l_r, and d are the distance from the center of gravity to the front of the vehicle, the rear of the vehicle and the side of the vehicle, respectively.

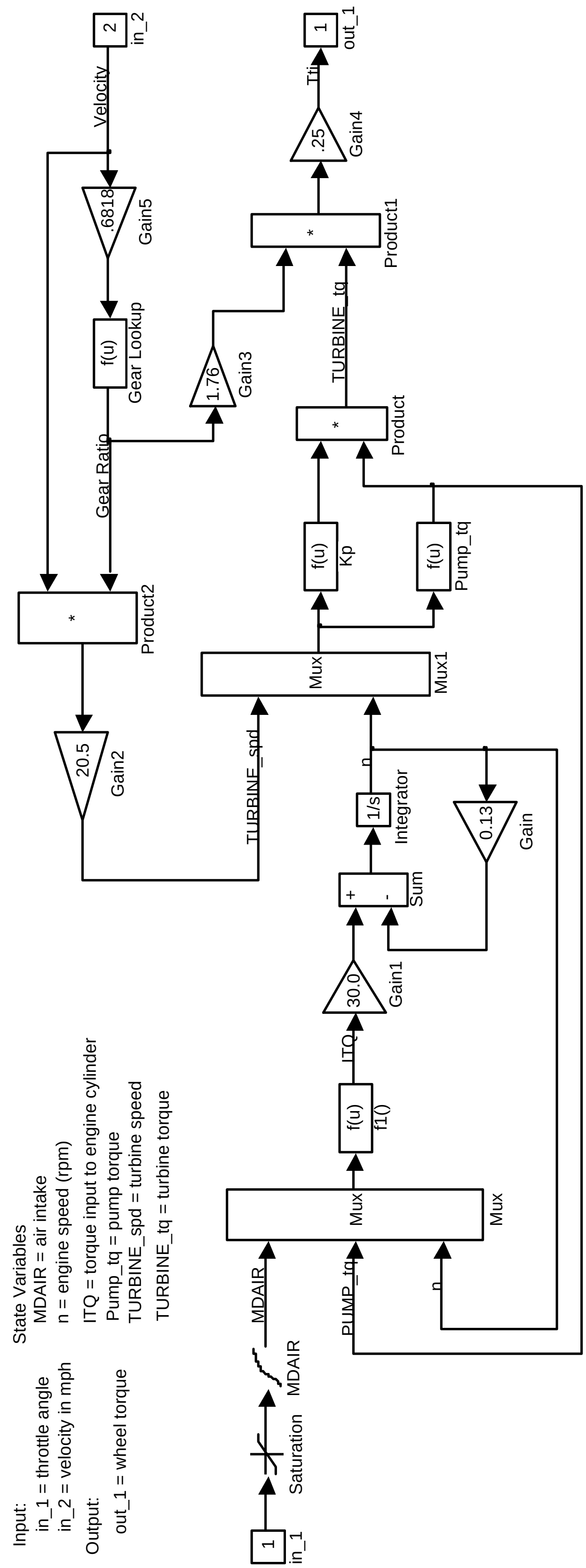


Figure 3-32 The Engine Model

Figure 3-27 shows the implementation of the vehicle dynamics in the vehicle model. The blocks Yaw, Long, and Lat are used to compute the motion of the vehicle. The blocks Yaw Out, Long Out, and Lat Out perform integration of the respective acceleration to yield velocity and position. The Absolute block computes the motion in terms of absolute coordinates. In addition to the longitudinal motion described above, the static friction, rolling resistance, aerodynamic drag, and braking force are used in determining the longitudinal motion as shown in Figure 3-33. The forces are computed from $0.2175 \cdot V_x$ for rolling resistance, $0.0161 \cdot V_x^2$ for aerodynamic resistance, and 73.33 lbs for static resistance.

3.6.3 Longitudinal Control

A longitudinal control model was developed utilizing three different techniques: feedback-linearization, proportional control, and sliding control. These controllers are discussed in detail with emphasis on their own capability to work in an AHS. The characteristics desired in a vehicle controller are:

- robustness for reaction to emergency maneuvers;
- smooth ride for passenger comfort with efficient use of throttle, brake, and coast maneuvers;
- the ability to provide to discriminate between emergency maneuvers and normal driving;
- realistically deployable in a vehicle;
- the ability to handle errors and delays in sensors;
- the ability to react to maneuvers encountered in an AHS system such as: entry/exit, platooning, autonomous intelligent cruise control, malfunction, and merging.

Before describing the longitudinal controllers, it is first worth explaining the use of the words "lead vehicle". Generally speaking, lead vehicle refers to the car directly in front of the vehicle. This should not be confused with the lead (first) vehicle of a platoon. When describing platooning, the lead vehicle will be pointed out as to whether it means the car immediately in front of the vehicle or the first vehicle of the platoon.

3.6.3.1 Feedback Linearization

Feedback Linearization was the first type of controller explored in the longitudinal controller design. In this model, the position, velocity, and acceleration of the lead vehicle is passed to the following vehicle, Figure 3-34. There are no sensors errors or delays taken into account for this control system. The feedback-linearization control model is shown in Figure 3-35. The output of 'Sum' is the desired torque to the vehicle. This torque is generated based on the rolling resistance, aerodynamic drag, coulomb resistance, position error, and velocity error. The position error is computed in 'xoverbar' which has the form:

$$\lambda_1(x\_in - x - spacing) \tag{4}$$

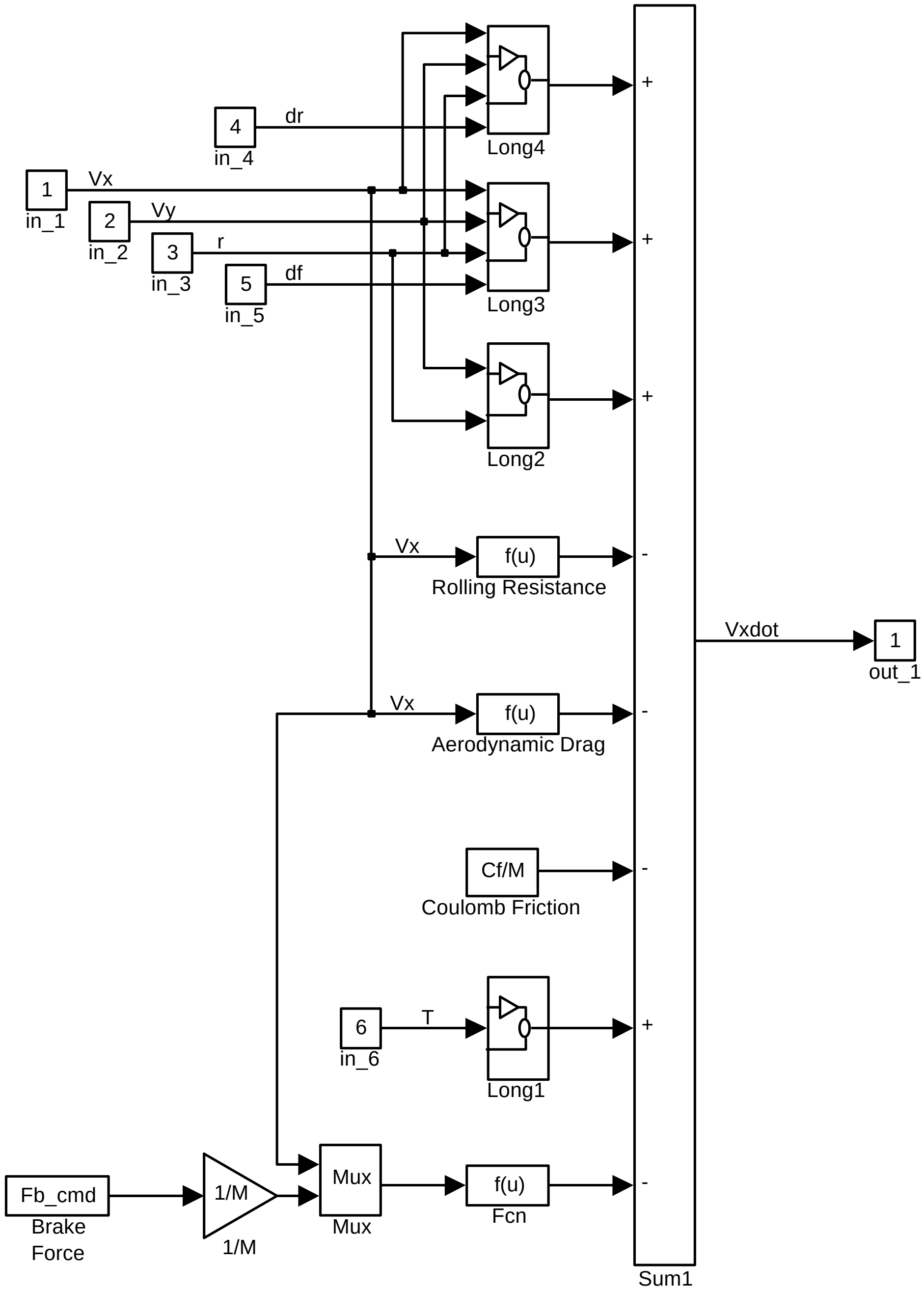


Figure 3-33 Longitudinal Vehicle Dynamics

xdes = lead vehicle position
Vxdes = lead vehicle velocity
Vxdot = lead vehicle acceleration

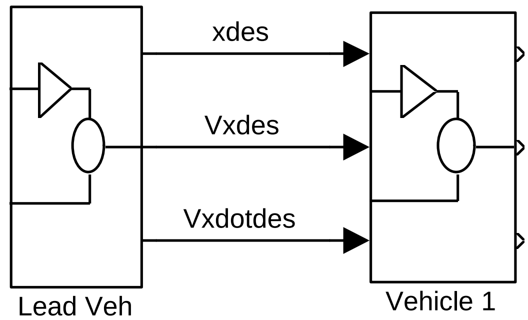


Figure 3-34. Longitudinal Control of a single vehicle using Feedback Linearization Control for the Throttle

The position error can easily be changed to regulate time headway where the separation distance between vehicles is a constant time, *h*. Then, 'xoverbar' takes the form:

$$\lambda_1(x\_in - x - h \times Vx\_in - spacing) \tag{5}$$

The velocity error is computed in 'x dot overbar' which has the form:

$$\lambda_2(Vx\_in - Vx) + Vxdot\_in \tag{6}$$

In our simulations, λ_1, λ_2 are both chosen to be 50 and the spacing between vehicles to be 17.37 m (57 ft). In later simulations involving sliding control and proportional control, a 0.5 sec headway plus 1.524 m (5.0 ft) safety gap is chosen as the spacing between vehicles. The torque output is converted to a throttle angle based on the 'Throttle Feedback Linearization'. This performs the inverse function of the engine model yielding throttle as an output which is in turn the input to the 'Vehicle Model'.

The results of simulations indicate very close vehicle following with this model. The lead vehicle was accelerated from 22.34 to 26.82 m/sec (50.0 to 60.0 mph). This will be used as a standard throttle control maneuver for the remainder of this report. It represents a more typical maneuver on an AHS, which is an acceleration up to a commanded velocity, then maintaining the commanded velocity. The following vehicle is shown to follow in the case of acceleration, velocity, and position as indicated in Figures 3-36 to 3-39. The variables Vxdotdes, Vxdot1, Vxdes, Vx1, xdes, x1 are used throughout the remainder of this section to describe the lead vehicle acceleration, following vehicle acceleration, lead vehicle velocity, following vehicle velocity, lead vehicle position, and following vehicle position, respectively.

Brake control was added to this model as shown in Figure 3-40. In this case, if a negative torque is required, the brake takes over and the throttle is kept at a minimum. A simple first order filter was used to simulate the brake delay as indicated in the 'Brake' box. The output of 'Fcn3' is the brake torque which is summed with the engine model torque in 'Vehicle Model'. Results of simulations with brake control also show very tight control as indicated in Figures 3-41 to 3-43. In these simulations, the

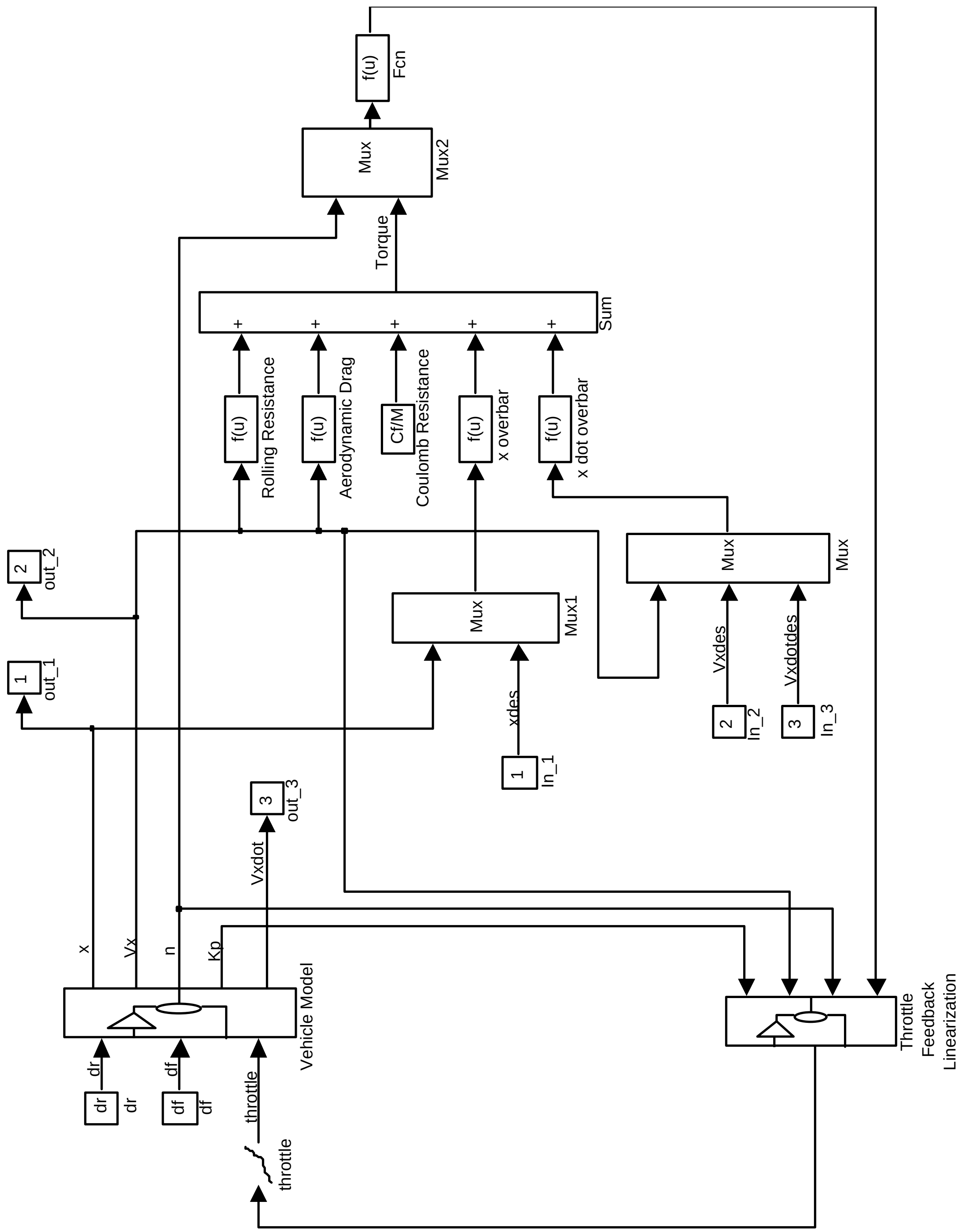


Figure 3-35 Feedback Linearization Throttle Controller

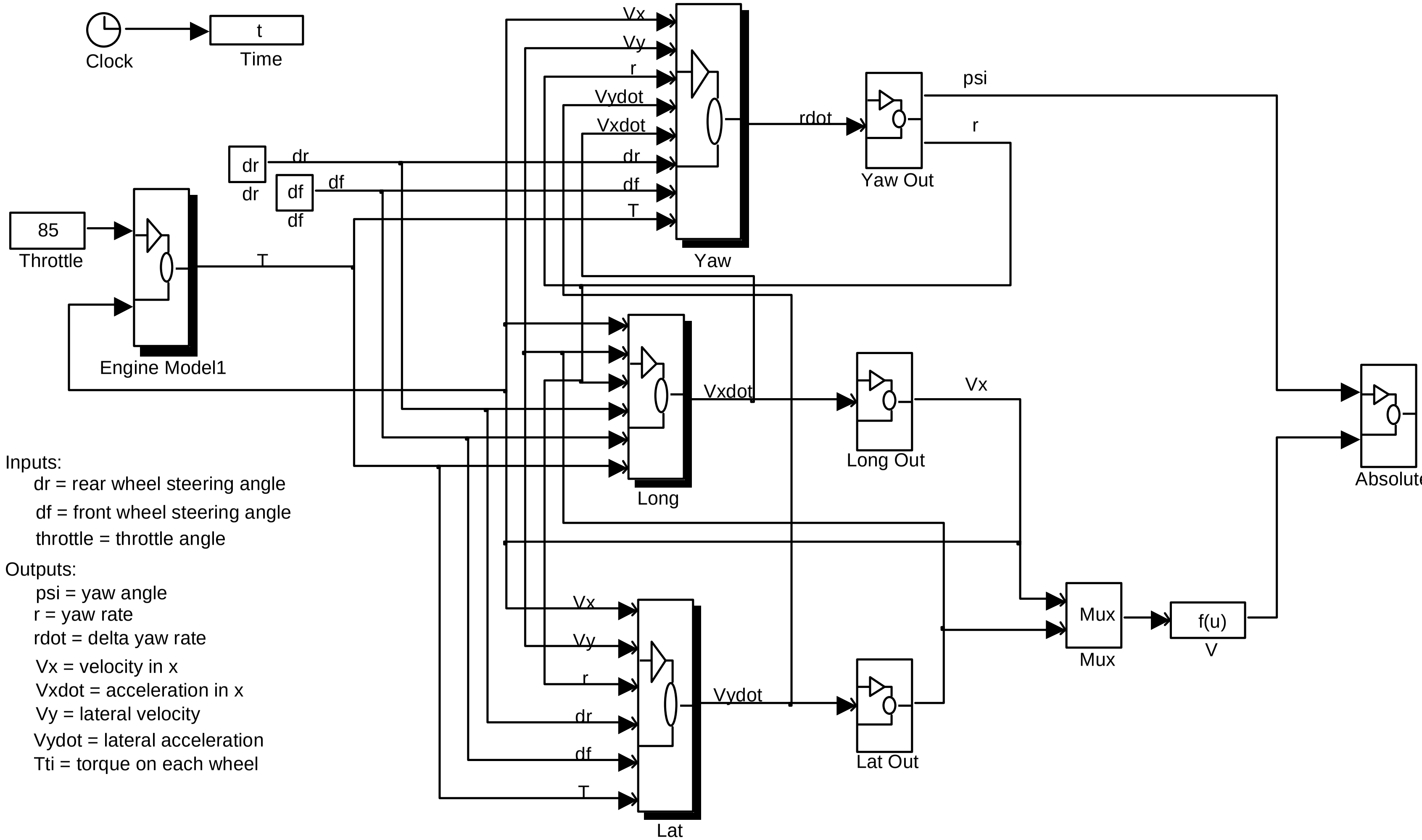


Figure 3-27 A vehicle model contains four components: Engine Model, and the Yaw, Longitudinal, and Lateral Dynamics

Performance of the vehicle model was measured in terms of 0 to 60 mph acceleration time at full throttle and the acceleration at 60 mph at full throttle. The model was optimized to provide a 0.0 to 26.82 m/sec (88.0 ft/sec or 60.0 mph) acceleration in 14 seconds and an acceleration of 0.98 m/sec/sec (0.1 g or 3.22 ft/sec/sec) at 26.82 m/sec. Figures 3-28 and 3-29 depict the acceleration and velocity profiles vs time for full throttle acceleration. Another vehicle characteristic of interest is the capability of the vehicle to slow down without braking, i.e. by coasting. By utilizing a vehicles capability to coast for reducing speed, fuel efficiency will be higher and rider comfort will increase. Brakes normally would not be used in an AHS except for emergency maneuvers. Figures 3-30 and 3-31 show the ability of a vehicle to reduce speed without using brakes. This vehicle model is used through out the remainder of the simulations.

3.6.2.1 Engine Model

The engine model is a modification to the engine model developed by Ioannou and Xu, 1994. A modification was made to change the characteristics of the vehicle from a premium-size car such as Lincoln-Town car to a low powered mid-size car. The reason for changing the performance of the vehicle is to model the lowest performing vehicle that would be driven on an AHS. In this way, operating characteristics can be developed that would ensure safe operation for all classes of vehicles. In addition to changing the performance of the vehicle, the units were changed from a miles-per-hour system to a feet-per-second system.

Figure 3-32 shows the engine model as implemented in Simulink. The engine model contains the engine, torque converter, and transmission. The throttle input is limited by the saturation function from 3 to 85 degrees. The engine speed, n (rpm), is an output from the engine and input to the torque converter. The gain on the turbine speed was reduced from 28.17 to 20.5 in the torque converter to lower the

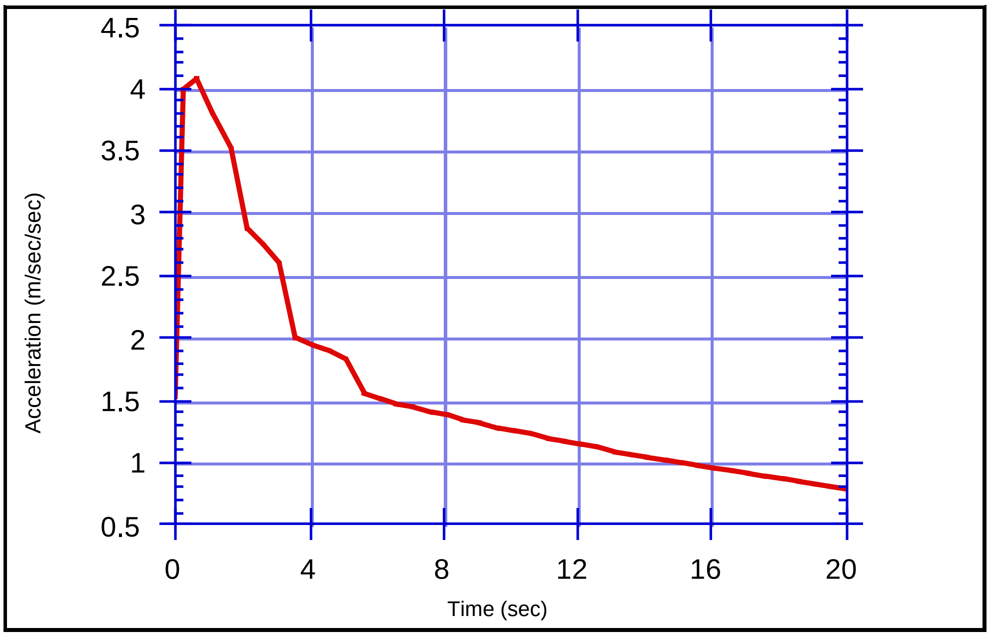


Figure 3-28. Acceleration for Full Throttle

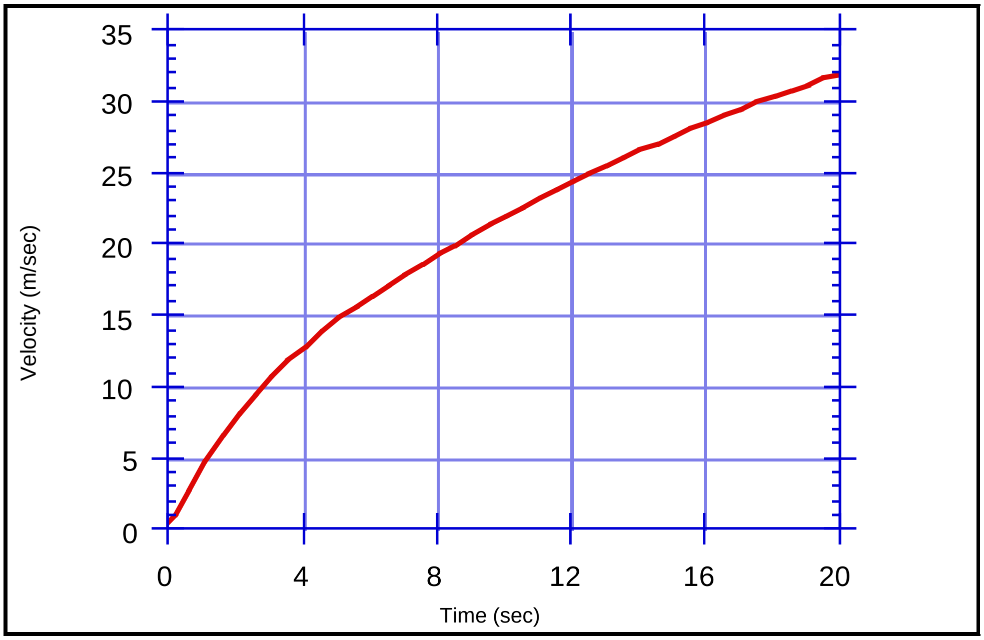


Figure 3-29. Velocity at Full Throttle

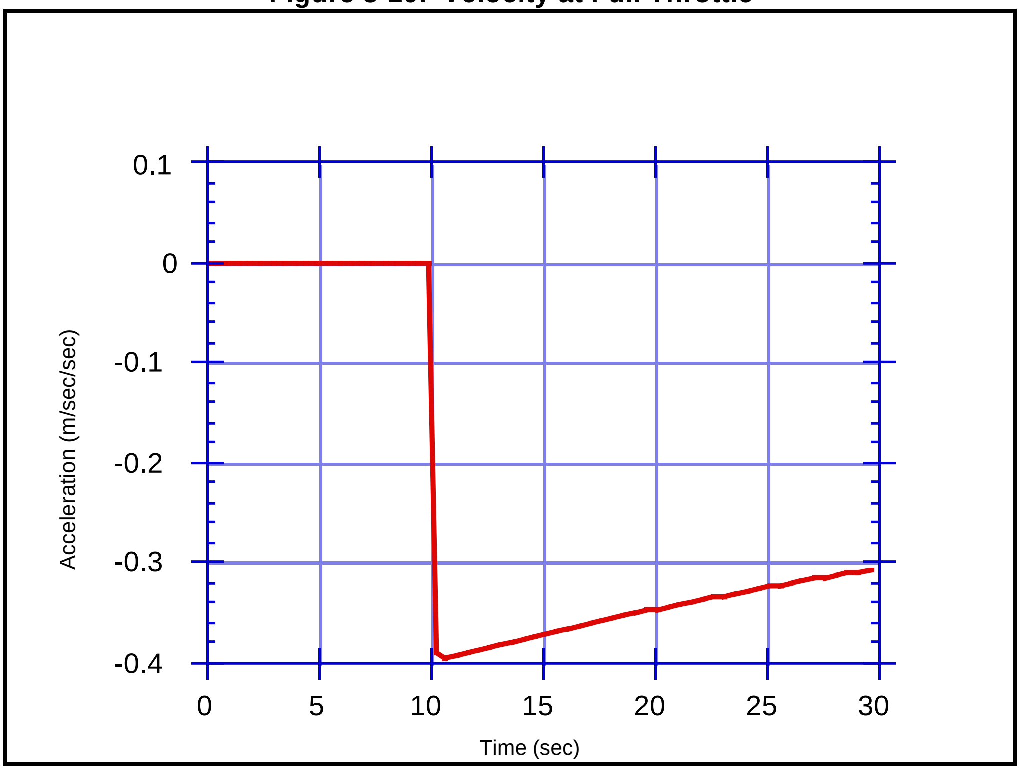


Figure 3-30. No Throttle Deceleration from 26.82 m/sec

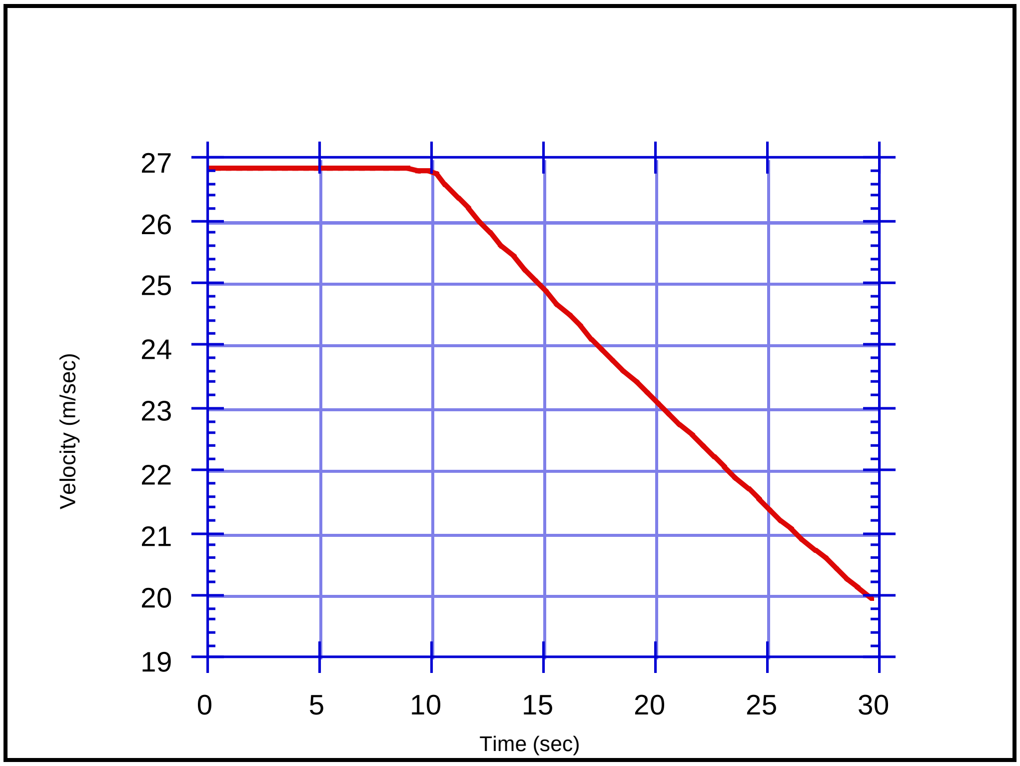


Figure 3-31. No Throttle Velocity Maneuver

3.6.2.2 Vehicle Dynamics

The vehicle dynamics model was modeled based on the work of Matsumoto and Tomizuka, 1992. In the vehicle dynamics model of Matsumoto and Tomizuka, an assumption was made that the velocity of the vehicle was approximately the velocity in the longitudinal direction. Although this is almost always the case, an equation of motion was added in the longitudinal direction giving three equations of motion:

longitudinal direction:

$$M(\dot{V}_x \quad V_y r) \quad X_1 \quad X_2 \quad X_3 \quad X_4 \qquad (1)$$

lateral direction:

$$M(\dot{V}_y \quad V_x r) \quad Y_1 \quad Y_2 \quad Y_3 \quad Y_4$$

(2)

yaw motion:

$$I\ddot{\psi} = l_f(Y_1 + Y_2) - l_r(Y_3 + Y_4) - d(X_1 + X_3) + d(X_2 + X_4) \qquad (3)$$

where X_i is the longitudinal force on each tire, Y_i is the lateral force on each tire, l_f , l_r, and d are the distance from the center of gravity to the front of the vehicle, the rear of the vehicle and the side of the vehicle, respectively.

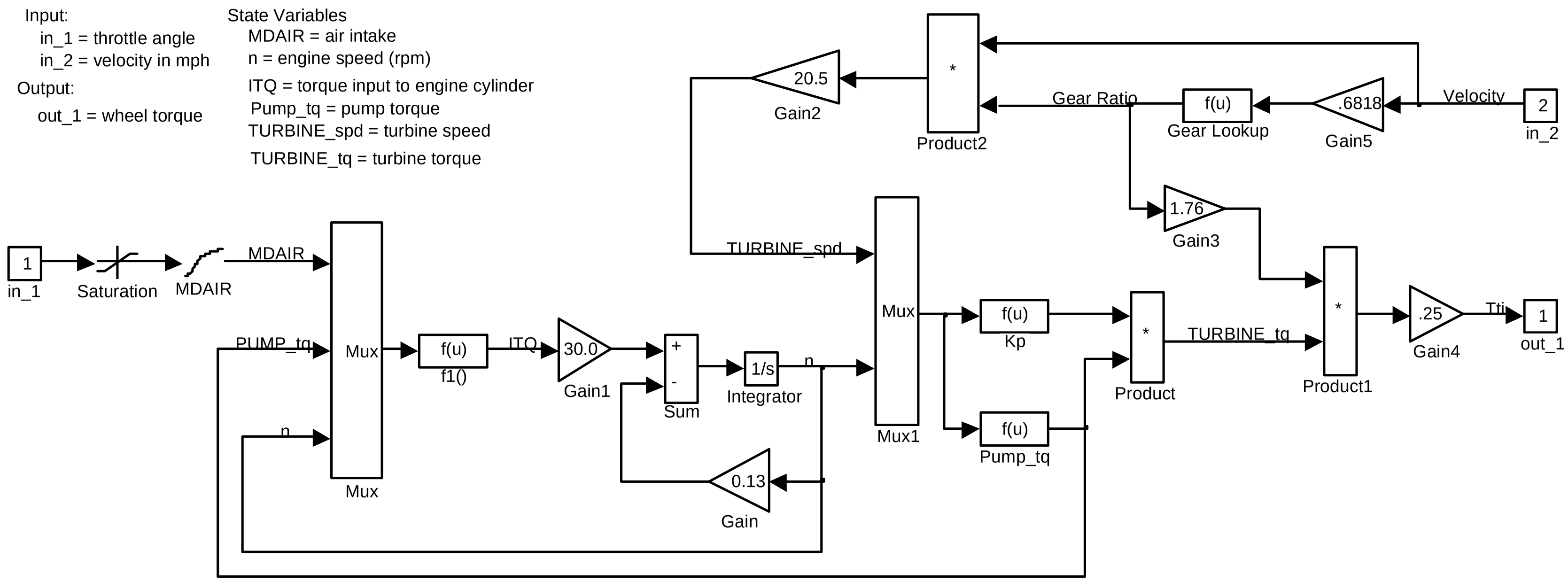


Figure 3-32 The Engine Model

Figure 3-27 shows the implementation of the vehicle dynamics in the vehicle model. The blocks Yaw, Long, and Lat are used to compute the motion of the vehicle. The blocks Yaw Out, Long Out, and Lat Out perform integration of the respective acceleration to yield velocity and position. The Absolute block computes the motion in terms of absolute coordinates. In addition to the longitudinal motion described above, the static friction, rolling resistance, aerodynamic drag, and braking force are used in determining the longitudinal motion as shown in Figure 3-33. The forces are computed from $0.2175 \cdot V_X$ for rolling resistance, $0.0161 \cdot V_X^2$ for aerodynamic resistance, and 73.33 lbs for static resistance.

3.6.3 Longitudinal Control

A longitudinal control model was developed utilizing three different techniques: feedback-linearization, proportional control, and sliding control. These controllers are discussed in detail with emphasis on their own capability to work in an AHS. The characteristics desired in a vehicle controller are:

- robustness for reaction to emergency maneuvers;
- smooth ride for passenger comfort with efficient use of throttle, brake, and coast maneuvers;
- the ability to provide to discriminate between emergency maneuvers and normal driving;
- realistically deployable in a vehicle;
- the ability to handle errors and delays in sensors;
- the ability to react to maneuvers encountered in an AHS system such as: entry/exit, platooning, autonomous intelligent cruise control, malfunction, and merging.

Before describing the longitudinal controllers, it is first worth explaining the use of the words "lead vehicle". Generally speaking, lead vehicle refers to the car directly in front of the vehicle. This should not be confused with the lead (first) vehicle of a platoon. When describing platooning, the lead vehicle will be pointed out as to whether it means the car immediately in front of the vehicle or the first vehicle of the platoon.

3.6.3.1 Feedback Linearization

Feedback Linearization was the first type of controller explored in the longitudinal controller design. In this model, the position, velocity, and acceleration of the lead vehicle is passed to the following vehicle, Figure 3-34. There are no sensors errors or delays taken into account for this control system. The feedback-linearization control model is shown in Figure 3-35. The output of 'Sum' is the desired torque to the vehicle. This torque is generated based on the rolling resistance, aerodynamic drag, coulomb resistance, position error, and velocity error. The position error is computed in 'xoverbar' which has the form:

$$\lambda_1(x\_in - x - spacing) \qquad (4)$$

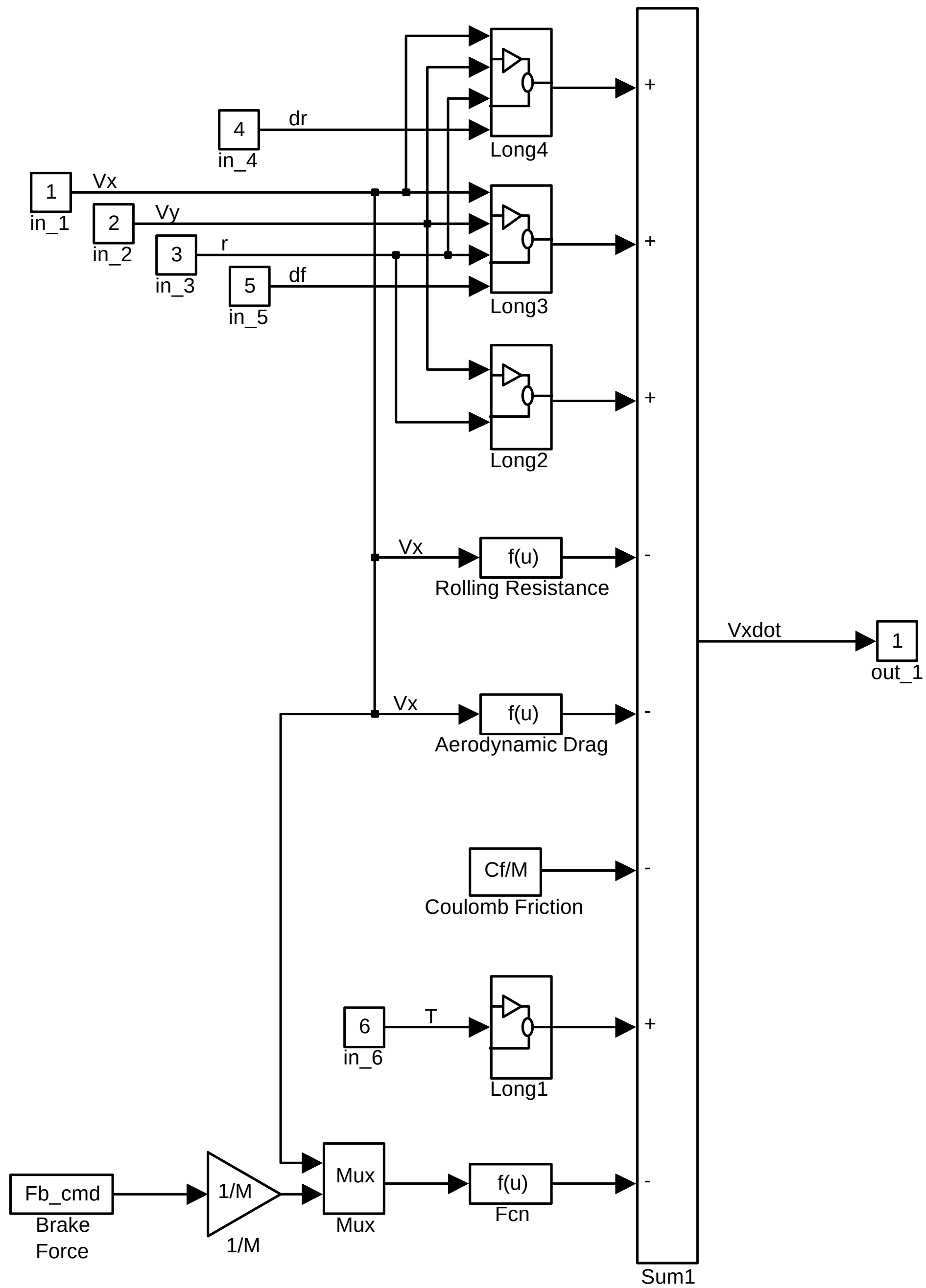


Figure 3-33 Longitudinal Vehicle Dynamics

xdes = lead vehicle position
Vxdes = lead vehicle velocity
Vxdot = lead vehicle acceleration

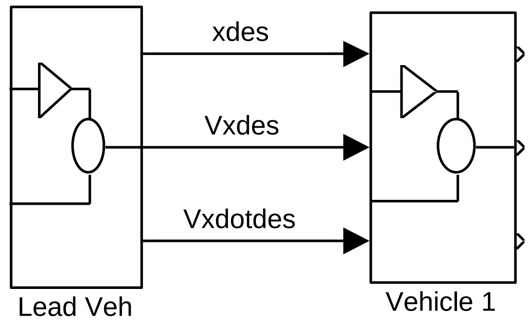


Figure 3-34. Longitudinal Control of a single vehicle using Feedback Linearization Control for the Throttle

The position error can easily be changed to regulate time headway where the separation distance between vehicles is a constant time, *h*. Then, 'xoverbar' takes the form:

$$\lambda_1(x\_in - x - h \times Vx\_in - spacing) \qquad (5)$$

The velocity error is computed in 'x dot overbar' which has the form:

$$\lambda_2(Vx\_in - Vx) + Vxdot\_in \qquad (6)$$

In our simulations, λ_1, λ_2 are both chosen to be 50 and the spacing between vehicles to be 17.37 m (57 ft). In later simulations involving sliding control and proportional control, a 0.5 sec headway plus 1.524 m (5.0 ft) safety gap is chosen as the spacing between vehicles. The torque output is converted to a throttle angle based on the 'Throttle Feedback Linearization'. This performs the inverse function of the engine model yielding throttle as an output which is in turn the input to the 'Vehicle Model'.

The results of simulations indicate very close vehicle following with this model. The lead vehicle was accelerated from 22.34 to 26.82 m/sec (50.0 to 60.0 mph). This will be used as a standard throttle control maneuver for the remainder of this report. It represents a more typical maneuver on an AHS, which is an acceleration up to a commanded velocity, then maintaining the commanded velocity. The following vehicle is shown to follow in the case of acceleration, velocity, and position as indicated in Figures 3-36 to 3-39. The variables Vxdotdes, Vxdot1, Vxdes, Vx1, xdes, x1 are used throughout the remainder of this section to describe the lead vehicle acceleration, following vehicle acceleration, lead vehicle velocity, following vehicle velocity, lead vehicle position, and following vehicle position, respectively.

Brake control was added to this model as shown in Figure 3-40. In this case, if a negative torque is required, the brake takes over and the throttle is kept at a minimum. A simple first order filter was used to simulate the brake delay as indicated in the 'Brake' box. The output of 'Fcn3' is the brake torque which is summed with the engine model torque in 'Vehicle Model'. Results of simulations with brake control also show very tight control as indicated in Figures 3-41 to 3-43. In these simulations, the

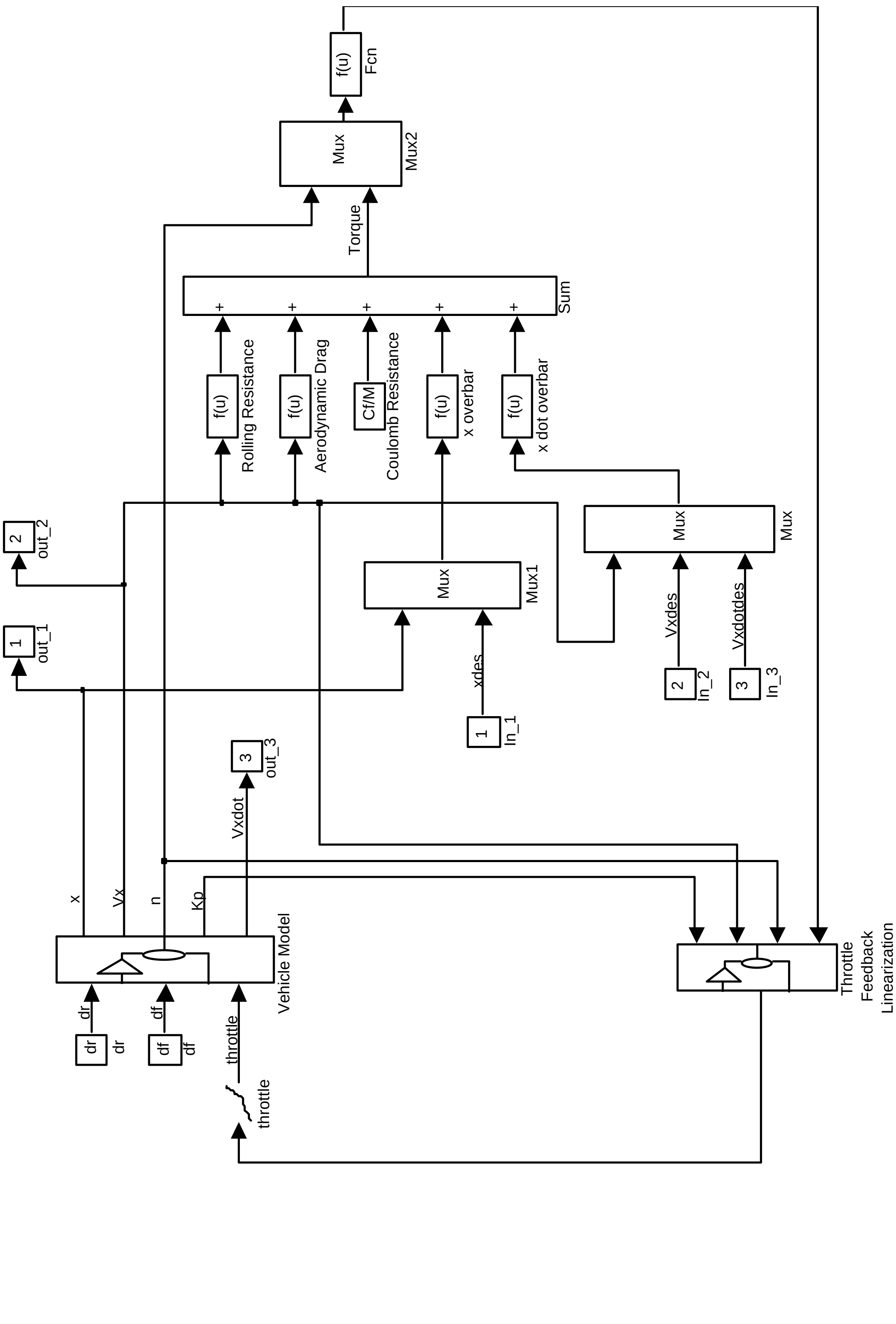


Figure 3-35 Feedback Linearization Throttle Controller

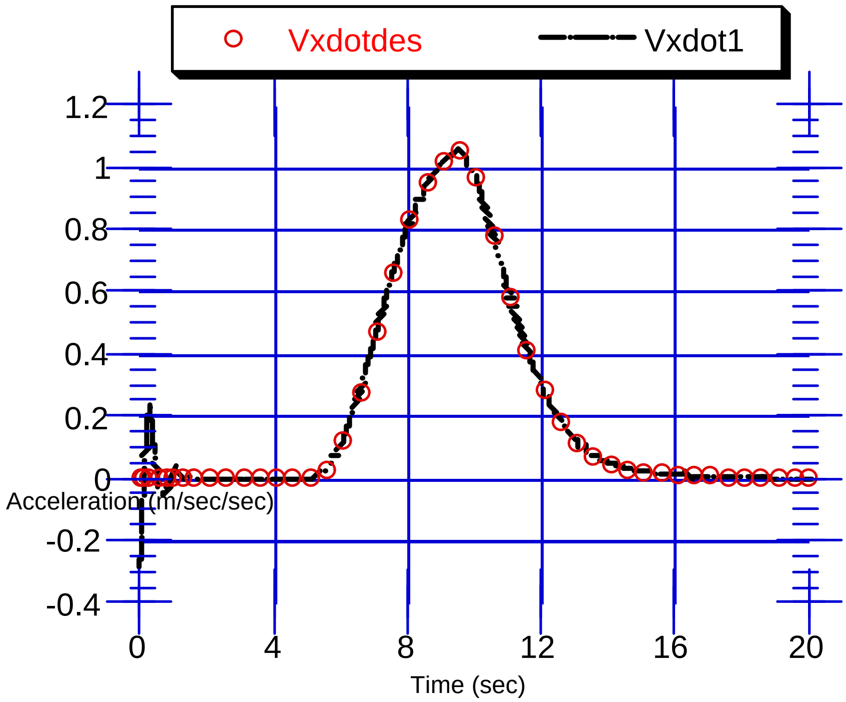


Figure 3-36. Acceleration of Lead and Following Vehicles using Feedback Linearization Control

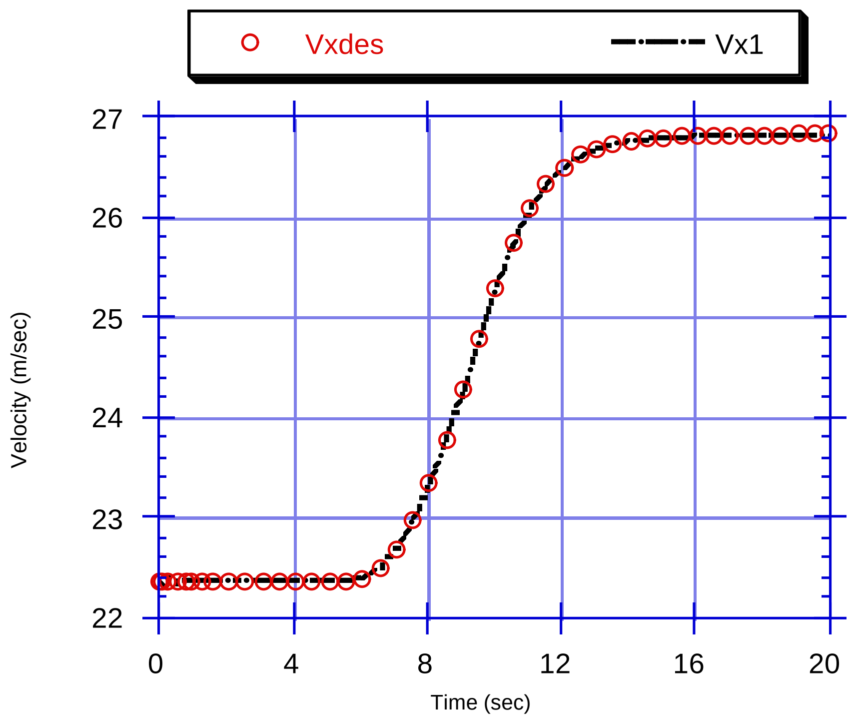


Figure 3-37. Velocity of Lead and Following Vehicle using Feedback Linearization Control

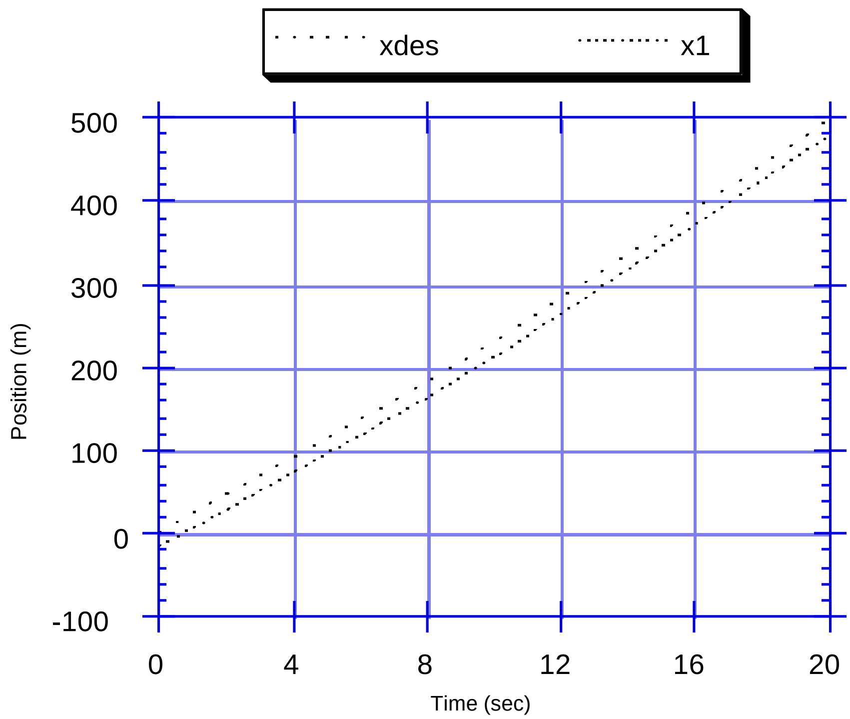


Figure 3-38. Position of Lead and Following Vehicles maintaining a 17.37 m (57.0 ft) gap using Feedback Linearization Control

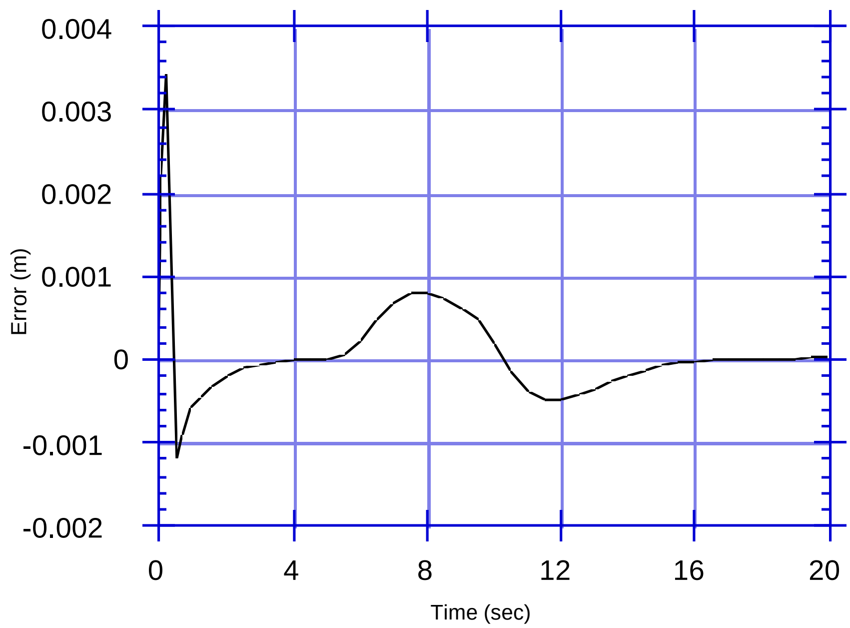


Figure 3-39. Distance Error between Lead and Following Vehicles using Feedback Linearization Control

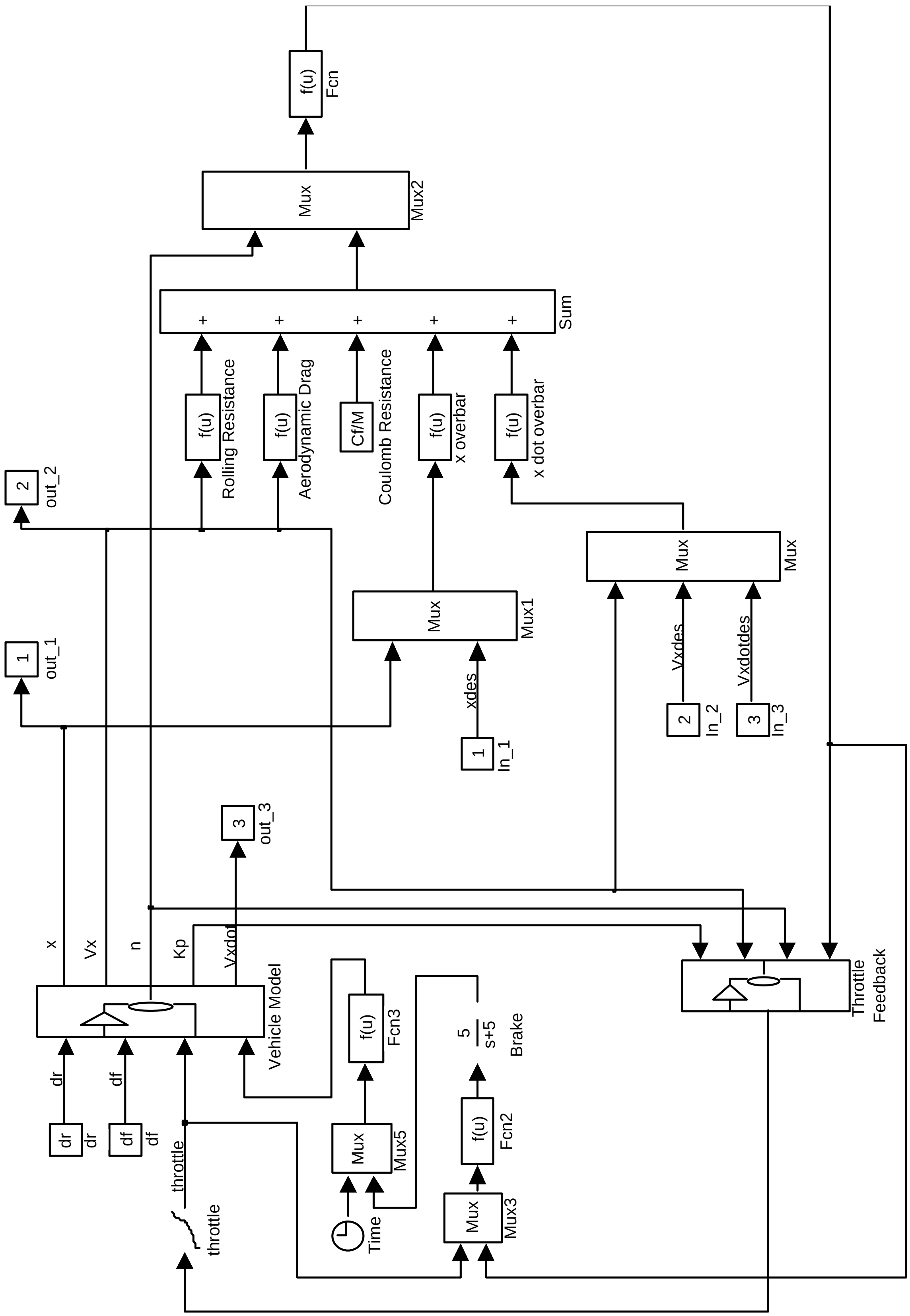


Figure 3-40 Throttle and Brake Control using Feedback-Linearization

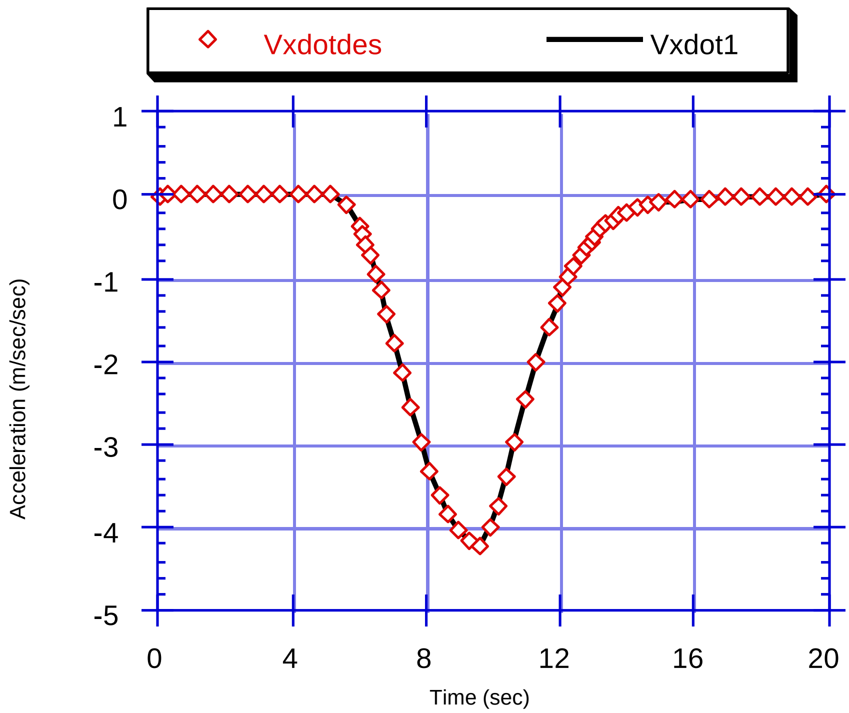


Figure 3-41. Feedback Linearization Braking Maneuver showing the Acceleration of the lead and following vehicles

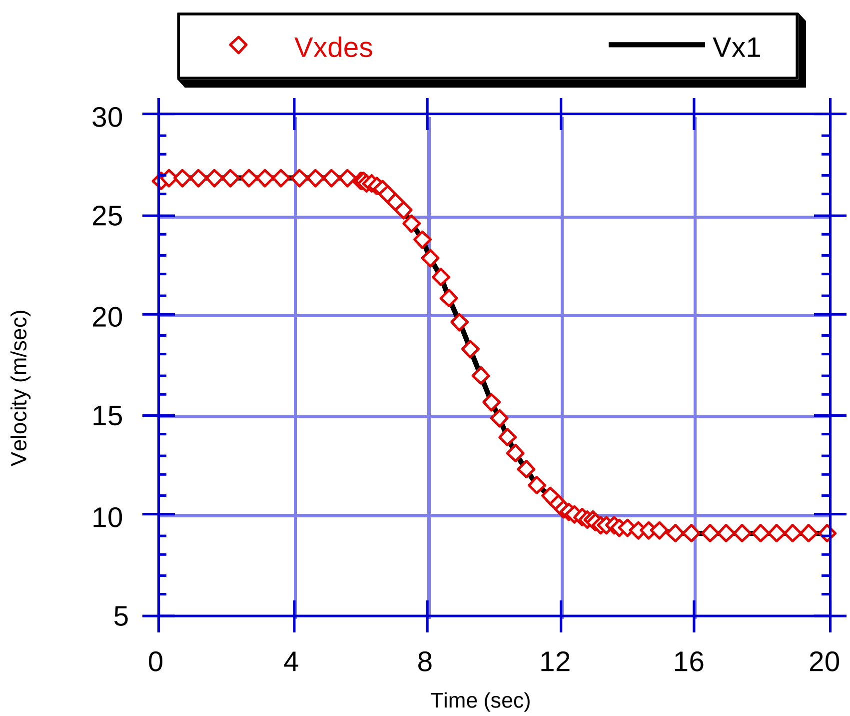


Figure 3-42. Feedback Linearization Braking Maneuver showing the Velocity of the lead and following vehicles

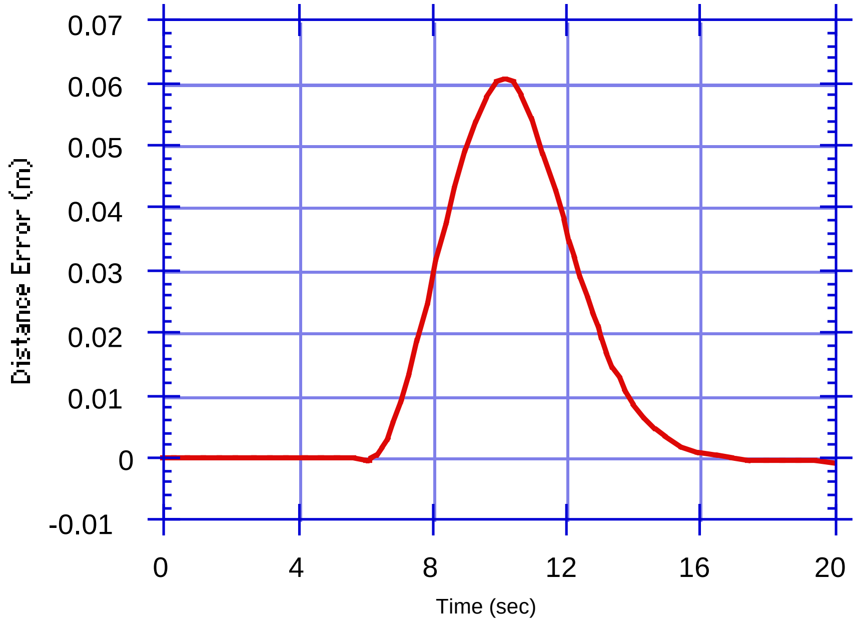


Figure 3-43. Feedback Linearization Braking Maneuver showing the Distance Error between the lead and following vehicles

lead vehicle was decelerated from 26.82 to 13.11 m/sec (88 ft/sec to 43 ft/sec). The resulting distance occurring during the braking maneuver is less than half a foot.

Feedback Linearization control was the first longitudinal controller developed in this study. Although this controller exhibits very tight control, it is impractical for use in an AHS environment. Typical sensor errors with gaussian distribution may have σ_{Vx} values as high as 0.3048 m/sec for velocity, and σ_x as high as 0.3048 m for distance. In addition, acceleration of the lead vehicle may not be available unless the infrastructure allows this information to be broadcast between vehicles. A simulation with a gaussian distribution of σ_x =0.3048 m and σ_{Vx} =0.3048 m/sec for sensor errors gives an undesired amount of throttle activity as shown in Figure 3-44. In addition to the effects of sensor noise on rider comfort, the inverse model required for this simulation may be difficult and costly to implement in a wide variety of vehicles. For these reasons other forms of longitudinal controllers were investigated.

3.6.3.2 Sliding Control

A longitudinal controller was developed utilizing sliding control, Hedrick, J.H. etal 1991. Sliding control is similar to feedback linearization control, except a precise inverse model is not required. A sliding controller takes the form:

$$u = \hat{u} - k \cdot sat(s/\Phi) \tag{7}$$

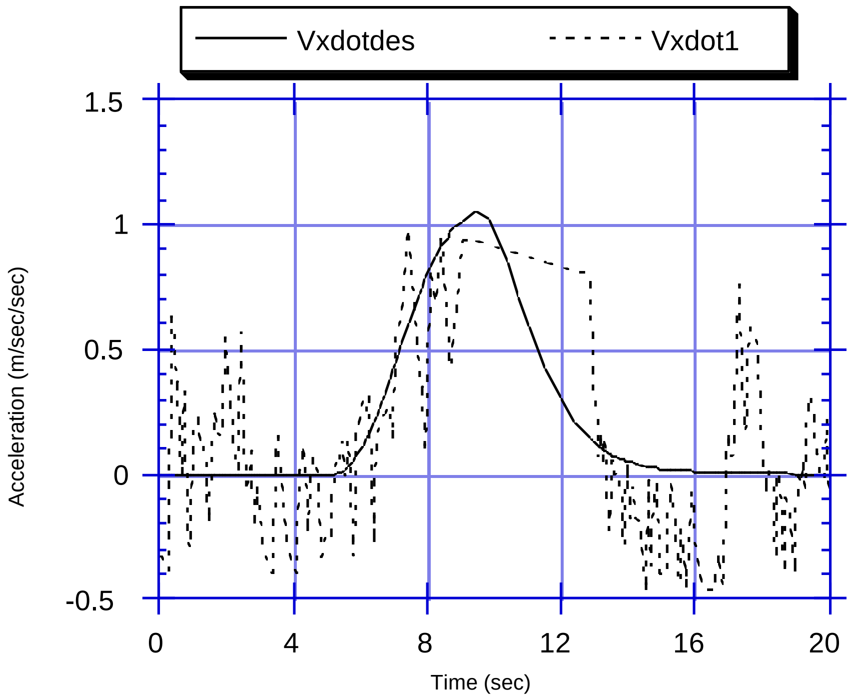


Figure 3-44. Sensor Noise Effects, with $\boxed{\sigma_x}$=0.3048 m and $\boxed{\sigma_{Vx}}$=0.3048 m/sec, on the Acceleration of a Feedback Linearization Controller Vehicle Follower

where u is the input, $\hat{u}$ is an estimate of the input, k is the control discontinuity, s is the sliding surface, and Φ is the boundary layer thickness, 100. A high boundary layer of 100 allows an improvement in noise immunity. When applied to a vehicle for longitudinal control, u represents $MDAIR$ (air intake) and $\hat{u}$ is an estimate of $MDAIR$. The control discontinuity, k, represents an uncertainty in one or more of the vehicle parameters. It is assumed to be bounded and taking the form:

$$k = F + \eta \tag{8}$$

where F is a bound of an uncertain vehicle parameter(s) and η is a constant chosen as 0.01. The bound, F, can be computed by taking an estimate of the for f_{max}. The result for F is as follows:

$$\hat{f} = V_x^2 \cdot rho \cdot Across / mhat \tag{9}$$

$$f_{max} = (V_x^2 \cdot rho \cdot Across / mhat) \cdot (4/3) \tag{10}$$

$$F = \left| \hat{f} - f_{max} \right| = (V_x^2 \cdot rho \cdot Across / mhat) \cdot (1/3) \tag{11}$$

where V_x is the longitudinal velocity, rho is the air density, $Across$ is the cross-sectional area of the front of the vehicle, and $mhat$ is the average mass of the vehicle.

The sliding surface, s, was chosen for headway control. In this case the sliding surface is defined as follows:

$$s = \dot{\tilde{x}} + l_1 \cdot \tilde{x} + l_2 \cdot \int \dot{\tilde{x}} \quad (12)$$

where $\dot{\tilde{x}}$ and $\tilde{x}$ are chosen for time headway errors as follows:

$$\dot{\tilde{x}} = Vx - Vxdes + h \cdot Vxdot \quad (13)$$

$$\tilde{x} = x - xdes + h \cdot Vxdot + 5(ft) \quad (14)$$

In sliding control, the system is commanded to the sliding surface, s. By staying on the surface, s, zero error is maintained. In this case, the derivative of s is zero. This yields (15):

$$\dot{\tilde{s}} = \ddot{\tilde{x}} + l_1 \cdot \dot{\tilde{x}} + l_2 \cdot \tilde{x} = 0 \quad (15)$$

where $$\ddot{\tilde{x}} = \dot{V}x - \dot{V}xdes \quad (16)$$

Now, (15) can be rearranged to solve for the acceleration required to stay on the sliding surface (16).

$$\begin{aligned} \dot{V}x &= l_1 \cdot (Vxdes - Vx - h \cdot Vxdot) \\ &+ l_2 \cdot (xdes - x - h \cdot Vx - 5) + \dot{V}xdes \end{aligned} \quad (17)$$

The output of the vehicle, $\dot{V}x$, can be related to the air intake input parameter, $MDAIR$ by the following derivation using the vehicle model discussed in 3.6.2.

$$\dot{V}x = \frac{4 \cdot T}{m \cdot r_w} - \frac{1}{m} \cdot \left(rho \cdot Across \cdot V_x^2 - C_r \cdot V_x - C_f \right) \quad (18)$$

where T is the wheel torque, m is the mass of the vehicle, r_w, is the wheel radius, C_r is coefficient of rolling resistance, and C_f is the coefficient of static friction. The total drag force, F_d due to wind, rolling, and static resistance is

$$F_d = -\left(rho \cdot Across \cdot V_x^2 - C_r \cdot V_x - C_f \right) \quad (19)$$

$$ITQ = 62558.4 \cdot MDAIR / n - Pump\_tq - 24 \quad (20)$$

where ITQ is the Engine Torque, n is the engine speed, and $Pump\_tq$ is the pump torque.

$$Pump\_tq = 2.07e^{-5} \cdot n^2 \cdot |tmp| \cdot tmp \tag{21}$$

where tmp is a relation between turbine speed, $Turbine\_spd$, and engine speed, n.

$$tmp = \arctan\left[25 \cdot \left(1 - Turbine\_spd / n\right)\right] \tag{22}$$

$$Turbine\_spd = V_x \cdot 20.5 \cdot kv \tag{23}$$

where kv is the gear ratio.

$$ITQ = (\dot{n} + 0135 \cdot n) \big/ 30 \tag{24}$$

$$Turbine\_tq = kp \cdot Pump\_tq \tag{25}$$

where $Turbine\_tq$ is the turbine torque and kp is the relation given by (26).

$$kp = \max\left[1, \left(2.3289 - 1.525 \cdot Turbine\_spd / n\right)\right] \tag{26}$$

$$T = 1.76 \cdot kv \cdot Turbine\_tq / 4 \tag{27}$$

After making a number of substitutions, the input, $MDAIR$, can be related to the desired output, $\dot{V}x$ by the following:

$$\dot{V}x = \frac{1.76}{m \cdot r_w} \cdot kv \cdot kp \cdot \left\{ \frac{62558.5 \cdot MDAIR}{n} - 24 - \frac{\left(\dot{n} + 0135n\right)}{30} \right\} - \frac{1}{m} \cdot \left(rho \cdot Across \cdot V_x^2 - C_r V_x - C_f\right) \tag{28}$$

Substituting (28) into (17) and solving for $MDAIR$ yields the input estimate, $\hat{u}$.

$$MDAIR = \frac{n}{62558.4} \cdot \left\{ \frac{m \cdot r_w \left[l_1 \left(-\dot{\tilde{x}} \right) + l_2 \left(-\tilde{x} \right) - \frac{1}{m} \cdot F_d \right]}{1.76 \cdot kv \cdot kp} + 24 + \frac{\left(\dot{n} + 0135n \right)}{30} \right\} \tag{29}$$

The sliding controller is implemented in Simulink as shown in Figure 3-45. A lookup table provides the throttle input from the sliding controller output $MDAIR$. The gains λ_1 and λ_2 were both chosen to be 1.

Simulations were run using the same acceleration profile as the feedback linearization controller, section 3.6.3.1. The results of a four vehicle simulation are presented in Figures 3-46 to 3-48.

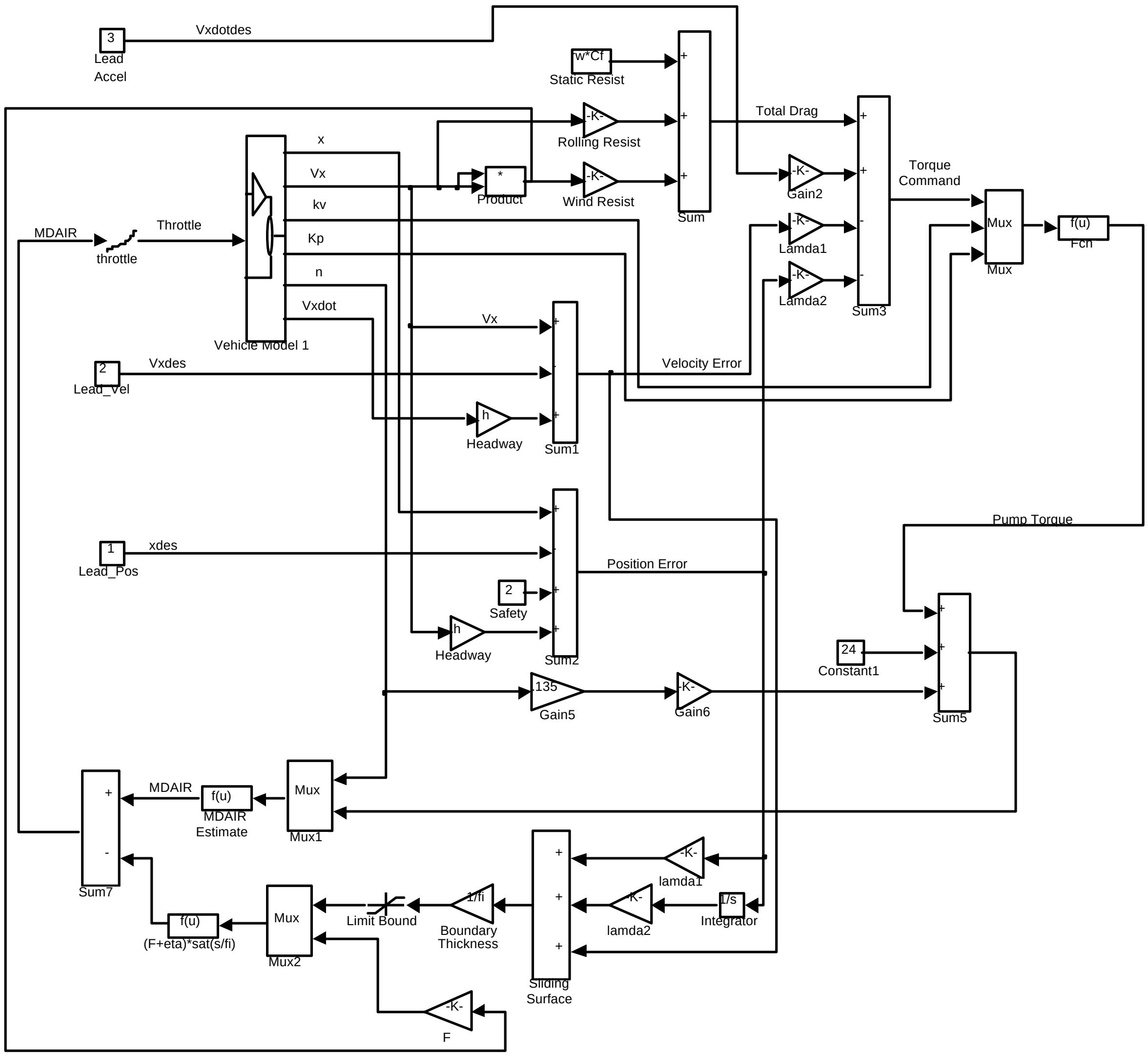


Figure 3-45 Longitudinal Control implemented using Sliding Control

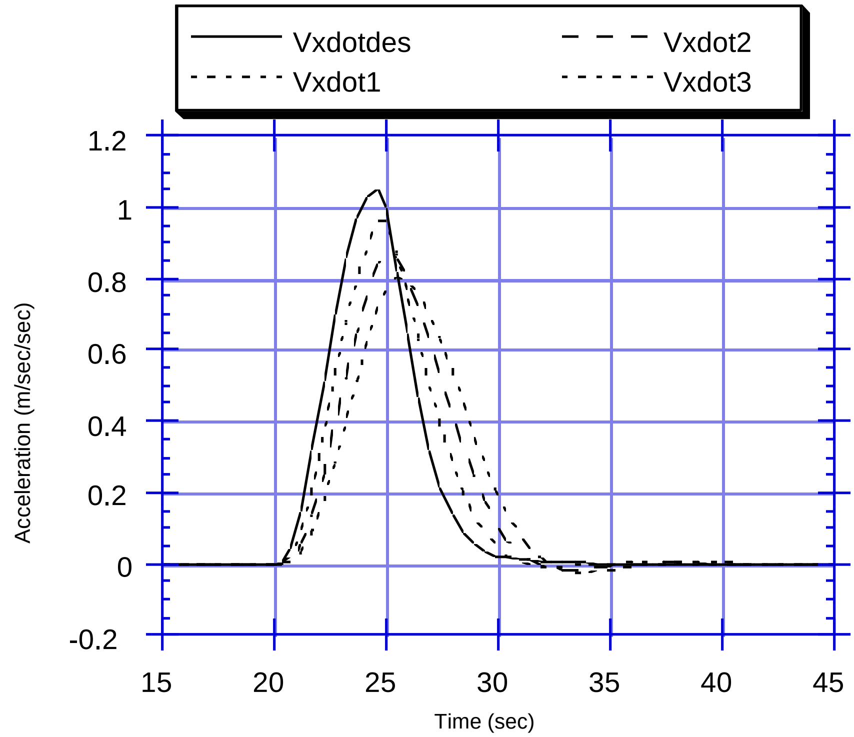


Figure 3-46 The accelerations of a four vehicles using sliding control.

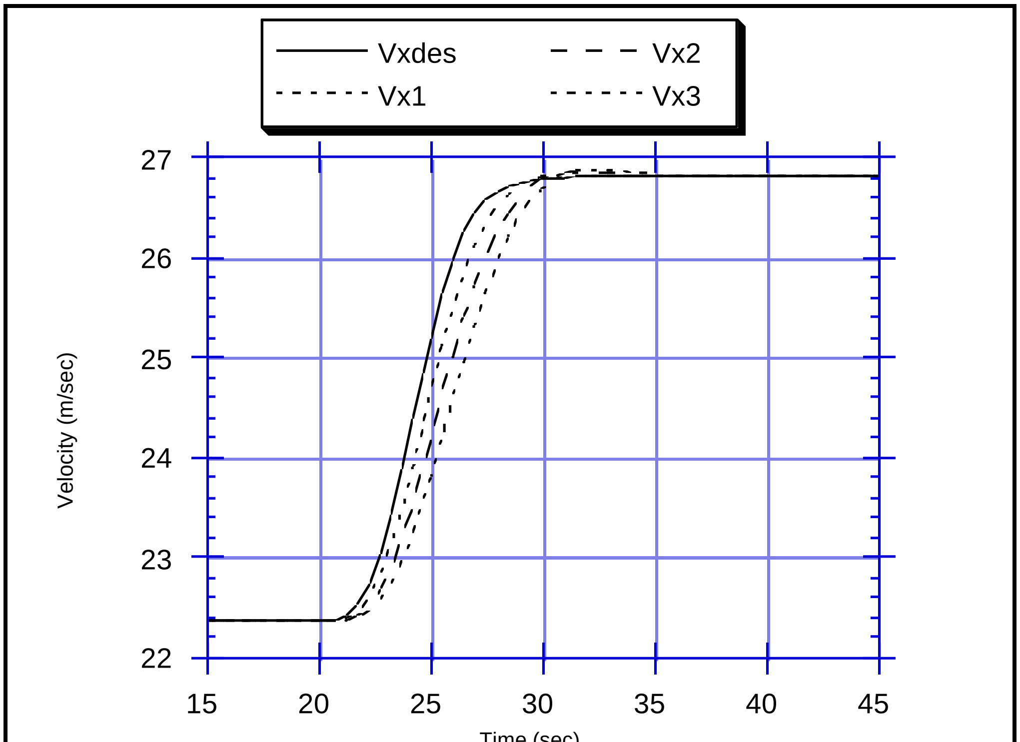


Figure 3-47. The velocity of four vehicles using sliding control

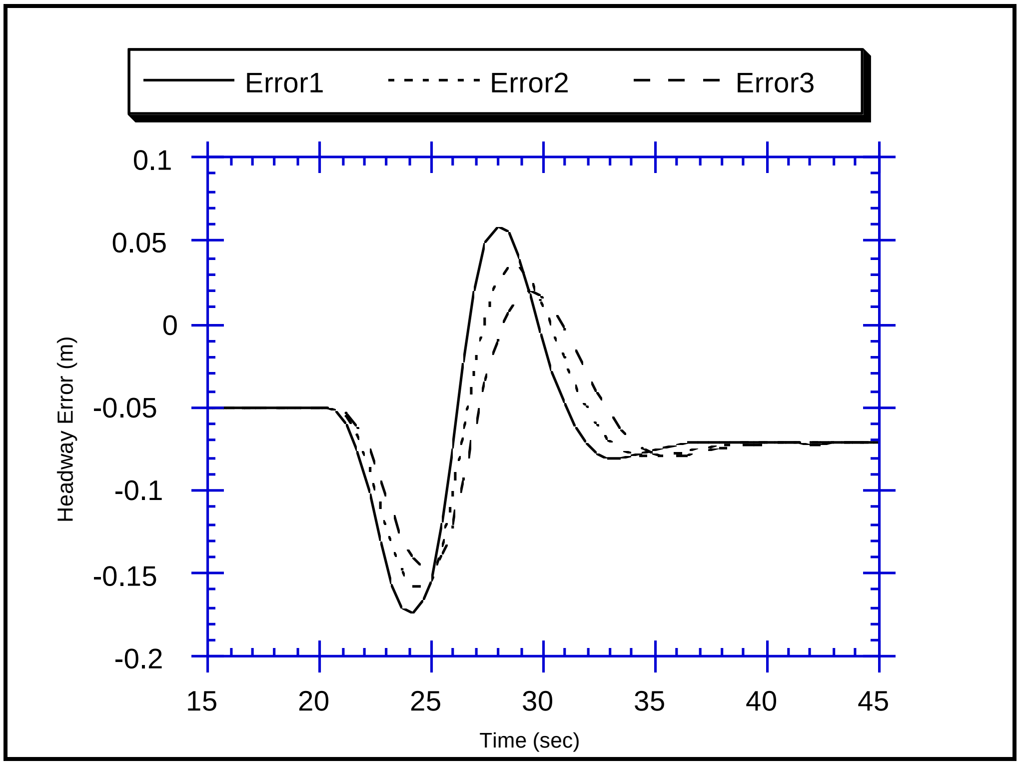


Figure 3-48. The distance error between vehicles using sliding control

The characteristics of a time headway controller are observed in Figures 3-46 to 3-48. Unlike the feedback linearization controller, where the accelerations of all followers nearly matched, the time headway controller has successively smaller accelerations in order to create a larger gap required at higher speeds. Naturally, successively smaller accelerations is a benefit to the AHS environment because it helps maintain stability of a stream of vehicles. If one were to consider the opposite, larger accelerations, then the stream of vehicles would become unstable as the commanded accelerations will eventually become unattainable due a limit on vehicle performance. In addition to successively smaller accelerations, the undershoot of the accelerations between 30 and 35 seconds of Figure 3-46 and the overshoot of velocity in Figure 3-47 indicate a potential instability. In the four vehicle simulation, the undershoot grows with successive vehicles. A 20 vehicle simulation indicates the undershoot continues to grow but at an exponentially decreasing rate. This will probably be acceptable in an AHS environment. Figure 3-49 illustrates the decay in both the undershoot and successively smaller accelerations by plotting out the acceleration min and max of each vehicle. Another important feature of headway control is the decreasing error illustrated in Figure 3-49. Without decreasing error, the stream of vehicle would become unstable.

It is evident from the results above that sliding control based on time-headway is an attractive vehicle controller, but these simulations are not indicative of a true AHS environment where sensor errors, sampling times, and throttle actuator delays must be considered. Typical sensor errors with gaussian distribution may have σ_{Vx} values as high as 0.3048 m/sec for velocity, and σ_x as high as 0.3048 m for distance.

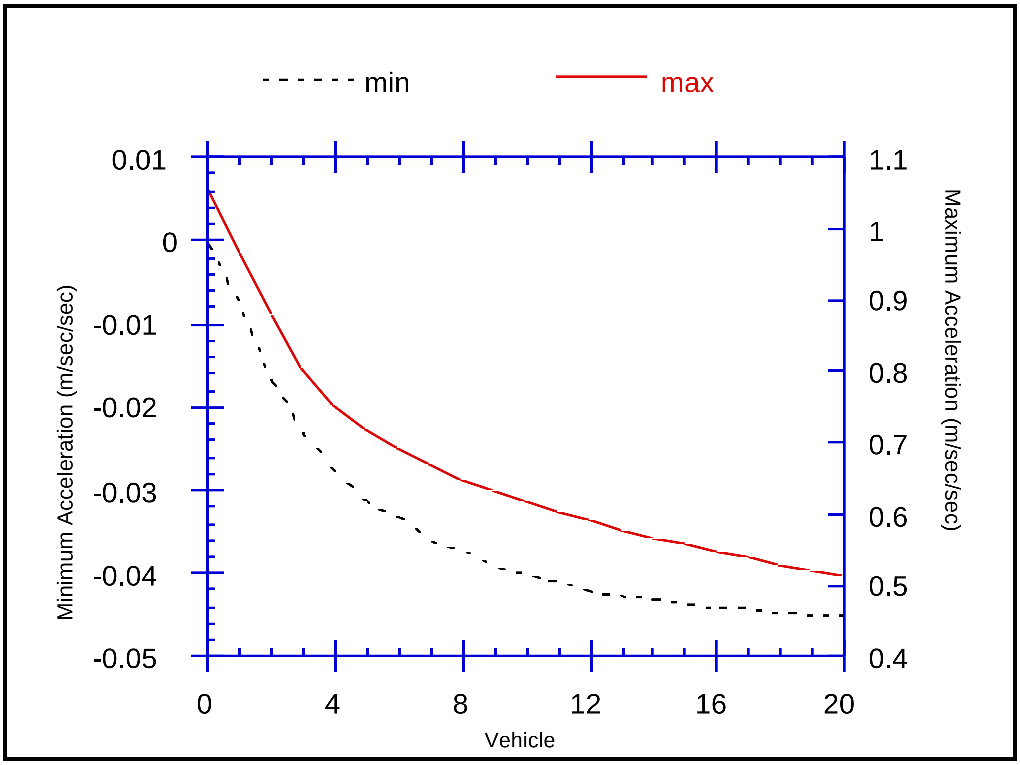


Figure 3-49. The decay of both the acceleration minimum and maximum through a maneuver provide stability of a stream of vehicles

Acceleration must either be derived from velocity or communicated via a vehicle to vehicle link. Figures 3-50 and 3-51 indicate the results of simulations using derived acceleration and different sensor errors as indicated. The sensor errors are considered to be guassian noise with σ_{Vx} and σ_x as noted.

Clearly, as the amount of AWGN increases, the performance of the ride decreases due to unwanted accelerations and jerk of the vehicle. As little as 0.003048 m distance and 0.003048 m/sec velocity errors are noticeable in the acceleration of the vehicle as illustrated in Figure 3-50. When the noise level is increased by an order of magnitude to 0.03048 m distance and 0.03048 m/sec velocity errors, the performance of the vehicle is severely degraded as depicted in Figure 3-51. The unwanted accelerations are in response to the sliding control properties of tight and robust control. The net result is rider discomfort due to unwanted accelerations and jerk, and an inefficient use of the vehicle leading to excess pollution and a reduced fuel economy. In addition to the unacceptable level of noise, it should be noted that the amount of unwanted acceleration increases with each follower. This increase will in a potentially unstable stream of vehicles.

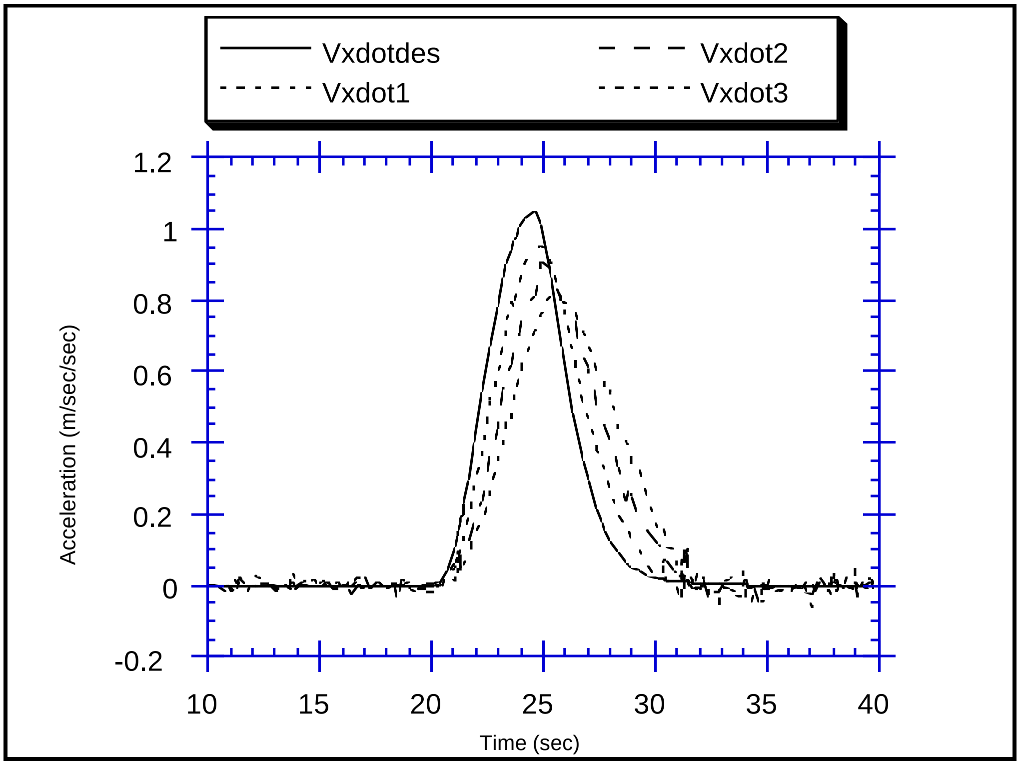


Figure 3-50. Acceleration of four vehicle simulation using derived acceleration and $\boxed{\sigma_{Vx}}$ = 0.003048 m/sec and $\boxed{\sigma_{x}}$ = 0.003048 m

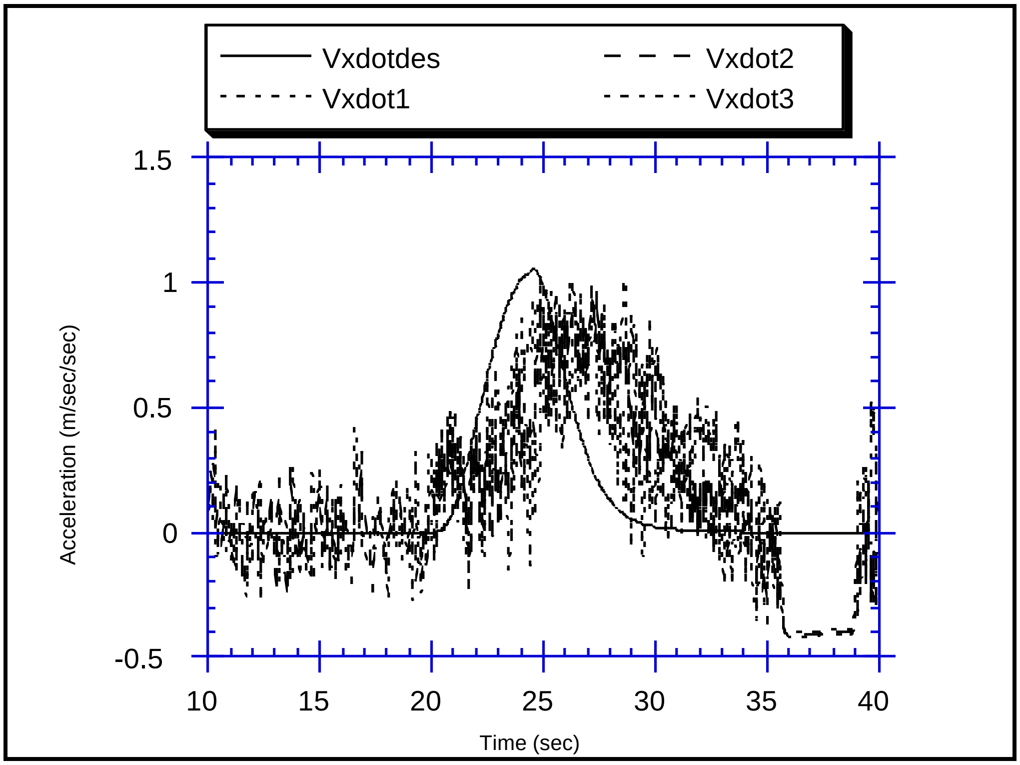


Figure 3-51. Acceleration of four vehicle simulation using derived acceleration

and $\boxed{\sigma_x}$=0.03048 m and $\boxed{\sigma_{Vx}}$=0.0.3048 m/sec

The gain of the vehicle may be reduced by decreasing λ_1 and λ_2 from 1.0 to 0.1 . The results of this simulation are given in Figure 3-52 and 3-53. In Figure 3-52, the magnitude of the unwanted acceleration is shown to be nearly the same as with the higher gains, Figure 3-51. The velocity of the followers is obviously unacceptable as shown in Figure 3-53.

Although sliding control provides for robust longitudinal control, it is evident that this controller, as it stands, is unsuitable for use on an AHS. Improvements may be made in sliding controller such as the use of Kalman filters and state estimators. This may provide a significant improvement in noise immunity but may also add unacceptable delays. In addition, the problem with increasing unwanted accelerations must be overcome in order to use sliding control. This effect is caused by a gain larger than one for each vehicle resulting in a stream of vehicles which is unstable. A vehicle may be stable for very low levels of noise, Figure 3-50, but high levels of noise could excite a controller into an unstable state as may be the case in Figure 3-52. A point follower approach could alleviate this problem, but at the cost of more infrastructure.

3.6.3.3 Proportional Control

Proportional control was the third and last controller investigated in the longitudinal simulation task. Proportional control offers a very simple controller that can easily be implemented in all classes of vehicles. In proportional control, the input to the plant is an error signal, the difference between a command and a state of the plant. The error signal may be integrated, differentiated, direct, or any combination before it is applied to the state input. Figure 3-54 shows the implementation of the proportional controller for both throttle and brake control. For throttle control, an inner loop and outer loop are formed. The inner loop consists of the "Accel Command" to "Brake/Throttle Inner Loop" to "Vehicle1" where the "Acceleration" of the vehicle goes back to the "Brake/Throttle Inner Loop" to form the inner loop. The inner loop takes the "Acceleration Command" generated by the outer loop and the "Acceleration" of the vehicle to form an error signal as shown in Figure 3-55. The error signal is then integrated and summed with the same acceleration command to form the throttle input. The integrated signal provides limited throttle movement insuring comfort passenger comfort while the direct acceleration command provides a robust throttle command reducing the amount of error in the system. Some additional logic is added insure that only the brake command or throttle command is active, but not both. The advantage of an inner loop allows separate and easier tuning of controller gains. A step input was applied to the acceleration command for determining the gains of the inner loop as a function of engine speed. The gains were set to provide a stable response with little or no overshoot of acceleration. The brake inner loop works in the same fashion as the acceleration inner loop.

The outer loop generates an error signal used as the "Acceleration Command" to the inner loop. The outer loop error signal has three components: an error signal proportional to distance error, an error signal proportional to velocity error, and the previous acceleration command. The distance error is based on time headway in a similar manner as the sliding control approach discussed in 3.6.2.2. The error signal is:

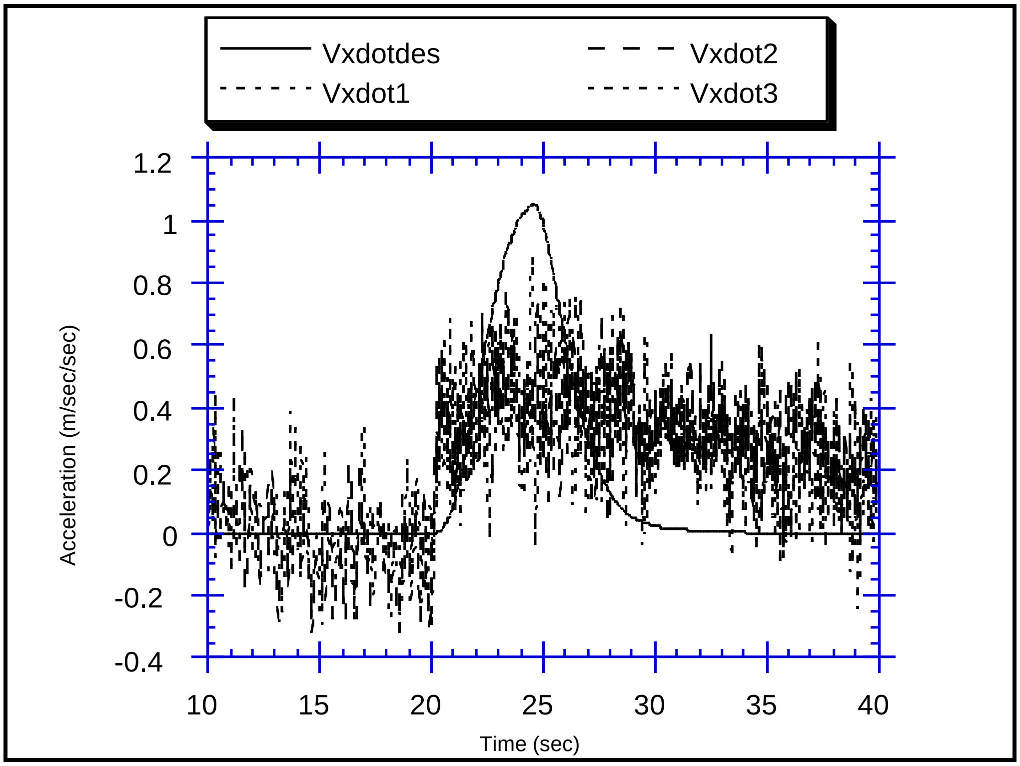


Figure 3-52. Effects of reduced gain on Acceleration with $\boxed{\sigma_x}$=0.03048 m and $\boxed{\sigma_{Vx}}$=0.03048 m/sec

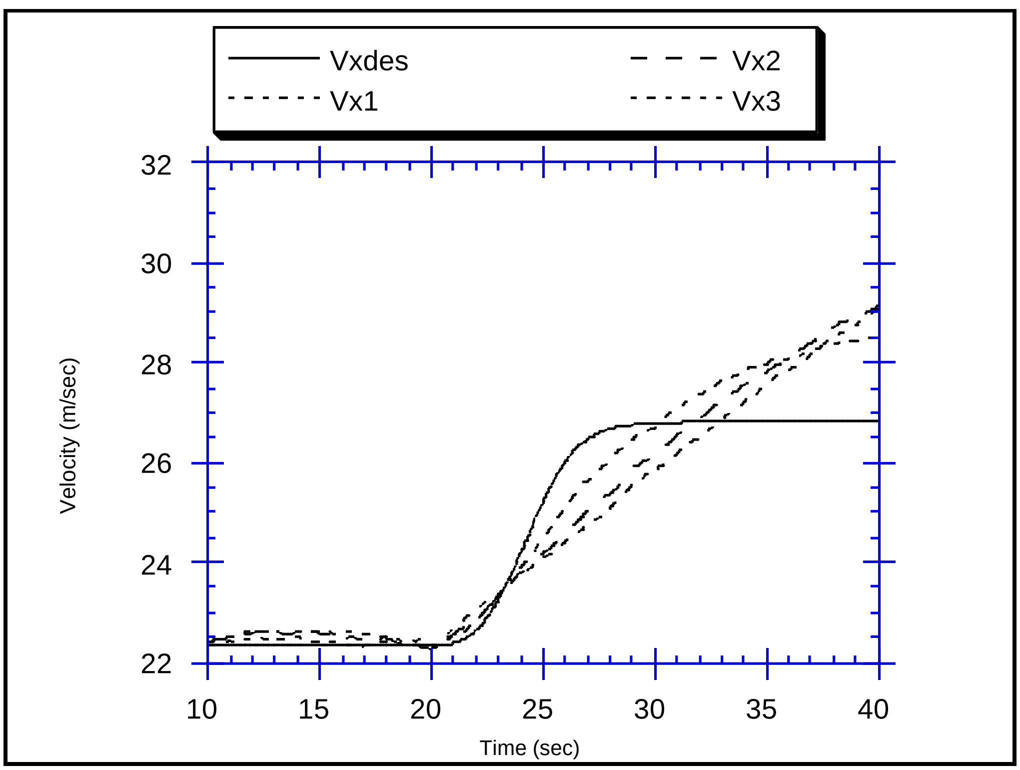


Figure 3-53. Effects of reduced gain on Velocity with $\boxed{\sigma_x}$=0.03048 m and $\boxed{\sigma_{Vx}}$=0.03048 m/sec

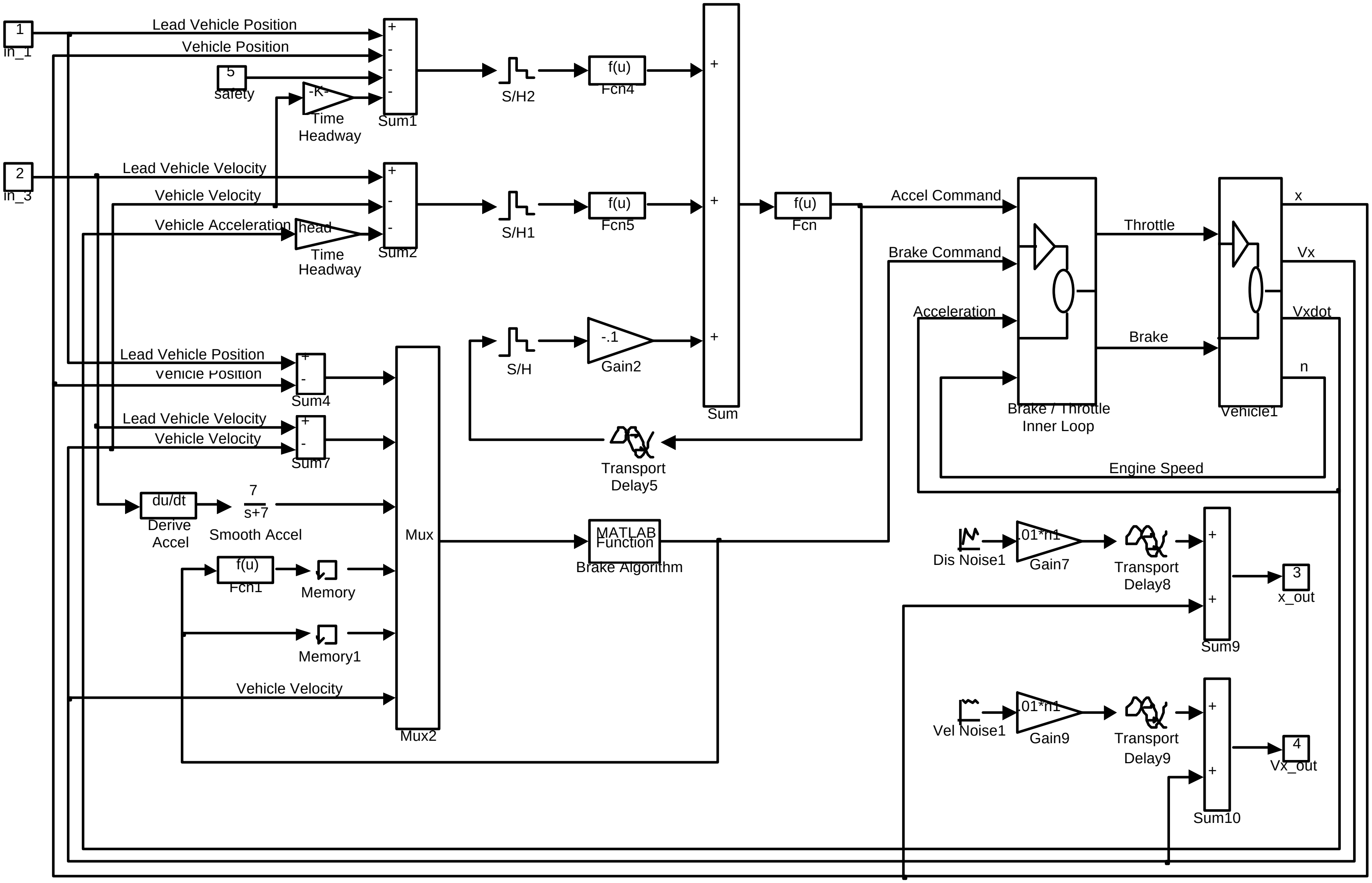


Figure 3-54 Longitudinal Control implemnted using Propotional Control for the Throttle and Brake

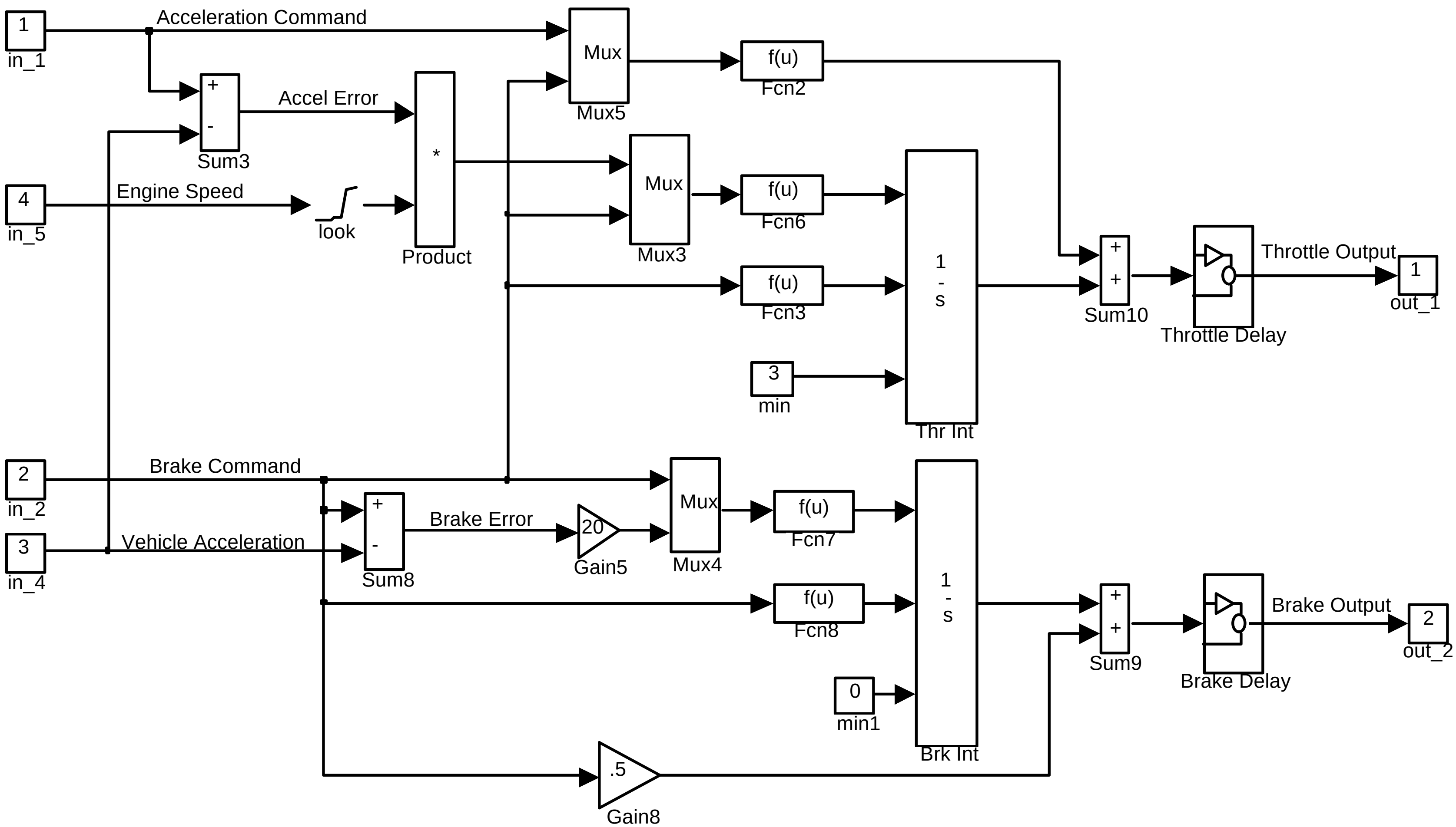


Figure 3-55 Inner Loop for Throttle and Brake Proportional Control

$$err1 = xdes - x - h \cdot Vx1 - 5(ft) \qquad (30)$$

where h is the time headway (.5 seconds n our simulations) and 5 ft (1.52 m) is a safety gap needed to insure no collision at low speeds. The velocity error is:

$$err2 = Vxdes - Vx - h \cdot Vxdot \qquad (31)$$

The previous acceleration command in the outer loop acts as a first order filter since its gain is -0.1. The gains of the error signals are tuned after inner loop tuning. Originally, the gains were simply chosen to be 0.1 for the distance error and 10.0 for the velocity error as shown below:

$$0.1 \cdot err1 \qquad (34)$$

$$10.0 \cdot err2 \qquad (35)$$

These gains provided a high level of noise immunity, but the maneuver errors were on the order of 10 ft with a very slow recovery, 100 seconds for the 22.35 to 26.82 m/sec acceleration maneuver. Then, higher gains for both the distance and velocity were examined. This resulted in tighter control at a compromise for noise immunity. Ideally, a system would have very low gains during steady state operation, i.e. constant velocity following, and high gains during maneuvers, i.e. velocity changes. A variable gain for both the distance and velocity was used in the simulation with the following form:

$$0.1 \cdot err1 \cdot [1 + 2 \cdot abs(err1)] \qquad (34)$$

$$10.0 \cdot err2 \cdot [1 + 5 \cdot abs(err2)] \qquad (35)$$

In both cases, the error signal contains a "DC" and "AC" component of the form:

$$Gain \cdot err \cdot [DC + AC] \qquad (35a)$$

The "DC" component, 1, provides a low gain for all error conditions. The "AC" component, $abs(err)$, provides very low gain during low errors and very high gain during high errors. The net result is a system which provides passenger comfort during steady state conditions and tolerable maneuver errors. The variable gains are implemenented in "Fcn4" and "Fcn6" for the distance and velocity, respectively.

The proportional controller, Figure 3-54, contains three sample and holds used to simulate delays in sensors. The sample and hold time is 50 msec. Both throttle and brake actuator delays are modeled as first order filters as shown in Figure 3-55. Reset integrators, "Thr Int" and "Brk Int" are used to insure either the Brake or Throttle control is active but not both. When the brake algorithm commands a brake force, the throttle is held to a minimum and the brake is activated by "Fcn3" and "Fcn8", respectively of Figure 3-55. Also, acceleration of the previous vehicle is not required for the throttle control portion of the proportional controller. The brake control algorithm does use the previous vehicle's acceleration, but this may be derived from the differential velocity between the vehicle and the previous vehicle. The proportional controller was simulated using 50 msec intervals, i.e. 20 Hz update rate.

Results of simulations with proportinal control are given in Figure 3-56 to 3-64.

In the first simulation involving proportional control, an acceleration is applied to the lead vehicle causing the velocity to increase from 22.35 m/sec to 26.82 m/sec (50 to 60 mph). There were no sensor errors use in the first simulation. In Figure 3-56 and 3-57, the acceleration and velocities of 6 vehicles are shown. The accleration and velocities contain some delays which is inherent to the time headway control. The distance error, $err1 = xdes - x - h \cdot Vx1 - 5(ft)$, is shown in Figure 3-58. With the proportional control, at least 0.61 m (2 ft) distance errors are encountered. The distance errors are quite slow to recover. The results show the distance error can recover from 0.61 m to .30 m errors from this maneuver in 25 seconds. Although this maneuver is slow to recover, an added benefit will result in a greater noise immunity as evident in Figure 3-59 to 3-64.

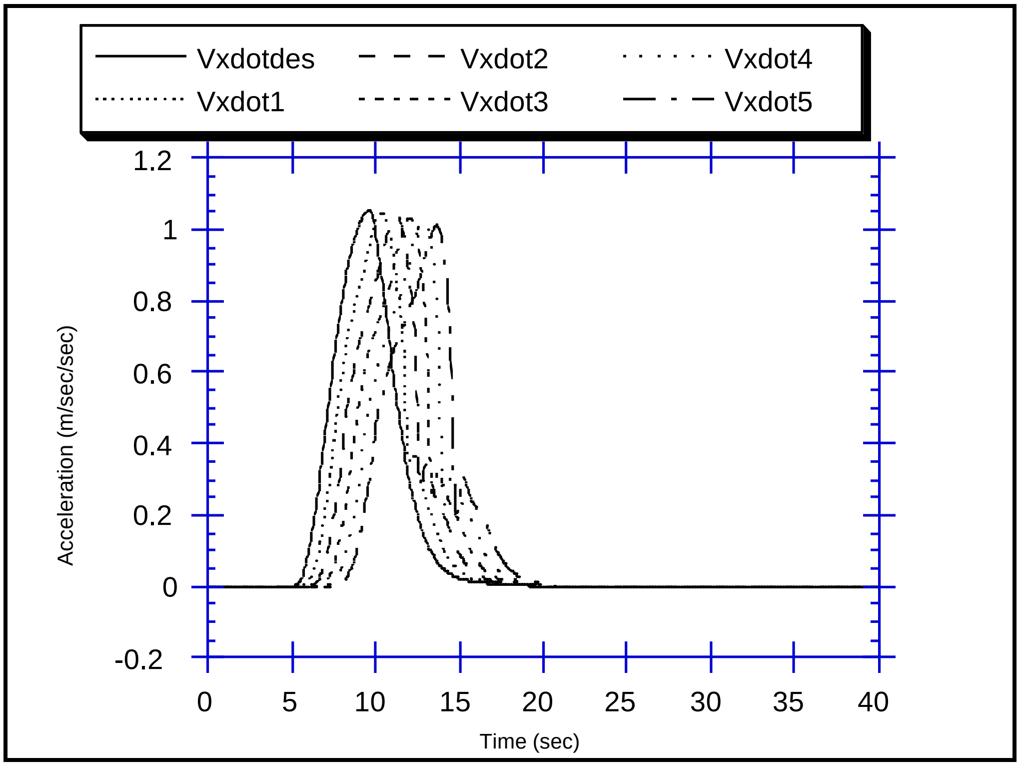


Figure 3-56. Acceleration of 6 vehicles using proportional control with no sensor noise.

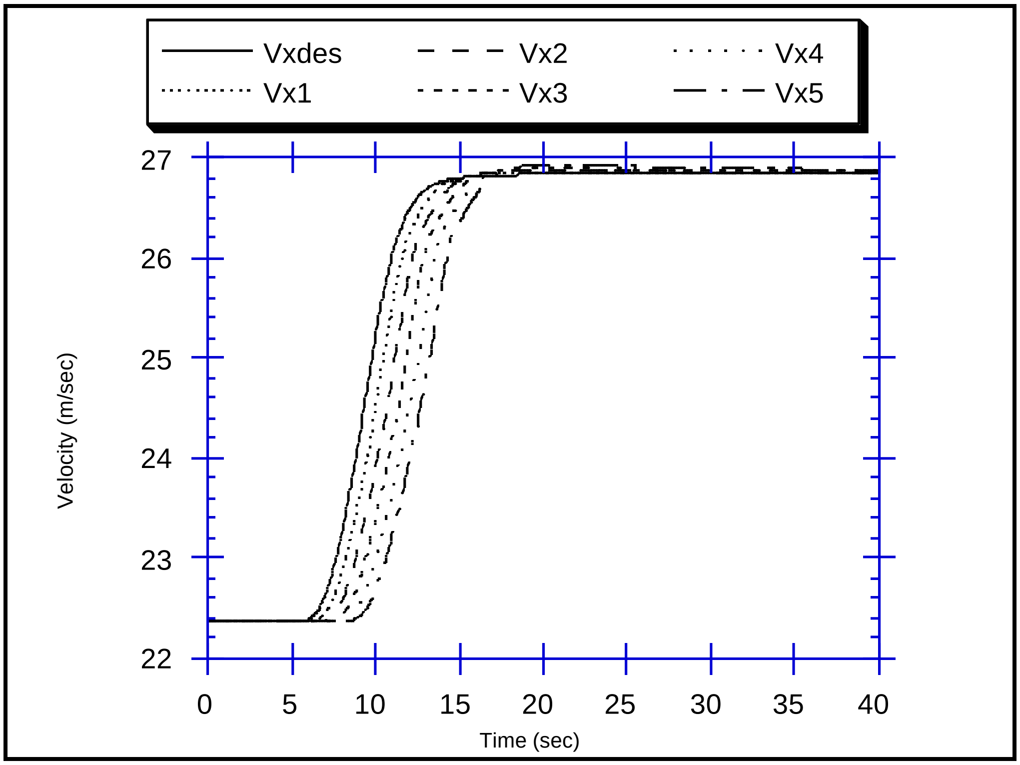


Figure 3-57. Velocity of 6 vehicles using proportional control with no sensor noise

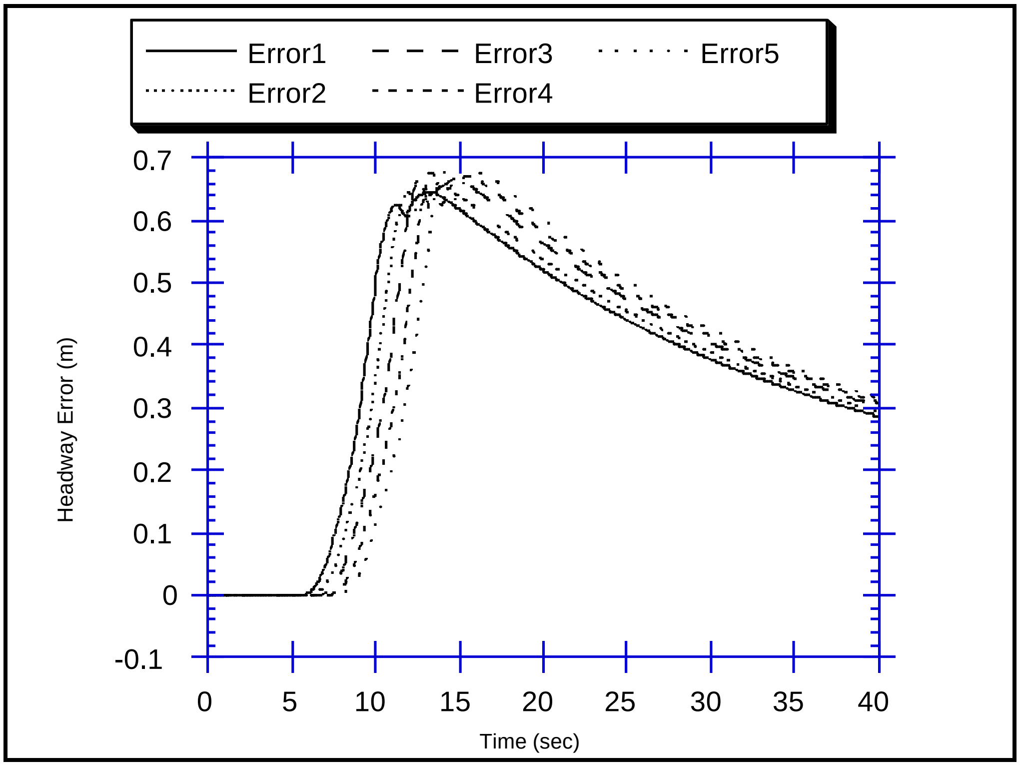


Figure 3-58. Distance errors for 5 gaps of 6 vehicles using proportional control with no sensor noise

The ability of the propotional controller to handle sensor errors with σ_x=0.03048 m and σ_{Vx}=0.03048 m/sec is demonstrated in Figures 3-59 to 3-61. Here, the velocity and distance errors are nearly the same as the no noise case. The acceleration shows a +/- .061 m/sec/sec noise during steady state in Figure 3-59. For the case with sensor errors of σ_x=0.3048 m and σ_{Vx}=0.3048 m/sec the acceleration shows a +/- .3048 m/sec/sec in Figure 3-62. Figure 3-63 showns the velocity of the followers to track well with the large sensor errors. The error in the gap degrades somewhat from the lower noise case. Here, the distance errors range from .3 m to 1.5 m. The distance errors are very slow to recover in the presensce of this noise. Although the error is large, sensor errors with σ_x=0.3048 m and σ_{Vx}=0.3048 m/sec may be accommodated if safety is maintained by a robust brake algorithm.

3.6.3.4 Braking Algorithm

A braking algorithm was developed with the premise that braking would not be a normal maneuver in an AHS. Braking is considered safety and/or emergency maneuver. The braking algorithm predicts the time a collision would occur based on the lead vehicle and following vehicle trajectories. If the time to collision is less than a specified time, a brake force is computed, the brakes are activated, and the throttle is deactivated. Figures 3-54 and 3-55 include this brake algorithm. The brake algorithm requires the same inputs as the throttle controller, that being lead vehicle position and velocity, Figure 3-54. In addition, the lead vehicle acceleration is derived from the lead vehicle velocity. The logic for switching between brake and throttle is illustrated in the inner loop block diagram, Figure 3-55. "Brake Command" is the output of the brake algorithm. Once this a negative number, the throttle will be disengaged by the reset integrator, "Thr Int", and the Brake check, "Fcn3". The "Brk Int" will likewise be activated by "Fcn8" when the "Brake Command " becomes negative. The brake algorithm is provided:

1) If brake was previously on $PB = 1$, or if the lead vehicle's velocity is less than the follower's velocity, then start the brake algorithm.

2) Compute

$$xtst = max\left[\left(xdes - x - 5 - .2 \cdot Vx\right), 1\right] \tag{36}$$

where $xtst$ provides is the distance error or a safety gap of 1..

3) Compute

$$tm = \frac{-2 \cdot xtst}{min\left[\left(Vxdes - Vx\right), -.1\right]} \tag{37}$$

where tm is the predicted time till a collision.

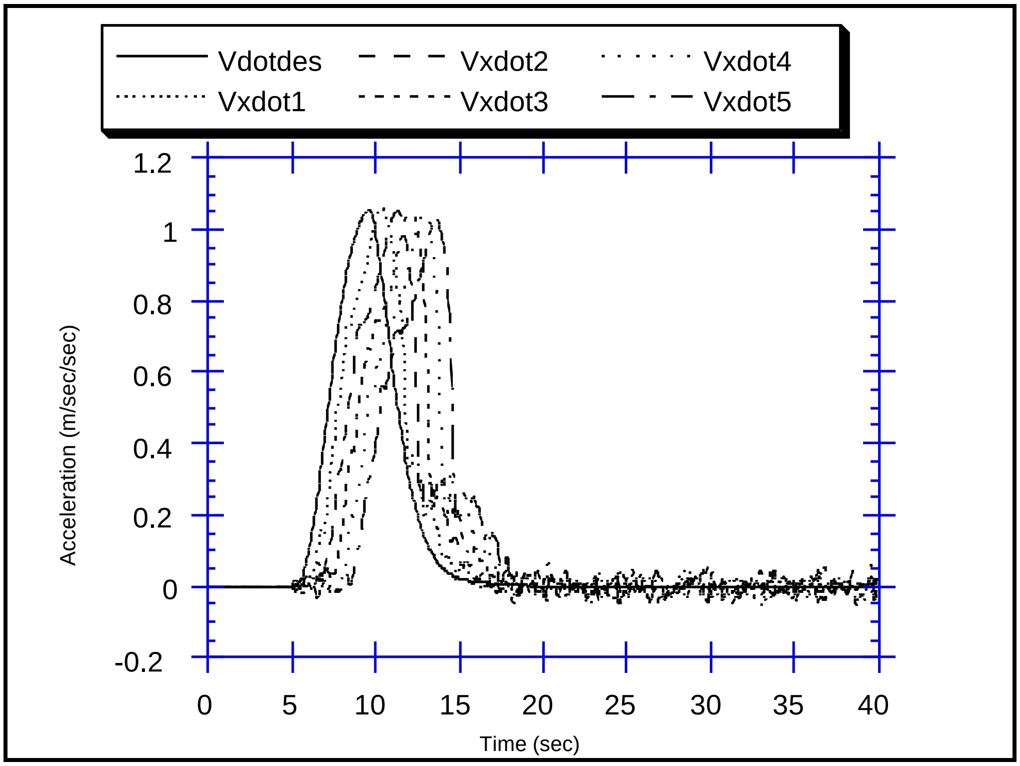


Figure 3-59. Accelerations of 6 vehicles using proportional control with $\boxed{\sigma_x}$=0.03048 m and $\boxed{\sigma_{Vx}}$=0.03048 m/sec

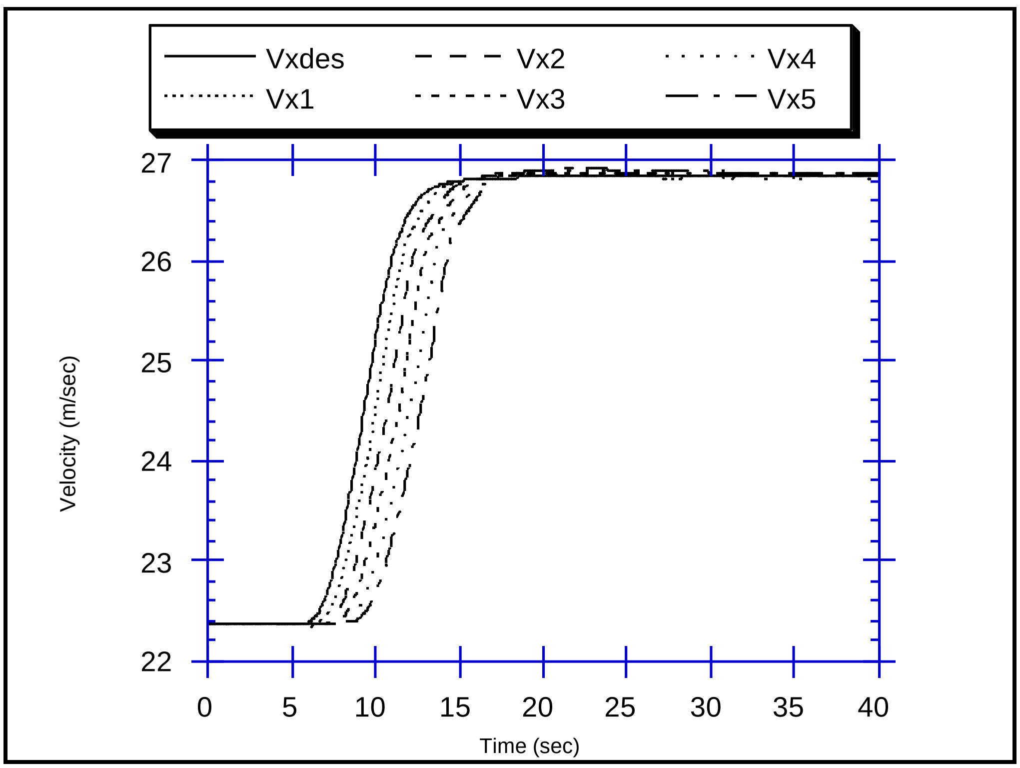


Figure 3-60. Velocities of 6 vehicles using proportional control with $\boxed{\sigma_x}$=0.03048 m and $\boxed{\sigma_{Vx}}$=0.03048 m/sec

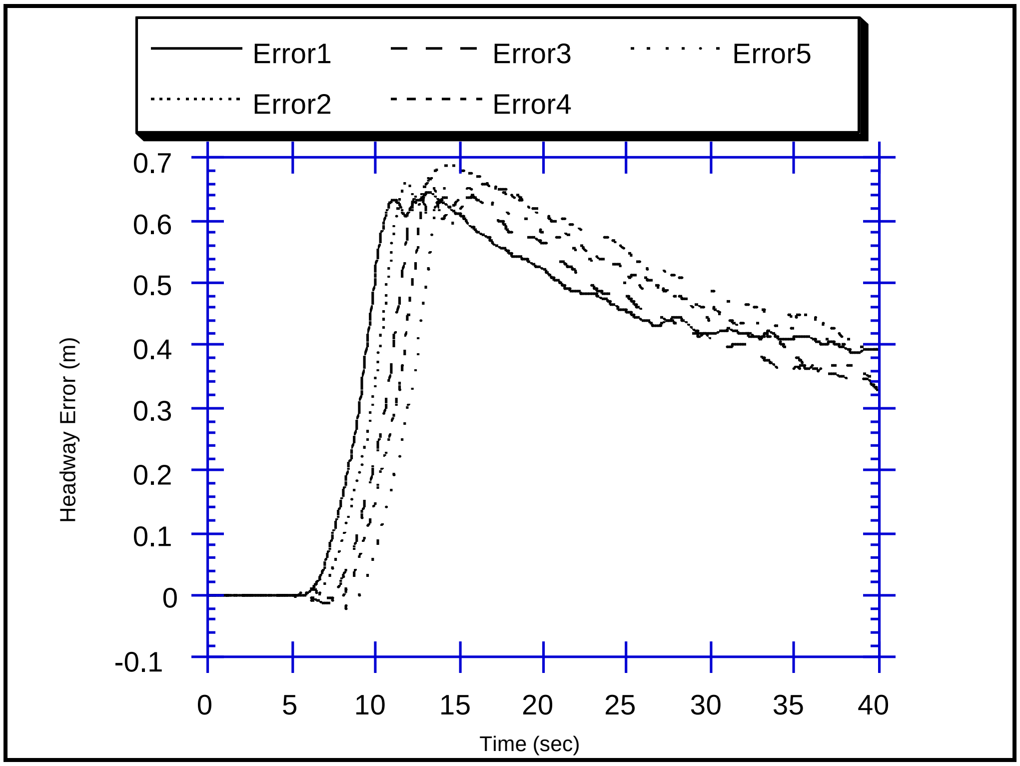


Figure 3-61. Distance errors for 5 gaps of 6 vehicles using proportional control with $\boxed{\sigma_x}$=0.03048 m and $\boxed{\sigma_{Vx}}$=0.03048 m/sec

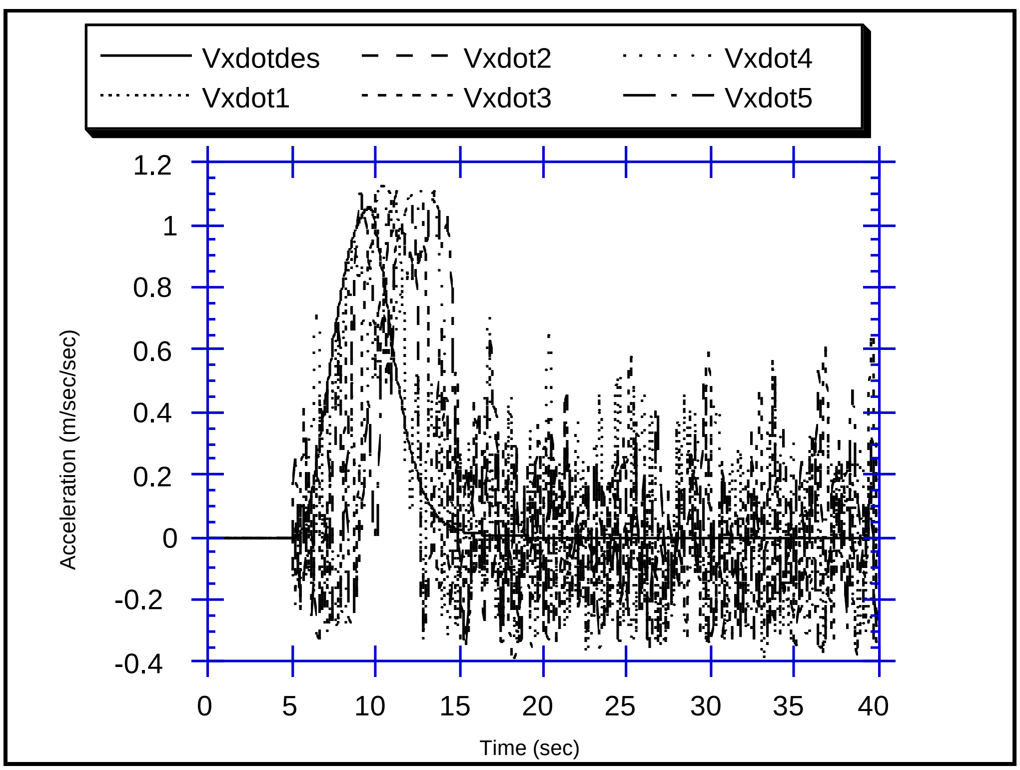


Figure 3-62. Accelerations of 6 vehicles using proportional control with $\boxed{\sigma_x}$=0.3048 m and $\boxed{\sigma_{Vx}}$=0.3048 m/sec

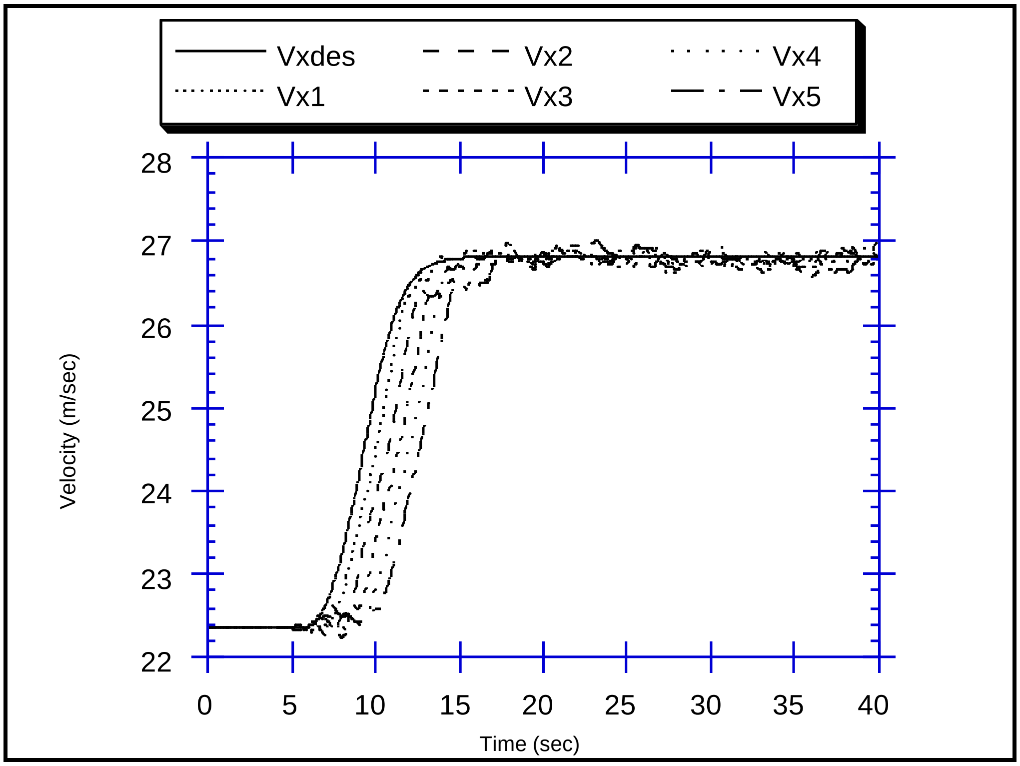


Figure 3-63. Velocities of 6 vehicles using proportional control with $\boxed{\sigma_x}$=0.3048 m and $\boxed{\sigma_{Vx}}$=0.3048 m/sec

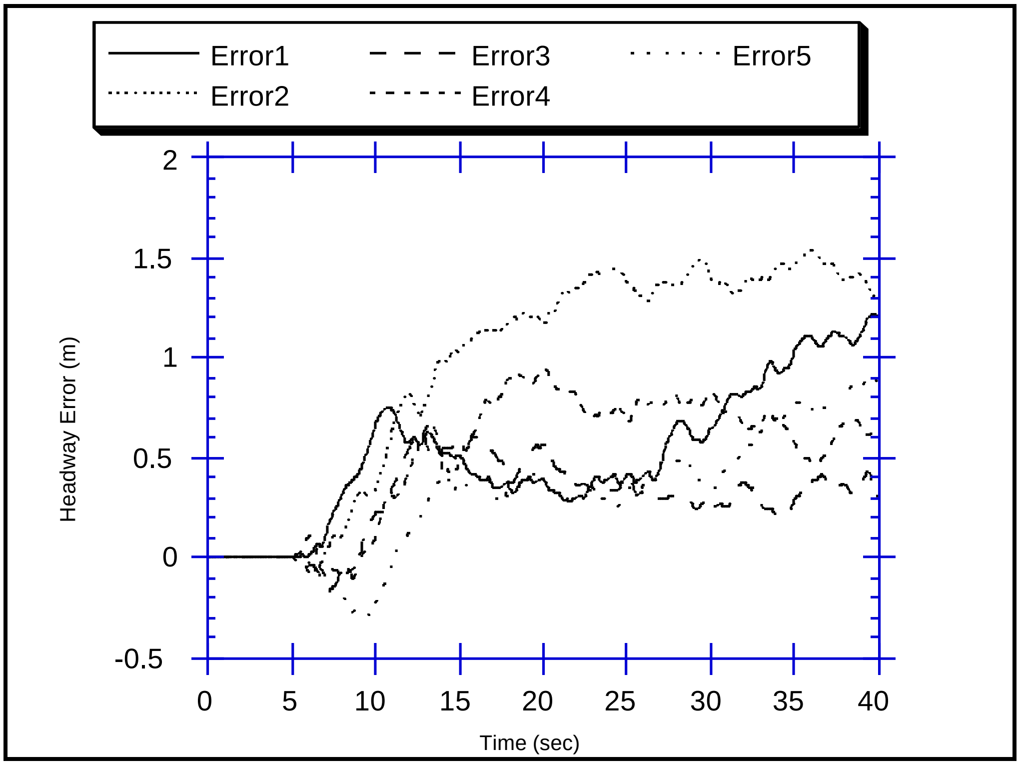


Figure 3-64. Distance errors for 5 gaps of 6 vehicles using proportional control with $\boxed{\sigma_x}$=0.3048 m and $\boxed{\sigma_{Vx}}$=0.3048 m/sec

4) If

$$tm < (10 + 50 \cdot PB) \tag{38}$$

Then, compute brake force, afb

$$a1 = \frac{2 \cdot Vxdotdes \cdot xtst - (Vxdes - Vx)^2}{2 \cdot xtst} \tag{39}$$

$$a2 = max(a1, -32.2) \tag{40}$$

where -32.2 ft/sec/sec (-9.81 m/sec/sec) is the maximum allowed brake force.

$$afb = min(a2, 0) \tag{41}$$

Else, set brake force to zero

$$afb = 0 \tag{42}$$

5) Compute the output brake force, out, based on the previous brake force, $afbp$, and the current commanded brake force, afb.

$$db = afb - afbp \tag{43}$$

$$db1 = max[-2.5, min(2.5, db)] \tag{44}$$

$$out = min(afbp + db1, 0) \tag{45}$$

There are five cases of braking results presented, which allows us to investigate the effects of deceleration level, measurement noise, platoon length, and headway policy.

In the first case, the lead car slows from 26.82 m/sec (88 ft/sec) to approximately 9 m/sec (30 ft/sec) with a smooth, symmetrical deceleration with a peak value of nearly 3.93 m/sec/sec (0.4 g). There are five following cars shown, and no noise in the measurements. The accelerations are shown in Figure 3-65, the velocities in Figure 3-66 and the distance between vehicles in Figure 3-67. This case shows several characteristics of this controller. First, there is a delay after the lead vehicle starts slowing and the following car starts responding. This is principally because the algorithm is designed with a threshold that is intended to reduce nuisance brake applications. Second, the deceleration quickly goes to the deceleration of the lead car, and then somewhat greater. Having the declarations get successively greater is not a desirable quality, but is deemed acceptable if it does not cause a problem at

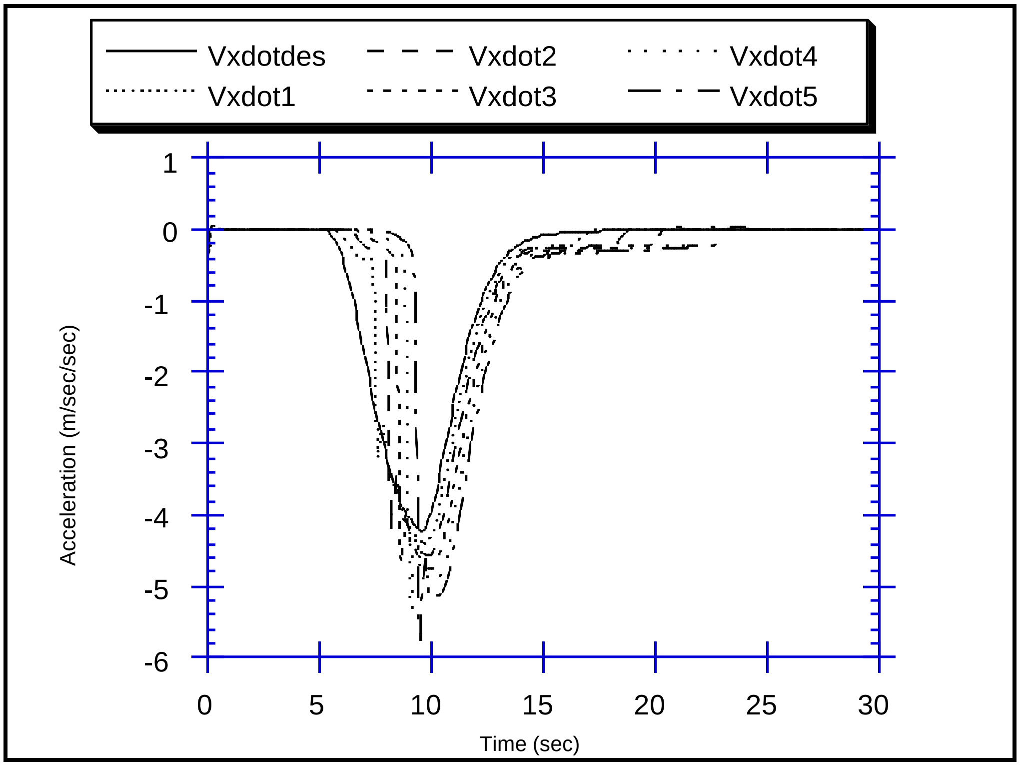


Figure 3-65. Accelerations of 6 vehicles with a 3.92 m (0.4g) lead deceleration and no sensor errors

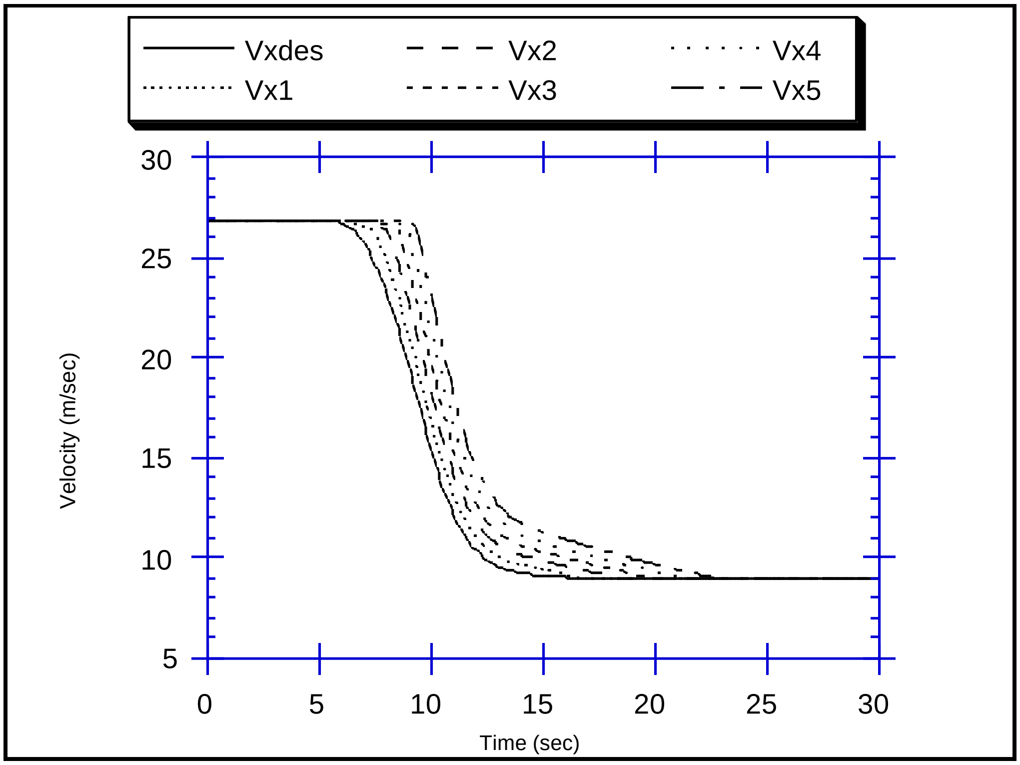


Figure 3-66. Velocities of 6 vehicles with a 3.92 m (0.4g) lead deceleration and no sensor errors

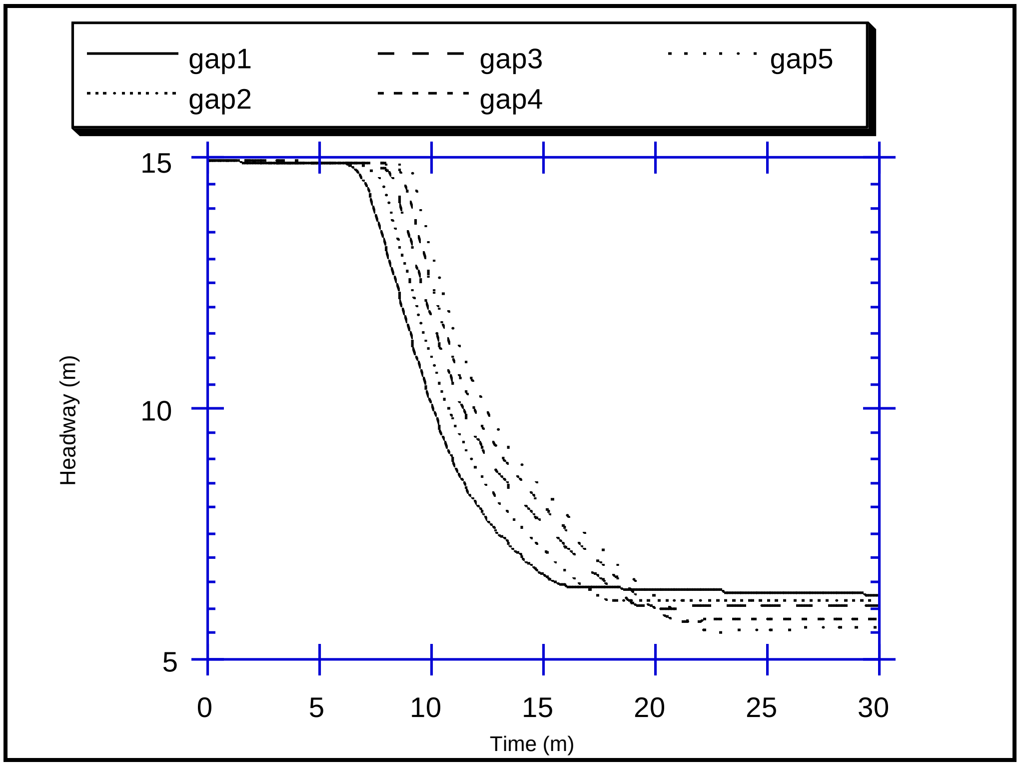


Figure 3-67. Gaps between 6 vehicles with a 3.92 m (0.4g) lead deceleration and no sensor errors

maximum brake application. It will not cause traffic instability because once the brake transient is over, the cars are returned to throttle control and the throttle controller does not normally cause large enough errors to trigger the brake. The algorithm displays a typical two phase braking, with an initial hard maneuver until the velocities are nearly matched, followed by a more gentle phase while the distance is adjusted. In the time between 15 and 25 seconds, the return to throttle control can be seen on the acceleration plot.

For next three cases, the lead vehicle brakes with increasing deceleration to just over 1 g, at which time its velocity has decreased from 26.82 m/sec to zero, and the acceleration becomes zero as well. For case two there are 5 following vehicles, and no measurement noise. The acceleration plot, Figure 3-68, still shows the delay before the brakes are applied, and the quick transition to the acceleration of the lead car, but there is no magnification of the lead car's deceleration, even though it would be possible early in the maneuver. The velocity plot, Figure 3-69 and the distance plot Figure 3-70 show the characteristic long tail to the maneuver after the lead car has stopped. None of the distances decreases below the minimum desired value of five feet even for this rather extreme maneuver.

The third case is the same as case two, with the exception that noise is added to the range and velocity measurements to the lead car. The noises were modeled as independent gaussian random numbers at the 20 Hz measurement rate with mean zero and standard deviation 0.3048 m (1 ft) and 0.3048 m/sec (1 ft/sec), respectively.

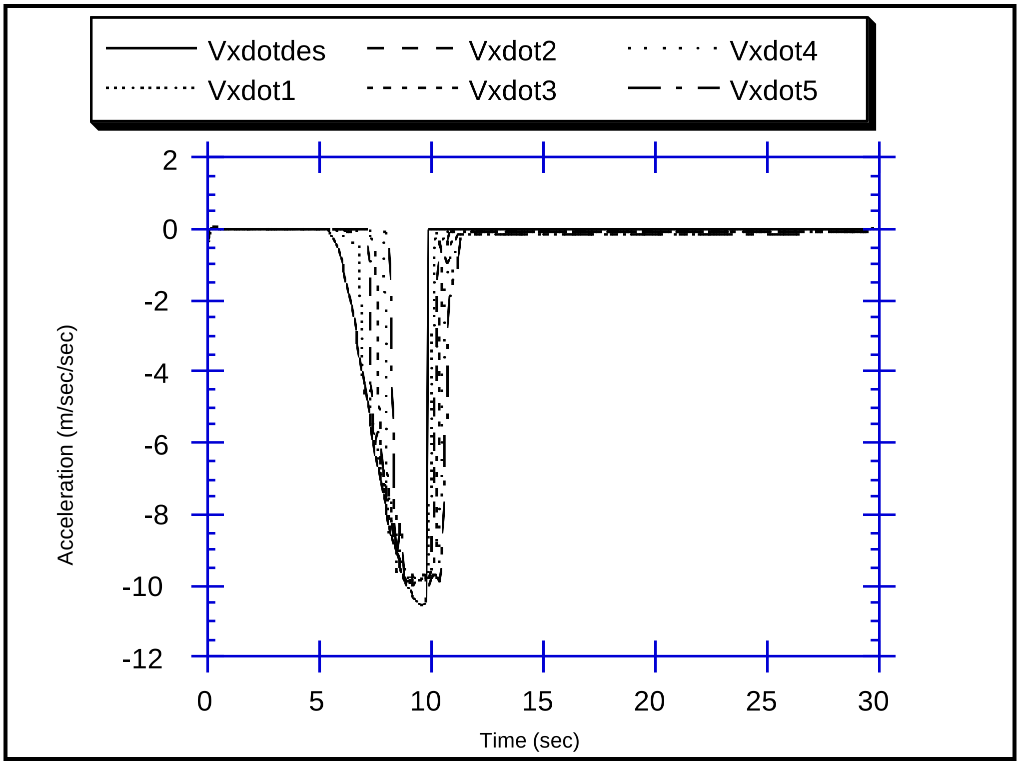


Figure 3-68. Accelerations of 6 vehicles with a 9.81 m/sec/sec (1.0g) lead deceleration and no sensor errors

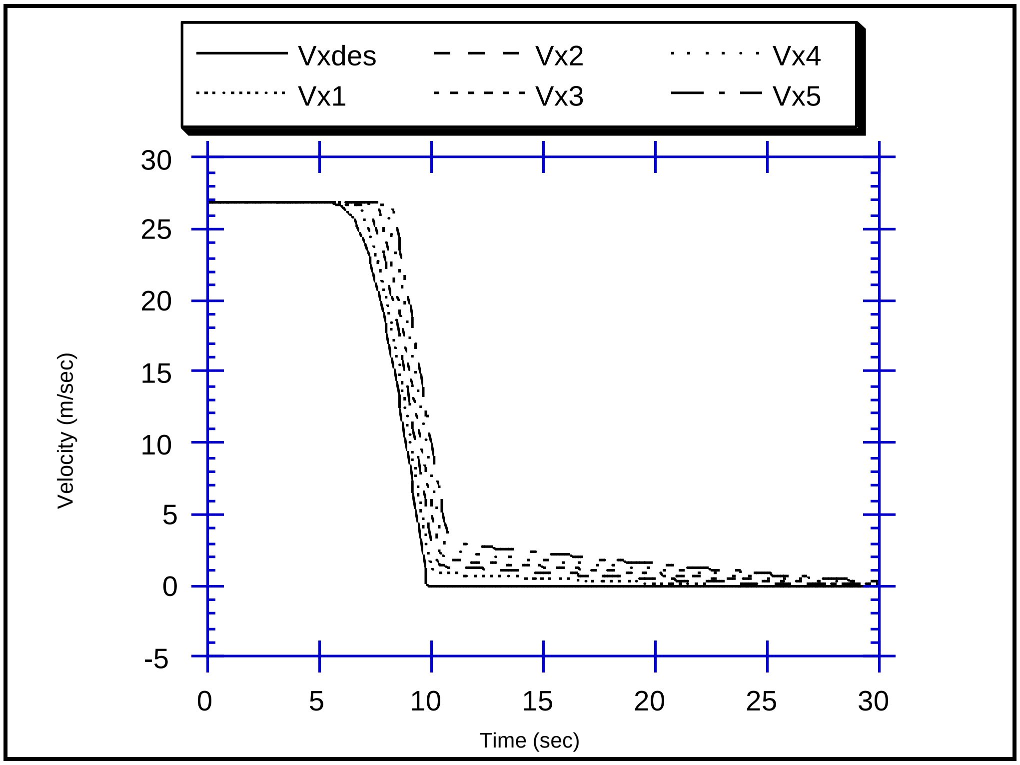


Figure 3-69. Velocities of 6 vehicles with a 9.81 m/sec/sec (1.0g) lead deceleration and no sensor errors

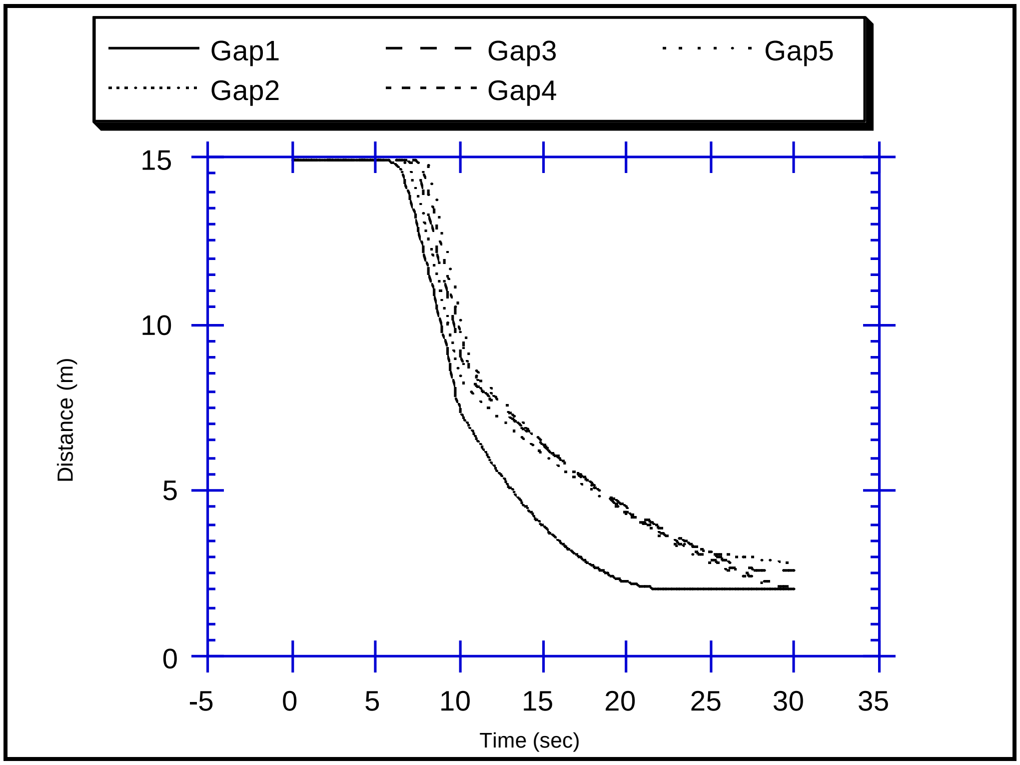


Figure 3-70. Gaps between 6 vehicles with a 9.81 m/sec/sec (1.0g) lead deceleration and no sensor errors

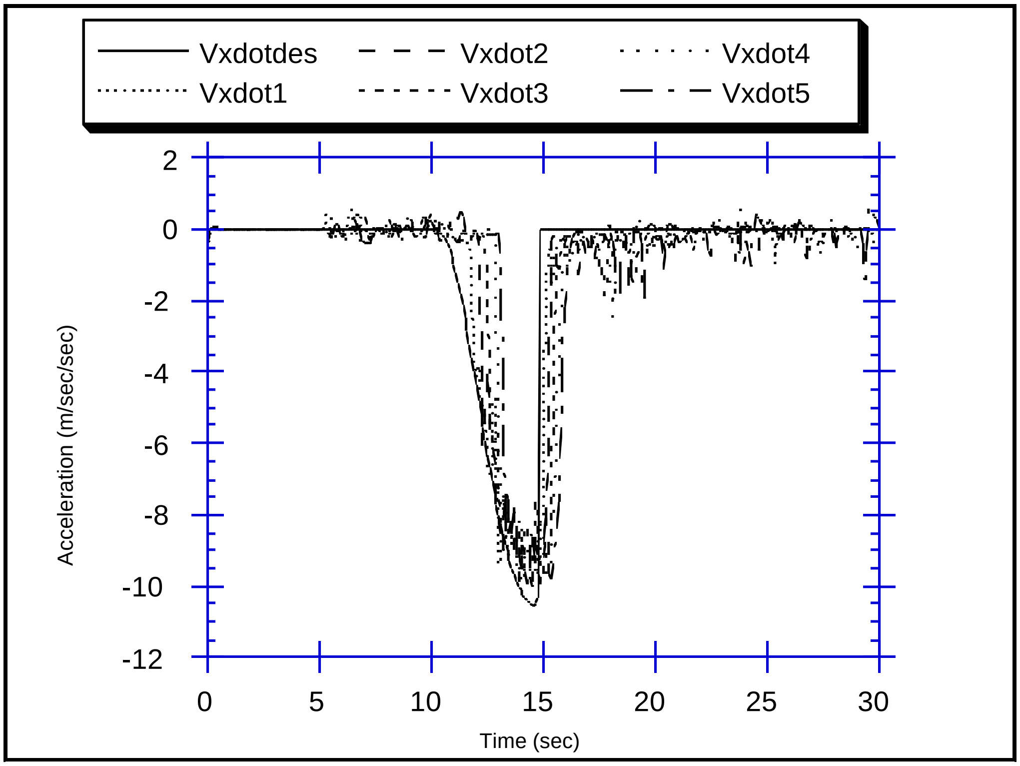


Figure 3-71. Accelerations of 6 vehicles with a 9.81 m/sec/sec (1.0g) lead deceleration and $\boxed{\sigma_x}$=0.3048 m and $\boxed{\sigma_{Vx}}$=0.3048 m/sec

The effects of the noisy measurements can be easily seen on the acceleration plot, Figure 3-71. There is an obvious high frequency noise on the acceleration whenever the slope is not too great. The effect on the velocity plot (Figure 3-72) and the distance plot (Figure 3-73) is more subtle. The distance plot shows that the distance between the vehicles starts to increase even before the braking maneuver, and that it ends up at values about five feet greater than in the no noise case. This makes sense because the algorithm will react hard to measurements that seem to show the lead vehicle slowing quickly, but not if it seems to accelerate.

The fourth case is the same as case two, except twenty following cars were used to show that there was no buildup of conditions that would cause an accident. The velocities of the cars are shown in Figure 3-74 and the distance between cars in Figure 3-75. The velocities show a smooth continuation of the pattern seen in Figure 3-69. The hard braking part of the maneuver lasts less long for each successive vehicle, then the speeds gradually decrease to zero. The distances show a somewhat different pattern starting after car number eight, but nothing shows as uncomfortable or dangerous.

In the last case, an extreme barking maneuver of 9.81 m/sec/sec (1g) deceleration in 0.5 seconds was tested against a 0.5 sec, 0.2 sec, and 0.1 sec headway policy with a safety distnace of 1.52 m (5 ft). For the 0.5 sec follower (Figures 3-76 to 3-79), all followers came to a complete stop within two meters of each other, not violating the 1.52 m safety gap. A 1.52 m safety gap was added to the headway

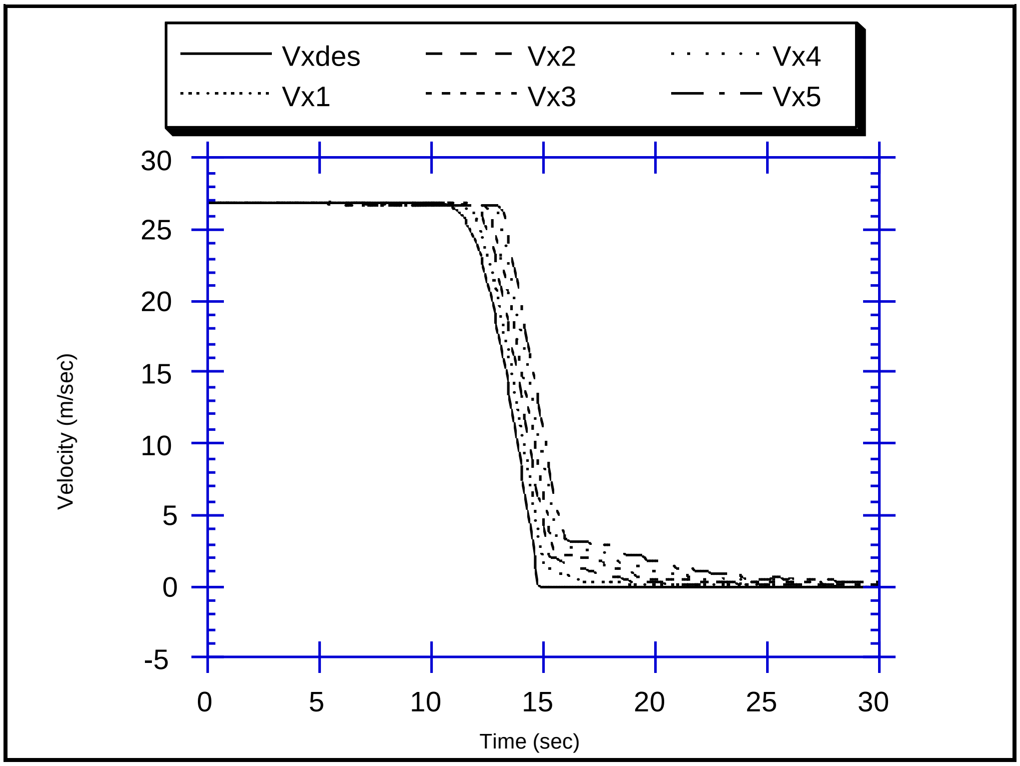


Figure 3-72. Velocities of 6 vehicles with a 9.81 m/sec/sec (1.0g) lead deceleration and $\boxed{\sigma_x}$=0.3048 m and $\boxed{\sigma_{Vx}}$=0.3048 m/sec

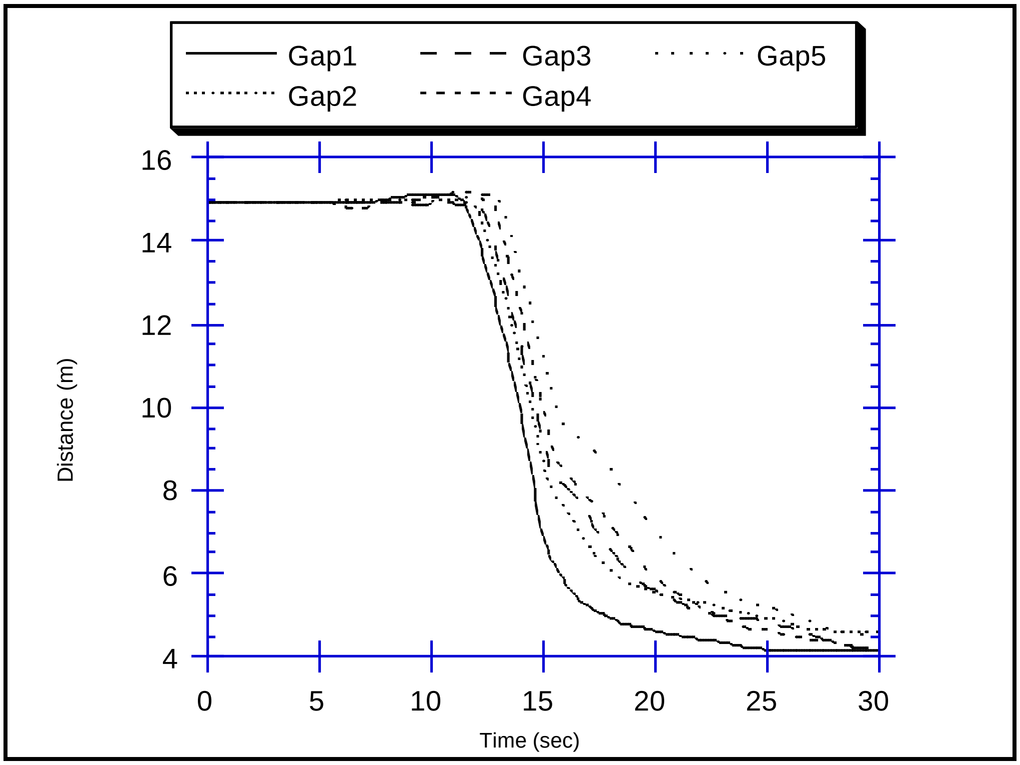


Figure 3-73. Gaps between 6 vehicles with a 9.81 m/sec/sec (1.0g) lead deceleration and $\boxed{\sigma_x}$=0.3048 m and $\boxed{\sigma_{Vx}}$=0.3048 m/sec

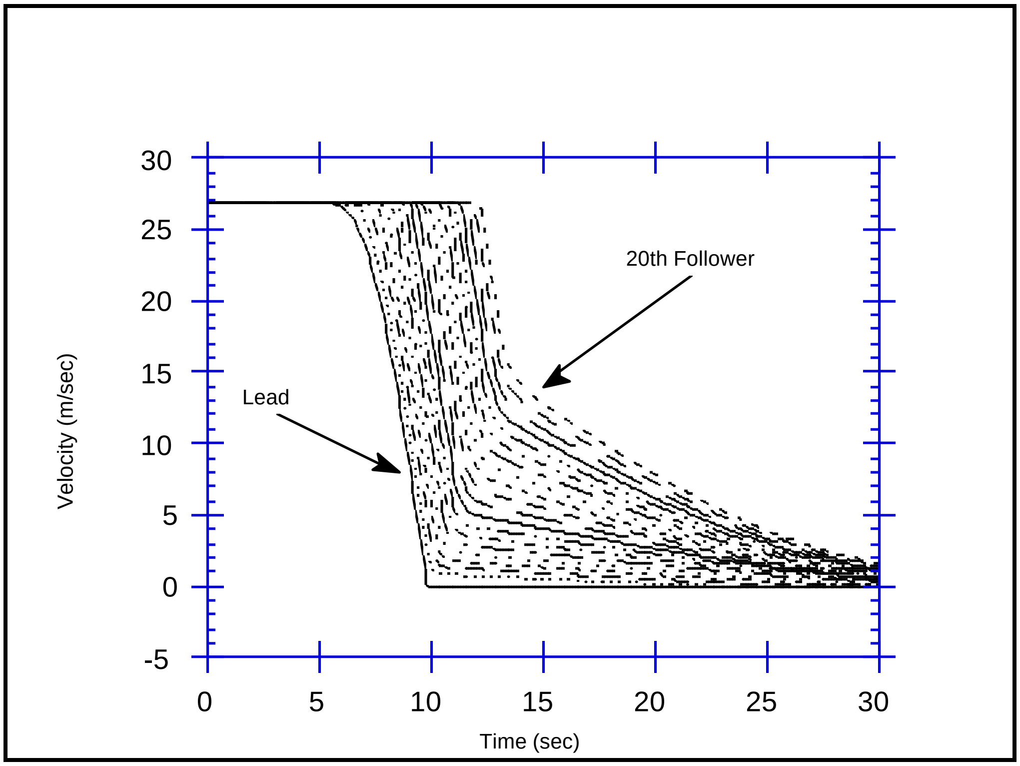


Figure 3-74. Velocities of 20 vehicles between with a 9.81 m/sec/sec (1.0g) lead deceleration and no errors

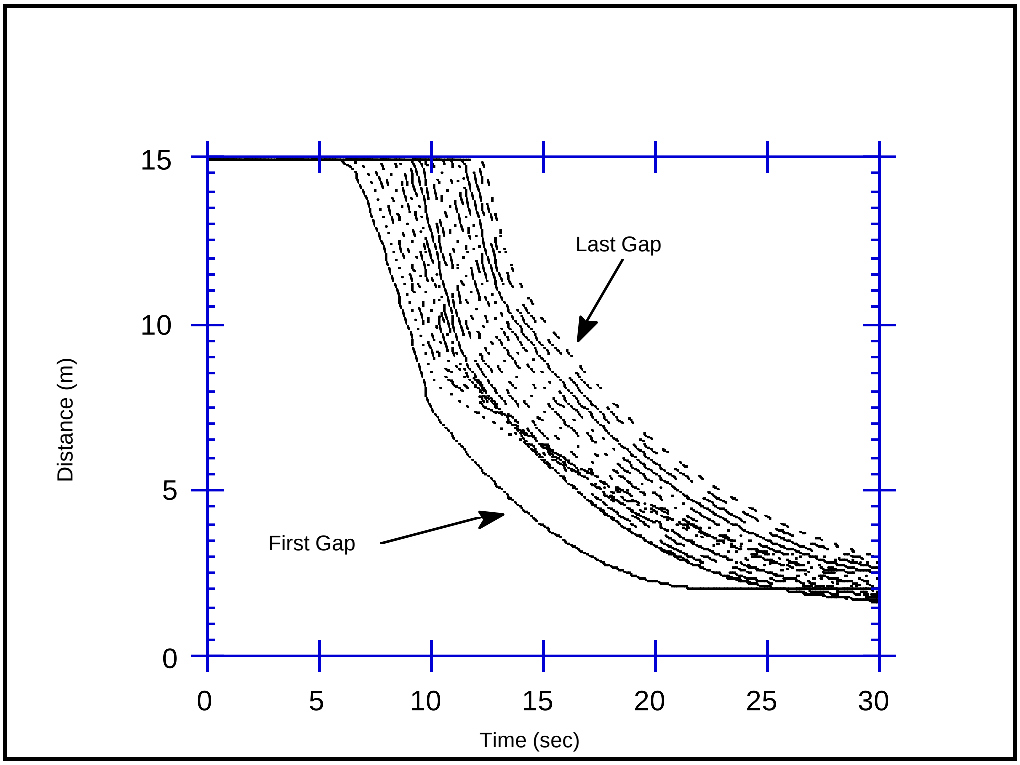


Figure 3-75. Gaps between 20 vehicles with a 9.81 m/sec/sec (1.0g) lead deceleration and no errors

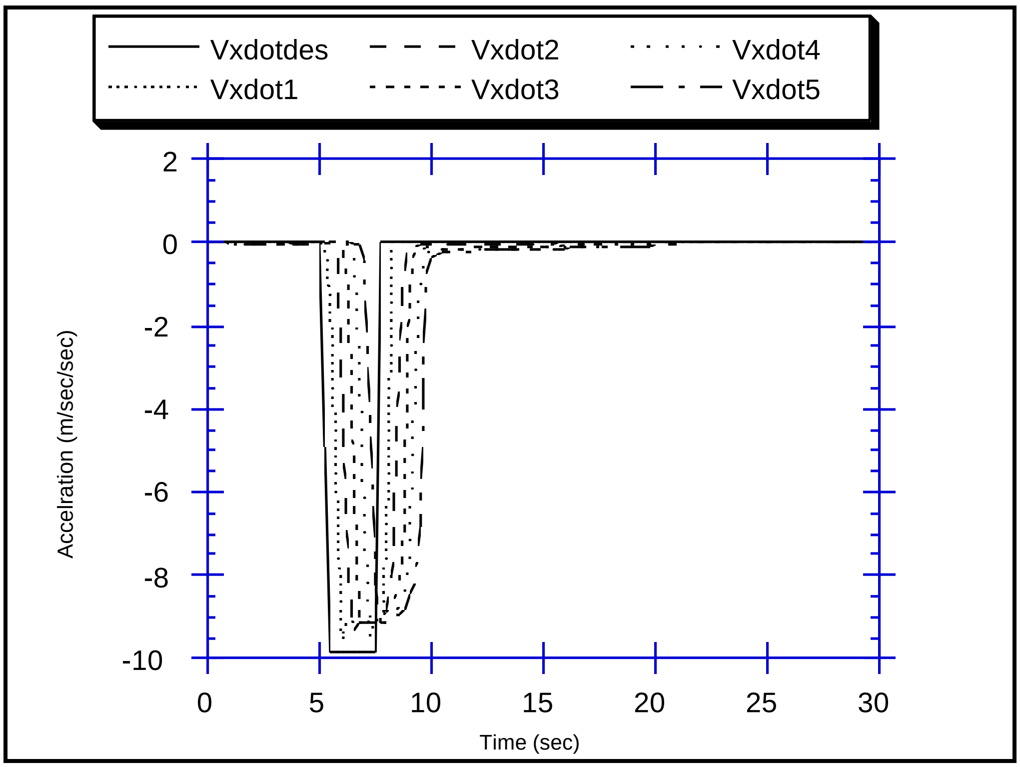


Figure 3-76. Acceleration of 6 vehicles with a 9.81 m/sec/sec (1.0g) lead deceleration, 0.5 sec headway, and no sensor errors

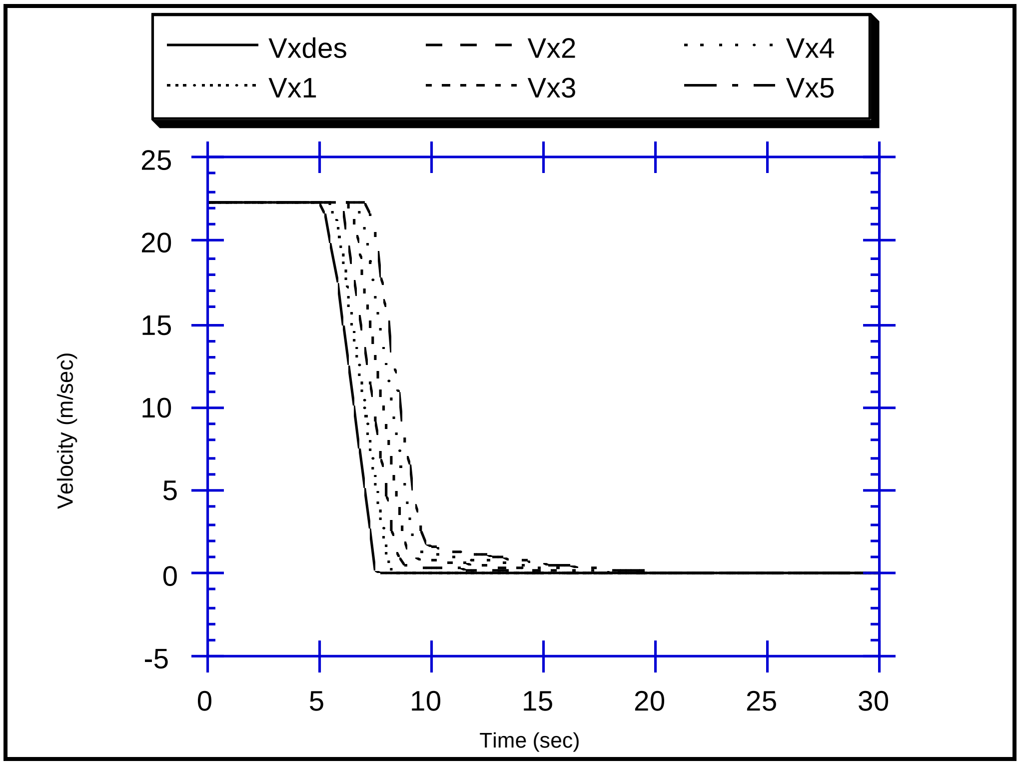


Figure 3-77. Velocity of 6 vehicles with a 9.81 m/sec/sec (1.0g) lead deceleration, 0.5 sec headway, and no sensor errors

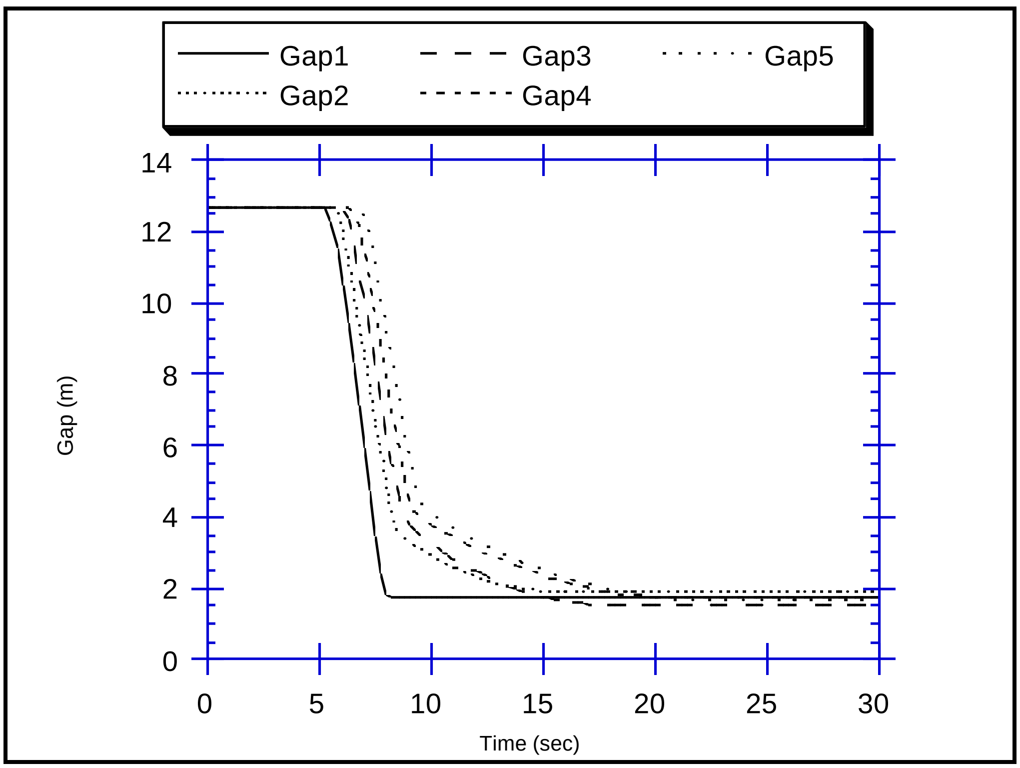


Figure 3-78. Distance between vehicles for 6 vehicles with a 9.81 m/sec/sec (1.0g) lead deceleration, 0.5 sec headway, and no sensor errors

controller as indicated in equation 30, in order tokeep the vehicles from touching during low speed operation. Although at one point, this safety gap is violated, as indicated by the negative error in Figure 3-79, the controller was quick to recover to maintain safe operation. For the 0.2 sec follower (Figure 3-80 and 3-81), the gap between the first vehicle and the first follower decreases to less than 1.0 m indicating a violation of the safety gap. This violation id also evident in the negative headway error in Figure 3-81. The remaining followers do not violate the safety gap criteria. For the 0.1 sec follower (Figures 3-82 to 3-83), a collision occurs as indicated by a negative gap in Figure 3-82. This provides a limit to the tested braking algorithm.

The results shown indicate that it is possible to develop a safe and effective braking algorithm that will not trigger the brakes for normal conditions, even in the presence of reasonable amounts of noise. Even a car pulling in ahead of a following car should not trigger this breaking algorithm as long as the lead car is going faster, but if the car pulling in is going slower, a large brake maneuver is expected.

3.6.4 Conclusions

This study indicates that even though it is possible to get very tight control of vehicle spacing under ideal conditions (no sensor errors and/ or very high sample rates) in more realistic conditions errors of many feet may be expected. With sensor noise, there is a trade off between tight control and noise smoothing. That is with a high gain, high bandwidth system that provides low errors in response to maneuvers, there is also a substantial response to measurement errors. We believe this will be an important tradeoff with any system design, although some designs may achieve a better combination than the designs investigated here.

It is possible to design a braking controller that has several desirable features. This algorithm will not cause accidents even if the lead car brakes at maximum deceleration. Sensor noise does not reduce safety. Noise does tend to increase the distance between vehicles, and at high enough levels will cause false brake applications (i.e., when the lead vehicle is not slowing). Under normal cruising conditions, even with moderate levels of noise the brakes are not commanded.

3.6.5 Recommendations For Future Work

This work could be extended in several ways. First, it is believed that information about the lead car's acceleration could be used to significantly reduce the effect of measurement noise. This information could be in any of several forms. The most obvious is that the lead car could transmit its measured acceleration over some communication link. This signal could be included in the car following algorithm, which would allow faster response with lower gains on the velocity and position errors, which would provide a better trade off between noise smoothing and responsiveness. A lower bandwidth and simpler communication would be for the lead car to provide an indicator that it is maneuvering (e.g., acceleration gt 0.05 g) . This would allow the following car to smooth the velocity and position estimates more heavily when the lead car is not maneuvering, and provide much less response to the noise. An even simpler option would be to provide a sensor for the lead car's brake lights. This could lead to a brake algorithm that is less sensitive to noise for normal cruising, and still provide very good accident avoidance.

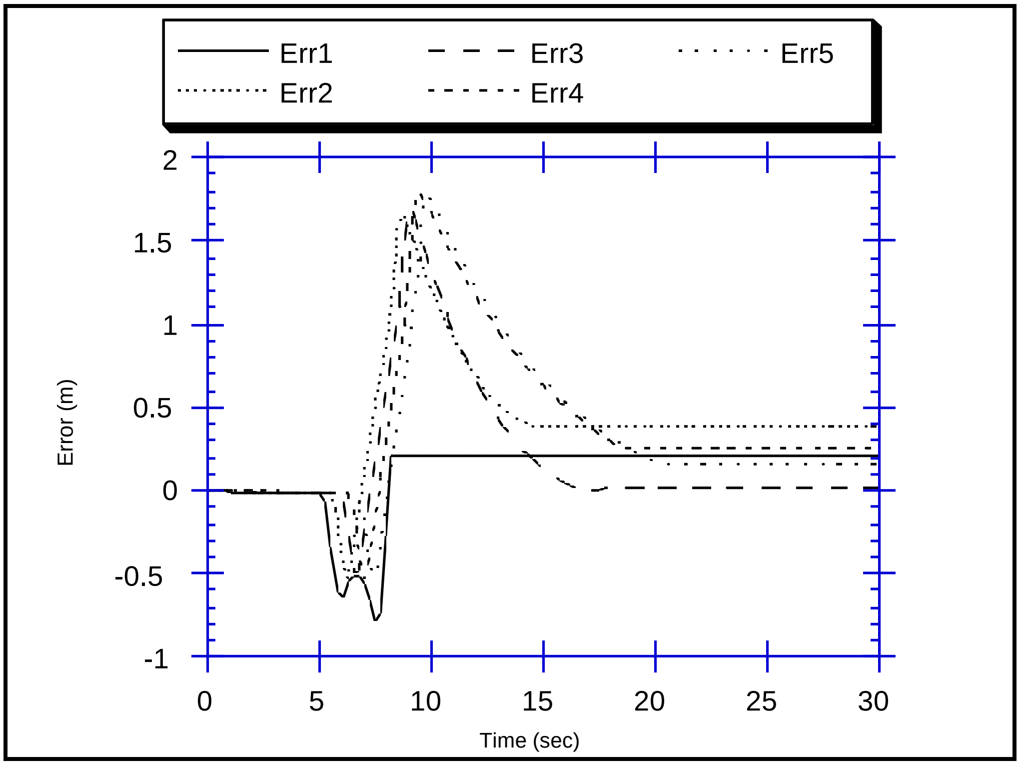


Figure 3-79. Headway error of 6 vehicles with a 9.81 m/sec/sec (1.0g) lead deceleration, 0.5 sec headway, and no sensor errors

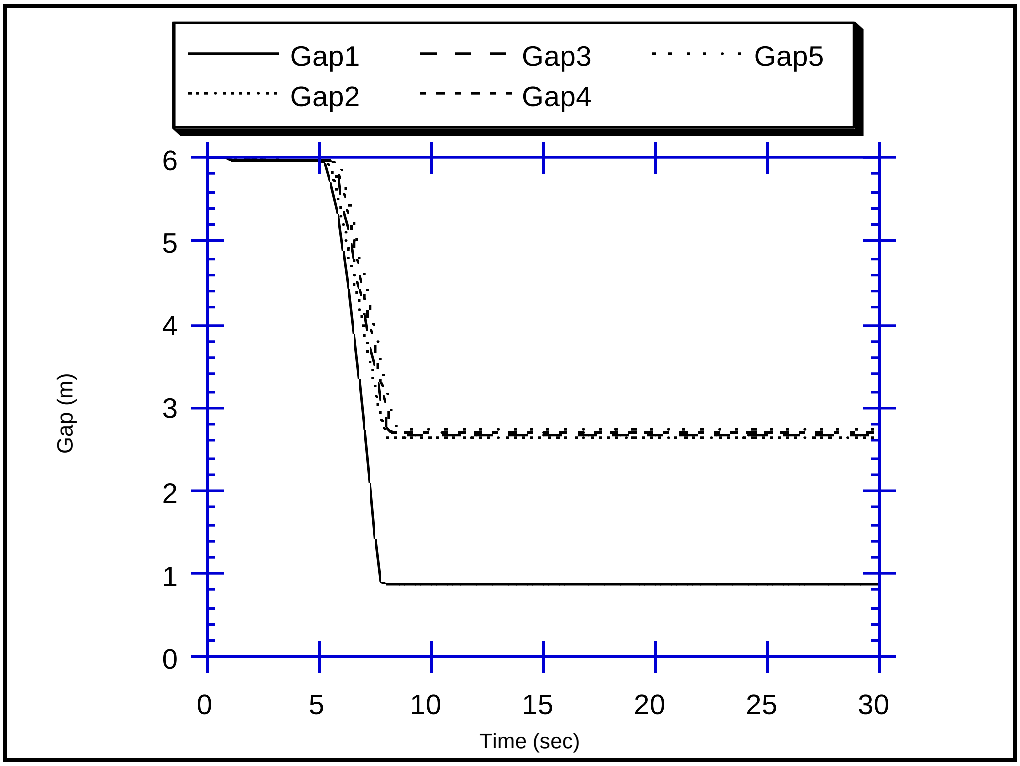


Figure 3-80. Distance between vehicles for 6 vehicles with a 9.81 m/sec/sec (1.0g) lead deceleration, 0.2 sec headway, and no sensor errors

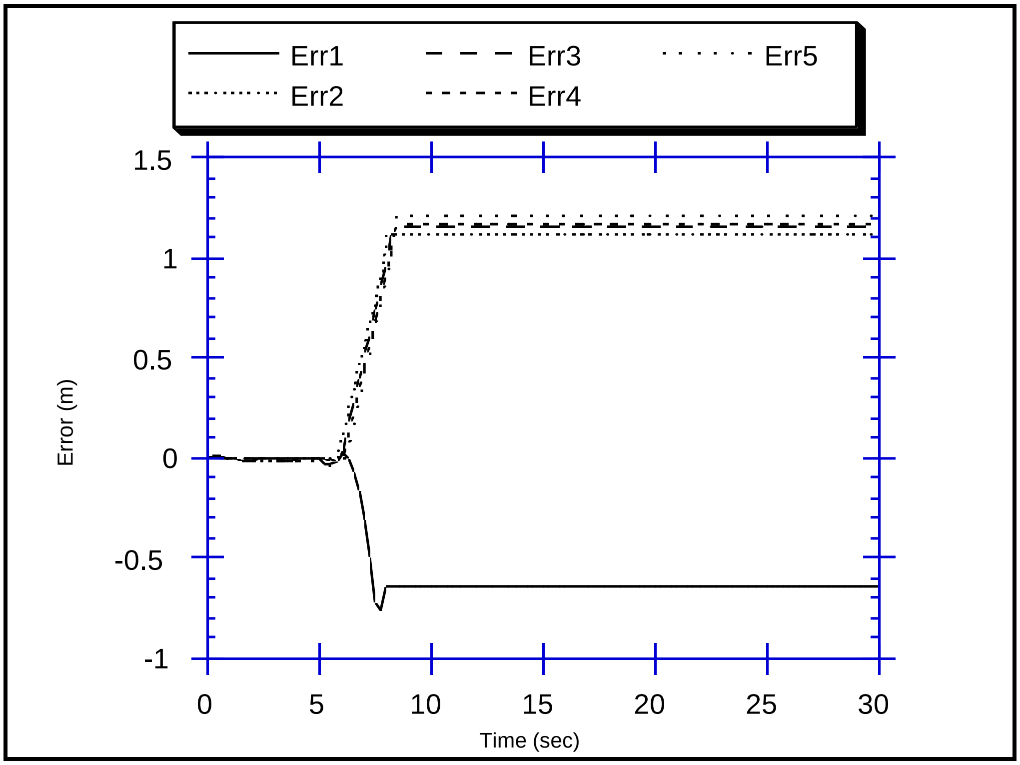


Figure 3-81. Headway error of 6 vehicles with a 9.81 m/sec/sec (1.0g) lead deceleration, 0.2 sec headway, and no sensor errors

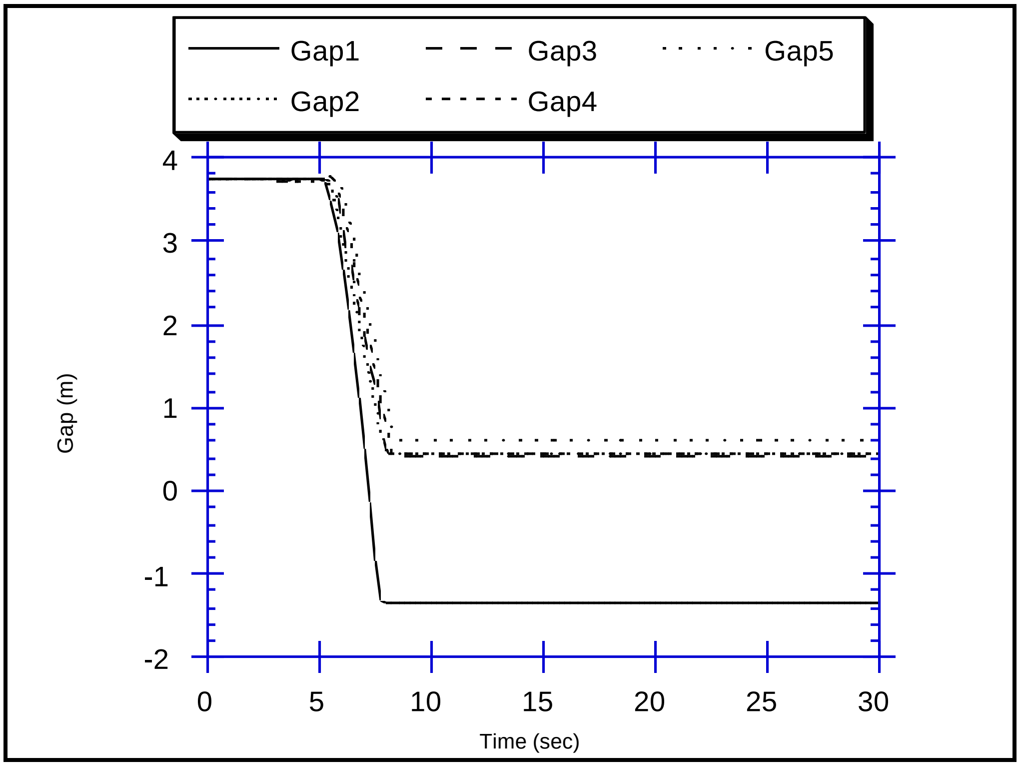


Figure 3-82. Distance between vehicles for 6 vehicles with a 9.81 m/sec/sec (1.0g) lead deceleration, 0.1 sec headway, and no sensor errors

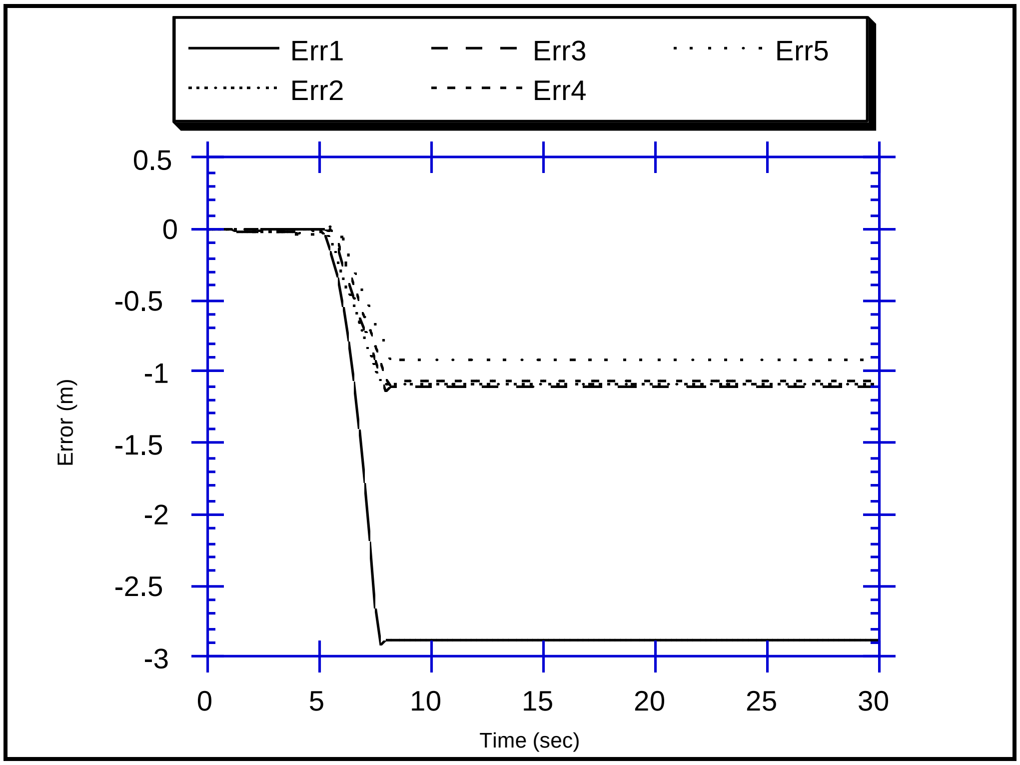


Figure 3-83. Headway error of 6 vehicles with a 9.81 m/sec/sec (1.0g) lead deceleration, 0.1 sec headway, and no sensor errors

Second, the various measurements of the lead car's state, combined with any of the signaled acceleration information, could be combined in a 'Kalman filter' or similar structure to give combined best estimate of the lead car's state. This estimate should allow an improved tradeoff between responsiveness and noise immunity.

A mix of vehicle responses in a platoon should be studied. For the present study, all of the cars had identical responses. This may be especially important if the maximum deceleration under braking is different for different cars. Also a problem may occur if the road surface changes so that maximum deceleration changes with longitudinal position.

The simulation should also be extended to include lateral dynamics and control. Studies should address lane changes, merging and demerging, and wet or icy pavement.

Related studies could also provide useful information to future control algorithm development.

Traffic flow studies should be performed to determine how changes in vehicle control systems change highway capacity. Examples of questions to be addressed are 'what is the effect on overall capacity if the control system responds somewhat slowly?' and 'How does spacing within and between platoons affect the ability of traffic to move to exit ramps at urban interchanges?'.

On road studies with instrumented vehicles could be made to study how noise in the measurements and in the control system affects gas mileage, emissions, and passenger comfort. This information is necessary to make informed decisions on the control system design tradeoffs between responsiveness and noise immunity.

3.7 RECOMMENDED SYSTEM CONFIGURATION

Three concepts promise to provide lateral guidance in almost all weather conditions and at all times of day. These are magnetic nails, overhead inductive transmission lines and an improved GPS system combined with map matching. Magnetic nails (Section 3.2.5) allow very precise guidance to centimeter accuracy but cannot be sensed until the vehicle is within about 2 ft. of lane center. This problem could be overcome by adding additional sensors on the vehicle which might provide valuable redundancy and improved lane changing capability. Magnetic nails can provide some roadway-to-vehicle communication on more-or-less permanent conditions such as turns.

Induction sensing was one of the first methods used to guide automated vehicles laterally (Section 3.2.6). Buried or roadside induction guide wires are severely limited by the fact that they induce image currents in or behind any conductor in the vicinity. These currents cancel the induction field at the conductor and therefore make guidance unreliable. Induction fields generated by overhead transmission lines are not influenced by this effect. They allow lateral guidance over a wider range, including lane changing, and can be modulated to provide roadway-to-vehicle communications. Such communications can be altered to reflect changing conditions.

Kinetic DGPS systems (KGPS) are exhibiting AHS-class accuracy in aircraft systems (Section 3.2.7). To some extent this is so because aircraft are continuously exposed to a relatively fixed constellation of Navsats. They can eliminate false carrier phase tracks and achieve centimeter accuracy after a few minutes of flight during which DGPS accuracy of a few meters is acceptable. Road vehicles need decimeter accuracy at all times. It is very possible that methods for initializing DGPS and managing temporary loss of some Navsats will be developed in the near future. A combination of KGPS and map-matching would provide a very attractive AHS lateral guidance concept.

Two concepts exist for longitudinal control. In vehicle-following, each car judges its distance to the car ahead (spacing) by on-board sensors. In point-following each vehicle follows a point that moves along the road at a specified speed.

Point following can be separated into two categories. One involves placing the measurement sensor onboard the vehicle, while in the other the sensors are located on the roadway. Examples of the first category are DGPS, overhead wires, and radio ranging systems such as a LORAN-like system. Examples of the second category include roadside cameras and ranging systems that use multiple receivers to range on beacon signals radiated from the vehicle. The second category, where the infrastructure determines the error signal, requires a high speed data link between the roadway and the vehicle to carry the error signal to the control loop. The infrastructure is inside the inner control loop. For longitudinal control the data rate of the communication link can be reduced somewhat. The vehicle could be commanded to maintain a given speed. If the infrastructure determines that a given vehicle has reduced the gap spacing to the car ahead to too low a value, a command could be issued to open the gap by a given amount such as 1 meter. The vehicle slows and resumes speed such that it creates 1 meter additional gap. Therefore, the infrastructure does not control the throttle directly but rather issues commands. The data rate of the commands could be one or two per sec. However, if an emergency situation develops a command must be issued with very little delay (within a few milliseconds). Thus, while the average communication data rates can be a few per sec, to each vehicle, rapid response must be provided for.

We feel that measuring position errors (either lateral or longitudinal) with infrastructure sensors and then communicating these data to the vehicles present a very serious safety issue in that control is lost if any of the infrastructure equipment, i.e., sensors, signal processing, computers and communications equipment should fail, or are interrupted. If the sensors are located on the vehicle, the control loop can be closed without involving the infrastructure.

If a point-follower type control system is chosen for AHS longitudinal control, one would probably want to have a headway measuring device on the vehicle to insure that adequate gap exists. Such a sensor would not have to be as complex as if it were the primary longitudinal control sensor as it is required to only verify headway to the vehicle ahead.

One final comment regarding point-following systems. Any of the point-follower systems will require rather extensive infrastructure equipment before any operation is possible. We feel that AHS will involve over a period of time. We also expect that intelligent cruise control (ICC) will be available on new vehicles within a year or so. These systems will use some form of headway measurement. There are competing systems that employ radar or laser techniques. It is expected that these systems will become more capable including full braking. Early auto control will likely involve an ICC and a form of lane keeping, such as magnetic markers. Lane changing would likely be the responsibility of the driver. An AHS system could be introduced that relied on a point-follower system, however, the problem of how one converts a manual lane to a dedicated AHS lane without a major disruption to the traffic flow remains. Would a sufficient number of vehicles be ready to operate on the AHS on day one to not upset the throughput? These issues need to be examined in far more detail than was possible on this brief and limited study.

A point-follower system is described in section 3.8 that utilizes video cameras at frequent intervals along the roadway as a postulated system for a cost trade study and does not constitute a recommended approach.

DGPS is probably sufficiently accurate for longitudinal control in combination with map-matching. An infrastructure-based manager may be able to broadcast parameters of the equations of motion for guide points in a certain region, thereby producing a point-follower system with less infrastructure that the one in the last paragraph. Such a system may be more applicable to rural AHS while the video system is more applicable in urban and suburban environments.

Two technologies for measuring headway are preferred. One is radar operating in the oxygen absorption band at 60 GHz or mm wavelength (Section 3.2.2). The other is data link ranging at the same frequency (Section 3.2.7.2.2). Both techniques "pollute" the electromagnetic spectrum in that they cause mutual interference among users. This pollution extends outward to an as yet ill-defined interference range. This range is reduced - a benefit - by operating in the absorption bands at 60 GHz (attenuation 20 dB/km), 200 GHz (attenuation 40 dB.km) and 350 GHz (attenuation 40 dB/km) and possibly at higher frequencies where the attenuation is even higher.

In the case of radar, it is further reduced by placing a retroreflector, a relatively inexpensive device, on the back of each vehicle. This could be mandated some time before the introduction of AHS and presence of the retroreflector could be a condition for checking into AHS. The ultimate replacement of a retroreflector is a beacon that responds to a radar-like interrogation. This is the basis of data link ranging - the interrogation may as well pass whatever information needs to be passed to the beacon, and the response may return whatever information should flow back (Section 3.2.7.2.2). The "chipping" of interrogation and response provides additional opportunities for post-detection integration. The benefit of such integration is greater for short packets at high rates, favoring links with greater bandwidth that are also more tolerant of Doppler shift. Interference range for data link ranging appears to be less (450 m) than for radar systems with a retroreflector (2900m). The results of this analysis are not definitive, however, and should be succeeded by a more detailed study.

A very serious problem - that of introduction to the market - besets data link ranging. Presumably early AHS users will live in an I1C1 (mixed AHS and conventional traffic) environment. They cannot depend on the lead car to have a data link though, as mentioned above, it may have a retroreflector. I1C1 uses will therefore need a radar.

Once early AHS systems become widely accepted, radar-equipped users may start to feel effects of mutual interference. At that time one may need to consider the benefits of data link ranging, where mutual interference can almost be eliminated by network management (Section 3.3.5).

We have addressed I_2 and I_3 and C_1 and C_2 configurations. They do not differ much in their demands on the lateral and longitudinal control. The car driver/owner is still responsible. At the I3C3 level, the infrastructure acquires responsibility of its own. Being the government, in some form or another, it is not easily sued, yet may be responsible for decisions made by its computers. Heavily infrastructure-based systems of AHS are particularly subject to abuse. A legal framework dividing responsibility for potential accidents involving interaction of privately and publicly owned AHS facilities may be needed in I3C3 AHS systems (Volume VIII, Chapter 1).

3.8 COMPARISON OF TWO AHS IMPLEMENTATION CONCEPTS

This section describes two longitudinal control concepts, a point follower concept and a vehicle follower concept. These are considered in conjunction with RSC C3 controls using either a I2 or I3 infrastructure RSC. The functional responsibilities and equipment locations are described for each configuration, and the cost differences between the configurations are identified.

3.8.1 Concept Definitions

The point follower concept is described in terms of a strawman configuration, termed Configuration A. This configuration derives accurate longitudinal position referencing from infrastructure-based sensors. Configuration B, the vehicle follower-based system, employs vehicle-based longitudinal position sensing. Both configurations use on board sensors for lateral control.

The C3 control function may, in principle, be satisfied by a longitudinal control and merging approach which utilizes either point follower or vehicle follower control principles.

- Point Follower (Type 1)

The AHS mainline flow consists of a set of slots moving at a constant velocity. The slots are large enough to contain a vehicle and its intervehicle spacing. The velocity may be changed from time to time by a control function. A set of control rules is provided for vehicle response under emergency conditions (Figure 3-84).

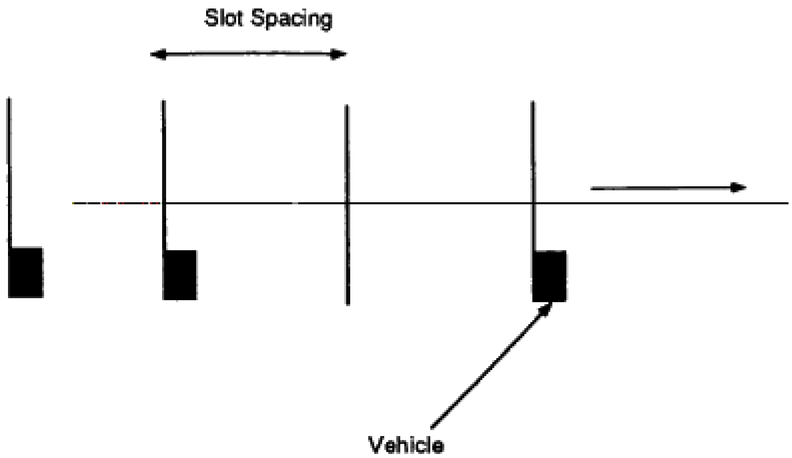
- Point Follower (Type 2)

The AHS mainline flow consists of a series of slots which contain closely spaced platoons (Figure 3-85). There is a fixed distance (for each mainline speed) between slots. Once a vehicle is in a slot, it will not leave the slot until it leaves the AHS or changes lanes. There may be several vehicle positions spaced at short headways within the slot. A vehicle may move to a new vehicle position within the slot to facilitate merging and demerging. When slots are sized for platoons of up to three vehicles, however, no constraints are imposed on slot entry by the vehicle AHS entry or exit points; i.e., by placing an entering vehicle either at the beginning or end of a platoon as appropriate, the platoon need not be broken in the middle to allow a vehicle to exit at its appropriate interchange. With longer platoons, the platoon must sometimes be broken to enable vehicles to exit; the probability of breaking the platoon increases with platoon length.

A set of control rules is provided for vehicle response under emergency conditions.

- Vehicle Follower

Mainline vehicle spacing, shown in Figure 3-86, is controlled relative to the preceding vehicle. Rules are provided for minimum vehicle spacing, platoon



- Slot spacing determined by infrastructure
- Each slot has explicit position vs time relationship
- Vehicle must control to slot position
- Vehicle may or may not occupy slot

Figure 3-84. Point Follower (Type 1)

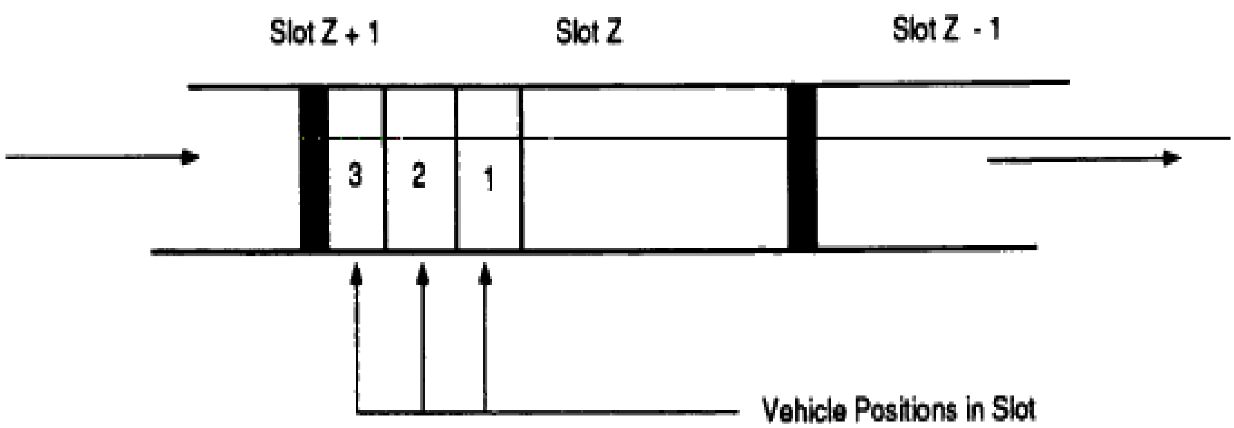
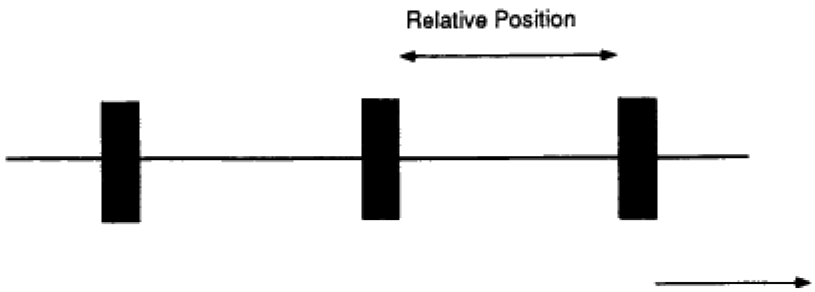


Figure 3-85. Point Follower (Type 2) with Three Vehicle Positions



- Position of Vehicle Relative to Preceding Vehicle is determined by a Vehicle Following Control Law

Figure 3-86. Vehicle Follower

management, and additional headway requirements for merging and demerging. While the mainline may have a design speed, the actual velocity of each vehicle is determined by the vehicle following rules. Vehicles may move relative to each other to respond to such AHS management requirements as providing gaps for merging and reorganizing platoons. Vehicle management prior to AHS entry or at AHS entry locations may be required in order to ensure the adequacy of opportunities to enter the AHS.

Because the vehicle follower concept depends on relative position and relative position derivatives with respect to the preceding vehicle (and possibly other vehicles in advance of the preceding vehicle), it is likely that the most efficient implementation of this concept is to locate headway sensors on the vehicle.

3.8.1.1 Point Follower Approach with Longitudinal Position Determination By Infrastructure Equipment Configuration

Because the Type 1 point follower configuration controls the vehicle to a predetermined longitudinal position (rather than to a relative position), the possibility exists that an infrastructure based location for the longitudinal position sensor is both more cost effective and more reliable than a vehicle based location.

Because the vehicle follower/vehicle based sensor configuration has been studied in considerable detail by others, our study has concentrated on the point follower/infrastructure based sensor configuration. Table 3-12 summarizes the assignment of major control functions between the vehicle and the infrastructure.

Table 3-12. Function Assignment for Point Follower With Longitudinal Position Determination by Infrastructure

Vehicle Functions
• Actuating devices for longitudinal and lateral control • Controllers for longitudinal and lateral control • Sensors for lateral control (possibly in conjunction with roadway devices) • Devices which may be necessary for vehicle control loop stabilization and approximate position determination (e.g., odometer, wheel tachometer, and accelerometer • If short headway platoons with intraplatoon vehicle spacing of approximately 1-3 m (3-9 ft) are implemented (Type 2 Point Follower), a relative position and velocity device (range limited to perhaps 3-9 m (10 to 15 ft)) is required on the vehicle. • Two way data communication with the infrastructure
Infrastructure Functions
• Devices to obtain longitudinal position of all vehicles on the roadway and to detect intrusive objects • Wireline communications along the roadway for interconnection of infrastructure devices • Computers to assign vehicle longitudinal positions and lane use, to detect improper control to these positions, and to provide emergency control commands • Computers to control AHS entry access • Two-way communication with the vehicle by wireless techniques • Strategic and tactical AHS entry controls

Figure 3-87 shows a functional block diagram for this configuration for the Type 1 point follower. The figure shows the preferred location for each of the major functions. The numbered blocks are sensors, computations, and controls which must be physically implemented.

Since this architecture represents a point follower, the vehicle adjusts its position to a time varying longitudinal command, XC, generated by Block 6. These commands may be generated as a time-based algorithm (XCP), which might be generated by a zone vehicle position planner (Block 5). This functional block generates an algorithm (distance vs. time profile) for each vehicle in the zone as well as start-up and shut-down functions for the zone. It also generates commands to initiate merges and demerges for vehicles desiring access to or egress from the AHS. Command profiles for these maneuvers are generated by Block 10. Inputs to the zone planner might be generated by a network flow planner, which develops variables such as density and speed for each zone as well as the approximate rate of vehicle admission to AHS ramps during each time period. The comparator error signal (Block 7) might be supplemented by an additional function (Block 8).

A zone might be defined to control the AHS section starting at an AHS entry point and continuing to the next AHS entry point. Thus, a zone might cover up to a 6.4 km (4-mile) AHS section. The point follower configuration defines a command longitudinal position vs. time in an analytic way. This is stored in the vehicle at AHS entry. It may be changed by the Zone Computer from time to time. It may also be changed by emergency commands received from the Zone Computer (e.g., stop, move to shoulder, slow to XX kph) which initiate vehicle stored position profiles. The normal communication data rates are relatively low. Two-way emergency information must, however, be delivered rapidly.

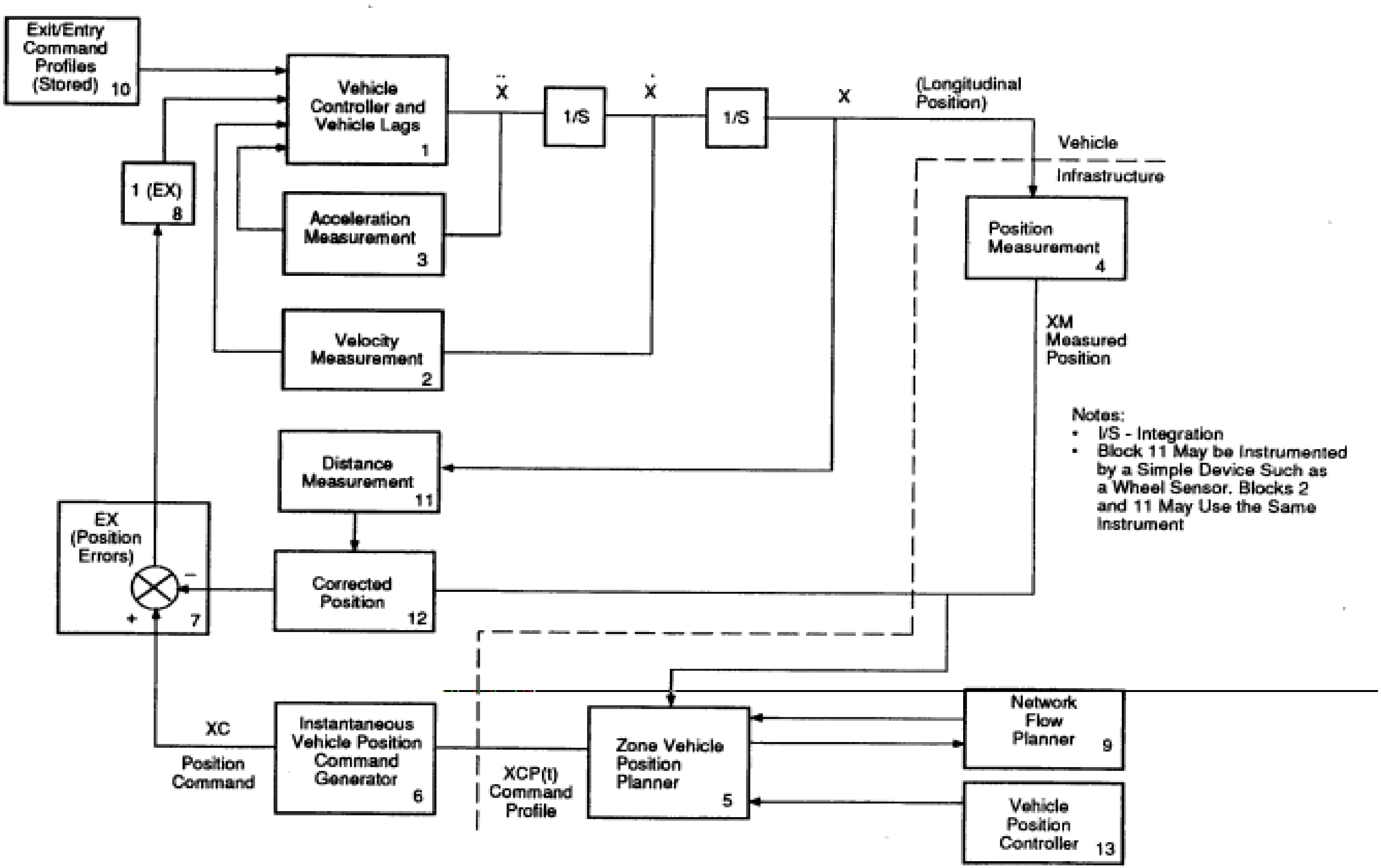


Figure 3-87. Functional Diagram for C3 Point Follower (Principal Position Determined by Infrastructure)

With this configuration, the only rates and accelerations needed are data from the vehicle being controlled, not from other vehicles. These data are determined from on-board sensors (Blocks 2 and 3). Short-term position data from a wheel sensor based upon integrating the velocity may also be required (Block 11). Periodic position resets (Block 12) would be provided by an accurate infrastructure based position measurement (Block 4). In this approach, the infrastructure sensor supplies an accurate time tagged longitudinal position reference on a periodic basis. This reference is used to update the dead reckoning position developed on board the vehicle, thus bounding the position and velocity errors developed by the vehicle sensors to an acceptable value.

The infrastructure position sensor does not provide sufficient accuracy for the non-lead vehicles of a Type 2 point follower. A very short range sensor on board to provide relative position determination is required for this configuration

An emergency may be detected either on board or by the infrastructure sensor. When a vehicle fails, it will send a failure message to the infrastructure if it knows it has failed and if it is able to send a message. The infrastructure, however, is basically responsible for diagnosing the failure. This is done by:

- Examining the vehicle's adherence to the longitudinal position profile as described earlier.
- Examining the vehicle's velocity by the infrastructure sensor as described earlier.
- Examining the lateral position of the vehicle and extent of intrusion into either the moving lane or the shoulder.
- Examining the RV link data or lack of data.

The Zone Computer determines an appropriate emergency response plan for all upstream vehicles.

A series of communication checks is required in both the vehicle and the infrastructure. If communication is lost due to a vehicle problem, a preplanned response (stop, move to shoulder) is executed by the vehicle. The infrastructure commands to the other vehicles are consistent with this response.

If the infrastructure equipment fails, the vehicles will stop. Restarting or clearing the AHS depends on the nature of the failure. The failure rate analysis reported in Task E shows that the failures due to infrastructure electronics equipment problems will be sufficiently rare so as to not pose a serious limitation.

In this configuration, the vehicle's longitudinal positions are determined by infrastructure based equipment for the following purposes:

- Position reference information for normal mode longitudinal control. In Block 12 of Figure 3-87, this information is combined with "high frequency" information from Block 11 to provide a complete frequency range of information.

- Out-of-tolerance longitudinal position/velocity detection information for the purpose of taking emergency corrective action.

- Out-of-tolerance lateral position/velocity information for emergency action.

- Position information to enable the infrastructure system to establish system-wide control commands.

- Identification of hazardous debris or obstacles on the roadway.

Block 13 in Figure 3-87 controls a signal providing entry access to the AHS. It is located in the transition lane for the I2 RSC or on a ramp in the I3 RSC at the interface location between the manual and automated highway. If a mainline slot is not available at a time which enables an entering vehicle to smoothly merge, the motorist is stopped by a red signal display. A small queue may develop; however, the motorist is granted entry to the AHS after a short wait. An analysis of the entry queue is described under Task I/J.

One way of developing high-accuracy position reference information (Block 4) is to use relatively closely spaced vehicle detectors. Those detectors could be of the video data processing type, or, alternatively, a microwave radar sensor could be used.

The following discussion treats a video processor using a video camera which does not conform to the NTSC standard (See Figure 3-88). Assume a 60 m (200-ft) vertical field of view, a 500-line scan, and a 12 m (40-ft) pole. The resolution at the top and bottom of the picture is one foot (higher in the middle). Assuming that the image is scanned at 100 times/sec at a vehicle speed of 60 mph, and assuming that two lines on the image must change before motion is confirmed, a position time constant of approximately 20 ms with a two-foot resolution capability can be achieved. Thus, the sensor's ability to detect an inappropriately controlled vehicle is good.

Depending on the actual performance capability, which would be identified by a detailed study, this type of sensor might not be sufficiently accurate for the control of a Type 2 point follower with its close headways. Such a system would be supplemented with a vehicle mounted short-range sensor.

Additional detail and assessment of the reliability of the infrastructure portion of this equipment are presented in Task E.

The point follower concept is not, in principle, limited to distance measurement by infrastructure based sensors. For example, it may be possible to develop position using on-board sensors such as GPS. This approach would require a reorganization of the functions shown in Figure 3-87 between the vehicle and infrastructure.

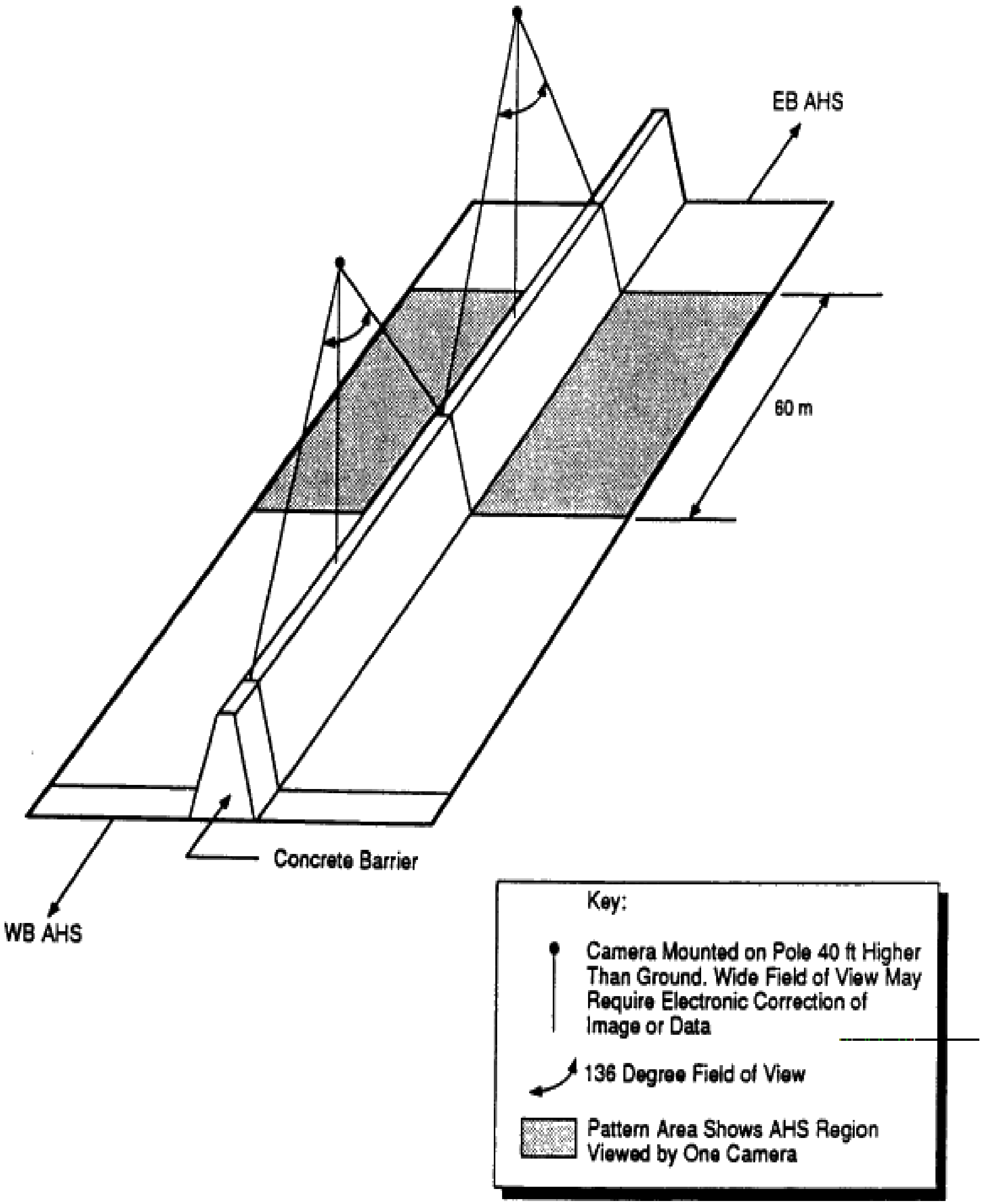


Figure 3-88. Example Arrangement of Video Cameras

3.8.1.2 *Vehicle Follower Approach with Longitudinal Position Determination by Vehicle Equipment (Configuration B)*

The distribution of functions between the vehicle and the infrastructure is shown in Table 3-13. Figure 3-89 is a functional diagram for the longitudinal control loop. Blocks 1, 2, 3, 9, and 10 correspond to similar blocks in Figure 3-87 for the point follower, and the functions are performed in the same location.

A vehicle-to-vehicle communication link will most likely pass velocity and acceleration of the vehicle ahead. A headway radar, block 7, will measure the distance to the vehicle ahead as well as the differential velocity between the vehicles. A vehicle-to-infrastructure communications link, block 6, will pass commands general information to each vehicle. The zone planner determines appropriate rates at entry locations. Block 11 provides the lateral control command by negotiating with other nearvby vehicles.

3.8.2 Cost Tradeoffs

The point follower/infrastructure based position system (Configuration A) requires position sensors at closely spaced intervals. The vehicle follower/vehicle based position system (Configuration B) requires an infrastructure based surveillance system (comparable to current freeway surveillance systems) for the purposes of incident management and provision of information to the motorists.

It is unlikely that performance (capacity and speed) will be significantly different between the alternatives as the performance factors tend to be determined primarily by

Table 3-13. Function Assignment for Vehicle Follower with Longitudinal Position Determination by Vehicle

Vehicle Functions
• Actuating devices for longitudinal and lateral control • Controllers for longitudinal and lateral control • Sensors for lateral control (possibly in conjunction with roadway devices) • Devices which may be necessary for vehicle control loop stabilization and approximate position determination (e.g., odometer, wheel tachometer, accelerometer) • Accurate longitudinal position determinations • Sensor to detect range and range rate relative to preceding vehicle • Detection of intrusive objects in roadway • Detection of adjacent lane vehicles, if necessary • Two-way data communication with the infrastructure • Two-way data communication with other vehicles • Tactical AHS entry control
Infrastructure Functions
• Wireless communications along the roadway • Computers to assign approximate vehicle longitudinal positions and ramp entry rates (strategic entry control) • Two-way communications with the vehicle

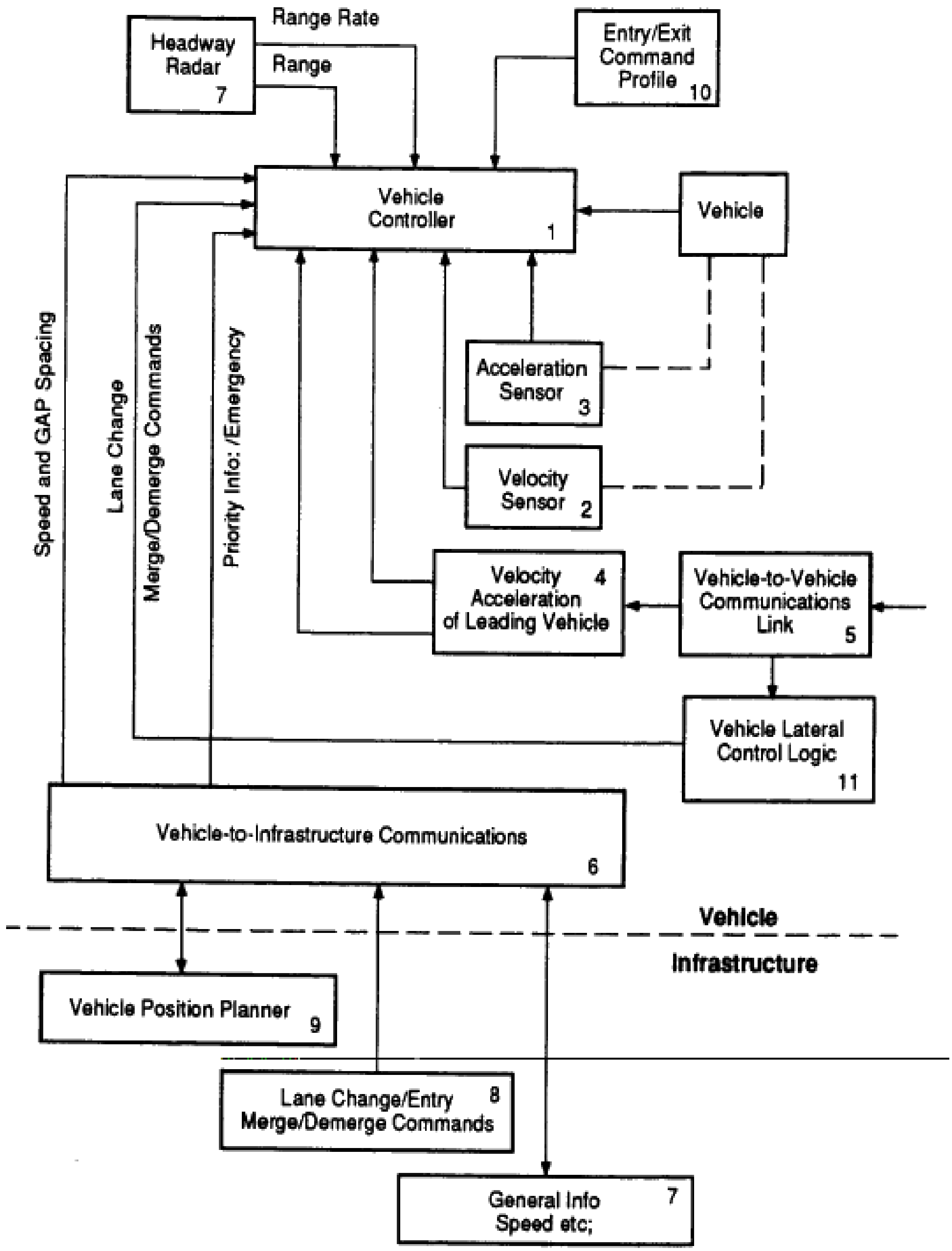


Figure 3-89. Function Diagram for C3 Vehicle Follower

the headway vs. safety margin tradeoffs and by constraints imposed by the non AHS roadways.

The remaining issues are discussed in the context of the following scenario. The pertinent limited access roadways and vehicles in Nassau County, New York, were considered. Table 3-14 provides an inventory of the freeway deployments considered, and Table 3-15 summarizes Nassau County vehicle registrations. Table 3-16 provides a summary of the physical constitution of one implementation of Configuration A. It is a fully redundant implementation and was used for comparison with the baseline. Further study will undoubtedly lead to an improved implementation.

From Table 3-16, it is seen that the system has a total of approximately 7000 infrastructure components, most of them based in the field. Some of this equipment is also required for Configuration B.

Table 3-14. Principal Sections of Limited Access Highways in Nassau County

Limited Access Highway	Approximate Centerline Mileage
Long Island Expressway (All)	19.2
Northern State Parkway (All)	19.2
Meadowbrook Parkway. (NSP to SSP)	5.6
Wantagh Parkway (NSP to SSP)	6.4
Seaford - Oyster Bay Expwy (LIE to SSP)	7.3
Southern State Parkway (All)	20.1
Total	77.8 (125 km)

Table 3-15. 1990 Nassau County Vehicle Registration

Limited Access Highway	Approximate Centerline Mileage Vehicle Registrations
Passenger vehicles	952,000
Commercial vehicles	46,000
Motorcycles	10,000
Mopeds	2,000
Total	1,010,000

Table 3-16. Electronics Component Count for Infrastructure for Intensive AHS Number

CAMERAS	4224
AUTOSCOPE	1056
TRANSMITTED/RECEIVER	320
RAMP ENTRY CONTROLS	48
ZONE COMPUTERS	96
CONTROL CENTER	2
COMMUNICATION DEVICES	1154
TOTAL	6900

The total design and installation cost for the infrastructure portion of the Configuration A control system is $111 million. Based on a 7% interest rate and a 15-year capitalization period, the annualized installation cost is $12 million. Economies can probably be achieved if design is coordinated with freeway surveillance design.

A comparable design and installation cost for the infrastructure portion of the Configuration B control system is $26.5 million.

Since the vehicle equipment will be more expensive for Configuration B (position sensing, relative position sensing, and roadway intrusion sensing), a tradeoff study was performed to identify the total difference in cost between the configurations. These data, presented in Table 3-17, present the capitalized infrastructure cost of Configuration B plus the capitalized cost for the vehicle equipment for Configuration B, less the cost for the vehicle equipment for Configuration A. These costs may be compared with the capitalized infrastructure control system cost of $12 million for Configuration A. Costs above the line in Table 3-17 represent the combination of AVI market penetration and incremental cost for which Configuration B is less expensive, and those below the line represent the combinations for which Configuration A is less expensive.

Table 3-17. Configuration B System Capitalized Cost (Annualized Cost for System in Nassau County - Capitalized Vehicle & Infrastructure Equipment Cost)

Incremental Cost Per Vehicle					
Market Penetration	$100	$200	$400	$1,000	$2,000
1.00E-01	4.7E+06	6.4E+06	9.7E+06	2.0E+07	3.7E+07
2.50E-01	7.2E+06	1.1E+07	2.0E+07	4.5E+07	8.7E+07
5.00E-01	1.1E+07	2.0E+07	3.7E+07	8.7E+07	1.7E+08
7.50E-01	1.6E+07	2.8E+07	5.3E+07	1.3E+08	2.5E+08
1.00E+00	2.0E+07	3.7E+07	7.0E+07	1.7E+08	3.4E+08

CAP RECOV
FACTOR
VEH 7% 8 YR 0.1675
INF 7% 15 YR 0.1098
INFRASTRUCTURE COST $27.53M

As an example, for an AHS market penetration of 50% and a vehicle equipment cost for Configuration B of $400 over Configuration A, Configuration B would result in an additional annual total cost in Nassau County of $37,000,000-$12,000,000 or $25,000,000.

3.8.3 Conclusions

The cost tradeoff shown in the example in Section 2.3 indicates that depending on the AHS market penetration and difference in vehicle equipment costs between the configurations, significant cost differences may occur. The potential difference is greatest when the AHS market penetration is high and the difference between vehicle equipment cost exceeds $200.

The control responsibility of the infrastructure equipment is considerably greater for Configuration A. Not only must it provide the basic information for normal longitudinal control, but it also must detect emergency conditions as evidenced by a vehicle's failure to conform to its planned time/ space trajectory. These reliability issues are discussed in Task E.

It should be recognized that the cost analysis presented above was based on implementation in Nassau County, New York. Nassau County has a large number of vehicles per freeway mile (approximately 13,000) suitable for AHS. This density figure is probably typical of the density in many metropolitan areas.

Based on the 1990 census, approximately 40 percent of the U.S. population resides in the 20 largest metropolitan areas. If a major objective of AHS is to obtain benefits from congestion reduction, the approach described could be a cost-effective deployment for that market.Smaller metropolitan areas, other urban areas, and rural areas are generally characterized by a lower density of vehicles per freeway mile. In these areas, AHS infrastructure intensive concepts of the type described will probably not be cost effective. The AHS capacity requirements, however, are likely to be considerably lower for those areas. The resulting increased headways will result in a simpler and less demanding longitudinal control system.

4.0 CONCLUSIONS

The preceding sections of this chapter have addressed the various studies and simulations that were conducted by the Calspan team. These studies mainly covered the areas of sensor technology, communications and longitudinal control loop simulation. While these studies are in no way complete, the team feels that while there were many issues raised, there were also some key results or findings.

This section is structured into three subsections; (1) Key Findings, (2) Issues and (3) Areas requiring further study and research.

4.1 KEY FINDINGS

During the course of the studies, several results became apparent. Because these results will have significant impact on further studies and research, we have referred to them as Key Findings.. Each of these finding are discussed below:

Sensors for lateral and longitudinal control must be capable of performing under severe adverse weather conditions

We feel that an AHS system should be capable of operation during adverse weather such as very heavy rain, dense fog and heavy falling snow. Many researchers are pursuing technologies that clearly will not function in severe weather. The argument that if it performs as well as a human, that's acceptable, does not make much sense to us. If, during severe weather, the lateral sensor can no longer locate the lateral position of the vehicle, or the headway sensor can no longer measure the headway, a serious safety condition exists. This is particularly true of lateral control. If a rain storm limits the performance of a headway sensor, other action can be taken, such as slowing (or stopping) all traffic. However, lateral guidance is required even if it is only used to steer the vehicle while a stopping maneuver is performed. During periods of severe weather, such a heavy rain or fog, the highway speed may be significantly reduced, provided that the sensors can continue to operate. To accommodate increased sensor errors, the gap spacing may be increased. Loss of lateral position information cannot be allowed to occur.

We currently have to accept the limitations of the human sensors to function in severe weather; we do not for an AHS - Sensor Technology exists to provide for continued AHS operation in very dense fog, heavy rain storms and blizzard conditions.

Most promising lateral control technology involves magnetic markers or overhead wires

Of the many techniques that various researchers have explored to provide lateral position information, the magnetic markers or "nails" appear to be the most attractive. They are inexpensive and of low cost to install in a roadway. They are passive (requiring no power), extremely durable, and will provide control in all weather conditions. Component failure will occur gracefully, i.e., if a given magnet should fail, vehicle operation can continue as one missing magnet will not affect performance.

Lateral control based upon overhead wires that radiate signals, while more costly to install, also operate in all weather. The wires can also be used to provide a moving reference for point follower type longitudinal control.

Radio ranging techniques can also be employed to provide longitudinal, and possibly lateral, control. These techniques are more complex but will provide an all-weather capability. Because of limited time and program funding, it was not possible to examine in detail those technologies during this study.

The accuracy required for lateral control is expected to be in the a few centimeters category which is very difficult to obtain with ranging techniques unless very large bandwidth signals are employed.

Headway radars will be required to provide high azimuth angle resolution

Headway radars used on an autonomous vehicle will be required to measure and locate the position of vehicles to determine the driving lane they occupy over ranges of approximately a few meters (feet) to 60 or 91 m (200 or 300 ft). Azimuth look or scan angles of ±45_ are likely to be required to confirm slots for lane change or merge/demerge. Because of the need to locate the vehicle in the azimuth plane, the headway radar will be required to have a beam width of a degree to two, thus the radar sensor beam will need to scan in azimuth, either mechanically or electronically.

Infrastructure-based systems may be cost effective

An AHS system configuration which is based on the use of infrastructure mounted sensors to obtain vehicle longitudinal position and to provide a portion of the longitudinal guidance signals and vehicle malfunction detection functions may have cost advantages over a system containing vehicle based sensors which perform these functions. The component reliability of the infrastructure equipment can be made sufficiently high through redundancy so that component failure does not contribute significantly to the reliability of the overall system.

Communication between vehicles may not be required for vehicles following at gaps of 0.5 sec, even during emergency maneuvers

Results of simulations show that, communication of the acceleration of the lead vehicle(s) is not necessary for braking maneuvers. The simulated design separated the brake controller from the throttle or accelerator controller. The accelerator controller is designed to maintain vehicle headway during normal maneuvers, while the brake controller is designed to avoid collisions. Simulation shows that no collisions occurred even with the lead vehicle braking up to 1 g. The conditions were: 0.5 sec plus 1.5 m (5 ft) nominal gap, 97 kph (60 mph) speed, up to 15 following cars, and all cars had the capability of 1 g maximum braking. The reduction in headway as speed decreased to zero was more than enough to make up for distance lost because of sensing and braking dynamics. The acceleration of the preceding vehicle was estimated from the rate of change of the differential velocity. Up to 0.30 m (1 ft/sec) noise like errors on the speed measurements did not degrade the safety of the brake system. Speed and distance measurements were made at a 20 Hz rate, using an independent noise sample each measurement. The minimum value for the gap to maintain safe braking has not been explored, but we expect it to be less than 3 m (10 ft). This finding is significant. Most researchers, ourselves included, have felt that each vehicle will need to pass its acceleration to following vehicles to prevent a collision during hard, emergency braking.

There is a tradeoff between longitudinal maneuver errors and noise immunity

In the design of a longitudinal controller for an AHS, there exists a classical tradeoff between tolerable maneuver errors and noise immunity. Typically, a longitudinal controller is designed to maintain a certain headway from the preceding vehicle. When the preceding vehicle changes speed, the following vehicle's control system will generate an acceleration command to maintain the headway. During the speed change, the headway error could range from inches to feet depending on the maneuver. In our simulations, an increase in speed from 48 kph (50 mph (73.3 ft/sec)) to 97 kph (60 mph (88 ft/sec)) at 0.1 g generated a 2 m (7 ft) distance error. The headway error gradually diminished to near zero in about 25 sec after the maneuver. If the bandwidth of the control system is increased, the headway errors can be reduced to less than 0.6 m (2 ft) with total recovery in less than 10 sec. Although the tighter control seems more desirable, the effects of sensor errors in the system make a high bandwidth control system impractical. We believe that typical sensor errors for ranging and doppler devices are likely to be 0.3 m (1 ft) and 0.3 m/sec (1 ft/sec), respectively. When these errors are used in a high bandwidth simulation, throttle displacement is larger, causing accelerations of ±2 ft/sec/sec during steady state cruising. The net result is an uncomfortable ride for the AHS user not to mention reduced fuel economy. As the bandwidth of the control system is reduced, the ride may be more tolerable with accelerations for steady state cruising at ±0.15 m/sec/sec (±0.5 ft/sec/sec). The net result is a tradeoff as shown below.

Control System	Steady State Accelerations	Max Error	Recovery
High Bandwidth	±0.6 m/sec/sec	±0.6 m	10 seconds
Low Bandwidth	±0.15 m/sec/sec	±2 m	25 seconds

In order to provide a high bandwidth control system providing rider comfort, improvements in the control system could be made. Improved decisions using Kalman filters or a different controller may provide lower errors and lower accelerations, but for each design a tradeoff between noise immunity and maneuver error must be made.

It should be recognized that the simulation used on this program did not assume that lead vehicles would communicate with following vehicles. The control system derived the lead vehicle acceleration from the differential velocity measurement which contain noise-like errors. If the leading vehicle passed its acceleration data to the following vehicle, a "cleaner" acceleration signal would be available. Thus, a high gain loop could have been used with better performance.

4.2 ISSUES AND RISKS

As the studies progressed, numerous issues and questions arose, many of which are obvious. We attempted to select those issues that may have not been identified by other researchers and, in our opinion, are significant. These issues are summarized in Table 3-18.

4.3 AREAS FOR FUTURE RESEARCH

The studies performed under this task have barely scratched the surface of the total problem of lateral and longitudinal control. Control of the steering, throttle, and brakes is, of course, the heart of an automatic highway system. From our studies there are several areas that we feel need immediate study. These areas are discussed below.

- The longitudinal simulation effort begun on this task should be continued and expanded to include lateral control. Studies should be made with multiple vehicles in a car-follower mode to develop tradeoff data between sensor accuracy, performance and ride comfort so that preliminary specifications can be developed for sensors and to evaluate various concepts for lane change, merge and demerge maneuvers.

- Promising sensor techniques for lateral position measurements and headway measurement should be developed and tested. Prototypes

Table 3-18. Issues and Risks

Issue No.	Issue/Risk Description Title	Description/ Recommendation	RSC Impact	PSA Task Impact	Where Discussed
LL-1	Forward-looking optical system operation in adverse weather	Optical systems must be able to function when looking into setting sun, and in falling snow and heavy rain.	All RSCs	LL, MM, SI	3.2.1
LL-2	Side-looking sensors that utilize barriers	Side-looking systems that require line of sight to the barrier must be configured to allow multiple lanes. Problem is one of "seeing" through other vehicles. Barriers elevated above the traffic?	All RSCs	LL, RO, VO	3.2.1.1.5
LL-3	Magnetic markers such as "nails" exhibit a limited range of lateral control	Range of control to sense lateral position errors is limited to approximately 2 ft. May require multiple detectors on the vehicle, spread in the lateral direction.	All RSCs	LL, VO	3.2.5
LL-4	Interference from other vehicles of active headway device.	Active headway measuring devices such as radars and lidars will cause interference to other vehicle systems, particularly in dense traffic areas--will require more complex signal processing and special system designs.	All RSCs	LL, VO	3.2.2
LL-5	GPS-based position location systems are subject to loss of signals.	GPS receiver may lose satellite signals due to masking of terrain or tunnels--must provide a method to maintain phase track during these periods.	All RSCs	LL, VO, RO	3.2.7
LL-6	Differential GPS WSINU Carrier Phase Tracking (CPT) complete with map matching may provide for lateral control and longitudinal control using point followers control	DGPS with CPT appears promising to provide lateral accessories of a few centimeters. Experiments need to be conducted with vehicular mounted equipment in urban areas, particularly in tunnels.	All RSCs	LL	3.2.7
LL-7	Lateral and longitudinal control systems will require a measure of the coefficient of friction between the tire and the road surface	It will be necessary to adapt the lateral and longitudinal control loop parameters for road surface conditions. Studies should be undertaken to develop techniques to measure the coefficient of friction--both vehicle based and infrastructure based.	All RSCs	LL, VO, RO	3.5.3

should be built and tested. In particular, the magnetic markers or nails developed on PATH program should be further developed and refined. The advantages of all weather, low cost and highly reliable make it a forerunner technique that should receive serious consideration.

- A detailed study, including simulations, should be made of the potential mutual interference problem of headway radars or lidars. These studies should consider the expected density of radars one would experience on a multiple lane, high density AHS roadway. Can the mutual interference be managed or is it a show stopper?

- Communication system concepts need to be defined and studied. These systems should consider the vehicle-to-vehicle and vehicle-to-roadway needs for lateral and longitudinal control, including lane changing merge and demerge for an autonomous vehicle system, as well as for general information flow.

- Considerable effort should be given to an evolution plan. The various technologies employed in IVHS equipment, such as intelligent cruise control, need to be evaluated from a perspective of how these technologies/systems can evolve into an AHS — can they? Or must new technologies be introduced. A road map is needed to determine how AHS can evolve and be implemented considering market penetration and minimal impact on existing traffic flow. While this study is not a lateral/longitudinal control issue by itself, it may heavily impact on the technology chosen for lateral and longitudinal control.

- Tests should be conducted with an instrumented vehicle to collect data on maneuver parameters such as longitudinal accelerations. The relationship between lateral and longitudinal accelerations and ride comfort need to be developed. Test should be made with a closed-loop longitudinal control system. Noise like errors should be introduced to cause various levels of vehicle accelerations that would be used to develop a relationship between accelerations and ride comfort.

- Tests should be conducted with a vehicle mounted differential GPS system that employs carrier phase tracking and pseudolites to evaluate the potential for using GPS combined with stored map data to provide lateral and longitudinal control. These tests should be conducted in urban areas and in tunnels.

APPENDIX A: LATERAL AND LONGITUDINAL GUIDANCE LITERATURE REVIEW

Abousalem, Mohamed A, and Krakiwsky, Edward J., "A Quality Control Approach for GPS-Based automatic Vehicle Location and Navigation Systems", IEEE-IEE VNIS, pp466-70, IEEE#0-7803-1235-X/93, 1993.

Summary: Kalman filtering has been the engine for processing kinematic data collected from positioning sensors in real-time mode for the past three decades. Centralized techniques in particular have been widely used in multi-sensor navigation systems, but as quality control has become a prime concern in kinematic positioning, decentralized filtering has evolved as a means of quality control by separating the performance of sensors constituting an integrated system. The federated filter, which is a special form of decentralized filters, has been thoroughly investigated at The University Of Calgary as it has showed some promising features regarding optimality and other practical aspects. Discussed in the paper is the theory of the federated architecture and the focus is the applications in the field of vehicle navigation using GPS. During both theoretical and practical research, it was concluded that federated designs suit optimality needs for systems output and allow the use of existing stand-alone softwares of individual sensors in an integrated sense without any major modifications. Also, quality control is feasible as a malfunction of one of the sensors would be detected and identified before the contamination of the global (combined) output of the system, and hense isolation of errors is feasible in real-time mode.

Allen, R. Wade, "Performance and Safety Considerations in Automatic and Four Wheel Steering Control Laws", Pr IVHS Annl Mtng,pp269-75, 1993.

Summary: This paper is intended to outline an appropriate stability safety analysis by means of a validated vehicle dynamics simulation, VDANL (Vehicle Dynamics Analysis, Nonlinear). Concentration is placed on the influence of maneuvering conditions on performance and stability of four wheel steering system.

Vehicle design requires trade-offs between performance and safety. Performance relates to basic vehicle responsiveness and handling qualities, and maneuvering limits in crash avoidance situations. Safety can encompass the ability to maneuver out of harms way, as well as vehicle stability problems that limit maneuvering.

Simulation analysis shows the sensitivity of vehicle/steering limit response is influenced significantly by the details of input control conditions such as steering profiles.

As maneuvering becomes extreme, tire saturation can have a significant effect on directional stability. Linear analysis and synthesis can address basic issues of vehicle handling under moderate conditions. Nonlinear analysis is required to analyze limit performance maneuvering where tire saturation can lead to plowout or spinout under transient, dynamic conditions. Nonlinear analysis of limit performance maneuvering conditions is critical from a crash avoidance perspective.

American Society of Photogrammetry, "Image Motion Compensation", Manual of Photogrammetry, Falls Church, VA, p195, 1980.

Summary: Requested into database by D. Boch

American Society of Photogrammetry, "Strip Cameras", Manual of Photogrammetry, Falls Church, VA, p207-9, 1980.

Summary: Requested into database by D. Boch

Andrews, Angus, "Theoretical and Empirical Analysis of PATH Magnetic Lane Tracking for the Intelligent Vehicle Highway System", PATH Research Report, UCB-ITS-PRR-92-9, August, 1992.

Summary: The principal objectives of the task reported include:

1. Characterize the statistical performance of the magnetic nails concept for estimating the positions of vehicles within their marked lanes. The performance is to be characterized in terms of the mean-squared position estimation error and its dependence on the sizes and orientations of the magnets used, the mean-squared noise in the sensor outputs (due to sensor noise and the ambient magnetic noise), and the relative spacing bet the sensor and the magnets in operation.
2. Develop a mathematical model for sensor noise due to the distortion of the earth field by regular patterns of ferrous reinforcing bars in the pavement.

This report includes summaries of the principal findings organized by objectives in chapters, with more detailed technical results presented in appendices.

Andrisano, O., et.al., "Propagation Effects and Countermeasures Analysis in Vehicle-to-Vehicle Communication at Millimeter Waves", IEEE 42nd Vehicular Technology, Vol.1, p312-16., 0-7803-0674-0,, 1992.

Summary: This paper presents an analytical approach to the problems of defining and evaluating performance limits of vehicle to vehicle communication via short range millimeter wave communication systems. In particular the anomalous propagation due to road reflection and multipath propagation effects are considered.

A 60GHz communication system was considered due to it's large RF bandwidth and immunity to cochannel interference. A model is presented.

System performance is evaluated in terms of packet error probability and the improvement obtained by Forward Error Correction is estimated.

Space diversity techniques, in particular height diversity of antenna, are investigated in conjunction with coding as a countermeasure technique for bad propagation conditions.

Improvements due to coding were limited.

Average packet error as a function of distance shows large improvements can be observed when applying height diversity with respect to coding and even space diversity. Improving performance becomes difficult when distance approaches 500mt.

Outage probability as a function of distance reveals, it is granted 200mt for the unprotected system, 275mt when coding is adopted, and 410mt when height diversity is adopted.

Arai, Alan, et.al., "Experimental Automatic Lateral Control System", PATH, UCB-ITS-PRR-92-11..

Summary: Paper on order.

Arnold, James A. and Bishop, J. Richard Jr., "Studies of IVHS Electromagnetic Compatibility Issues", IEEE-IEE VNIS, pp348-62, IEEE#0-7803-1235-X/93, 1993.

Summary: This paper describes the approach of the Federal highway Administration (FHWA) to gather information and analyze issues relating to electromagnetic compatibility (EMC) of Intelligent Vehicle-Highway Systems (IVHS). The FHWA will use this information to develop a set of guidelines to ensure the safety and reliability of IVHS systems with respect to EMC, as an aid to IVHS system developers and equipment designers.

As part of the EMC task, the FHWA will analyze current and proposed IVHS systems, highlighting areas where the potential for EMC problems exist. Analyses will be targeted at a system level. In this paper, efforts to define the expected electromagnetic environment of the roadway, the frequency/spectrum availability based on geographic area, and system coverage for specific and generic cases will be described, as well as the ongoing examinations of how the electromagnetic environment of the roadway affects IVHS systems and how IVHS systems affect the electromagnetic environment of the roadway.

Asano, Masaharu, et.al., "New Approach in Automotive Control--An Experimental Variable-Response Vehicle--", IEEE IECON, Vol.1, p123-28, , 0-87942-689-6, 1991.

Summary: Nissan has developed an experimental vehicle, the IN-

Vehicle Simulator (IVS), which can independently control vehicle motions: bounce, pitch, roll, yaw and lateral movements. This vehicle can analyze physical evaluations of vehicle motion, analyze and model human behavior during driving, and evaluate the control algorithm. The vehicle body is composed of several modules.

The IVS has been developed as the research tool for realizing more pleasant and comfortable riding vehicles using control technology.

Ashton, Winifred D., "The Theory of Road Traffic Flow", Methuen, London, John Wiley, N.Y., 1HE/333/A8, 1966.

Summary: An excellent review of the state of the art in traffic engineering as of 1966. It covers the flow-concentration curve (or fundamental diagram of traffic), it's derivation from follow-the-leader models of traffic flow, gives theories of instability for two-vehicle (local) and traffic stream (asymptotic) conditions. The book then addresses kinematic theory and fluid analogies, developing partial differential equations of traffic flow that illustrate the wave-like nature of disturbances in traffic. There is a special section on varified (Boltzmann) traffic that is useful for analyzing sparse, rural traffic. The effect of traffic signals, intersections, including left turns (the British author calls them right turns) and bottlenecks are analyzed. Discussions of traffic simulation and accident statistics conclude the test.

Auslander, David M., and Huang, An-Chyau, "Real Time Software Requirements for Vehicle Control Systems", PATH Technical Memorandum, Memo 92-2, August, 1992.

Summary: This memorandum explores some of the issues associated with recent development for control of research vehicles. It is in a means of unifying the software development among various PATH research groups, and, as such, as a focus for continuing discussion rather than a "solution". In that spirit, the authors would like to encourage readers to comment on the thoughts expressed here, and to discuss needs of specific research groups in the software area.

Beji, Yousser, "Effect of Longitudinal Control on Capacity", PATH Working Paper, UCB-ITS-PWP-87-3, December, 1987.

Summary: In the following discussion, some implication of increasing the capacity by controlling the speed and spacing of vehicles moving on a roadway are reviewed.

Two scenarios of special interest are discussed. The first is the “brick-wall safety separation” case, in which a safe stopping distance for a following vehicle is provided if the lead vehicle stops instantly in its lane. The second is the “controlled acceleration/deceleration and stopping” case, which assumes that all vehicles travelling in a platoon can accelerate and decelerate

identically and simultaneously so that no rear-end collisions will occur in case of braking by any one of them.

Summarizing the results, one may state that maximizing the spacings may not be achievable by a driver aided controller unless creating the conditions needed for introducing a completely automated control system. This preliminary theoretical investigation suggests that application of spacing control on vehicles travelling in a platoon may not be effective as to improve traffic flow.

Bender, J.G., et.al., "Systems Studies of Automated Highway Systems", Office of Research and Development Wash.,DC 20890, FHWA/RD-82/003 Final Report, July, 1982.

Summary: The recommended systems concept is a smart vehicle with self-contained power supply operating on a passive guideway. This is judged to yield almost the same guideway capacity and cost benefits as the average distribution of intelligence and offer a more desirable system control structure. The majority of the fleet is recommended to be modified via DEPs (detachable electronic packages). This DEP is a highly modularized package which is attached before the vehicle approaches an AHS entrance. Advantages include the economical use of an AHS by the occasional user and those unwilling to permanently modify their vehicle. Permanent built-in automation is also available as an option. Vehicles must be AHS certified for max dimensions and minimum performance specifications. Because the specifications must be set to include the majority of production vehicles, system velocities significantly above 55 mph are not anticipated. AHS analyses indicate that first implementation be located in an urban area and is recommended to be a test and demonstration implementation.

Staged construction is recommended for the AHS network.

Capacities per lane will approach twice that of conventional highways and the cost of providing capacity will be well below the cost of conventional highways.

Bender, James G., "An Overview of System Studies of Automated Highway Systems", IEEE Vehicular Tech, Vol.40, No.1, February, 1991.

Summary: Investigation of AHS have confirmed it’s feasibility provided that the transition can be made cost effective and practical in terms of impact on existing roads and infrastructure. This report presents candidate system concepts and implementation strategies.

Concept development addressed the system structural, system operational, and vehicle subsystem technological aspect of an automated transportation system.

The AHS is structured in two distinct ways:

1. Mechanization subsystem-Travel unit subsystem, guideway subsystem, and wayside subsystem.

2. Functional subsystem-Trip management, diagnostic,lateral

and longitudinal control, communication, propulsion/braking, and energy source and distribution functions.

Implementation strategy development is presented. This includes a list of criteria employed in the evaluation.

Some important analysis results follow:

1. Smart systems were found to have lower system cost per lane and a lower capacity per lane than average systems. Vehicle platooning will substantially increase lane capacity.

2.The use of detachable electronics packages (DEPs) decrease the user cost per trip per mile. However, DEPs increase the time necessary for entry/exit processing.

3. Intercity demand was found to be more sensitive to travel cost than to travel time while urban demand was more sensitive to travel time than to travel costs.

4. Network pervasiveness determined the urban utilization to a greater degree than did the costing or subsidization of AHS.

5. Electrified vehicles consumed substantially less energy at the vehicle/AHS system level than internal combustion engine vehicles and conventional battery vehicles.

6. Increasing the AHS cruise velocity increased system utilization even though user cost per trip and per mile traveled increased.

7. Land area requirements for intercity deployments varied only slightly with concept but were found to be about 50% larger for urban DEP concepts as for other urban concepts. The decreased width of AHS traffic lanes resulted in only minor land savings.

8. AHS with internal combustion engine vehicles showed no pollution change as compared to conventional highways for intercity deployment and only minor changes for urban deployments.

9. The number of AHS vehicles and their hardware pose the greatest reliability threat as opposed to wayside equipment.

The recommended system concept is a smart vehicle with a self-contained power supply operating on a passive guideway. A highly modularized DEP, attached to the vehicle before the vehicle approaches an AHS entrance, is recommended for the majority of the AHS fleet.

Beneke, J. Bock, D.H., and Kidder, A.R., et.al., "DNSS (Defense Navigation Satellite System) Applications to Army Position Fixing, Navigation and Survey Requirements", Cornell Aeronautical Laboratory; Report VF-2986-B-1, February, 1971

.

Summary: The scope and cost of US Army participation in the DNSS user equipment that the Army may need to meet operational requirements is described. In the process of identifying features of the DNS System concepts proposed by US Air Force and US Navy were merged to provide optimal utility to all defense forces. Report recommendations were implemented in what is now known as the Global Positioning System.

Berbineau, M., et.al., "A Solution for a Transparent GSM Retransmission System into Confined

Areas", IEEE-IEE VNIS, pp291-94, IEEE#0-7803-1235-X/93, 1993.

Summary: The DRIVE-ATT program seeks to apply advances in Road Transport Informatics (RTI) in order to achieve an Integrated Road Transport Environment (IRTE) in which there will be significant benefits of traffic efficiency, road safety and reduced environmental pollution. An example of the new RTI technologies are radio cellular systems. These applications will depend upon the widespread availability of two-way communications between vehicles and control centers. Radio propagation inside tunnels and urban radioelectric shadowed areas is disturbed with strong attenuation, multipath, wave guide and masking effects. Thus special care must be taken if we want to avoid communication failure in RTI applications based on radio frequency system in those specific areas. This directly explains the interest of radio transmission in confined areas. To achieve the extension of the RTI road/vehicles digital communication systems to the coverage of confined areas, specific electronic and electromagnetic problems have to be solved. This paper based on the works of the DRIVE ATT consortium ICAR, gives elements to realise a pan-European GSM (Global System for Mobile communications) radiating retransmission system in those confined areas.

Blackwell, Earl G., "Overview of Differential GPS Methods", SRI International, Menlo Park, CA, January, 1985.

Summary: Differential GPS allows for the removal of certain position errors by implementing a local reference GPS receiver. Errors include satellite clock error, error in the satellite's broadcast ephemeris data, and signal propagation delays. This paper presents an overview of GPS, differential GPS error budgets, and four methods of differential GPS.

The first method of differential GPS is uplink of pseudorange corrections for participant on-board processing. Any number of participants can receive and use the differential correction data, and the corrected position data are available on board the vehicle for precision navigation purposes. However, uplink capability and on-board incorporation of correction data is necessary.

The second method is uplink of position corrections for participant on-board processing. The correction data is determined from the difference in the reference receivers surveyed position coordinates and GPS measured coordinates. Disadvantages include: Uplink data capability and correction processing provisions are necessary; It may be necessary to downlink a selected set of 4 satellite vehicles.

Method three is downlink of participants' raw-measured data for ground differential processing. Differential corrections take place in the measurement domain allowing processing at the reference receiver's location. No uplink is required and advantage can be taken of the ground computers data processing capabilities. Although, a large amount of raw data must be downlinked.

Method four is downlink of uncorrected participant position data for ground differential processing. This method reduces the data load requirements over method three.

Method one and two provide position data on-board the user's vehicle. Method one is advantageous for large numbers of user vehicles.

Bloomberg, Loren D., and May, Adolf D., "Freeway Detector Data Analysis for Simulation of the Santa Monica Freeway--Summary Report", PATH , UCB-ITS-PWP-93-10, August, 1993.

Summary: A team at the University of California at Berkeley is investigating the benefits of Intelligent Vehicle Highway Systems (IVHS) using a simulation model of the Santa Monica Freeway in Los Angeles. To accomplish this, detailed demand data (vehicle volumes and occupancies) are needed for mainline stations and ramps on the freeway. A pilot study was conducted in December, 1992 to assess the viability of collecting these data. It was decided that a manual data collection effort was needed; this effort and the analysis of the data are summarized in this report.

Bock, Y., Editor, "Global Positioning System, An Overview", Springer Verlag, May, 1993.

Summary: This book was requested by T. Leney following a Calspan library search.

Brobeck, William M., "A Method of Communicaiton on the Automatic Highway", IEEE-IEE VNIS, pp304-6, IEEE-IEE #0-7803-1235-X/93, 1993.

Summary: The system described is designed around the use of a shift register running the length of the automatic highway. Receiving and transmitting antennas are located along the centerlines of the lanes. Signal formats, data rates, and the general process of providing all automatic cars with the positions and speeds of all other cars, including manually operated cars, around them in their own and in adjacent lanes, are described.

The design example describes the shift register cycle, data format, and transmission rates of a suggested system. In the example, each automatic car receives the locations of, and information from all cars within a half mile ahead of and behind its own position in its own and adjacent lanes several hundred times a second. Information from the roadside can also be sent to all the automatic cars.

Caltran, "Highway Electrification and Automation"..

Summary: The elements of the highway electrification inductive energy transfer system include an ac power supply and distribution system, a roadway inductor immediately beneath the surface, a pick-up inductor underneath the vehicle, and an on-board power control system. 60 kw of power transfer were demonstrated from the roadway to an electric bus. Displacement of the vehicle

4” from center lane reduces power coupling by 50%. The control system draws only the required power. Effects of the magnetic field on humans needs further investigation. The measured power transfer efficiency from the utility source to the battery terminals of a vehicle is approximately 65%.

Vehicle lateral control using a discrete magnetic marker referencing system was tested. The markers had a longitudinal spacing of 39”. An experimental vehicle followed a path, including a 90 degree curve with a lateral acceleration of 0.27g, at speeds of 30-40 mph. Under normal conditions, tracking was within 2” of lane center. Under abnormal conditions, tracking was within 6” of lane center.

Longitudinal control was accomplished using radar sensors, throttle control actuators and radio communication of speed and acceleration. Testing involved distances of 75, 50, and 30 feet at speeds of 45 to 75 mph. This results in headways as short as 1/2 second (7000 vehicle/lane/hour). Test conditions included constant speed, acceleration and deceleration. While tacking on grades of <= +-3%, spacing was maintained within a few feet. This is the first proof of controlling internal combustion engine vehicles with this accuracy.

Cassidy, Michael J., and May, Adolf D., "The 1985 Highway Capacity Manual: Supplemental Report for California Conditions", PATH Research Report, UCB-ITS-RR-88-1, February, 1988.

Summary: This report identifies areas of the 1985 Highway Capacity Manual (i.e., procedures, equations, values) which may not be completely applicable to California roadway conditions. The report also documents areas of the Manual which may be in need of validation, modification, or simple clarification. Wherever possible, this report provides guidelines aimed at assisting the reader in exercising professional judgement when dealing with potential “problem areas” of the Capacity Manual.

The contents of this report are a result of a critical review performed on the entire 1985 highway Capacity manual. Reviews of each chapter in the Manual were independently performed by researchers at the Institute of Transportation Studies and by over 100 traffic and transportation professionals who each volunteered to review one or more chapters.

It is hoped that this report will benefit transportation professionals using the 1985 highway Capacity Manual to analyze and design traffic facilities in California and elsewhere.

Cassidy, Michael J., and May, Adolf D., "Research Problem Statements for the 1985 Highway Capacity Manual", PATH Research Report, UCB-ITS-RR-88-2, February, 1988.

Summary: This report presents research problem statements related to the 1985 Highway Capacity manual. This list of research problem statements identifies research needs currently existing in the 1985 Manual.

The research needs were identified as a result of a critical review performed on the entire 1985 highway Capacity Manual. Reviews of each chapter the manual were independently performed by researchers at the Institute of Transportation Studies and by over 100 traffic and transportation professionals who each volunteered to review one or more chapters.

It is hoped that this report will help direct future research efforts in the area of highway capacity.

Cassidy, Michael J., and May, Adolf D., "The 1985 highway Capacity Manual: Supplemental Report for California Conditions", PATH Research Report, UCB-ITS-RR-88-1, February, 1988.

Summary: This report identifies areas of the 1985 highway Capacity manual (i.e., procedures, equations, values) which may not be completely applicable to California roadway conditions. The report also documents areas of the Manual which may be in need of validation, modification, or simple clarification. Wherever possible, this report provides guidelines aimed at assisting the reader in exercising professional judgement when dealing with potential "problem areas" of the Capacity Manual.

The contents of this report are a result of a critical review performed on the entire 1985 Highway Capacity Manual. Reviews of each chapter in the Manual were independently performed by researchers at the Institute of Transportation Studies and by over 100 traffic and transportation professionals who each volunteered to review one or more chapters.

It is hoped that this report will benefit transportation professionals using the 1985 highway Capacity Manual to analyze and design traffic facilities in California and elsewhere.

Cassidy, Michael J., et.al., "Operation of Major Freeway Weaving Sections", PATH Research Report, UCB-ITS-RR-89-Draft, November, 1989.

Summary: This report documents ongoing efforts directed at developing an improved technique for designing and analyzing major freeway weaving sections. Initial tasks in this project involved the collection of large of traffic data operating on major freeway weaving locations in the State of California. These data were used to evaluate the reliability of existing weaving analysis and design techniques.

The results of these evaluations suggest that existing weaving procedures cannot accurately predict the operational quality of freeway weaving areas. Thus, efforts were undertaken to develop improved techniques The proposed design/analysis methodology predicts the spacial distribution (i.e. presegregation and lane-changing activity) of vehicles within the weaving area as a function of traffic flow and geometric conditions.

A total of ten (10) weaving test sites were used for collecting empirical data in this research report, however, details the data analyses performed on a single test site. Results of these analyses indicate that modelling the traffic flow patterns of vehicles traveling in the weaving area

represents a sound approach to designing and analyzing weaving sections.
This research will continue.

Cassidy, Michael J., Skabardonis, Alexander, and May, Adolf D., "Operation of Major Freeway Weaving Areas: Recent Empirical Evidence", PATH Working Paper, UCB-ITS-WP-88-11, December, 1988.

Summary: This paper essentially describes efforts to 1.) identify factors significantly influencing traffic operations on major freeway weaving sections, 2.) assess the predictability of measures of effectiveness (i.e. speed and density), and 3.) develop improved procedures for predicting weaving section performance.

Catling, Ian, et.al., "The SOCRATES Projects: Progress Towards a Pan-European Driver Information System", IEEE-IEE VNIS, pp319-26, IEEE#0-7803-1235-X/93, 1993.

Summary: During the DRIVE 1 program, the SOCRATES project developed the concept, and demonstrated the feasibility, of using cellular radio to exchange digital traffic information between control centers and equipped vehicles, in order to provide dynamic route guidance and a range of other applications of Advanced Transport Telematics (ATT).

In DRIVE 2, there are three pilot projects taking forward the SOCRATES concept into practical implementations. These projects are taking place in London, Gothenburg and the Hessen region around Frankfurt.

A fourth DRIVE 2 project, the SOCRATES Kernel Project, serves as a focus for all SOCRATES developments and a method of coordinating the progress being made in each of the pilot projects.

This paper describes the progress in each of the pilot projects and presents the scope of the Kernel project. This includes the investigation of the commercial case for implementing SOCRATES systems.

Chan, Patrick, Cassidy, Michael J., and May, Adolf D., "Operation of Freeway Ramps and Multiple Weaving Sections: Research Proposal and Candidate Sites", PATH Working Paper, UCB-ITS-WP-90-4, September, 1990.

Summary: The 1985 Highway Capacity manual (HCM) (1) contains procedures for designing and analyzing freeway components. Those procedures, however, do not reliably reflect current roadway operations in the State of California. The inability of existing analysis procedures to reflect existing operating conditions on freeways is a concern to the State of California. These procedures also treat the individual freeway components as independent elements. An integrated system-wide approach is needed to more reliably model freeway operations. The objective of the research work is to provide designers and traffic engineers with the most reliable tools possible to design and analyze freeway systems.

Chande, et.al., "Intelligent Navigator for Automobiles", IEEE 41st Vehiclular Technology, pp1115-1121, CH2976-9/91/0000-1115, 1991.

Summary: Automobile maneuvering through strange places using maps and directions is inconvenient and unsafe. This paper presents development and design of an intelligent navigational system for automobiles. The system employs a P.C interfaced to the sensors mounted on a vehicle. It can be used with structured road networks a provides facility to plan and visit intermediate (unstructured) places between source and destination. The graphic display provides an overall comprehension of the topology of a region while additional turn indicators on dash board help guide driving without loss of concentration.

Chang, K.S., "Experimentation with a Vehicle Platoon Control System", VNIS, October, 1991.

Summary: This paper presents results and analysis of experiments carried out in the PATH program of longitudinal control of integrated platoon control systems (IPCS). The IPCS consists of a control system, communication system, data acquisition system, and various sensors including a radar system.

The radar antennas, which steer with the front wheels, measure distance and closing rate between a vehicle and the vehicle in front of it. Special circuits in the radar system recognize operating conditions that could affect the control algorithm, and set various flags as status indicators. These flags, and all measurements, are put into a data acquisition board to be processed.

Communication is established between a vehicle and the vehicle following it by means of spread spectrum digital radio transceivers. Information pertaining to time clock, vehicle speed and acceleration are exchanged.

A multitasking operating system, VRTX-PC, allows tasks to run under different priorities and various scheduling policies. The following tasks are performed using VRTS-PC: control law calculation, communication, data acquisition, data transfer, data storage, and user interfacing. The operation loop in the following car always starts upon receiving a transmission data packet from the lead vehicle.

Error handling routines for communication link loss and data acquisition overflow\overrun were established.

Testing involved only two cars. This included a lead vehicle and a following vehicle which was under automatic control in the longitudinal direction. Upon completion of first and second phase testing, experimental results showed that the IPCS functioned properly. However, multi-vehicle platoons require a more complicated communication scheme than used in this experiment.

Chang, Kuor-Hsin, and Georghiades, Costas N., "A Position Estimation Algorithm for Vehicle Following", American Control Conference, Vol.2, p1758-61, 0-7803-0211-7, 1992.

Summary: A distance estimation algorithm for vehicle following in automated highways is presented. The idea is to install two transceivers at the back of the leading vehicle and two transceivers at the front of the following vehicle. Estimating the traveling time of two data sequences between transceivers, different distances between the transceivers of the leading and following vehicles can be measured. From these estimated distances, the turn angle of the leading vehicle can be calculated. Taking the estimated distance and turn angle into account, then the following vehicles can adjust their speed and change their direction to follow the leading vehicle. The performance of this distance estimation algorithm is evaluated analytically and through computer simulation.

Chen, Leon L., and May, Adolf D., "Freeway Ramp Control Using Fuzzy Set Theory for Inexact Reasoning", PATH Research Report, UCB-ITS-RR-88-10, May, 1988.

Summary: This paper presents an application of an Expert Fuzzy Controller to entrance ramp control at the San Francisco-oakland Bay Bridge. Freeway traffic flow, especially under incident conditions, is highly nonlinear, time-variant, and cannot be precisely modeled in real-time. By drawing upon expert knowledge from bridge operators and an existing automatic controller, a rule base was developed which responds well in both incident and nonincident situations. Fuzzy reasoning, in this case, uses a simple set of operations, which makes it especially attractive for practical applications.

The controller considers various levels of congestion, changing levels of congestion, a control region, queueing at an incident, and information from a distributed detector array, to determine metering volumes. Because the controller uses linguistic variables and rules, it is possible to incorporate strategies developed by freeway operations personnel.

The Expert Fuzzy Controller has been tested in simulation, using the FRECON2 dynamic freeway model, and shows excellent results. A series of test cases with incidents of varying location, duration, and severity was examined. In severe cases, the controller was able to reduce the impacts of the incident by more than 300 passenger-hours, when compared to the existing controller. When compared to an idealized controller, the fuzzy controller is able to extract 40 to 100 percent of the maximum obtainable reductions in passenger-hours.

Chien, C.C., and Ioannou, P., "Automatic Vehicle Following", ACC, Vol.2, p1748, 92ch3072-6,, 1992.

Summary: This article presents a comparison of several vehicle following strategies including models of human drivers and a slinky-free

autonomous follower strategy.

Chin, Hoong C., and May, Adolf D., "Speed-Flow Relationships of Uncongested Flow", PATH, UCB-ITS-WP-90-3, July, 1990.

Summary: The relationship between speed and flow of basic sections on freeways are typically represented by the speed-flow in the Highway Capacity Manual. Recently, in a proposed procedure to analyze multi-lane highways, a set of speed-slow curves have been introduce rather different from those in the Highway Capacity Manual. working paper examines the speed and flow character a number of freeway sections and compares them with the speed-flow curves in the Highway Capacity Manual and those in the w procedure. In the latter, the freeway sections are analyzed as divided multi-lane highways with "no" access point.

Speed and flow data were obtained using automatic vehicle detectors at one site (Caldecott Tunnel) and video recordings at the others (San Francisco-Oakland Bay Bridge, US 101- San Francisco and US 101- Marin). In the first case, the quality and quantity of the data allowed a well-defined speed-flow relationship to be observed. However, this cannot be said of the other sites where data are obtained from video recordings.

in general, the highway Capacity Manual tends to under-estimate the speeds d the capacity of the sites investigated. This is most clearly seen in the cases of the Caldecott Tunnel and the Bay Bridge where high speeds have been observed at flows well in excess of 2000 pcu/hr/lane. The speed-flow curves in the new methoeem to represent conditions at the sites better than the HCM curves.

Chira-Chavala, T., and Yoo, S.M., "Feasibility Study of Advanced Technology HOV Systems", PATH Research Report, UCB-ITS-PRR-92-2, December, 1992.

Summary: The objectives of this study are to identify strategies for early deployment of longitudinal control technologies on the highway, and to evaluate potential impacts of these strategies on traffic operation, highway capacity, and traffic accidents.

One approach for early deployment of longitudinal control technologies on the highway involves incremental implementation.The approach evaluated in this study involves two phases, as follows:

Phase 1: Adopting ICCS on All Roadways.

Phase 2: Early Deployment of Longitudinal Control Systems with Close-Formation Platooning in One-Lane Transitways.

The evaluation in Phase 1 focuses on assessing changes in the number of traffic accidents and some traffic-operation characteristics affecting safety on the roadway, as a result of adopting the hypothetical ICCS. Traffic-operation characteristics affecting safety include the following: frequencies of hard acceleration and deceleration, harmonization of vehicle speeds, vehicle headway characteristics, and traffic perturbation characteristics. In addition, potential effect of the hypothetical ICCS on the highway capacity is also

addressed. The evaluation is performed for two types of the ICCS controller--one requires data on both the headway and the speed of the vehicle in front as the control input Ii.e., gap/speed controlled ICCS), and the other requires only data on the headway (i.e., gap-controlled ICCS). The evaluation of the accident impact of the hypothetical ICCS is accomplished through case-by-case analyses of police accident reports. The evaluation of the traffic-operation characteristics affecting safety, due to adopting the hypothetical ICCS, is accomplished through vehicle simulation.

Chira-Chavala, T., et.al., "Feasibility Study of Advanced Technology HOV Systems Volume 4: Implementation of Lateral Control Systems in Transitways", PATH Research Report, UCB-ITS-PRR-92-6, December, 1992.

Summary: The objectives of this study are to:

- Identify lateral guidance/control systems that use discrete magnetic markers as the roadway reference for incremental implementation in existing transitways, as a stepping stone toward the eventual deployment on all roadways.
- Assess the safety and traffic impacts of these incremental systems.
- Identify human-factors issues related to the implementation of these systems, as well as possible approaches for addressing these issues.

Chira-Chavala, T., Lechner, Edward H., and Empey, Dan M., "Feasibility Study of Advanced Technology HOV Systems Volume 2A: Feasibility of Implementing Roadway-Powered Electric Vehicle Technology in El-Monte Busway: A Case Study", PATH Research Report, UCB-ITS-PRR-92-3, December, 1992.

Summary: The objective of this study is to assess the feasibility of early deployment of the roadway powered electric vehicles (RPEV) technology in existing high-occupancy-vehicle (HOV) facilities in California. These are hybrid electric-electric vehicles using an “inductive” coupling power transfer principle, whereby energy in the battery is supplemented by energy transferred to the vehicle through an inductive coupling system (ICS). RPEV’s can operate both on and off the electrified roadway. To meet the objective, the following tasks were performed:

1. Synthesize the current status of the technology development for RPEVs.
2. Select on HOV facility for a site-specific feasibility evaluation.
3. Determine the scale of electrification and level of energy transfer required for the selected site.
4. Determine preliminary design of the inductive coupling system (ICS) for the selected site.
5. Assess the daily energy demand of this system.
6. Develop a technology demonstration plan, and identify issues pertinent to the implementation.

7. Estimate probable costs of the technology demonstration plan.

Cohen, Clark E., et.al., "Real-time Cycle Ambiguity Resolution Using a Pseudolite for Precision Landing of Aircraft with GPS", Dept. of Aeronautics and Astronautics, Stanford University, March-April, 1993.

Summary: An approach to GPS carrier phase cycle ambiguity for aircrafts is introduced. The method presented implements pseudolites (ground-based, pseudo GPS satellite). As the aircraft flies through the pseudolites broadcast “bubble” the changing geometry provides a means of resolving all three positional dimensions. Advantages include robust and dependable operation, built-in integrity checking, a built in data system, and low cost. The landing system presented is designed to function perfectly even with the minimum of four satellites in view. Flight experiments demonstrated altitude measurements to within a few centimeters.

Cohen, Clark e., and Parkinson, Bradford W, "Aircraft Applications of GPS-Based Attitude Determination", Dept. of Aeronautics and Astronautics, Stanford University..

Summary: GPS offers an efficient and cost-effective real-time heading and attitude reference for aircraft applications. It presents the potential to provide high quality dynamic response data to feed into autopilot design. A single GPS receiver could, in theory, effectively perform the functions of more than half of the cock-pit instruments currently in use.

Using Trimble TANS Vector altitude receiver and 486 Laptop aboard a Piper Dakota aircraft, Stanford University measured aircraft altitude.

Cohn, Marvin, "A Millimeter Wave Retrodirective Transponder for Collision/Obstacle Avoidance and Navigation/Location", IEEE-IEE VNIS, pp534-38, IEEE#0-7803-1235-X/93, 1993.

Summary: A small, low power drain and low cost transponder will be described, which as a result of it’s retrodirective property, has numerous automotive applications. The principle of operation of the retrodirective transponder (RTD) is based on the well known Van Atta array that has the ability to take an incident RF wave and reradiate it back in the direction from which it came, i.e., retrodirectively. While passing through the RDT’s integral monolithic GaAs modulators, the RF wave can be modulated by information that is thereby automatically transmitted back to the interrogator.

Contact, "NavCore® V Operations Manual", Rockwell International..

Summary: This is a description of Rockwell GPS receiver engine, a term that reflects that a fair amount of computing is done on this board. The receiver operates on L1; band with the C/A code, accepts signal level; in the range -163 to -130 dBW and suffers burnout; from inputs in excess of -10 dBW. Cold start, after initial application of power or after a move of more than 100 km with only keep-alive power takes 15 minutes. The receiver has five channels, four of which track satellites for navigation purposes while the fifth one multiplexes through all satellites in view to collect ephemerides. In this fashion the receiver is always ready to switch satellites if one should become obscured. A recent advertisement for the credit card size; NavCore® MicroTracker and letters given prices (~$500) and conditions of sale are inserted in the operations manual.

Cremer, Michael, and May, Adolf D., "An Extended Traffic Model for Freeway Control", PATH Research Report, UCB-ITS-RR-85-7, May,.1985.

Summary: In this paper a macroscopic dynamic model for freeway traffic flow simulations is presented and extended. The reported work was motivated because a basic version of this model developed for traffic flow on interurban freeways was shown to have some shortcomings when applied to urban freeways with nonuniform topological configurations. Particularly, unrealistic traffic simulations were obtained from the former model at bottlenecks as caused by a reduction of lanes at on-ramps with higher flow rates. Thus, special emphasis was placed on improvements of the model to show more realistic behavior at bottlenecks.

Crow, Steven C., "Starcar Design and GPS Control", SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, ISSN#0148-7191, 1992.

Summary: This paper explores a new transportation concept based on a confluence of aeronautical, automotive, and information technologies. The concept employs the Navstar Global Positioning System for navigation and control, Skyways to manage flight operations, and Starcars that function as automobiles and airplanes.

The role of the Global Positioning System is to locate the Starcars within the Skyways accurately enough to facilitate automatic landings. To prove the feasibility of precision GPS control, we equipped an automobile with a differential GPS control system and sophisticated estimation software. The vehicle can steer itself around a prescribed path with accuracies within 1m.

Modern kit airplanes are about ten times more efficient than automobiles for travel at high speeds. The paper presents a specific Starcar design that combines features of a Lancair 320 airplane and Mazda RX-7 automobile. The Starcar is five times more efficient than the automobile but about half as efficient as the airplane, haps a reasonable price for portal-to-portal convenience.

Cugiani, Corrado, et.al, "Millimeter-Wave System for the Real-time On-Board Acquisition of the Vehicle Lateral Position", The 3rd International Conference on Vehicle Navigation & Information Systems, IEEE , 1992.

Summary: This paper describes a lateral position reference system, under development within the Eureka-Prometheus project.The system consists of FM-CW Radar and of a reflective passive target located on the roadside.

In the proposed system, the radar, with a carrier frequency of 35GHz, 2.4GHz of bandwidth, and 10dBm of output power level, observes lateral scenery. This is accomplished by analyzing the frequency spectrum of the IF signal to detect the various obstacles present in the scenery by means of a DSP floating point processor. The lateral range is electromagnetically investigated within a bounded region and the distance from the motorway boundary is computed.

The use of integrated microstrip technology for the whole RF subsystem allows a very compact assembly.

Peculiarities of the proposed system discussed herein include:

1. Double reflector reference targets (e.g. 90 degree corner reflector).
2. The use of circular polarization to illuminate the corner reflector.
3. The IF signal processing subsystem must perform heavy calculations in real-time.

Cugiani, Corrado, et.al., "Millimeter-Wave Guard Rail Tracking System for Vehicle Lateral Control", IEEE-IEE VNIS, pp521-24, IEEE#0-7803-1235-X/93, 1993.

Summary: An on-board millimeter wave system able to provide the real-time lateral position of the vehicle with respect to the guard-rail is presented. The distance is measured from a reference line obtained by a 90 degree corner reflector embedded in the metallic guard-rail. A modulation of the back scattering signal obtained by interleaving corners with different size allows the recognition of the reference line also in unfavourable situations.

Daganzo, Carlos F., "Simple Upper Bound Formulae for the VRP Distance", PATH Research Report, UCB-ITS-RR-92-1, January, 1992.

Summary: This note presents upper bounds for the minimum distance needed to visit n points in a unit circle, with a vehicle fleet based at its center and allowed to visit a maximum of q points per vehicle tour.

DeMeis, R., "GPS Positions itself for Starring Role", Aerospace America, p32, May, 1993.

Summary: SPS; is the Standard Positioning Service;, formerly C/A;, PPS; is the Precision Positioning Service;, formerly P;, SA; is Selective Availability; which, when it is on, ruins performance of SPS. 2 to 3 minute averaging and differential GPS; should reduce errors to 2 to 5 meters for SPS with SA off. Carrier phase comparison; permits interferometry; (e.g. attitude angle estimation) with an error of 5 mm plus one part per million of the base line.

deMiguel, P., "Determination of Vehicle Lateral Position on Unrestricted Road Images", VNIS 3rd International Conference, IEEE ,pp197-202, 1992.

Summary: This paper briefly describes three groups of methods of measuring a vehicle's lateral position on the road using image processing techniques. The methods presented are edge detection, template correlation and texture analysis.

Test results show that texture analysis seems to provide the most reliable information, although at a higher complexity expense. The method that showed the best reliability/complexity ratio using the texture technique was the gradient standard deviation.

The texture approach detects roads limits by searching for the painted line and looking for imaging differences between the road, shoulder and ground by the road side. The gradient standard deviation method computes the gradient standard deviation on an irregularly shaped window centered on each considered point. Local maxima are computed, and the line is detected as a local maximum with a wide area of small standard deviation on its left, and an area of higher standard deviation on its right.

Detlefsen, W. , et. al., "Reliability of 5.8 GHz Short Range Links in Vehicle-Roadside Communication", IEEE-IEE VNIS , IEEE#0-7803-1235-X/93, 1993.

Summary: This paper investigates a 5.8 GHz mobile channel, with respect to technical aspects and propagation conditions, as a link for vehicle-roadside communication . Vehicle-roadside communication is implemented by means of a roadside beacon and an on-board unit (OBU). In downlink mode, the beacon transmits an ASK modulated signal to be demodulated by the OBU detector diode (500 kbit/s data rate was used experimentally) . For uplink, the antenna element reflectivity is changed, allowing the OBU to modulate a continuous wave transmitted by the beacon (125 kbit/s datarate is used in trials).

Multipath propagation effects were reduced, up to 45 m from beacon with no strong fading, by using frequency and space diversity techniques.

Experimental testing found that the short distances between the receiver and transmitter, between a few meters and some ten meters, yield fast changing channel characteristics. The short distances allow a high received signal level. Field trials show a reliable data link can be achieve with a short range communication link using 5.8 GHz.

Dierendonck, A.J. Van, Fenton, P., and Ford, T., "Theory and Performance of Narrow Correlator Spacing in a GPS Receiver", Navigation (J. of ION) 39, 3, 1992 .

Summary: Delay lock loops (DLL); typically have a one chip delay. Author points out that shorter delays may be better because of better noise correlation, but this approach is not applicable with less expensive t-dither, evidently a method where correlation is measured by varying delay between chips or groups of chips.

Eghtesadi, Manochehr, "Inductive Power Transfer to an Electric Vehicle- Analytical Model", IEEE Vehicular Technology Conf., Orlando, Fl, pp100-104, IEEE#90ch2846-4, May, 1990.

Summary: Inductive power transfer- A method is described for transferring tens of kilowatts of electric power to vehicles on a roadway.

El-Sheimy, N., and Schwarz, K.P., "Kinematic Positioning in Three Dimensions Using CCD Technology", IEEE-IEE VNIS, pp472-75, IEEE#0-7803-1235-X/93, 1993.

Summary: In this paper the problem of extracting accurate three dimensional coordinates from a cluster of CCD cameras (Charged-Coupled Devices) is studied. The cameras comprise the imaging component of the VISAT system developed at the University of Calgary. This system integrates an Inertial Navigation System (INS), satellite receivers of the Global Positioning System (GPS), and a cluster of CCD cameras. The cameras are mounted on a road vehicle moving with a velocity of 50-60 Km/h. Object coordinates are required with an accuracy of 30 cm within a radius of 50 m of the vehicle. The INS/GPS information is used to geo-reference the images collected by the CCD cameras. The shutters of the cameras and the output of the INS system are synchronized by the clock of the GPS receiver. As a first step, a brief introduction to the VISAT system will be given. Then, system calibration and the translations required to convert image coordinates into three-dimensional coordinates will be discussed. The factors affecting the accuracy of the derived object coordinates will be analyzed as a function of the GPS/INS accuracy, pixel size, camera geometry, calibration accuracy, and vehicle speed.

Emoto, Takeshi C, and May, Adolf D., "Operational Evaluation of Passing Lanes in Level Terrain: Final Report", PATH Research Report, UCB-ITS-RR-88-13, July, 1988.

Summary: As traffic flow intensity increases on rural highway systems,

the governmental agencies responsible for these systems face a growing problem. namely, conversion to multi-lane highway facilities may not be possible because of a lack of funding, project improvement stipulations requiring the incorporation of less expensive design modification, a combination of these two reasons, or a number of other funding related reasons.

In the absence of severe funding restrictions, conversion of two-lane rural highways experiencing undesirable levels of service to multi-lane highways would in most cases be the best solution. However, in the case of limited funding other cost-effective solutions which are within the constraints of the given budget must be found.

One such lower-cost solution is the addition of a single lane to the two-lane, two-way roadway, more commonly known as a passing lane, at selected sites. Although passing lanes have shown great promise as a lower-cost solution, knowledge about their operational effectiveness and more specific design guidelines are limited. This report presents the results of an evaluation of passing lanes in level terrain operating at high traffic flow levels. The operational evaluation of these passing lanes was conducted through the analysis of data collected at one site along the California State highway System. This evaluation was aided by the of the TRARR model developed at the Australian Road Research Board. In addition to the examination of the TRARR, a brief examination of the RURAL developed at the Institute of Transportation Studies which was experimented with in this project is presented.

Emoto, Takeshi C., and May, Adolf D., "Operational Evaluation of Passing Lanes in Level Terrain", PATH Working Paper, UCB-ITS-WP-88-1, February, 1988.

Summary: This working paper is for the project "Operational Evaluation of Passing Lanes in Level Terrain". This project examines passing lanes which have been constructed where growing traffic intensity combined with variable driver and vehicle characteristics in undesirable levels of service. The primary objectives of this project are:

a.) evaluate the operational effectiveness of these passing lanes.
b.) To propose initial design guidelines for these passing lanes.

of this working paper is to report on the following tasks which have been thus far for the project described above.

a.} Assessment of current knowledge.
b.) Inventory of California passing lanes.
c.) Design of field experiments.
d.) Analysis of available simulation models.
e.) Identification of future research needs.

This working paper will be used as the study base for the remainder of the tasks for this project.

Ervin, R.D., et.al., "Quantitative Characterization of the Vehicle Motion Environment (VME)"..

Summary: A concept is presented for creating a measurement system that can quantify the specific motions which vehicles exhibit as they move in traffic, under the full array of traffic operations. Such quantification is seen as crucial to the development of automatic collision prevention systems and has spin-off utility for the study of many other issues in human factors and vehicle and highway engineering. This study has addressed the experimental and analytical challenges involved in wide-area sensing, large-volume data processing, and both deterministic and statistical analyses of the data which will characterize this so-called , “Vehicle Motion Environment” (VME). The basic concept which appears to be feasible for such measurements involves a remote sensor which is installed at the roadside, probable on a tall pole, and which produces electro-optic images of the traffic stream and converts them into a permanent data file of the quantified trajectory for each motor vehicle passing through the field of view.

The paper covers the performance specifications for the VME measurement package and the subsequent processing needed for deriving the variables of interest. Various applications of the VME system are also addressed.

Eskafi, Farokh, et.al., "SMARTHPATH: An Automated Highway System Simulator", PATH, PATH TECH MEMO 92-3, October, 1992.

Summary: SmartPath simulates an Automated Highway System (AHS). The program may be used to understand how the AHS would perform in terms of highway capacity, traffic flow, and other performance measures of interest to transportation system planners and drivers. SmartPath is a microsimulation: the system elements and control policies are each individually modeled. Several elements and policies are parametrically specified. The user can change these parameters to study how the performance varies.

The executable file, sm_sim, can be obtained from the authors. The user must supply an input file to initialize the parameters used in the simulation. These parameters are described in Appendix 1: How To Use SmartPath. The simulation runs on a Sun Sp0arc station. A separate program, sim_anim, takes the simulation data and produces a three-dimensional, color animation of the output. The animation program runs on a Silicon Graphics Indigo station. Appendix 2: How To use the Animator explains its use. SmartPath can also run on the SGI station.

This paper summarizes the key design features of the AHS, and the assumption underlying the design, namely, the availability of certain elements: vehicles with appropriate sensors and actuators; highways with appropriate sensors; the ability to communicate between vehicles and between a vehicle and the highway. The paper explains how the simulation is organized, and an example illustrates the use of Smartpath.

Feijoo, C., Ramos, J., and Perez, F., "A System for Fleet Management using Differential GPS and VHF Data Transmission Mobile Networks", IEEE-IEE VNIS,pp445-48, IEEE#0-7803-1235-X/93, 1993.

Summary: In a number of industries and services, communication with the land vehicles of the fleet has been done through VHF radio systems. This mode of operation brings the question about the possibility of using this same VHF equipment to transmit and receive data position fleet management due to this fundamental advantage. The viability of differential GPS system for fleet management through a data link in VHF band has been proved , and the guidelines for appropriate parameters selection have been supplied. However, some coverage problems have appeared, showing that in case of critical applications like a data link for air navigation DGPS, it is necessary to re-design the system. In this way, it is possible to increase the data exchange using GMSK instead of just MSK, an improvement at present being considered. Actually, the system is under final test fields for it's implementation as a fundamental piece for land fleet control.

Fenton, Robert E., "A Headway Safety Policy for Automated Highway Operations", IEEE Trans on Vehicular Tech, Vol. VT-28, No.1,pp22-28, February, 1979.

Summary: The maximum capacity, cost and safety of an automated highway system are largely dependent on the selected headway policy, ie., the specification of a minimum acceptable headway (as a function of speed) for mainline operations. Here a policy, designed to avert collisions due to "reasonable" lead-car decelerations, is presented and evaluated in the context of achieving high capacity (>=3600 vehicle/lane/hr) over a range of typical speeds- 13.5 to 30 m/s. This involved detailed analysis to determine both the relationships between, and the requirements on the seven parameters which are embedded in this policy. These pertain to systems level operations, the capabilities of a vehicle's automatic control system and the vehicle/roadway interface. The trade-offs associated with safety, capacity, and cost are identifies and three general approaches to selecting parameters for an operational system are specified.

Fenton, Robert E., and Mayhan, Robert J., "Automated Highway Studies at the Ohio State University- An Overview", IEEE Transactions on Vehicular Tech, Vol.40, No.1, February, 1991.

Summary: A long range program, conducted at Ohio State University from 1964 to 1980, on various aspects of automated highway, including lateral and longitudinal control, are highlighted in this paper.

Longitudinal control studies, conducted during the 1960's and 1970's, encompass modeling of vehicle longitudinal dynamics, and evaluation of car-follower and point-follower techniques.

The car following approach applies control to a vehicle, in a line or platoon of vehicles, by determining the longitudinal state of that vehicle with respect to other vehicles. Car following studies, conducted from '64 to '71, focused on basic problems associated with vehicle control. Several control laws are presented in this paper. Field tests showed safe, efficient control, and occupant comfort was achieved. The car-following approach to longitudinal control was abandoned due to lack of a forward looking, vehicle based radar system, an essential component of the control system.

The point following approach became the subject of research. A square-wave approach to discrete reference signal generation appeared most promising.

A point-follower longitudinal controller is presented. The designed controller was characterized, in numerous tests, by small position errors and passenger ride comfort.

The lateral control studies, encompassed the modeling of vehicle lateral dynamics, the development and implementation of lateral reference systems, and design, implementation, and testing of vehicle lateral controllers.

A two-degree freedom "bicycle" model to describe the lateral motion of an individual vehicle is discussed. Results using this model and result from field tests for lateral accelerations less than 0.2g showed excellent correlation.

Extensive studies were conducted with a reference system which used a wire, laid along a lane in various configurations, and excited with alternating current. However, sensitivity to ferrous and other materials led to the development of a phase-sensing system. In 1977, the FHWA decided that active reference systems should not be employed under the road or at wayside. It was decided to use a short-range two frequency radar designed to detect a guard rail reflector uniformly positioned. Full scale tests showed tracking error no more than twice the wire following system. Redesign and state of the art radar should correct tracking error to equal wire following.

The efforts presented and tested during this project were conducted using 1960-1970 technology.

Fenton, Robert E., and Selim, Ibrahim, "On The Optimal Design of an Automotive Lateral Controller", IEEE Trans on VehicTech, Vol.37,No.2,pp108-13, May, 1988.

Summary: An optimization approach is used to design a velocity-adaptive, lateral controller to meet requirements pertaining to lateral position tracking accuracy, robustness, and ride comfort. The resulting controller, which is nonlinear with velocity, requires full-state feedback and thus an observer is included. The observer/controller compensator was implemented using a 16-bit microcomputer and evaluated in a laboratory study wherein vehicle lateral dynamics were simulated on an analog computer. Excellent lateral control, close tracking, a good insensitivity to disturbance forces.resulted...

Fernandez Maloigne, Christine, "Texture Analysis for Road Detection", URA CNRS 817m Kabiratiurem, France..

Summary: This paper discusses texture analysis for vehicle lateral control. Texture is the spatial repetition of a basic pattern in different ways in the space. There are two types of texture: 1.Macrotexture- Visual basic pattern; 2. Microtextures- Chaotic but regular, basic primitive becomes a reduced group

of pixels. Mixed textures do exist. A statistical method of discrimination based on run length matrices (RLMs) is described.

To obtain homogeneous images, all images must be preprocessed. A translation of the image is made around a constant and medium gray level. This lightens images that are too dark and vice versa. Contrast enhancement, inspired by Willis' Filters, is based on detection of object edges by homomorphic image processing.

In order to speed up the processing and to obtain images of similar contrast, images are coded. The principle is to compute a gray level function F, using cooccurence matrices, and the values which raise to a maximum F give the thresholds of the different regions. Ultimately, a histogram of the number of runs associated with each gray level is developed. (A run is characterized by adjacent and consecutive points of an image having the same gray level.)

The image to be processed is then divided into elementary squares of 10x10 pixels. A vector is calculated for each region. The vector, composed of Galloway's Parameters, facilitates the calculation of the resemblance between the region and a model of road.

The results of testing appear promising. In 92% of the cases, the road is correctly detected.

Fischer, H. J., "Digital Beacon Vehicle Communications at 61 GHz for Interactive Dynamic Traffic Management", The British Library Document, Supply Center, Boston Spa, Wetherby, West Yorkshire, United Kingdom, LS23 7BQ..

Summary: We proved by measurements, that millimeter waves in the range of 60 GHz are very well suited for beacon vehicle communications. We examined different kinds of modulation schemes appropriate to low cost receiver equipments, to simultaneous operation of the communication equipment and the radar equipment and to bidirectional communications. The data rate depends on the application and may exceed 5 Mbit/s. The speed of the vehicles may be in the range up to 50 m/s, approximately.

The RF-frontends are designed as millimeter wave monolithic integrated circuits (M3IC). Once the European authorities will have defined common frequency bands for those applications it will be possible to start the development and production of M3ICs.

Fujioka, Takehiko, et.al., "A Case Study on an Automated Driving Highway System in Japan", Transportation Research Board 72nd Annual Meeting , Session No. 94B, January, 1993.

Summary: Super Expressway for Automated Driving 21 (SEAD21) is a continuation of Super Expressway 2000 (SE2000), which was a proposed pilot system for automated driving based on the application of the inductive cable. The SEAD21 study aims at offering automated driving systems with automatically traveling cars utilizing devices such as ITV camera, laser radar

and supersonic wave radar.

AIST MITI, mechanical engineering labs, have succeeded in controlling a car with no driver at 100 km/h by using inductive cables. Cars have also successfully been controlled with machine vision using stereo-camera at 30 km/h and with white line and obstacle detective devices. The equipment necessary for the automated driving system include:

1. White lines, reflectors, guardrails
2. Communication cable for vehicle control (steering and speed)
3. Beacon
4. Obstacle detecting ITV and picture processing device
5. Various sensors for collecting information
6. An area controller
7. A control center. The equipment necessary in the vehicle include:

1. ITV or Laser Radar
2. Magnetic field detecting sensor & receiving antenna
3. Speed sensor, torque sensors, steering sensor, and other various sensors which detect vehicle conditions
4. steering and speed control device
5. Beacon receiver

In the rampway, steering and acceleration are controlled manually. A distance sensor installed on the car will control the gap between cars.

A car computer judges the distribution of cars on the lane and controls the timing to get into the flow.

Each car is given instructions pertaining to speed, for the section of roadway it is on, by the roadway computer. Steering and the gap between cars are controlled by the autonomous driving device. Inductive cables are laid in the middle of the lane.

If the car is not switched to manual while exiting, the vehicle will stop automatically.

Gallant, J., "System Revolutionizes Surveying and Navigation", EDN, p31, January, 1993.

Summary: This article is a general description in compact form. A table of some GPS sets is included. The L2 frequency; is 1227.60 MHz, uplink; from Colorado Springs is at 2227.50 MHz, downlink; at 1783.74 MHz. Other ground control stations for GPS are in Hawaii, Kwajalein, Ascension Islands and Diego Garcia. Satellite altitude; is 10,898 miles (type unspecified). The P;, precise or protected code; (P(t)) is chipped at 10.23 MHz and has a 266.4 day repetition period. Each satellite has a unique one week segment of that code. Signals at the L1; and L2 ;frequencies are described by the equations;:

$$L1(t) = P(t).D(t).\cos(wL1t) + C(t).D(t).\sin(wL1t)$$

$$L2(t) = P(t).D(t).\cos(wL2t)$$

Here C(t) is the coarse/acquisition (C/A); code that is specific to a given satellite, chipped at 1.023 MHz and repeats once each millisecond. D(t) is a 1500 bit data message; that is transmitted at 50 bits per second, i.e. over a period of 30 seconds. This message includes the ephemeris of the satellite that is transmitting, a low-accuracy almanac; for all satellites, data on clock accuracy and satellite health.

Glathe, Dipl.-Ing. Hans-Peter, "PROMETHEUS-Common European Demonstration: A Tool To Prove Feasibility", IVHS America, 1993.

Summary: PROMETHEUS is a joint effort by the European automotive industry to improve the transport and traffic situation in Europe. The integration of vehicle control and traffic control has evolved as the essential means to higher efficiency and safety in road traffic. The implementation of such an integrated system is a difficult process requiring the demonstration of technical feasibility, the assessment of the impact on traffic and a consensus on the interfaces between different components. The Common European Demonstrations (CED) serve these purposes. As an exemplary CED takes a closer look at the AICC, an innovative system with extended cruise control functions is taken. Like no other system before, AICC will improve safety , comfort and driving style. The intelligent vehicle of the fuiture must help the driver in a manner which is natural and acceptable. The driver must remain an integral part of the driving and vehicle control task. Further interdisciplinary research will be needed to achieve systems integration. Implementation of PROMETHEUS results requires the integration of public and private interests.

Glimm, Jochen, and Fenton, Robert, "An Accident-Severity Analysis for a Uniform Spacing Headway Policy", IEEE Transactions on Vehicular Technology, Vol.VT-29, No.1, p96-103, 0018-9545, February, 1991.

Summary: The achievable capacity of an automated highway system is closely related to system safety by means of a headway policy. The severity and “cost” of each collision related to such a policy is discussed in this paper.

There are seven parameters relevant to VsHt, where Vs = desired mainline speed, Ht = desired time headway. Of these Ht is relatively insensitive to the maximum permitted position deviation, Xt, and jerk limit, Jm. However, Ht is quite sensitive to the maximum permitted speed deviation, Vt, delay time, T, lead car deceleration, A1, and following car deceleration, A2.

An accident collision model is introduced.

An accident severity index, S^2, as a function of relative speeds of the collision vehicles and their absolute speeds is presented. S^2 is a function of eleven parameters. Several parameters were fixed: The desired mainline speed = 26.8m/s, vehicle length = 3.66m, desired time headway = 1s, maximum permitted position deviation = .305m, maximum permitted speed deviation = .305m/s, collision acceleration of the following vehicle = 98.1m/s^2 (10g), jerk limit = 76.2m/s^3, and velocity step function weighting factor = 0.5. Serial buildup of reaction delay and single parallel delay configurations were considered. The behavior of S^2 was examined as a function of the variation of each individual parameter in a selected parameter set. The results were presented in a normalized form. Three emergency braking situations were evaluated. The following observations were made:

1 The lead vehicle deceleration to which a platoon can respond should be as large as possible.

2. Accident severity was, in some cases, greatly increased with a serial reaction delay (as opposed to a single parallel delay).

3. A moderate increase in the parallel reaction delay resulted in a relatively small change in accident severity.

4. Accident severity was very sensitive to decreases in the deceleration capabilities of the following vehicles.

It was noted that the accident-severity measure used was overly simplified.

Gomi, Takashi, and Laurence, Jean-Christophe, "Behavior-Based AI Techniques for Vehicle Control", IEEE-IEE VNIS, pp555-58, IEEE#0-7803-1235-X/93, 1993.

Summary: In behavior-based artificial Intelligence (AI), intelligence is realized as an emergent process which arises from interactions between otherwise “unintelligent” simple behaviors of agents and between these agents and their environment. This is a drastic departure from the more conventional notions of AI based on codified knowledge structure and it’s interpretation in a Cartesial manner. Behavior-based AI has previously demonstrated greater potential as a candidate for a control stratgy for intelligent autonomous vehicles.

A set of algorithms which uses Subsumption Architecture (SA) for controlling vehicles operating in close vicinity has been developed. SA is a dominant Behavior-based AI technique. The algorithms collectively generate desirable manouver capabilities for vehicles which must travel through a dynamic interactive environment.

This paper describes a successful application of the approach to a small-scale but fully situated and embodied vehicle control problem using scaled down mobile robots. Despite the relatively small number of sensors mounted around the robots, excellent collision avoidance performances were obtained. Control software turned out to be much smaller than that implemented by conventional techniques for similar functionalities.

Incremental adjustments of behaviors on both robots were carried out with ease and they yielded the desired improvements.

As far as the experiments indicate, domain knowledge can better exist situated, suggesting separation of domain specific knowledge from the process structure may not be a workable approach.

Gray, Jennifer, Lavallee, Paul P., and May, Adolf D., "Segment-wide On-Line Control of Freeways to Relieve Congestion and Improve Public Safety: Executive Summary", PATH Research Report, UCB-ITS-RR-90-11, June, 1990.

Summary: This paper is an executive summary for the project entitled "Segment-Wide On-Line Control of Freeways to Relieve Congestion and

Improve Public Safety".

The project consisted of a number of working papers that examined various areas of freeway on-line control Working papers are documented in the References section at the end of the report. The three major areas investigated include:

-monitoring of traffic detection information and incident control strategies;

-Detector diagnostics;

-Ramp entry control strategies.

Gris, Arturo E., "Evaluation of Potential Hybrid Electric Vehicle Applications Volume II: Appendices", PATH Research Report, UCB-ITS-PRR-91-5..

Summary: Appendix A.1 Simulation of the scenarios with the same vehicle.

Appendix A.2 Simulation of the scenarios with selected vehicles

Appendix A.3 Comparison of simulation results with track test results

Appendix B Top speed and acceleration power requirements

Appendix C Designs without air conditioning

Appendix D Sensitivity of the designs to changes in batter specs

Appendix E Designs with air conditioning

Appendix F Alternate sizing method for hybrid vehicles

Appendix G Practical limitations of engine-generator sets

Gris, Arturo E., "Evaluation of Potential Hybrid Electric Vehicle Applications- Volume I", PATH Research Report, UCB-ITS-PRR-91-4..

Summary: Electric and hybrid vehicles possess characteristics that make them favoable for different applications. The purpose of this reportis to identify potentially promising market segments for electric and hybrid vehicle technologies.

ifferent market segments are represented by driving scenarios and repesentative vehicle (automobile, mini van, van or bus). Each driving scenario combines SAE J227a cycles and constant velocity travel, with some portions of the cycles being on specified graDes. A simulation program is used to calculate the energy required for each driving scenario. The energy to provide air conditioning is calculated based on the air conditioning power demand for the different vehicles. The power rating required for each ehicle is chosen to satisfy the performance demanded by the driving scenario, an acceleration requiement and a top cruise speed requirement.

Each configuration, electric and series hybrid, is evaluated with sodium sulfuir, niclel iron, nickel zinc, lead acid and lead acid ghel cell batteries for the different driving scenarios without and with air conditioning. Limitations, advantages and disadvantages of each design are then discussed.

Hager, Rolf, et.al., "Network Management in Short Range Mobile Radio Networks:Performance Tuning Optimizes Collision Behavior", IEEE 42nd Vehicular Technology, Vol.1, p307-311, 0-7803-0674-0, 1992.

Summary: This paper evaluates several network management algorithms to increase the performance of short-range mobile radio networks concerning collision avoidance and reduction of collision duration measured in frames. It is shown that a suitable choice of transmission power with indendent antenna systems fulfills requirements of applicaitons while increasing the communication performance. The evaluations are made by simulations of a three lane unidirectional highway.

Hatch, Ron, "Instantaneous Ambituity Resolution", Magnavox Advanced Products and Sytems Co., Torrance, CA..

Summary: A method is described for initializing a GPS system quickly (in a few minutes) using more than four GPS satellites. The method works over a few tens of km. This document contains a good bibliography.

Hauksdottir, Anna Soffia, and Fenton, Robert E., "On Vehicle Longitudinal Controller Design", University of iceland, Reykjavik, Iceland; Ohio State University, Columbus, ohio 43210, IEEE#TH0231/88/0000-0077..

Summary: Two methodologies for designing a longitudinal controller for an automated vehicle are prented and compared. The first, parameter scheduling, involves a linearization of vehicle dynamics about a number of operating points, and the specification of an observer/controller compensator for each of those points. The second emphasizes an explicit accounting for nonlinearities in the selection of a nonlinear observer/controller compensator. In both approaches, a lag compensator wamployed to reduce tracking errors. The utility of these approaches was evaated by designing a controller for vehicle operion on dry roads under nonemergency conditions and then evaluating controlled vehicle performance by digital computer simulation.

Excellent results were obtainesd from the former approach when a sufficiently large number (30) of operating points, and a correspong number of observer/controller compensators, were employed. Comparable excellent results were obtained from the latter. er, in both cases, the designed system was sensitive to large changs in critical vehicle parameters as may occur within the range of possible operating/environmental conditions.

Hedrick, J.K., et.al., "Automated Highway Systems Experiments in the PATH Program", IVHS America,pp131-46, May, 1992.

Summary: The accomplishments to date on the experimental evaluation of advanced vehicle control systems (AVCS) technology for highway automation in the California PATH program are summarized. Lateral and longitudinal control systems are examined separately. Current technology is implemented.

PATH work on longitudinal control emphasizes vehicle-follower control over that of point-follower control. The speed and acceleration of the vehicle in front and that of the lead platoon vehicle is received by each vehicle. Each vehicle is equipped with an integrated platoon control system (IPCS) unit including a computer, a communication system, a radar system, sensors and actuators. Experiments were performed using only two vehicles, a manual lead vehicle, and longitudinal controlled follower. Transmission and reception tasks were of a much simpler nature than would be required in a multi-vehicle platoon. The experimental results provided impressive spacing error and riding comfort.

A lateral roadway reference system implements permanent magnetic markers. The magnet fields are acquired via four magnetic sensors. The signal is digitized and fed into the controller. Lateral displacement of the vehicle and road geometry information are extracted.

An accelerometer, yaw rate sensor, and steering angle sensor are used to derive an estimate of tire/road cornering force. The lateral control system performance and calibration of the magnetic marker reference/sensing system are evaluated by means of line scan cameras and reflective tape.

The lateral controller uses a preview control algorithm which combines a feed forward algorithm with feedback. Both are described in this report.

Experimental results show that tight lateral tracking can be achieved by the preview control algorithm on a sharp curve under both nominal and non-ideal conditions at relatively low vehicle speeds (20km/hr to 60km/hr).

Hedrick, J.K., et.al., "Longitudinal Vehicle Controller Design for IVHS Systems", ACC, Vol. 3., p3107-3112, 0-87942-566-0,FP14 16:30, 1991 .

Summary: This paper presents a throttle/brake control algorithm designed to control intervehicle spacing of a platoon of automated vehicles.

A simplified vehicle model is presented.

Due to the nonlinearities in engine and powertrain dynamics, a nonlinear controller design method, called the sliding control method, was used. A multiple surface approach is also utilized. Three surfaces are defined.

The rear brake pressure was solved for as the control variable. A total brake pressure that accounts for the distribution of brake pressure front to rear was commanded.

The first simulations were performed on a two car platoon. The simulation includes a torque converter model, drive axle compliance and front and rear rotational degrees of freedom. With the rear vehicle following a typical change of velocity profile, tracking accuracy resulted in a maximum spacing error of 4cm. (1m is nominal spacing.)

Simulations of a four car platoon were conducted. Although tracking results were good, an amplification of each vehicle's peak error was noted as one proceeds down the platoon. Communication of the lead vehicle's

velocity and acceleration to all trailing vehicles eliminates the error amplification problem.

Heller, Mahlon, and Huie, Mimi, "Vehicle Lateral Guidance Using Vision, Passive Wire and Radar Sensors", IEEE-IEE VNIS, p505, IEEE#0-7803-1235-X/93, 1993.

Summary: This paper describes research performed in the area vehicle lateral guidance using vision, passive wire and radar sensors.previous research work performed by others focused on the development of a single system. However, it is important to compare the feasibility of different sensing systems on a common platform to determine the best alternative that may be integrated in an automated highway system. A test vehicle is equipped with each of the three sensors and a common steering controller platform. Lateral displacement information from each of the sensors is interfaced with the common steering controller platform to provide a basis for comparison. A quarter mile test track has been prepared to test vehicle in actual operation. Results from experimental data is evaluated in this paper. In addition, the control law, individual sensing systems and the overall system architecture is discussed.

Hessburg, Thomas, and Tomizuka, Masayoshi, "A Fuzzy Rule-Based Controller for Automotive Vehicle Guidance", PATH Research Report, UCB-ITS-PRR-91-18, August, 1991.

Summary: A fuzzy rule-based controller is applied to lateral guidance of a vehicfor an automated highway system. The fuzzy rules, based on human drivers' experiences, are developed to track the ceer of a lane in the presence of external disturbances and over a range of vehicle operating conditions. In the case of a severe road curvature, rules are developed to provide feedforward steering action, utilizing preview information regarding the characeristics of the upcoming curve. A nonlinear el is used to simulate the performance of the fuzzy rule based controller for a variety of scenarios.

Hessburg, Thomas, et.al., "An Experimental Study on Lateral Control of a Vehicle", PATH Research Report, UCB-ITS-PRR-91-17, August, 1991.

Summary: This paper summarizes, with respect to lateral control of a vehicle, a magnetic reference/sensing system, a dynamic model, the control law, and results of testing of an experimental car.

The magnetic reference system uses a series of discrete magnetic markers placed in the roadway. Hall effect magnetomenters acquire the magnetic field from the markers. The magnetic field measurements are used to determine lateral displacement. A “table look-up” approach and linear interpolation approach, which uses both components of the acquired magnetic field measurements, is discussed. Experimental results show that error is introduced by the linearization of the measured magnetic field versus lateral displacement characteristics with respect to the height of the magnetometers.

A linear model of the experimental vehicle was used to simulate vehicle response. Experimental test results indicate that a feed forward loop added to the PID controller improves tracking over curved sections of roadway. However, the limitations of such a controller were observed as operating conditions deviated from the nominal conditions. A more sophisticated control law must be developed.

Hirano, Makoto, "Development of Vehicle-Following Distance Warning System for Trucks and Buses", IEEE-IEE VNIS , IEEE#0-7803-1235-x/93, 1993.

Summary: A vehicle-following distance warning system is outlined.

A laser radar unit emits a beam. The distance to the preceding car is measured based on the time from the beam emission to it's return. If the safe vehicle-following distance is violated, a buzzer intermittently sounds and an orange lamp goes on. A second louder alarm sounds dependendant on the situation. The equipment to implement the system include a light emitting unit, light receiving unit, dirt detecting unit, control unit, display unit, speed sensor (outputs own vehicle speed), steering-angle sensor, and a wiper switch. Specifications and functions are discussed.

Experimental results on five trucks and thirty-one people, are presented. The system appears helpful to safe driving.

Hitchcock, A., "A First Example Specification of an Automated Freeway", PATH Research Report, UCB-ITS-PRR-91-13, June, 1991.

Summary: This paper sets out a specification for an automated freeway in a fully formal manner. A series of safety analyses have been carried out on the specification. The objective of the program of work of which this is part is to derive a technique of safety analysis for such systems. The system reported here is the first example on which a trial analysis has been demonstrated. The analysis depends on the precise nature of the system specified. It is therefore necessary that this be recorded unambiguously. This requires great detail. In any case the method of analysis recommended by hitchcock, 1992a does require formal documentation. This paper is consequently intended as an exemplar of such documentation. This applies especially to the appendices. here a formalized language has been proposed, which is analogous to some computer languages.

Hitchcock, A., "Fault Tree Analysis of a First Example Automated Freeway", PATH Research Report, UCB-ITS-PRR-91-14, June, 1991.

Summary: A particular design to demonstrate the techniques of complete specification and fault tree analysis is examined.

It is concluded that:

a. A specification has been made of an automated freeway. A set of hazards and a safety criterion have also been specified.

b. Fault tree analysis was practical. No branch of the tree had more than four elements. Faults were detected, but it is reasonably clear that they can be corrected.

c. It is therefore possible to construct an automated freeway which meets these safety criteria.

It should be noted that ther is some gap between the assertion that the design meets the safety criteria and an assertion of safety. The principal reason for this is that it has been assumed that a within-platoon accident cannot of itself be a catastrophe. This is the assumption usually made by those working on platooned systems. It is in fact not obvious that it is valid in all cases. If an accident which occurs while vehicles are joining or leaving a platoon, the consequences can be serious. This case is not really covered in the basic work of Shladover 1979. More research is desirable here.

Hitchcock, A., "An Example of Quantitative Evaluation of AVCS Safety", California PATH, University of CA (Berkley) ..

Summary: Based on a postulated one-lane automated highway system on the Santa Monica freeway, safety of various features of an AVCS system were expressed. In particular, to prevent casualties when a collision on manual lanes intrudes on automated lanes, a divider is necessary. Access from manual to automated lanes is achieved through a gate. Although such a design may cause some accidents, no serious casualties would be generated. If no divider separates the automated lanes form the rest, a particular kind of secondary accidents will result in additional deaths amounting to 4-5 per year (Present rate is approximately 8).

The method outlined can be extended to any other accident in an automated system as long as the nature and frequency of inititating events or failures is specified.

Hitchcock, Anthony, "Fault Tree Analysis of an Automated Freeway with Vehicle-Borne Intelligence", PATH, UCB-ITS-PRR-92-15, December, 1992.

Summary: This paper describes the fault tree analysis of the second example design. This design is characterized by extreme emphasis on vehicle-borne intelligence, and by the presence of a multiplicity of automated lanes. It is a platooned system. At the end of this paper there is a brief discussion of the relative merits of vehicle-based and infrastructure-based intelligence, nly from the viewpoint of safety.

The analysis starts with definition of the hazards to be avoided. Here a hazard is defined as a precursor to a condition inwhich one further failure could lead to a catastrophe. A catastrophe is a high-delta V collision between platoons. In such a collisioultiple deaths and injuries are likely. The

qualitative safety crition chosen is that two independent failures should have to occur before a catastrophic hazard arises. This means that three near-simultaneous independent failures are necessary to cause a high-delta-V collision.

In he end, such criteria should be quantitative. Estimates would be made of the frequency of catastrophes. Alternatively, estimates would be made of the reliability required to make this frequency small enough. This would require data on reliability of existing system components. This includes tires, automatic transmissions, and vehicle presence detectors. Such data is not immediately available. Research on this topic is planned. Inthe meantime the present qualitative analysis can reveal whether or not a design concept is basically sound. The analysis points the way to the critical items for quantitative analysis.

Hitchcock, Anthony, "Methods of Analysis of IVHS Safety

Executive Summary", PATH Research Report, UCB-ITS-PRR-92-13, December, 1992.

Summary: The objective of this work was:

"To develop and demonstrate methods by which safety of IVHS can be assured, aessed, and evaluated."

The principal individual tasks were:

- Specification and analysis of hazards in AVCS-2/3 systems (Automated Freeways)
  - a.) Development of techniques
  - b.) Investigation and demonstration of techniques: System #1
  - c.) Investigation and demonstration of techniques: System #2
- -Methods of analysis of AVCS-1 Systems (Driver Aids and Copilots)
- -Communication of results to industry, administration, etc.
- -Final Report

In part two of this report, a number of recommendations regarding probich need solution are made. Here, however, we refer only to recommendations affecting action now.

Hitchcock, Anthony, "Message Volumes for Two Examples of Automated Freeway", PATH Research Report, UCB-ITS-PRR-93-1, March, 1993.

Summary: In this paper calculations are made of the volume of messages tranmitted between vehicles or between vehicles and the infrastructure, in order to estimate the demand of AVCS systems for frequency allocations.

Thalculations made are of message volume only: the choice of transmission protocol and the allowances that must be made for retransmission of garbled messages are not discussed. Nor, although the two systems could be said to "span the range" between purely vehicle-borne intelligence and purely infrastructure-borne intelligence, should these conclusions be assumed to apply to all systems.

In both caes, the apparent demand for transmissions of control data, if unconstrained by technological simplification, is found to be impracticably large. However, in each of these cases, means exist by which the demand can be reduced to 1-2 kbaud. There is also a demand for bandwidth for emergency messages. It is small, but the importance of quick reaction to such messages may make it desirable to reserve a channel for them alone.

In a full-scale emergency situation, messages are few and short. The maximum demand arises, in each case, in fault conditions of rather less immediacy. The critical case seems to be the situation where a failed vehicle causes a length of automated lane to close. If delay and complexities are to be avoided, it is necessary that all vahicles in the affected lane change lanes rather promptly. The resulting flurry of messages represents the maximum demand.

in both saces this volume of demand translates into a requirement for between 10 and 15 kbauds. This figure may not apply generally. There could well be other systems, as yet unspecified, that have much larger or smaller demands.

Hitchcock, Anthony, "Methods of Analysis of IVHS Safety", PATH Research Report, UCB-ITS-PRR-92-14, December, 1992.

Summary: This is the final report of the PATH program's MOU(Memorandum of Understanding) 19-"Methods of Analysis of IVHS Safety." The total report comprises six separate documents. This is the primary one. There is also an executive summary, wich summarises what is said here.

Section 1 explains the administrative background to the research. Details are givethe achievements on the minor tasks required byt. The first of these was to carry out a literature survey. A bibliphy on safety of IVHS was prepared and sent, in draft, to the librariansin the Transportation Library at the Institute of Transportation Studies, Univ. of CA, Berkeley. There it formed one of the bases for the PATH bibliographic databases.

Section 2 of this report describes two complete specifications of possible automated freeway systems and fault tree analyses of them.

Section 3 discusses safety considerations for driver aids and copilots. In particular, AVCS-1 devices, which are vehicle-mounted devices which warn drivers of potential dangers or take control in dangerous situations, are analyzed.

Section 4 sets out the consequences of the research and discusses how it can be applied.

Hitchcock, Anthony, "IVHS Safety: Specification and Hazard Analysis of a System with Vehicle-Borne Intelligence", PATH/Transportation Research Board 72nd Annual Meeting, Wash.,DC, 930435, January, 1993.

Summary: This system relies on intelligence which is mainly vehicle-based. The proposed automated highway has several lanes, divided into blocks. The lanes are separated by dividers which contain gaps, called gates, through which lane changes are made. On the sending side of each gate is a “turning-point”, an electromagnetic or other signalling device, which, when activated, gives a signal to the lateral control system of a vehicle beginning a turn. Gates are equipped to advise lane changing vehicles. Vehicle mounted odometers are zeroed at the end of each block. This enables the recording of absolute position along the lane. This information may be used to identify position to other vehicles. Each vehicle is equipped with the following:

1. A longitudinal control system-a forward sensor.
2. A lateral control system-no suggestions made.
3. A self-monitor-detects faults in sub-systems on vehicle.
4. A communication sytem- to transmit and receive messages.
5. A supervisor- an overall controller. This system features a busy flag set while engaging in maneuvers.

Three basic maneuvers are defined to enable the system to perform it’s functions. These are merge, split, and change lane. Only a free agent may initiate a change-lane maneuver. A force-split maneuver is called under fault circumstances. Forced split has absolute priority. A flag is set in the supervisor when faults are detected. Different flags define different faults. The supervisor arranges to move the faulty vehicle out of the system. This requires a fifth maneuver called emergency-change. The emergency-change “shepherds” the vehicle between neighboring platoons. There will be circumstances in which a self-monitor cannot detect a vehicle fault. Probes are employed in these cases. The platoon leader’s probe tests the forward sensor by periodically sending forward a message. The response and expected response are analyzed to determine if it should declare itself faulty. The in-platoon probe deals with a situation when a vehicle in a platoon develops a fault in communication with neighboring vehicle in it’s lane. A forced split is enforced by means of acknowledgement of the control data message passed down through the platoon. The platoon leader does not receive this message. On-ramps are to be equipped with a separate exit for vehicles refused entry. The off-ramps are to be equipped with an area for vehicles whose driver does not resume manual control. The driver must position the vehcile for a change-lane maneuver prior to exit. Messages are sent before and after change reminding the driver to resume control. A positive reply is needed .There is question as to the possibility of alternatives to a faulty vehicle leaving the highway.Forseen, but rare, faults arising from fault tree analysis:

1.Vehicles in a platoon crush together.

2.Distancing requirements are violated. This happens for a brief period of time during merge and split maneuvers.

3.An object drops onto the automated lanes.

4.A manually controlled vehicle enters automated lanes.

5.A change-lane maneuver allows a vehicle to enter before a platoon imposing the threat of collision if the vehicle strikes a gate- easily remedied.

Holger, H., "Applications of Microwaves and Millimeterwaves for Vehicle Communications and Control in Europe", IEEE MTT-S International Microwave Symposium, Vol.2, p609-12, 0-7803-0674-0, 1992.

Summary: Traffic is becoming a serious problem throughout the world, as it is a major problem in Europe. The ever increasing demand of road transportation has created negative effects related to traffic safety, efficiency and economy; for the future the protection of the environment is an additional challenge. Today it is widely accepted, that the solution to traffic congestion and increasing pollution lies in the application of advanced technologies to control and direct the flow of vehicles. Pan European projects like PROMETHEUS or DRIVE are supporting such solutions. Four major areas of applications have to be distinguished: Automatic Debiting Systems (ADS), Road Traffic Informatics (RTI), Microwave Doppler Sensors (MDS) and collision avoidance radar. Millimeter-wave systems have found an increasing interest, due to their specific advantages, as well as the lack of frequencies for new services.

Homburger, Wolfgang S., Kell, James H., and Perkins, David D., "Fundamentals of Traffic Engineering", PATH, Institute of Transportation Studies, University of CA at Berkeley, UCB-ITS-Cn-92-1, January, 1992.

Summary: These notes are designed mainly for one-week short courses on the fundamentals of traffic engineering, with a California audience in mind.

Traffic Engineering is an ever-changing profession. new standards, guidelines, and basic tests rapidly replace older reference volumes. This 13th edition again includes new and revise material needed by students and practicing traffic engineers. This book includes transportation characteristics, human and vehicular characteristics, traffic stream characteristics, volume studies and characteristics, spot speed studies, travel time and delay studies, roadway and intersection capacity, accidents and safety, parking studies and characteristics, mass transit systems, transportation demand studies, transportation planning and travel demand management, traffic legislation, introduction to traffic control devices, traffic signs and markings, traffic signals, traffic signal control systems, geometric design of streets and highways, geometric design of intersections and interchanges, intersection control, pedestrian control, speed zoning and control, curb parking and control, major street operations, freeway operations, off-street parking and terminals, roadway lighting, environmental impact studies, air pollution, highway traffic noise, energy consumption in transportation, and traffic engineering administration.

Hongola, Bruce, Tsao, Jacob, and Hall, Randolph, "Users' Guide and Design Description Smartpath Simulator--Version MOU62", PATH , UCB-ITS-PWP-93-8, August, 1993.

Summary: This document contains the user instructions and software design description for Version MOU62 of the SmartPath Simulator. The version of the simulator including user instructions is described in [1].

The primary motivation for the concept of Automated highway Systems (AHS) is the desire to significantly increase the performance of future

highways without requiring a significant amount of extra right-of- the automation technology supporting AHSrmance categories of AHS operation include safety, throughput and human factors. echnological feasibility and driver/public acceptability, MOU62 concentrates on the performancerent AHS, where safety is represented as parametric input to the throughput model.

Hsu, Ann, et.al., "The Design of Platoon Maneuver Protocols for IVHS", PATH Research Report, UCB-ITS-PRR-91-6, April, 1991.

Summary: The control heirarchy for merge split and lane change maneuvers as defined in this paper consists of a link layer controller, a platoon layer, a regulation layer, and a physical layer. A communication architecture for a platoon merge maneuver is described.

The platoon layer of this heirarchy, which is the target of this paper, holds the state information, state = (car ID, highway name, lane number, section number, platoon ID, platoon number target size, target speed, car position in platoon, platoon size, platoon speed, flag indicating if car is already engaged in a maneuver).

The merge protocol design involves:

1. A flow diagram/algorithm of the necessary actions of the platoon and regulation layers of the heirarchy in implementing a merge of vehicle A & B.
2. Interpretting the actions as a synchronization of message exchange of two separate state machines.
3. Detailing protocol as interacting state machines in COSPAN,. a formal language.
4. Verifying if the protocol behaviors are acceptable.

Icking, Christian, Klein, Rolf, and Ma, Lihong, "The Optimal Way for Looking Around a Corner", IEEE-IEE VNIS , IEEE#0-7803-1235-x/93, 1993.

Summary: Autonomous vehicles should move in the most efficiet manner. This includes finding their way around or learning unfamiliar territory. The problem presented is as follows: Two walls form a wedge of angle less than 180 degrees, where the angle is not known. Standing by one wall, it is desired to find the shortest path which allows a line of sight to the other wall. This paper discusses a method of motion planning utilizing the concept of competitive algorithms. This strategy is claimed to guarantee the length of the path walked to see around the corner is bounded by the length of the shortest path to do so, times the constant c ~ 1.21218.

Ioannou, Petros A., et.al., "Autonomous Intelligent Cruise Control", IVHS America, May, 1992.

Summary: This paper develops an autonomous intelligent cruise control (AICC) system for automated vehicle following, examines it’s effect on traffic

flow and compares it's performance with that of the human driver model. No information is exchanged between vehicles in this AICC system and yet it is free of oscillations and slinky-effects.

A control law for AICC systems based on constant time headway safety distance, calculated using a reasonable worst stopping situation scenario, is proposed. Three human driver models are reviewed. These are the linear follow-the-leader model, linear optimal control model and the look ahead model.

A safety distance policy is discussed. A time headway of 0.2 seconds together with some constant spacing may be a potential candidate for safe automatic vehicle following.

A vehicle model and longitudinal control laws are proposed. The human driver and automatic vehicle following models were simulated. The traffic flow rate of the automatic vehicle following model is much higher than the three human drivers. Automatic vehicle following also leads to much higher traffic flow rates.

The comparisons presented in this report indicate a strong potential for AICC to smooth traffic flows and increase traffic flow rates considerably.

Jiyu, Liu, "Multipath and GPS Station Selection", GPS World, March, 1991.

Summary: This paper lists reflection coefficient and consumption (reflection loss) for water, rice fields, general ground and forest ground at 2, 3, 4 and 11 GHz and recommends use of an absorber fence; to avoid multipath; errors.

Juberts-Nist, M., and Reviv, D., "Vision Based Mobility Control for AVCS", IVHS America Annual Meeting,pp576-83, 1993.

Summary: The research described focuses on using machine vision for highway automation as a potential component of future AHS. Machine vision minimizes the impact of AVCS on infrastructure. This paper describes progress made at the National Institute of Standards and Technology in using the vision based approach for autonomous vehicles. This paper encompasses brief descriptions of highway tests of NIST's preliminary version of a vision based AVCS, algorithm development for vision based car following, control architecture, highway tests of road following, algorithm development for vision based car following.

Autonomous vehicle lateral control was demonstrated on a Maryland Highway at speeds up to 90 kmh for a combined distance of 25km. Vision based algorithms for autonomous car following were successfully tested in real-time using video recordings. Successful tracking of the lead vehicle was maintained on both straight and curved sections of the roadway.

The results indicate that a vision based approach to autonomous vehicle mobility control is a viable way of satisfying many of the technology needs of future AHS.

Juhala, Matti, and Karppinen, Antero, "Justina- An Autonomous Land Vehicle", VNIS, p164-165, 0-7803-0771-2, 1992.

Summary: This paper describes a normal production car modified for the development of autonomous operation. The steering system throttle and brakes are controlled by computer. An image processing system detects road markings. The vehicle has been equipped with differential GPS for navigation in future off-road applications. Testing has shown that an accuracy of +-3 meters can be achieved, with a differential GPS and dead reckoning system, while driving on a preprogrammed test course.

Kady, Mark A., and Ristenbatt, Marlin P., "An Evolutionary IVHS Communication Architecture", IEEE-IEE VNIS , pp271-76, IEEE#0-7803-1235-X/93, 1993.

Summary: A broad IVHS communication architecture is described which features near-term implementation and affordability for basic user-services (real time traffic reports, tolling, safety warnings) and includes higher level services such as navigation and route guidance. Four enabling communication techniques are exploited: 1. wide area broadcasting services including the near-term RDS (RBDS) FM subcarrier and future DAB (Digital Audio Broadcast) systems integrated into entertainment receivers; 2. short-range vehicle to roadside communication (VCR/electronic tolling); 3. new IVHS frequency allocations in the 220 MHz band; and 4. a full coverage MAYDAY system. These four techniques appear capable of flexicly delivering the entire range of IVHS user-services and offer options for traffic authorities to match their local conditions.

The digital RDS subcarrier is used to identify traffic announcements on both the main audio channel and possible subcarriers containing traffic reports to effect an affordable Traveler Advisory system. An open-road VRC approach using microwave frequencies provides a range of user-services (tolling, traveler services, in-vehicle signing). Safety warnings and local information channel are delivered via a digital 220 MHz communication system. MAYDAY, a specialized emergency messaging service, is handled by existing or developing services such as cellular telephone.

Kao, Wei-Wen, "Integration of GPS and Dead-Reckoning Navigation Systems", VNIS, Vol.2, p635-43, 32,0-7803-0489-6, 1991.

Summary: Dead reckoning systems and GPS are two commonly used techniques for vehicle navigation systems. While both methods suffer from different drawbacks, superior performance can be obtained by combining these two techniques. In this paper a vehicle positioning system that integrates both the GPS and the dead-reckoning system is presented. This system uses the GPS signals to adaptively calibrate the dead-reckoning sensors as well as to

"rescue" the system from unexpected position errors.

The dead-reckoning method, through the use of a map-matching algorithm, provides feedbacks for calibrating the GPS position errors. Experimental results using the ZEXEL NavMate Navigation and Route Guidance System demonstrate the effectiveness of the integrated positioning system.

Karaasian, Ufuk, et.al., "Two proposals to Improve Freeway Traffic Flow", PATH , UCB-ITS-PRR-90-6, April, 1990.

Summary: Two proposals are presented. The first organizes vehicles in platoons in which the lead car is manually driveand the rest are under automatic spacing control. A plausible model of the resulting traffic flow indicates that for an average platoon size of 20, the freeway capacity increases by a factor of four. The second proposal begins with a macrocopic model of freeway congestion and then presents a control law for reducing congestion. Simulation of the resulting closed loop model indicates dramatic reduction in congestion.

Kehtarnavaz, W. Sohn, "Steering Control of Autonomous Vehicles by Neural Networks", ACC, Vol.3, p3096, 91ch2939-7, 1991.

Summary: A vision based system is analyzed. Left and right lane boundaries (GM Lanelock), stereo images (A&M Bart=Binocular Autonomous Res. Team), turn radius R, steering wheel angle j:j=k1R^k2 k1(v), k2(v). Path planning is eliminated by training simulation.

Kemeny, A. and Piroird, J.M., "Advanced Telematics in Road Transport", DRIVE Conference, Brussels, February, 1991.

Summary: Cooperative Driving is one of the main application areas to improve road safety and traffic efficiency. The Simulator for Cooperative Automotive Network (SCAN) project, developed by Renault, Direction de la Recherche, France, is a network of graphics stations, each station representing a Cooperative Vehicle, functioning in real time. It's major constitutive units include a decision making engine, a communicaiton system, enabling communication with other vehicles as well as with the infrastructure, and a three-dimensional graphics computing and display unit with an appropriate man-machine interface, cockpit or mouse-keyboard.

SCAN enables the validation of inter-vehicle communication concepts as well as the driver assessment of the new product in a variety of traffic conditions. The reconfigurable simulation software also for applicability testing of various positioning or communication systems and ergonomics analysis, especially for head-up display design.

The objective of the DRIVE project V1048, DOMINC (Driving on Motorway IN Cooperation) is to study advanced Control Strategies and Methods

for Motorway RTI systems of the future. Large scale motorway traffic flow simulation is achieved by interfacing SCAN with SPEACS (Simulation Package for the Evaluation of Advanced Control Strategies), developed by Mizar and CSST in Italy. Among a large number of vehicles, generated in this case by the experimental model of SPEACS, some equipped vehicles are communicating with each other, driven interactively by SCAN.

King, P.J., et.al., "Autonomous Intelligent Cruise Control- A Review and Discussion", IEEE-IEE VNIS, p493, IEEE#0-7803-1235-X/93, 1993.

Summary: PAPER NOT AVAILABLE FOR PUBLICATION
This paper discusses work that is currently being undertaken between the Control Theory and Applications Center and Jaguar Cars Limited area of autonomous intelligent cruise control (AICC), with particular emphasis directed towards issues related to automatic control. Throttle and brake actuators are used to control the distance and relative velocities between a vehicle and the preceding vehicle.

Inthis paper the control issues are discussed and problems encountered in the investigation of AICC systems generally are highlighted. It is anticipated that, subject to clearance through the European PROMETHEUS steering committee, results from simulation studies involving a model of a typical large family automobile and it's associated braking, throttle and sensor system will be included in the final paper.

Klein, Lawrence A., et.al., "Detection Technology for IVHS", IVHS America, Wash, DC, April, 1993.

Summary: Detector technologies for IVHS applications, that are to be tested during a program sponsored by FHA, are identified.

Microwave radar detectors transmit energy at the speed of light in frequency bands near 10.5 to 24.0 GHz. They tend to be insensitive to weather and operate both in the day and night. Problems may be generated by some detectors which lock on to the strongest backscattered signal. FMCW signals may be used to measure both presence and speed for stationary or moving vehicles.

Ultrasonic detectors emit sound waves with frequencies between 20 and 200 kHz. Volume, speed, occupancy, presence and queue length can be measured. However, attenuation and distortion from environmental factors can be of concern.

Active infrared detectors, a laser radar that transmits electromagnetic energy in the near infrared spectrum, is subject to conditions which can scatter and attenuate energy (ie. fog, rain, snow, mist).

Passive IR detectors, which measure energy in their field of view, can be affected by fog and rain.

Video image processors analyze video imagery. They can be influenced by view angle, physical stability, image quality, and the number of lanes observed.

Inductive loop detectors can provide presence, count and occupancy, and, finally, magnetometer detectors are used where point or small area location of a vehicle is required.

Klingenberg, Dipl.-Ing. Wolfgang, "Location Referencing Systems for Dynamic Route Guidance Applications", IEEE-IEE VNIS, pp441-44, IEEE#0-7803-1235-X/93, 1993.

Summary: Dynamic route guidance applications can be distinguished into systems supported by RDS/TMC, short range (beacon)- or cellular radio systems (e.g. SOCRATES). The quality of all three classes depends on accurate information (in time an location) about the traffic situation. This information is exchanged between the mobile part (e.g. the cars) and traffic centers. The time relation can be covered by independent real-time clocks in both parts of the system. But for the location relation a referencing system is needed.

Today an agreed location referencing system- as a part of ALERT/C protocol for traffic messages- exists in Europe for RDS/TMC applications. The possible locations, that can be referenced by this coding is limited to main roads, regions, areas... Cellular radio- and short range systems need to reference all road elemnts in a street network. This paper presents the "Standard Location Reference Number SLRN", a solution for a common location referencing system. It will be implemented in the SOCRATES (Cellular Radio) pilots for the first time. The SLRN can support all three classes of applications. SOCRATES has brought the SLRN proposal into the European standardization committee CEN TC278. It is the subject of standardization together with ALERT/C, of which an European Prestandard (EN V) is expected for the end of 1993.

Klobuchar, J.A., "Ionospheric Effects on GPS", GPS World, April, 1991.

Summary: This paper explains the method by which normal and pathological (e.g. aurora) conditions of the ionosphere; interfere with the propagation of GPS signals and what can be done about it.

Koliadin, Vladimir L., "Satellite Radio Navigation and Dead Reckoning Systems Combining for Vehicle Location", IEEE IEE VNIS, p471, IEEE#0-7803-1235-X/93, 1993.

Summary: PAPER NOT AVAILABLE FOR PUBLICATION

The problem, addressed in the paper, is how to reduce the cost increase reliability and meet the precision requirements to vehicle location systems operating as part of an on-board navigation system. An approach to the problem is to combine GPS navigation receiver with traditional dead-reckoning systems, and to use processing to calculate the current position. Some problems connected with such an approach, concerning optimal hardware and software organization, and relevant data processing strategy are discussed.

Komoda, Norio, et.al., "Cooperative Vehicle/Highway Systems for Automated Vehicle", IVHS America,pp113-23, May, 1992.

Summary: Toyota has been developing a prototype AVHS in order to accomplish fundamental technologies and system architectures.

Vehicle systems have on-board high speed vision systems consisting of a small size television camera and an image processing computer. This system is used to detect both white lane markers and vehicles ahead. A laser beam radar system to detect distance and obstacles is complemented by an infrastructure based obstacle detecting system which uses ITV cameras. Electrically controlled steering, brake, and throttle are used for lateral/longitudinal control. A vehicle-road telecommunication system and traffic control center are used for information exchange.

Testing showed lane sensing to be satisfactory except during severe conditions such as sunset or sunrise.

The prototype vehicle lateral control system has succeeded in tests running along the lane at 50 km/hr. Lateral deviation of the automated vehicle showed better stability than that of a manual operated vehicle.

The on-board scanning laser radar experience several problems. One such example is misdetection in rainy weather.

The roadside vision system would be one of the most effective ways to detect obstacles on the road and can probably perform as a reliable back-up system for the on-board obstacle detector.

Kornhauser, Alain L., "Neural Network Approaches for Lateral Control of Autonomous Highway Vehicles", VNIS, Report No. 912871, October 1991.

Summary: In an effort to analyze various designs of artificial neural networks, intended to facilitate automated steering aspects of intelligent highway vehicles, a computer graphical simulation system has been constructed. The system, called the Road Machine, is used as the experimental environment for analyzing, through simulation, alternative neural network approaches for controlling autonomous highway vehicles.

The Road Machine is composed of five major modules: road design; vehicle dynamics; image processing; neural network design and training; autonomous driving simulation. Each module is described in detail. Two types of neural network control structures are under investigation. These are back-propagation and adaptive resonance.

Kossack, Juergen Dr., and McQueen, Bob, "European Progress Towards Standardization in

ATT Communications", IEEE-IEE VNIS, pp307-11, IEEE#0-7803-1235-X/93, 1993.

Summary: This paper describes the organizational context and the approach being adopted towards the achievement of pan-European standardization for ATT Communications.

The paper provides a brief overview of ATT applications that require the use of short range communication links, stressing the importance of defining a pan-European standard that will enable inter-operability of equipment and encourage Europe-wide implementations. The work being carried out by CEN Technical Committee TC/278 Working Group 9, on the definition of standards requirements for the Dedicated Short Range Communication Link, is also described, along with a commentary on the signifigance of this work, in relation to ATT applicaitons.

Kotaki, Minoru, et.al., "Development of Millimeter Wave Automotive Sensing Technology in Japan", IEEE MTT-S International Microwave Symposium, Vol.2, p709-12, 0-7803-0612-0, 1992.

Summary: The Ministry of Posts and Telecommunications in Japan organized a committe to study millimeter wave sensing technologies in 1984. Sensors for automotive vehicles have been mostly studied as appropriate applications of millimeter waves. This paper presents the outline of three types of radars e.g. FM-CW, 2D-imaging, and pulse Doppler, and also data measured through the laboratory and road tests. Among those, the FM-CW system shows good performance on freeway test and under adverse environmental conditions.

Krakiwsky, E.J., "Tracking the Worldwide Development of IVHS Navigation Systems", GPS World, p40, October, 1993.

Summary: List of all IVHS navigation systems.

Krakiwsky, Edward J., "The Diversity Among IVHS Navigation Systems Worldwide", IEEE-IEE Vehicle Navigation & Information Systems Conference, Ottawa, 0-7803-1235-X/93, 1993.

Summary: Reported in the paper is the fact that there are over 100 IVHS navigation systems being built worldwide. Japan and the United States are the leaders in developing systems, with the second grouping of countries being Germany, United Kingdom and Canada. Europe as a block, however, is a productive as the two leading countries. Various positioning technologies suich as GPS, RDSS, dead reckoning, signposts, map matching, and teresstrial RF systems are used more in some countries than in others and these trends

are reported herein. Also, countries taken in regional blocks use certain positioning technologies more prominently than those used in the other blocks. Examples of novel systems in the four basic categories (autonomous, fleet management, advisory, and inventory) are given to illustrate the trend towards specific market penetration and thus the diversity amongst systems. The paper closes with a brief description of future trends.

Krakiwsky, Edward J., "The Diversity Among IVHS Navigation Systems Worldwide", IEEE-IEE VNIS, pp433-36, IEEE#0-7803-1235-X/93, 1993.

Summary: Reported in this paper is the fact that there are over 100 IVHS navigation systems being built worldwide. Japan and the United Stateshe leaders in developing systems, with the second grouping of countries being Germany, United Kingdom and Canada. Europe as a block, however, is as productive as the two leading countries. Various positioning technologies such as GPS, RDSS, dead reckoning, signposts, map matching, and terrestrial RF systems are used more in some countries than in others and these trends are reported herein. Also, countries taken in region blocks use certain positioning technologies more prominently than those used in the other blocks. Examples of novel systems in the four basic categories (autonomous, fleet management, advisory, and inventory) are given to illustrate the trend towards specific market penetration and thus the diversity amongst systems. This paper closes with a brief description of future trends.

Kremer, Werner, "Data Transmission Characteristics in Short Range Inter-Vehicle Communication System (IVCS)", IEEE 42nd Vehicular Technology, Vol.1, p298-302, 0-7803-0674-0, 1992.

Summary: This paper deals with the data transmission characteristics in the short range inter-vehicle communication system (IVCS) as presented on the last VTC'91 {1},{2}. The quality of the microwave communication channel is characterized by the fact that both, sender and receiver are in motion. The communication link will be modelled theorectically by the prediction of expected signal-to-noise ratio SNR which is determined by two factors, the sender-receiver distance and the fading phenomenon. The characteristics of that channel will be examined and selected FEC-coding techniques will be applied, including BCH-, Burst, Reed-Solomon-and Convolutional Codes each with different coderates. It will be shown that FEC codes gain improvements of the channel, without significant differences between various coderates. The Viterbi-algorithm for Convolutional codes shows the best improvement of the transmission capability, even with low coding overhead.

Kremer, Werner, et.al., "Computer-Aided Design and Evaluation of Mobile Radio Local Area Networks in RTI/IVHS Environments", IEEE Journal on Selected areas in

Communications, Vol 11, No.3, pp406-21, IEEE#0733-8716/93, April, 1993.

Summary: Definition of new applications for RTI/IVHS (road transport informatics/intelligent vehicle highway systems) has lead to a new characteristics of short-range mobile radio networks, referred to as mobile radio LAN's. The simulation environment MONET3 is introduced, which allows evaluation of protocols to operate in networks with hundreds of stations. In this paper, we provide a discourse on RTI/IVHS communication system design. We motivate the process-oriented simulation approach and the measurement-based (and slightly simplified) channel model. The necessity of interconnecting a dedicated movement simulator originally designed for the purpose of traffic engineering in RTI systems, to the simulation environment is shown Furthermore, simulaiton results highlighting the defined performance evaluation measures for multipoint communication are presented

Lachapelle, G., et.al., "GPS versus Loran-C for Vehicular Navigation in Urban and Mountainous Areas", IEEE-IEE VNIS, pp456-59, IEEE#0-7803-1235-x/93, , 1993.

Summary: This paper compares and assesses GPS, Loran-C and an integrated GPS/Loran-C with respect to vehicular navigation. Results of testing in an urban area of Calgary during two periods in June'93, between 0000 and 0130 and between 0630 and 0830, found GPS to yield better signal availability than Loran-C. Although integrated use of GPS/Loran-C improved availability only a few percent, the use of the integrated system improved availability to 95% in mountainous regions as compared with 65% for GPS and 75% for multichain Loran-C.

Langley, R. B. , "The Orbits of GPS Satellites", April, 1991.

Summary: This paper that gives a brief review of orbital mechanics and describes the elements of the GPS ephemeris.

Langley, R.B., "The GPS Receiver: An Introduction", GPS World, January, 1991.

Summary: A paper that provides an overview of GPS receiver;s at a very understandable level but in a necessarily brief format. Reference is made to a paper ("Why Is The GPS Signal So Complex") in the My/Je 90 issue of GPS World.

LaPorte, Todd and Metlay, Daniel, "Technology Observed: Attitudes of a Wary Public", Science, Vol. 188, p121-27, April, 1975.

Summary: Evidence suggests that the public is wary as to the impact of technology. New technology is no longer perceived as automatically beneficial. This current assessment of the public reaction to technology is somewhat of a generalization. in actuality, a more mixed picture emerges. An isolated "potential public" associates a number of related conditions to technological development. Their anti-technological feelings are linked to the fact that the social consequences of technology can produce conditions which threaten important values.

Lee, Richard W., "Case Studies of Public-Private Partnerships in the Provision of Urban Transportation", PATH Graduate Report, UCB-ITS-GR-86-1, June 1986.

Summary: This report consists of four case studies performed in conjunction with an investigation of the effects of local government requirements and incentives for private sector provisions of transportation facilities, transportation services, and traffic reduction programs. The four case study areas- Seattle-Bellevue, Minneapolis- St. Paul, Los Angeles, and the San Francisco Bay Area- were selected because they have adopted innovative local ordinances and programs encouraging or mandating private entities (generally major employers and developers) to play more than a passive role in the provision of local passenger transportation.

Leiman, Lannon, Ostrom, Barbara K., and May, Adolf D., "FREWEV- A Design and Analysis Model for Major Freeway Weaving Sections: User's Guide", PATH Working Paper, UCB-ITS-WP-91-3, June, 1991.

Summary: FREWEV is an interactive menu driven computer program for designing and analyzing major freeway weaving sections. FREWEV enables the user to design a freeway section by entering input on graphic screens and then to analyze the freeway section using the techniques described in the Research Report "A Proposed Analytical Tecynique for the Design and Analysis of Major Freeway Weaving Sections".

This USER'S Guide has been written for Version 1.0 of the FREWEV model which currently is capable of analyzing four types of major freeway weaving sections each with either five or six lanes in the weaving section. Additional applications will be added to this guide as they are incorporated into the model.

FREWEV is written for the IBM PC and requires a math coprocessor. printouts of the freeway geometry require a printer with the IBM character set.

Leiman, Lannon, et.al., "FREWEV: A Design and Analysis Model for Major Freeway Weaving Sections: User's Guide", PATH Research Report, UCB-ITS-RR-92-5, March, 1992.

Summary: Major weaving sections are a major source of congestion on freeways. The conflicts between vehicles making lane changes can creat significant problems both at and upstream of the weaving location.

This report implements a method to calculate and analyze point flows at various locations within a weaving section. The method also estimates the amount of lane changing as a measure of the likelihood of successfully negotiating a weaving section.

Included in the report is information on the operation of the program and the data embedded in the program.

The data is based on empirical data from nine California freeway sites with origin-destination flows and ramp spacings extrapolates using the microscopic freeway simulation model, INTRAS.

Lowbridge, P.L., Brigginshaw, P.M., and Kumar, B., "Millimeter Wave Technology for Collision Avoidance and Cruise Control", GEC Plessey Semiconductors, UK, GEC Marconi Ltd., Hirst Research Center, UK..

Summary: The advantages to be gained by using the millimeter wave portion of the frequency spectrum (30 to 100 GHz) are very well documented. However, as the frequency increases, so, generally speaking, does the cost. Recent large investments, mainly under defense contracts, into equipments operating in the range of 30 to 100 GHz have now proven the significant advantages from a systems' perspective and have also given the components and subsystems suppliers initiative to investigate possible ways of cost reduction for such systems.

One specific area of significant interest over the past years has been in the use of millimeter wave radar (mainly 94 GHz) in short range anti-armour weapon systems. The function of the radar is to measure very accurately the distance to the target, and the closing velocity. Such radar subsystems are produced at GEC Plessey Semiconductors (GPS) in Lincoln, England.

With the degree of electronics present within automobiles (cars, lorries, etc.) increasing, and with the development of cruise control, and subsequently, collision avoidance systems, it is natural to apply the millimeter wave radar technology to this application. This paper describes the way that the technology developed for further enhanced and used in a vehicle mounted application allowing a cruise control system to be implemented. Such systems will be developed over the next few years to enable full collision avoidance.

Lowbridge, Paul, et.al., "A Low Cost mm-Wave Cruise Control System for Automotive Applications", Microwave Journal, October, 1993.

Summary: This paper discusses a mm-wave system for cruise control on automobiles. Concentration is placed on the device sensor that determines the distance from the active cruise control equipped vehicle to the vehicle in front together with the rate of change of that distance. The selected sensor

operates at 77GHz, on the principle of frequency modulated continuous wave (FMCW) radar, using proven technology.

An FMCW radar, based on a Gunn oscillator, transmits a frequency modulated signal and compares the signal returning from the target to the frequency of the oscillator. Both distance and relative velocity may be derived. In order to extract accurate information, a linear sweep is critical. The linearity of the oscillator relies on the linearity of a frequency discriminator, which is a digital device operating at 10MHz.

A single crystal quartz microstrip is employed as the transmission media. Descriptions of construction, including a 77GHz VCO, a linearizer circuit, an FMCW circuit, and quasi-optical antennas, are included in this article.

A full FMCW radar system with a fixed beam antenna fitted to a production vehicle has undergone field trials. The vehicle successfully used the ACC in closed loop mode.

Mallinson, P. and Stove, A.G., "Car Obstacle Avoidance Radar at 94GHz", Philips Research Laboratories, Redhill, Surrey, IMechE#C391/081, 1989.

Summary: This paper will describe work carried out by Philips (primarily at the Research Laboratories in Redhill) on Car Obstacle Avoidance Radar. I shall be describing a realisable radar system using millimeter wave FMCW techniques at 94 GHz. Millimetric radar is still relatively novel at 94 GHz, but progress is fast an mass production is now possible (e.g. using plastic microwave assemblies with a high degree of cost effective microwave integration techniques). The system which will be described in detail, consists of a 94 GHz Front End (the scanning antenns, microwave feed, RF circuitry and IF downconversion), a powerful data processor/funnel and a variety of display options.

The advantages of the millimeter wave solution will be explored in detail and will include such discussion points as:

-The dimensions of a system are inherently small due to the short wavelengths involved.

-Accurate and narrow beam patterns are easy to form with a suitable antenna.

-Beams are easy to steer using pseudo optical techniques.

-Complexity per unit volume is favourable due to progress in the millmeter wave components.

-The front end can now be moulded in metallised plastics (including the scanning antenna) and assembled using mass production techniques.

The results of a number live field trials will be presented, as will our ideas on the forms that a practical, car obstacle avoidance radar might take.

Manigel, J., and Leonhard, W., "Computer Control of an Autonomous Road Vehicle by Computer Vision", IEEE IECON’91, Vol.1, p19-24, 0-87942-689-6, 1991.

Summary: A method is described for guiding an autonomous vehicle along roadways based on visual signals. The vehicle is to follow a white

guideline on a flat road sensed by a CCD-camera. The camera, mounted behind the windscreen of the vehicle, looks forward and down, detecting an area between 5 and 25 m ahead. An image processor (based on Transputers T800) scans the image for the border-line of the road. The line coordinates detected by the image-processor are transmitted via Transputer-Links to a Transputer-Network. The implemented algorithm uses geometric coordinate-transformation and a dynamical model (Kalman-Filter) to identify the road-curvature ahead and the relative position of the vehicle on the road. The reference angle for the electrical steering servo is computed from the lateral deviation, the yaw-angle deviation, the road-curvature and velocity of the vehicle. All together it takes about 60ms per image for recognition and control. So far the method has been tested by simulation and with a VW-Bus Caravelle on typical Autobahn-scenes at a velocity of up to 120 km/h. Much more work is necessary to arrive at a practical solution.

Mannings, R.T., "Communications In Drive"..

Summary: The European DRIVE program has stimulated the development of many diverse ways to use Road Transport Telematics to improve the safety and efficiency of the European road system. Pilot systems are being established in most Europea countries and each pilot is tending to take a different approach in tackling the problems. In some pilots the focus is on services to private motorists, some to fleet and freight and some to public transport. The mobile communications selected for each site also vary enormously, depending upon the particular interests of the specific participants in each of the pilotojects and in national policies and cultural differences.

The requirements for mobile communications systems are considered before describing the systems. The current status of European standardization in these areas is reviewed. Finally, the convergence of communications systems is discussed.

Matsumoto, N., and Tomizuka, M., "Vehicle Lateral Velocity and Yaw Rate Control with Two Independent Control Inputs", Transaction of the ASME, Vol.114, December, 1992.

Summary: Ideally, in automatic lateral control, the lateral motion and yaw motion of the vehicle should be controlled independently. This requires at least one additional control input independent of front steering angle. This paper explores three extra types of control inputs:

1. A differential driving torque between the two front wheels;
2. That between the two rear wheels;
3. The rear steering angle. A model of the lateral and yaw motions of a vehicle is discussed. Lateral and yaw motions are then expressed in the state space form.

The steady state responses of lateral velocity and yaw rate to the three additional control inputs were compared to one another. Analysis shows that the front and rear independent steering allow a wider variation of lateral velocity and yaw rate in the steady state.

A lateral velocity and yaw rate control law with front and rear independent steering is presented. The cornering stiffness, which reflects road conditions, was estimated by the recursive least squares method. The dynamics change due to velocity and cornering stiffness variation, was accomodated by continuously changing feedback and feedforward gains dependent on varying parameters.

Based on simulation study on the nonlinear vehicle model and experimental study on a laboratory vehicle, overall performance was found to be satisfactory.

May, Adolf D., "Freeway Corridor Analysis", PATH Research Report, RR 81-5, ISSN#0192 4095, August, 1981.

Summary: This paper has two major themes. The first theme is to describe existing traffic simulation models and their applications in freeway corridor analysis. The second theme is to demonstrate the need for integration of research, education, and implementation activities as a key for the enhancement of simulation modelling practive. The overall objective of this paper is to provide a state-of-the-art document on freeway corridor models and to encourage researchers and practitioners to work closer together in simulation modelling.

Five families of freeway corridor models are currently available and include CORQ, FREQ, INTRAS, MACK, and SCOT models. An overview of the historical development and application experiences with these five model families is presented in Chapter 2.

The institute of Transportation Studies is currently embarked on a program attempting to integrate research, education, and implementation activities with the aim of enhancing the simulation modelling process with emphasis on model application. Experiences in translating research into practive through education and implementation efforts are presented in Chapter 3.

The peper concludes with an extensive bibliography which is an attempt to include all published papers which describe the development and application of avialable freeway corridor models.

May, Adolf, and Haldors, Bruce, "Second Annual Symposium on Advanced Traffic Management Systems (ATMS) and Advanced Traveler Information Systems (ATIS)", PATH , UCB-ITS-PRR-91-1, November, 1990.

Summary: The purpose of the Symposium on Advanced Traffic Management (ATM) and Advanced Traveller Information Systems (ATIS) was to allow researchers involved in ATM/ATIS work to become familiar with other research in the ATM/ATIS areas in the state of California. The symposium was a one-day event held on November 5, 1990, in the Bechtel building on the campus of the University of California at Berkeley. This document provides a brief summary outlining the presentations made at the symposium. Included in the appendix is a list of the names and addresses of the presenters.

McDonald, Keith, "Econosats: Toward an Affordable GPS", GPS World , p44, Spring, 1993.

Summary: Author is president of Satellite Technology Systems, Arlington, VA, former scientific director of Defense Navigation Satellite System (DNSS;, original name of GPS) and until 1990 was in charge of Federal Aviation Administration; Satellite Applications and Technology.

McHale, Gene, "Headway and Lateral Control System/Results of Transmission Experiment Using Leakage Coaxial Cable (LCXs) in the kQuasi-Microwave Bandwidth", Mitre, November, 1993.

Summary: This report investigates the use of Leakage Coaxial Cable (LXCs) in the quasi-microwave band for vehicle/roadside communication. LCXs were installed along a test course in an effort to measure electrical field strength and bit error rate. Transmitter output was fed into the cable to emit electric waves. Vehicle receiving equipment measured the data. Frequency, LCX installation height, power feed method, and supplied power were varied.

The results obtained indicate:

1. Less variations compared to field strength distribution in a tunnel close to the calculated value.
2. Receiving field is quite stable, preventing the occurrence of errors at low receiving level.
3. Offers the possibility of use in high-speed data communications that is 512kbps or more.
4. LCX installation height does not much affect the cable characteristics. The relationship to the location of the vehicle antenna is important.
5. Changes in communication quality that result from variations in speed require no consideration.
6. Transmitter output is acceptable at a relatively lower level.

The following considerations need to be evaluated:

1. Shielding and reflection effects caused by large vehicles running alongside each other.
2. LCX installation method
3. Interference problems adjacent lanes go opposite directions.

McMahon, D.H., Hedrick, J.K., and Shladover, S.E., "Vehicle Modelling and Control for Automated Highway Systems", ACC, Vol.1, pp297-303, IEEE Cat.#9ch2896-9, 1990.

Summary: Longitdinal control of a platoon of vehicles is analyzed in this paper. A nine state non-linear model is developed and a sliding control technique is applied.

The powertrain model developed in this paper, includes four state variables for the engine, two for the transmission, and three for the drivetrain. The engine has three controls (throttle angle, air to fuel ratio, and SA) and two time delays (the intake-to-torque and spark-to-torque production delays). Th e transmission and drivetrain have no controls and one control (pedal deflection), respectively.

Longitudinal control involves tracking the vehicle in front and maintaining a constant headway. A two sliding surfaces approach to control is developed. The primary surface is defined to be used as a “synthetic control”. From this, the desired trafectory of the second sliding surface is defined, which upon differentiation leads to the control variable. Throttle angle is investigated as a control.

Simulation involved two vehicles with an initial velocity of 54.6 mph and headway of 1m. At t=2 seconds, lead car acceleration of 0.5 m/s maximum was initiated and then constant speed was resumed. The maximum position error was 4.5 cm.. Steady state error was -0.8cm..

The vehicle model was than subjected to: 1. 30% modelling error in drag coefficient; 2. 10 mph constant frictional wind gust; 3.2.5% modelling error in engine friction. The results varied very little from the results of ideal condition simulation.

McMahon, D.H., Narendran, V.K., Swaroop, D., and Hedrick, J.K., "Longitudinal Vehicle Controller for IVHS: Theory and Experiment", ACC, Vol.2, p1753, 92ch3072-6, 1992.

Summary: After developing a pc-based controller for throttle and brake control, a highly communicative, VORAD, two car platooning system was tested on an HOV lane of I-15.

Mechlih, Hachemi, "Sliding Mode Path Control for an Autonomous Vehicle", IEEE-IEE VNIS, pp543-46, IEEE#0_7803-1235-X/93, 1993.

Summary: A new path control algorithm for path tracking of autonomous vehicles (AV) is proposed, using both theoretical arguements and simulation experiments. The AV considered here is a tricycle configuration with front driving and steering wheel, and two passive load-bearing rear wheels. A variable structure path control (VSPC) is used to maintain the AV’s state trajectory on the desired path. The reference trajectory represents the sliding or switching surface. The front steering angle and the drive velocity are controlled using a modified model reference adaptive control. The dynamic model of the AV and the unexpected disturbances are assumed to be completely unknown. Simulation results are presented to illustrate the usefulness of this algorithm.

The aim of this paper has been to drive an autonomous vehicle along a desired trajectory in a fixed arrival time. The idea of changing the structure on the desired trajectory have been successfully applied to control the steering wheel of the vehicle to accurately follow the desired trajectory. The drive speed was calculated accordingly to the fixed goal reaching time. The modified model reference adaptive control has shown to be capable to ensure a satisfactory performance and stability when the dynamic of the autonomous vehicle and the unexpected disturbances are assumed to be completely unknown.

Mecklenburg, K., et.al., "Neural Control of Autonomous Vehicles", 42nd VTS Conference. Vol.1,pp303-06, 0-7803-0674-0, 1992.

Summary: Lateral control of an autonomous road vehicle by a neural network is presented. The inputs into the controller such as relative vehicle position and yaw angle are delivered by dynamical video scene processsing. Nonlinear conflicting requirements of safety and comfort have to be satisfied by the controller. The controller has been trained by our model-based training algorithm. In contrast to other neural network learning algorithms, it uses an explicit plant model to ensure fast and precise convergence. it does not require large training data sets- one or two representative initial states are mostly sufficient. Simulations as well as practical tests with speeds up to 80 km/h on public highways have confirmed the expectations.

Meinel, Holger H., "Applications of Microwaves and Millimeterwaves for Vehicle Communications and Control in Europe", IEEE MTTS-S Digest, CH3141-9/92/0000, 1992.

Summary: Traffic is becoming a serious problem throughout the world, as it is a major problem in Europe. The ever increasing demand of road transportation has created negative effects related to traffic safety, efficiency and economy; for the future the protection of the environment is an additional challenge. Today it is widely accepted, that the solution to traffic congestion and incresing pollution lies in the application of advanced technologies to control and direct the flow of vehicles. Pan European projects like PROMETHEUS or DRIVE are supporting such solutions. Four major areas of applications have to be distinguished: Automatic Debiting Systems (ADS), Road Traffic Informatics (RTI), Microwave Doppler Sensors (MDS) and collision avoidance radar. Millimeter-wave systems have found an increasing interest, due to their specific advantages, as well as the lack of frequencies for new services.

Miller, R. K. and Rupnow, M.E., "Global Positioning System,Survey of Technology and Markets", Future Tech Surveys, 1991.

Summary: This book was requested by T. Leney following a Calspan library search.

Misra, P.N., et.al., "GLONASS and others", GPS World, August 1993 (table), and May, p28.

Summary: Ag 93,Table of IVHS applications of GPS;. GLONASS; My 93 p 28

Nakamura, Mitsutaka, et.al., "Experimental Studies of Vehicle Lateral Control By Detection of Reflective Marker", IVHS America Annual Meeting,pp592-96, 1993.

Summary: The objective of this study is to develop, with as little impact as possible on the current highway system, a method of lateral control for vehicles. The proposed method offers a cost-conscious lateral control method with little change in infrastructure by utilizing retro-reflective lane detector markers which are currently available on many highways.

Laser radar assures detection of at least one reflective marker by potentially illuminating three. The laser radar acts as a data acquisition center for the reflected light.

A combination of a photo diode and an avalanche diode is implemented to calculate target distance. A 128 element linear charge coupled device (CCD) also detects returning light and determines the angle between the lane marker and vehicle direction. This information is sent by the controller area network (CAN) to a digital signal processor (DSP). The DSP in turn feeds and algorithm to determine steering angle. The CAN sends the steering angle information to the lateral control driver which initiates the steering mechanics to engage.

The vehicle was tested along an asphalt track in ideal weather and lighting conditions. Although the vehicle successfully negotiated the track, excessive tracking error along curved areas may indicate refinement of steering control angle.

The ideal environment in which the vehicle was tested raises an important question as to test results in non-ideal conditions.

Necsulescu, D.S., Kim, B., and Green, D.N., "Fusion of Inertial and Kinematic Navigation Systems for Autonomous Vehicles", IEEE-IEE VNIS ‘93, pp462-65, EEE#0-7803-1235-x/93, 1993.

Summary: A combination of odometry and intertial navigation for vehicle navigation is discussed. The benefits of an INS, including a superior position estimate, are complimented by the physical robustness and reliability of the encoders, low weight, power consumption and cost, and a zero time-dependent drift of odometry. Particularly, INS is subject to considerable sensor noise at slow speeds where odometry becomes more accurate. Erroneous sensor data, which is treated as noise, does not degrade the performance of the optimal estimator. Integration of an INS and odometry is beneficial during slippage and non-slippage conditions.

New York State LThruway Authority, "Highway Electrification and Automation Development Program", NYS Thruway Authority, NYS DOT, NYSEnergy Research & Development Authority, September, 1993.

Summary: On Order by John Pierowicz

Newell, G.F., "A Moving Bottleneck", PATH Research Report, UCB-ITS-RR-93-3, March, 1993.

Summary: The theory of Lighthill and Whitham is used to describe the flow past a slow moving vehicle or convoy which blocks one lane of a two-lunidirectional roadway. The conclusions from the theory are not very realistic for light traffic. To avoid obviouistic predictions, it is necessary to assume that the free speed on the single unblocked lane is higher than the average free speed for two lanes. Foe or high density traffic, the theory may give satisfactory predictions of queueing behind slow vehicles.

Newell, Gordon F., "A Simplified Theory of Kinematic Waves", PATH Research Report, UCB-ITS-RR-91-12, September, 1991.

Summary: In the theory of "kinematic waves", as described originally by Lighthill and Whitham in 1955, the evaluation of the shock path is typically rather tedious. If, instead of using this theory to evaluate flows or densities, one use it to evaluate the cumulative flow A(x,t) past any point x by time t, a formal solution for A(x,t) can be evaluated directly from bounmdary or initial conditions. If there are shocks, however, this "solution" will be multiple-valued. The "correct" solution, which is the lower envelope of all such formal solutions, will automatically have discontinuities in slope describing the shock path. To evaluate A(x,t) at any particular location x, it is not necessary to follow the actual path of the shock; the solution is obtained directly in terms of the boundary data.

Niehaus, Axel, and Stengel, Robert, "Probability Based Decision Making for Automated Highway Driving", VNIS , 0-7803-0489-6, October, 1991.

Summary: Intelligent guidance for headway and lane control (IGHLC) is a rule based expert system that performs the guidance function for an autonomous vehicle on limited access highways. The task is to analyze system inputs and determine an appropriate trajectory for the vehicle, resulting in lateral and longitudinal commands. Many sources of guidance information have been proposed (Radar, magnetometers, computer vision.). Each source provides

varying degrees of precision, but none is error free. This paper presents a probabilistic framework for handling uncertain information explicitly. This method, called worst case decision making, selects the worst plausible evolution as a basis for allocation resources.

WCDM has been applied to an IGHLC expert system for automated highway driving. Simulations show that uncertaintly can be a major issue when determining an appropriate guidance command. WCDM proves to be an effective tool to correctly analyze the traffic situation and avoid danger.

Northfield, Howard, and Sheikh, A.U.H., "An Autonomous Vehicle with Fuzzy Logic Navigational Control", IEEE-IEE VNIS, pp486-89, IEEE#0-7803-1235-X/93, 1993.

Summary: This paper, describes the design and construction of an autonomous vehicle with fuzzy logic navigational control. The design incorporates a 16 bit, on board Motorola's MC68HC16Z1 microcontroller to coordinate the vehicle operations. Fuzzy logic is used in conjuction with the controlling software for steering and guidance. The optical guidance follows a UV sensitive track on which position information is encoded. Steering is performed through timing pulses from the microcontroller to a stepper motor connected to a home designed steering mechanism. The vehicle may be ordered to a chosen location by a remote hand-held transmitter using frequency shift keyed data transmission on a radio link. The remote unit incorporates logic cell array (LCA) supporting circuitry. Track obstruction is detected by a front end infrared detection unit and a touch sensitive bumper.

Parsons, Robert E., "Lateral Guidance Systems Requirements Definition", PATH Research Report, UCB-ITS-PRR-88-1, October, 1988.

Summary: This paper presents a summary of the review of non-mechanical based systems for lateral sensing and control, which can further be classified as having either a continuous or discrete reference sub-system that can be active or passive in nature. The options presented have been grouped as either a reference following sensor system, or a passive reference/side-looking sensor system.

Patwardhan, S., et.al., "Robust Failure Detection in Lateral Control for IVHS", ACC, Vol.2, p1768-72, 0-7803-0211-7, 1992.

Summary: This paper deals with instrument fault detection in automatically navigated cars. Analytical redundancy methods are pursued in this application. The basic idea is to build three observers, each of which uses two out of three measurements. If the observers are insensitive to model uncertainties, and if one of the sensors fails, then error output of only one observer will be zero. By knowing which error output is zero and which is not, one can identify the faulty sensor. An observer scheme with eigenstructure assignment was used as the basic fault and identification method. Simulations were performed on a sixteen state nonlinear model and experiments were done using a model car. The feasibility of the algorithms were verified on the experimental car.

Peng, Huei, and Tomizuka, Masayoshi, "Lateral Control of Front Wheel Steering Rubber Tire Vehicles", PATH, UCB-ITS-PRR-90-5..

Summary: Paper on order.

Peng, Huei, and Tomizuka, Masayoshi, "Optimal Preview Control for Vehicle Lateral Guidance", PATH, UCB-ITS-PRR-93-4, August, 1991.

Summary: The continuous time deterministic optimal preview control algorithm is applied to lateral guidance of a vehicle for an automated highway. When a human driver steers a vehicle, his ability to look ahead (preview) the upcoming road, is crucial to control the vehiclo that it remains in the center of the lane, especially at sharp cornersand winding sections. In this report, an optimal preview control algorithm is introduced which utilizes the preview information pertaining to road curvature as well as superelevation angle for vehicle lateral control purposes. The optimal control law consists of both feedback control action and feedfoward preview control action. The feedforward previed control action significantly improves the tracking performance while maintaining a small closed loop bandwidth so that the ride quality is not impaired. Frequency-domain analyses and numerical simulation results show the improvements obtained in both the frequency domain and the time domain.

Peng, Huei, and Tomizuka, Masayoshi, "Preview Control for Vehicle Lateral Guidance in Highway Automation", 1991.ACC, Boston, Mass, pp3090-95, 0-87942-566-0,FP12 15:00, 1991.

Summary: Continuous deterministic preview control is applied to the vehicle lateral control problem. It is shown that the preview control consists of a feedback term and two feedforward terms. If the preview control algorithm is applied on the FSLQ augumented system, the feedback term will be exactly the same as the FSLQ feedback control law. Therefore, the advantages of the FSLQ control law remain in the preview control law. Frequency-domain analysis and numerical simulation results are presented to show the improvements introduced by utilizing preview control in both the time domain and the frequency domain.

Peng, Huei, and Tomizuka, Masayoshi, "Vehicle Lateral Control for Highway Automation", ACC, vol.1, p788, 90ch2896-9, 1990.

Summary: The objectives of lateral control for highway automation are to let vehicles track the center of a lane with small error and to maintain good ride quality under different vehicle speeds, loads, wind gust disturbances and road conditions. In this paper, the lateral feedback and feedforward controllers are designed to satisfy these objectives by utilizing the frequency-shaped linear quadratic (FSLQ) control theory. This design method allows that the ride quality be included in the performance index explicitly, and the high-frequency robustness characteristic be improved by properly choosing the weighting factors. It is shown that a controller with fixed gains does not perform satisfactorily under all conditions. Therefore, an estimator for cornering stiffness of the tires is proposed to enhance performance. Simulation results show that this adaptive control approach works satisfactorily under a variety of conditions including intermittent measurement of lateral tracking error.

Peng, Huei, et.al., "Experimental Automatic Lateral Control System for an Automobile", PATH Research Report, UCB-ITS-PRR-92-11, November, 1992.

Summary: The objective of this project was to prove the concept of an automated lateral control system with a full scale automobile using the components developed by PATH and IMRA. The system components include a discrete roadway reference system, on-vehicle magnetic sensing system, a computer control system and a hydraulic actuator.

The test conditions investigated were limited to low vehicle speeds (<= 60 km/hr). In additional to nominal conditions (dry road, tires at standart pressure), the system's performance was also investigated with low tire pressure (30% of nominal in the front two tires), wet road conditions, offset magnetic markers (maximum of about 2 cm), missing magnetic markers, and increased vehicle load (additional 227 kgf). Two control algorithms were developed for the tests: Proportional-Integral-Derivative (PID) control, and Frequency Shaped Linear Quadratic (FSLQ) control. In both cases, a preview action was found to be necessary. The system's performance was evaluated using lateral deviation and lateral acceleration.

Peng, Huei, et.al., "A theoretical and Experimental Study on Vehicle Lateral Control", PATH and IMRA America..

Summary: This paper presents the results of experimental work on the lateral control of a full scaled vehicle. Two control laws were tested: A simple PID control law ; An optimal preview control law. Control law theory, experimental set-up and results are briefly discussed. A discrete magnetic marker roadway referencing system is used.

The PID control law, obtained by placing the closed loop poles,

was used for comparison purposes.

Optimal preview control theory, which incorporates the frequency-shaped linear quadratic, was used to design feedback and feedforward control law. Optimal preview control theory utilizes vehicle tracking error and road geometry information to generate the front wheel steering commands. This improves tracking performance around curved sections and also ride quality.

A sensitivity reduction method was implemented in an effort to reduce vehicle lateral response sensitivity to speed and cornering stiffness.

A method had been proposed, by Verde and Frank, to perturb the state variable weighting matrix Q in the performance index in the LQ problem to reduce the system sensitivity. A similar procedure was used in this paper. However, no assumption was made, in this paper, about the relationship between the feedback gain vector and system parameters.

A numerical curve fitting formula, proposed by Bakker and Paceka, was used for the tire model. Equations for lateral and longitudinal tire forces, along with modifications are presented.

Closed loop tests, using a Toyota Celica test vehicle, showed that the feedforward part of the preview control law has to be used with both PID and FSLQ control algorithms for the vehicle to follow the test track. Tight lateral tracking (<10cm) can be achieved by the preview algorithm on a sharp curve (0.27g). Testing in non-ideal conditions showed that the system is robust with respect to speed, load, tire pressure and measurement noises.

Pikula, Mark S., and Cavas, George, "Using Variable Reluctance Sensors for Differential Odometer Applications", Ford Motor Co, 912788..

Summary: The purpose of this paper is to present a signal analysis and then describe a sensing circuit for detecting variable reluctance voltages at very low vehicle speeds.

A fine tooth iron ring containing 50 teeth is mounted on the brake rotor. As the iron ring moves past a sensor, an output signal is generated. The sensor package, consisting of a permanent magnet, a 5000 turn coil and tow iron bars to direct flux, converts the mechanical motion to an electric signal. The signal amplitude is related to the rate at which the teeth rotate past the sensor. The goal is to be able to extract information at low vehicle speeds when the rate change of flux approaches zero.

The wheel sensor circuit design is based on an adaptive sense amplifier, the LM1815. The circuit contains three stages: 1.Stage one conditions the incoming signal from teh sensor; 2. Stage two provides adaptive hysteresis to the input signal and then outputs an one-shot pulse every cycle; 3. Stage three performs a level shift for interfacing to the microprocessor. Software filtering is used to help compensate for sensor variations.

Circuit testing verified calculated performance. The circuit meets requirements for : 1.Minimum signal threshold without triggering on the noise; 2./ A DC bias set at Vcc/2 allows for a full signal; 3. Variable hysteresis adjusts to signal; 4. Bias and high frequency cut-off protect against signal going negative.

Vulnerability to noise in the bandwidth that exceeds threshold gain is a problem.

Raffaelli, Lamberto, and Stewart, Earle, "Millimeter-wave Monolithic Components for Automotive Applications", Microwave Journal, Vol.35, No.2, p22-32, February, 1992.

Summary: The mm-wave monolithic technology developed in the military has resulted in the production of chips applicable to the automotive sensor system. Low cost, high reliability, good performance, and repeatability yield MMIC technolgy ideal for large volume automotive commercial application. In Europe, two bands have already been allocated for mm-wave frequencies for car-to-station communication links and collision avoidance radars. Several chips are discussed in this paper. Technology transfer from goverment to commercial applications is necessary.

Raffaelli, Lamberto, et.al., "77 GHz Transmitter for Automotive Radar", Applied Microwave adndWireless, p80, 1993.

Summary: This paper describes a MMIC Radar Transmitter with 400 mW output and 2.8W power consumption. Cost is projected at $400 in quantities of 1000 and $60 in quantities of 100,000.

Rao, B.S.Y., et.al., "Investigations Into Achievable Capacities and Stream Stability with Coordinated Intelligent Vehicles", CA PATH/Transportation Research Board 72nd Annual Meeting, , Wash.,DC, January, 1993.

Summary: This paper examines the achievable capacities of IVHS. The primary cause of traffic stream disturbance is the entrance and egress of vehicles. By using a detailed simulator, SMARTPATH, the passage of intelligent vehicles along highways is simulated. Three strategies to enter and leave automated lanes were examined and the corresponding maximum flow rates were measured. The following assumptions are made: Platooning is only possible in automated lanes; There is one automated and one transition lane; A free agent or platoon leader keeps a safe distance from the vehicle ahead; The range of detection of a vehicle is 60m<D<80m, the speed, v, is 25m/s, actuator delay is 0.2s for full braking to be effected, interplatoon spacing is approximately 8m, intraplatoon spacing is approximately 1m, maximum platoon size is 20 vehicles.

The first case study allowed vehicles entering the automated lane from a transition lane to do so immediately if no vehicles are within a safe distance. Although high flows are attained, rider comfort is low due to decelerating and accelerating in reaction to vehicles in front.

Case two smooths flow by considering the merging vehicle part of the platoon it is about to join. It may enter the back of the automated platoon only 2d behind it. However, egress of vehicles caused a large drop in flow.

Case three sorts the platoon by exit positions.

Although these methods can achieve peak flow rates of 9000 veh/hr, these rates of flow cannot be sustained. The sustainable flow is about 5500 veh/hr. The split maneuver at exit points is the main cause of stream disturbance.

Remondi, Benjamin, "Real-Time Centimeter-Accuracy GPS: Initializing While in Motion (Warm Start Versus Cold Start)", Jour.of the Inst. of Nav., Vol.40,No.2,p.199, Summer, 1993.

Summary: This paper presents the benefits of geometric constraints to on-the-fly (OTF) kinematic GPS initialization. In particular, examples are provided in which a priori knowledge of the average height of a ship's antenna phase center is available during OTF initialization and, another, where a priori integer ambiguities are assumed. This information is easily obtainable, improves reliability, and reduces the number of epochs.

Remondi, Benjamin W., "Kinematic GPS Results without Static Initialization", US Dept of Commerce, May, 1991.

Summary: This paper presents a method of initializing GPS while in motion. Periodic survey monuments reveal kinematic truth. Reference receivers are typically less than 1 km to the rover receiver. Kinematic GPS with static initialization is used to establish the truth trajectory. Kinematic GPS without static initialization, as described in this paper, is used to establish a trajectory, or part of a trajectory. A comparison of the two trajectories allows verification that the correct integer lanes have been isolated.

Robinson, Bruce W., et.al., "Improved Freeway Analysis Techniques: Ramp and Weaving Operations for Freeway Lane Model", PATH Research Report, UCB-ITS-RR-92-4-Final Report, March, 1992.

Summary: Many recurring operational problems on freeways occur because of the turbulence caused by traffic entering the freeway and the presegregation of exiting traffic in the vicinity of ramps.

This report proposes a method to estimate point flows at various locations immediately downstream of on-ramps and upstream of off-ramps in the right-most two freeway lanes. The point flows are computed from multi-variate linear regression equations using each origin-destination flow and the length between ramp pairs as independent variables.

models have been developed for isolated on-ramps, isolated off-ramps, on-off ramps, on-on ramps, and an on-off-off ramp multiple weave site all with four freeway lanes and an on-off ramp combinations with three freeway lanes. All ramps are single lane with no auxiliary lanes.

The equations are based on empirical data from seven California freeway sites with origin-dstination flows and ramp spacings extrapolated using the microscopic freeway simulation model, INTRAS.

Rockwell International Science Center, "Potential Payoffs from IVHS: A Framework for Analysis", CA PATH Program, Institute of Transportation Studies, Univ. of CA at Berkeley; LBerkeley, CA; PATH Research Report, UCB-ITS-PRR-92-7, August, 1992.

Summary: The purpose of this study is to provide a logical framework for the identification and evaluation of alternative IVHS functions, to help sort out the most important from the less important, and to specifically relate the various IVHS functions with the public sector goals they might serve.

Rokitansky, Carl-Herbert, and Wietfeld, Christian, "Comparison of Adaptive Medium Access Control Schemes for Beacon-Vehicle Communications", IEEE-IEE VNIS, pp295-99, IEEE#0-7803-1235-X/93, 1993.

Summary: Efficient medium access control schemes are essential for beacon-vehicle communications because of the limited communication zone and randomly arriving vehicles. In this paper several options of data collision recovery mechanisms (such as random delay and persist mechanisms) are presented and evaluated through simulation based on realistic traffic scenarios, antenna configurations and channel characteristics. It is shown that by choosing the appropriate protocol options and control parameters a high system performance can be achieved. The presented medium access control protocol options are currently introduced in European standardization bodies for dedicated short-range communications.

Rothblatt, M., "Urban Area Performance of GPS Receiver with Simultrac Capability", National Telesystems Conference NTC-92, 92ch3120-3, 1992.

Summary: A description is given of an automatic vehicle location (AVL) system to be used by fleet operators to tell where vehicles are within 15 meters (SA off). Location is available 90% of the time if outages last less than 30 seconds and 99% of the time if outages last less than 20 minutes. (The reviewer guesses that such a case, a 20 minute outage occurring 1% of the time, must be accounted for by parking the vehicle, e.g. for a delivery, in a particularly unsuitable urban canyon.)

Sathisan, Shashi Kumar, "Airline Safety Posture: A Sudy of Aircraft Maintenance Related Indicators", PATH Dissertation Series, UCB-ITS-DS-89-5, July, 1989.

Summary: In this study, the various causal factor of airline accidents were looked at, with attention directed to those related to aircraft maintenance. First, a theoretical framework for modeling the possible escalation of small equipment problems into more severe incidents and, further on, into accidents, was discussed. It was proposed that our knowledge of and experience with small maintenance problems could be used to predict the occurrence of more serious problems in the future. However, only the framework for such a model was discussed without attempting to develop an operational model.

e possible influences on safety posture of airlines and aircraft were discussed. The airline, its aircraft fleet mix, aircraft age, stage length and scale of operations were identified as having significant influences on safety posture. Statistical techniques were used to quantify and assess the significance of the factors influencing safety posture.

Scapinakis, Dimitris A., and May, Adolf D., "Demand Estimation, Benefit Assessment, and Evaluation of On-Freeway High Occupancy Vehicle Lanes: Level I, Qualitative Evaluation", PATH Working Paper, UCB-ITS-WP-89-4, June, 1989.

Summary: Seventeen criteria are thus identified for HOV priority lane implementation. Many of them are qualitative in nature and some are relative to others. it is apparent that a proposed HOV lane priority treatment does not have to meet every single criterion described above. However the more criteria that are satisfied, the more likely will be for the proposed treatment to succeed when implemented. Also, the number of criteria satisfied may be used in assigning priorities to certain projects among a list of potential projects being evaluated.

The recommended methodology, of evaluating sites for HOV lane priority treatments has been applied to existing freeway HOV lanes in California. it took 10 to 15 minutes per site and the participants felt it was an effective process. The procedure has been further validated comparing the predicted rank order of the facilities, to operators' rank of operational success. The results indicate a good distribution of site scores.

The qualitative Level I analysis is intended for screening of possible candidate sites. While it may provide some indication to the success of HOV lane implementation it does not consider demand response. For this reason Level I should be used as an integrated part of the complete three level methodology.

Schneiderman, Henry, and Albus, James, "Progress and Prospects for Vision Based Automatic Driving", IVHS America Annual Meeting, 1993.

Summary: Most vision based technologies fall into two categories: region based statistical class methods and feature tracking methods. Statistical class methods include both supervised and unsupervised methods.

Supervised statistical class methods group pixels into categories whose statistics have been prespecified. Successful navigation of vehicles using this method have been reported. Drawbacks include: 1.Once a system misinterprets an image, the system will probably not recover. 2. Continuity in road appearance between successive images is required. 3. Driving speeds have thus far been limited by large amounts of computation.

Unsupervised statistical class methods, where no prior pixel categories exist, has a report of successful navigation on unconstructed, paved and unpaved roads under various conditions using a method called UNSCARF.

Feature tracking methods, as the name implies, locate the road based on distinct features such as painted lane marking. Numerous successes are listed in this report of feature tracking methods. Feature tracking algorithms tend to require less computation and are therefore able to achieve higher speeds. However, specific road features are necessary. The system becomes unreliable if these features are not detectable.

A brief description of several other methods is presented.

Sharpe, R.T., "GPS Receiver Configurations", Magnavox..

Summary: Short paper describes processes of GPS acquisition and tracking using different receiver configurations.

Sheikholeslam, S., and Desoer, C.A., "A System Level Study of the Longitudinal Control of a Platoon of Vehicles", Trans. ASME, Journal of Dyn. Sys., Vol. 114, p286, ISSN 002-0434, June, 1992.

Summary: Simulation of highly communicative platoon using cars varying from 900 to 1900 kg curb mass are slinky-free although deviations grew with communications delay. Several other delay factors, e.g. engine dynamics, were not modelled.

Sheikholeslam, Shahab, and Desoer, Charles, "Indirect Adaptive Control of a Class of Interconnected Non-linear Dynamical Systems", Int. J. Control, Vol.57, No.3, pp743-65, ISSN#0020-7179, February, 1992.

Summary: We consider the class of interconnected non-linear dynamic systems suggested by the problem of longitudinal and lateral control of a platoon of vehicles on automated highways. After describing the physical setting from which the control problem arises, we propose a local indirect adaptive control scheme for this class of interconnected non-linear systems. Then, we establish that hte proposed local adaptive control scheme is suitablwe for monotoniclly decreasing the magnitude of deviations of each dynamic system’s state from its sink manifold provided that (a) the exogenous input is varying sufficiently slowly and (b) the parameter error is sufficiently small. As a consequency, these deviations are bounded with a bound independent of the number of subsystems in the interconnection.

Sheikholeslam, Shahab, and Desoer, Charles A., "Combined Longitudinal and Lateral Control of a Platoon of Vehicles", ACC, Chicago, Ill.,. Vol. 2.,pp1763-67, 1992, 0-7803-0211-7, 1992.

Summary: The authors consider the problem of combined longitudinal and lateral control of a platoon of non-identical vehicles on a curved lane of highway. Based on nonlinear models of vehicles' combined longitudinal and lateral dynamics, the authors propose nonlinear control laws for a platoon of vehicles accelerating on a curved lane of highway. The implementation issues regarding the needed sensors, estimators, guidance system, and communication link are discussed. Simulation results show that the proposed control laws perform well, for roads with suitably large radius of curvature, under nominal operation.

Sheikholeslam, Shahab, and Desoer, Charles A., "Design of Decentralized Adaptive Controllers for a Class of Interconnected Nonlinear Dynamical Systems: Part 1", PATH Technical Memorandum 92-1, February, 1992.

Summary: We consider the class of interconnected nonlinear dynamical systems suggested by the problem of longitudinal control of a platoon of vehicles on an automated highways. After describing the physical setting from which the control problem arises, we propose a decentralized adaptive control scheme for this class of interconnected nonlinear systems. Then, we establish that the proposed adaptive control scheme is suitable for monotonically decreasing the magnitude of deviations of each dynamical system's state from it's sink manifold provided that a) the exogenous input is varying sufficiently slowly and b) the state-observer error is sufficiently small. An important feature of this adaptive control scheme is that these deviations are bounded independent of the parameter errors.

Sheikholeslam, Shahab, and Desoer, Charles A., "Longitudinal Control of a Platoon of Vehicles with No Communication of Lead Vehicle Information", ACC, Boston, Mass., Vol.3, pp3102-06, 1991.

Summary: Evaluates the performance of longitudinal control laws with no communication of lead vehicle information. After using exact linearization methods, the authors propose a linear control law for each vehicle which uses only the information from the preceding vehicle in the platoon.

Sheikholeslam, Shahab, and Desoer, Charles A., "Combined Longitudinal and Lateral Control of a Platoon of Vehicles: A System-level Study", PATH Technical memo , 91-3,

Spetember, 1991.

Summary: This paper considers the problem of combined longitudinal and lateral control of a platoon of vehicles on automated highways. A platoon consists of N non-identical vehicles following a lead vehicle. Previous studies separated the problem of longitudinal control of a platoon of vehicles from the lateral control of each vehicle within the platoon: in the case of longitudinal control of a platoon of vehicles, these studies showed that suitable control laws can be designed for a platoon of 16 vehicles traveling on a straight lane of highway [7], [8], [9]; in the case of lateral control of a vehicle, these studies propesed control laws based on a linear model of vehicle's lateral dynamics with the assumption that the vehicle's speed remains constant on a curved lane of highway [5]. In the present system-level study, we propose nonlinear control laws for a platoon of non-identical vehicles accelerating on a curved lane of highway. These control laws are based on nonlinear models of vehicles' combined longitudinal and lateral dynamics.

The organization of the paper is as follows: section 2 summarizes the notation; in section 3, we derive the kinematic equations for the i-th vehicle (i=1,2,...,N) in a platoon; in section 4, we describe the dynamic equations representing the i-th vehicle's engine and steering actuator dynamics (for i=1,2,...,N) and then derive the equations of motion for the i-th vehicle's center of mass; in section 5, using both the kinematic and the dynamic equations for the i=th vehicle, we propose a lateral control law for this vehicle and longitudinal control laws for the platoon; the implementation issues regarding the needed sensors, estimators, guidance system, and communication link are discussed in section 6; in section 7, we show the simulation results for a platoon of 5 vehicles following a lead vehicle, accelerating on a curved lane of highway, under the proposed control laws.

Shladover, S.E., "California PATH Research on AVCS: RecentAccomplishments and Future Plans", IVHS America,p58, 1993.

Summary: This report summarizes key accomplishments of the PATH in AVCS. The following categories of projects are discussed:

- concept modeling and development
- enabling technology developments
- safety designs and evaluations
  proof-of-concepts tests
- short-headway platoon evaluations
- AVCS impact evaluations

Summaries presented may be used for reference to other materials.

Shladover, S.E., "Longitudinal Control of Automotive Vehicles in Close-Formation Platoons", Jrnl Dynamic Systems, Measurement, and Control Vol.113, No.2, p231-41, June, 1991.

Summary: The capacity and safety of freeways can potentially be increased substantially if the vehicles are operated in platoons, using automatic longitudinal control systems to maintain very small spacings (of the order of 1 meter) between vehicles. This paper explains many of the technical considerations in the design of such control systems, employing a general nonlinear simulation model to develop quantitative results. The effects on control system performance of external forces, process and measurement noise, and sampling and quantization of measurements are shown. The importance of accelereation and jerk limits is demonstrated, and examples are used to illustrate how the control system must be designed to accommodate variations in the severity of the maneuvers it is expected to execute, as well as variations in propulsion system dynamics.

Shladover,Steven E., et.al., "Automated Vehicle Control Developments in the Path Program", IEEE Transactions on Vehicular Technology, Vol.40, No. 1, February, 1991.

Summary: This report summarizes the accomplishments to date on the development of AVC technology in the PATH.

The proposed system assumes platooning with vehicle spacing of 1M. This should double or triple road capacity. “Brick wall” safety criterion is not a requirement.

The path work on longitudinal control emphasizes vehicle-follower control. A non-linear vehicle power-train program called “LONSIM” has been developed. The inputs are throttle and braking. Outputs are vehicle acceleration, velocity and position.

To facilitate close safe spacing, the control system in each vehicle must have timely access, within a few hundredths of a second, to the following: 1.Speed and acceleration of a vehicle 2. Distance to the preceding vehicle. 3. Acceleration and speed of the preceding vehicle. 4. Acceleration and speed of the first vehicle in the platoon. Telecommunication as a means of transmitting speed and acceleration are discussed.

Three potential technologies are presented for information transmission between vehicles. These are ultrasonic, optical (infrared), and radio. Faced with difficulties in ultrasonic and radio transmission, an optical communication system is discussed.

Longitudinal control laws for platoons are presented. Analysis shows through the appropriate choice of design parameters vehicle spacing deviations do not get magnified as a result of the lead vehicle’s acceleration from it’s initial steady-state velocity to it’s final steady state velocity.

Based on application of control theory to vehicle dynamic models, an intelligent sensing/reference system was decided upon for lateral control. Inexpensive permanent magnetic markers are to be installed in the center of the traffic lane. A vehicle-borne sensing system acquires pertinent information while passing over these markers. A practical algorithm for deriving vehicle lateral position measurements from magnetic fields of buried permanent magnets has been developed and tested. Approaches for preview road information transmission are under investigation. Experiments were conducted to investigate the effectiveness of the IRRS, showing that environmental

conditions have minimal interference on the system.

Lateral control law development is described for the feedback controller, feedforward controller and estimation of cornering stiffness. Numerical simulation results for nominal and off-nominal conditions showed acceptable performance.

Shresta, Ramesh L., "Use of Real-Time DGPS Base Station Concept to Collect Point Location Data for a GIS", IEEE-IEE VNIS, p460, IEEE#0-7803-1235-X/93, 1993.

Summary: PAPER NOT AVAILABLE FOR PUBLICATION

The Global Positioning System (GPS) is a timing and navigation service provided by the Department of Defense (DoD) and it can provide quick and precise locations from the sub-meter to the 100 meter level. Since many Geographic Information System (GIS) applications require an accuracy of about 10 meters, much interest has been placed in the differential GPS (DGPS) base station concept. This concept assumes that GPS errors at present at the base GPS receiver are also present in equal amounts at a user GPS receiver. These errors can be computed either by post processing or processed real-time.

This paper presents research conducted to evalu use of a real-time DGPS base station. Of particular importance is what type of accuaracy can be reasonably attained? It also explores the logistics required with a base station as well as the type of hardware that is required.

Initial results indicate that the real-time DGPS base station conceptcan meet the accuracy needs of the many GIS communities. Test results from a research project funded by teh St. Johns Water Management District (DISTRICT) using DGPS will be presented. The objective of the research and development is to evaluate and quantify the positional accuracy of the DISTRICT's existing GIS database and make recommendations for the hardware and software development.

Skabardonis, Alexander, Cassidy, Michael J., and May, Adolf D., "Operation of Major Freeway Weaving Areas: Findings from the Application of Existing Analytical Methods and Simulation Modeling", Path Working Paper, UCB-ITS-WP-88-12, December, 1988.

Summary: Weaving areas are critical elements for the operation of the freeway network, involvincomplex vehicle interactions. This repnts the findings from the application of existing weaving analysis techniques ulation modeling on existing weaving areas in Cfornia. The work was performed as part of an on-going research project to develop improved pres for design and analysis of freeway weaving areas.

Field data on geometric and traffic characteristics were collected at eight major weaving sections throughout the State using v recording. The results from the application of six existing empirical methoshowed significant discrepancies between the measured and estimated speeds for both the weaving and non-weaving vehcles. The INTRAS microscopic simulation model was applied to the same test sites. Goood agreement was obtained betweened and predicted speeds for the entire range of trafficitions. Consistent results also were obtained from the application of the model to predict thcity of weaving sections.

These findings indicate that there is a high priority research need to developoved design/analysis methods for major freeway weions. The new procedures should be based on field data, augmented with simulation results. The report discusses futurections in the on-going research to develop such procedures.

Snow, R., "GPS Basics", Interstate Electronics Corporation, 1001 E. Ball Road, Box 3117, Anaheim, CA 92803..

Summary: A viewgraph presentation on GPS that gives a very basic explanation.

Soljanin, E. and Georghidas, C., "The Near-far Problem in Spread-Spectrum Road-Automobile Communication", ACC, Vol.2, p1777, 92ch3072-6, 1992.

Summary: Code division multiple access (CDMA) communications are limited if user range varies greatly.

Staba, Gail R., "Development of Comprehensive Passing Lane Guidelines, Volume II: Appendix", PATH Research Report, UCB-ITS-RR-91-2, January, 1991.

Summary: This report documents research efforts directed at developing improved guidelines for designing and analyzing two-lane, two-way rural highway passing lanes. Phase I of this project involved selecting field study sites, collecting and analyzing passing lane data. Phase II involved a follow up field study and analysis of passing lane entrance design. Additional work included computer simulation of passing lane sections to perform sensitivity analysis and to test proposed guidelines.

A total of five passing lane sections were used to collect empirical data in this research. At one site an after study was performed to collect and analyze data for an alternative passing lane entrance design. Thireport details the data collection and analysis performed at all sites.

The TRARR and the TWOPAS computer simulation models were used to test findings and suggested guidelines in light of observed fielddata. Details concerning model calibration are included in this report.

Additional analysis of the number of passes which occurred on studied passing lane sections was accomplished. The information gained from this work resulted in additional information about the benefit of a passing lane and the primary vehicle types that benefit.

Staba, Gail R., et.al., "Development of Comprehensive Passing Lane Guidelines Volume I: Final Report", PATH Research Report, UCB-ITS-RR-91-1, January, 1991.

Summary: This report documents research efforts directed at developing improved guidelines for designing and analyzing two-lane, two-way rural highway passing lanes. Phase I of this project involved selectingfield study sites, collecting and analyzig passing lane data. Phase II involved a follow up field study and analysisof passing lane entrance design. Additional work included computer simulation of passing lane sections to perform sensitivity analysis and to test proposed guidelines.

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Stansell, Thomas A. Jr., "RTCM SC-104 Recommended Pseudolite Signal Specification", Jour. of the Inst. of Navig., Vol33, No.1, Spring, 1986.

Summary: This paper introduces a GPS-like pseudolite signal structure which does not interfere with reception of GPS satellite signals even when a receiver is very close to a pseudolite transmitter. A time division signal structure in which the pseudolite signal is transmitted in short, low duty cycle pulses which interfere with the satellite signals for only a small fraction of the time is suggested. The pseudolite does not interfere with the GPS signal more than 10% of the time, resulting in no more than 1 dB loss in the received GPS average signal power. A non-GPS Gold code is used. The signal structure, however, must be as similar to the GPS satellite signal as possible to simplify receiver design. Following are some recommendations:

1. The pseudolite antenna should be positioned and it's pattern shaped to optimize it's benefits while minimizing interference with non-users.

2. Two pseudolites using the same code may be placed as close as 130km, but a spacing of 300km is suggested.

3. Two pseudolites using different code may be placed a minimum of 54 km apart.

Receiver design is discussed.

Stove, A.G., "Automotive Radar at 80-90 GHz", IEEE MTT-S IntntMicrowave Symp Vol.2, p613-, 0-7803-0612-0, 1992.

Summary: The idea of equipping cars with radar has been around for a long time, but it is only with the arrival of low cost compact millimeter-wave radars that such systems have become practicable. The paper will discuss a technology for low-cost mass production of automotive radar sensors and two systems applications for such sensors. The systems applications are an Intelligent Cruise Control (ICC), which uses a relatively simple forward-looking sensor, and the other is as a more sophisticated Obstacle Warning Radar (OWR).

Stove, A.G., "80 GHz Automotive Radar", Eighth International Conference on Automotive Electronics (Conf. Publ. No.346), p145-9, ISBN#0-85296-525-7, 1991.

Summary: The ideaof equipping cars with radar has been around for a long time, but it is only with the arrival of low cost, compact millimeter wave radars, that such systems have become practicable. The availability of suitable radar sensors and of sophisticated digital signal processing has opened up two important applications for millimeter wave radar in cars: one is as a relatively simple forward-looking sensor for an Intelligent Cruise Control (ICC) and the other is as a more sophisticated Obstacle Warning Radar (OWR), to warn the driver of potential hazards in his path in degraded visivility. This paper describes some of the background technology for millimeter wave automotive radar and presents experimental results both for an ICC for a radar sensor for an OWR.

Streisand, Susan L., "A Communication Architecture for IVHS", PATH , UCB-ITS-PRR-92-10, December, 1992.

Summary: An area being studied by the California PATH is automatic control ofvehicles on the highway. A proposed control methodology requires communication among various components of the system: independent vehicles, roadside computers and monitors, and vendor-operated databases. This paper presents an architecture for these communication functions based on the OSI reference model. We study the communication needs of proposed IVHS (Intelligent Vehicle highway Systems) applications, the physical characteristics of various communications media, and protocols which will form the ocmponents of the system. We propose using different communication methods for the different communication needs. We then examine the Data Link and Network layers. Certain communications needs such as timed packets, addressing and routing of messages, and error detection, are handled by these layers. We explain the network management processes. Finally, wer illustrate message addressing, communication primitives for applications, and a method of determining vehicle position.

Suchko, Michael S. K., "DGPS Broadcasts using the Radio Broadcast System (RBDS) for IVHS", IEEE-IEE VNIS, pp312-18, IEEE#0-7803-1235-X/93, 1993.

Summary: GPS has become the primary choice in Intelligent Vehicle Highway Systems (IVHS) for vehicle location monitoring. The use of GPS technology in the autonomous mode is not accurate enough in urban environments where accurate vehicle location monitoring is difficult. The major problem in vehicle location monitoring has been providing some form of efficient DGPS correction broadcast.

Cost effective solution to providing DGPS corrections for IVHS is using the new broadcast data technology Radio Broadcast Data Standard (RBDS). The standard defines the broadcast format for transmitting data over existing FM radio station Subcarriers.

Sugasawa, F., et.al, "Development of Simulator Vehicle for Conducting Vehicle Dynamics Research", Int. Journal of Vehicle Design, Vol.13, No.2, p159-167, 1992.

Summary: For research into human sensory perception and abilities for vehicle handling and stability, and experimental vehicle was developed that can control the response of the yaw rate and lateral acceleration independently. The front and rear wheel steer angles are controlled respectively by the electrohydraulic control system. Using this vehicle, subjective evaluations were carried out in which the yaw rate and lateral accdeleration characteristics were varied independently and changes in the driver’s perception of the vehicle feel were examined.

Sweeney, Lawrence E. Jr., et.al., "Comparitive Performance of Various Automotive Navigation Technologies", IEEE-IEE VNIS, pp437-40, IEEE#0-7803-1235-X/93, 1993.

Summary: The first practical in-vehicle automotive navigation systems (introduced in 1985) utilized dead reckoning combined with digital map-matching to keep track of vehicle positions and to show them in real time on digital map displays. Dead reckoning was based on wheel sensors and a magnetic compass, and map-matching was based on extremely accurate digital maps.

This dead-reckoning/map-matching technology has advanced considerably during the decade of it’s development. Not only has digital map accuracy, coverage, and completeness improved, but inclinometers and gyroscopes have been added to improve dead-reckoning performance.

In recent years, other vehicle location and tracking technologies have emerged including Global Positioning Satellites (GPS), differential GPS, radio-location (resembling Loran or inverse Loran), cellular phone tracking, and electronic benchmarks (or signposts) in or near the roads. Loran C is also under consideration.

All of these technologies have advantages and limitations related to features, performance, accuracy, reliability, and cost. A satisfactory system for widespread commercial and consumer applications may require a combination of techniques to provide acceptable performance.

This paper will describe advantages and limitations of the various vehicle location and tracking techniques, and will discuss how their limitations can be overcome by combining or improving techniques. Tradeoffs between features, performance, and cost will also be presented for some specific applications.

Takaba, Sadao, "The Current Status of the IVHS/RTI Programs in Japan", IVHS America 1993 Annual Meeting, 1993.

Summary: This paper introduces four projects currently underway in Japan:
1. Vehicle Information and Communication System (VICS)
2. Advanced Road Transportation System (ARTS)
3. Advanced Safety Vehicle (ASV)
4. Super Smart Vehicle System (SSVS)The VICS project aims at early implementation of the sytems already developed. The other projects aim at research and development for the future realization from 2000 to 2010. A new project, Universal Traffic Management System (UTMS), was recently proposed.

Takimoto, Yukio, and Kotaki, Minoru, "Automotive Anticollision Radar", Applied Microwave, Fall, 1992.

Summary: The authors present experimental results of millimeter wave automotive sensing system tests conducted by member companies of the study committee commissioned for this purpose by the Ministry of Posts and Telecommunications in Japan.

Taniguchi, Masaaki, "The Current Status of PVS", IVHS America Annual Meeting, pp124-30, 1992.

Summary: This paper presents a brief review of development of the basic system requirements for autonomous driving and describes subsequent evaluation testing.

A video camera based vision system was implemented for detection of road markers on the road surface. Observed point information was processed in terms of inputs of recognition and planning information. Target point processing required breakdown of the target point into a series of separate weighted points. An edge extraction technique, used for detecting white lines, takes into account previous vision information.

The camera vision mode of lane detection can be automatically changed to an ultrasonic sensor mode. An intermediate mode, called the path interference fuction, estimates the path for a certain distance, approximately ten meters ahead of the vehicle, based on previous vision information. Ultrasonic sensor mode is initiated when the camera vision mode cannot be restored and the path interference function becomes inoperable.

Evaluation confirmed the feasibility of autonomous vehicle operation. Future work is necessary to improve reliability and introduce a more complex environment.

Taniguchi, Masaaki, et.al., "The Development of Autonomously Controlled Vehicle, PVS"..

Summary: This paper describes the construction of the Personal Vehicle System (PVS) and presents the results of driving tests.

The PVS has two operating modes:

1. Camera vision for detecting white guidelines on the road.
2. Ultrasonic sensors to detect guardrails alongside the road.

The vehicle system also includes wheel speed sensors, laser radar, dedicated actuators for controlling the throttle, brakes and steering system, and three braking systems. A control system performs image processing, sensor signal processing, actuator control, and main control.

Experimental testing displayed stable vehicle operation for target conditions. The vehicle executed smooth turns even at intersections. Obstacle avoidance proved successful. The vehicle tended to lack stability in the ultrasonic sensor mode.

This vehicle does not have the ability to operate on unfamiliar roads where no map information is stored in memory.

A fail-safe function should be incorporated in the system to account for missing vision information circumstances.

Taylor, Charles, "IMDNs Revolutionize Mobile Data Communications and Vehicle Location", IEEE-IEE VNIS, pp327-29, IEEE#0-7803-1235-X/93, 1993.

Summary: A trend is emerging that will change the way people communicate and are tracked in mobile environments. This trend involves a very simple, cost-effective solution that, to date has been overlooked. Millions of mobile users will benefit from greater functionality, reliability, quality and price performance through a pioneering combination of remote radio-location and mobile data communications.

A new breed of Intelligent Mobile Data Networks (IMDNs) have set new levels in the mobile arena and are designed to better satisfy the needs of today's mobile communications user. A radio-locating IMDN provides a low-cost, high-performance communications and vehicle location solution for mobile applications. Currently mobile applications are not well-served due to limited and/or expensive automated vehicle location (AVL) technologies and traditional mobile communications approaches. While delivering reliable, high-speed digital data message packets, a radio-locating IMDN provides fast, accurate information on the location of the mobile user. Low-cost equipment and network service will enable more effective management of mobile assets and the growth of new mobile information service offerings.

Tongue, Benson H., Yang, Yean-Tzong, and White, Matthew T., "Platoon Collision dynamics

and Emergency Maneuvering I: Reduced Order Modeling of a Platoon for Dynamical Analysis", PATH Research Report, UCB-ITS-PRR-91-15, August, 1991.

Summary: The purpose of this three-year project is to develop an operational model of vehicle platoon dynamics under emergency conditions and to evaluate the platoon's dynamical behavior under non-nominal, or emergency, conditions. New platoon protocols and/or controller modifications will be formulated after analyzing the platoon response data in order to minimize damage to the platoon and the vehicles' occupants.

During the first year of this research, a comprehensive review of previous work dealing with the dynamics and control of platoo of vehicles was undertaken. Following this, a nonlinear reduced order model (ROM) was developed from an accurate, and high order, model. Regression analysis, based upon the least-squares algorithm, was applied to the response of a full order modl in order to determine the reduced order vehicle model.

preliminary results have shown that the reduced order model provides an accurate esponse match with the original model at a substantial computational savings. A platoon model has been developed and coded and preliminary simulations of platoon dynamics have been performed in which system parameters such as sampling time, desired headway, vehicle spacing and road grades were varied.

This progress report discusses the results of the modeling phase of this work. A detailed literature review is included as Appendix B. A second report, dealing with the platoon dynamical simulations, is currently in preparation.

Tribe, Raglan, "Automotive Applications of Microwave Radar", The British Library Document, Supply Center, Boston Spa, Wetherby, West Yorkshire, United Kingdom, LS23 7BQ..

Summary: Microwave radar is a method for detecting the position and velocity of a distant object. A beam of electromagnetic radiation, with a wavelength between 30cm and 1mm, is transmitted and reflected back to the transmitter by the object. Velocity and range can be derived by measuring the doppler frequency shift and the time of flight of the transmission. These techniques have been used widely in aerospace and defense applications for many years. Recently, the advent of low cost devices has led to an increase in consumer applications.

This paper investigates applications of microwave radar in the automotive environment. Many of these applications are considered by reviewing work at Lucas that has been conducted over the last 25 years. Applications investigated are obstacle detection and avoidance, longitudinal vehicle control, improved vehicle dynamics and instrumentation. In each case, the technologies are described and results presented that show the advantages and disadvantages of the microwave techniques.

TRW Systems Group, "Study of Synchronous Longitudinal Guidance as Applied to Intercity Automated Highway Networks", TRW Systems Group, Wash, DC., 06818-W666-RO-00, Under Contract C-353-66 (Neg) for the Office of High Speed Ground Transportation, U.S. Department of tion, September, 1969.

Summary: This report documents the results of the Synchronous Longitudinal Guidance (SLG) study as applied to automated highway networks.

The report is organized as follows. Section 1 contains a background of the SLG projects, an introduction to the basic concepts used in SLG, objectives and methods of the study, and conclusions reached as a result of the study. Sections 2 and 3 discuss results of analytical work done to verify various properties of the algorithms used for local vehicle control and for interfacing highway elements within the network. Work done in simulating the allocation algorithm for three networks is summarized in section 4. A brief comparison between SLG and manual highway design is given in section 5. Finally section 6 contains recommendations for further study of SLG concepts. Supplementary information which contains computer block diagrams, programs, sample printouts is available upon request.

Tsao, H.-S. Jacob, and Hall, Randolph W., "A Probabilistic Model and a Software Tool for AVCS Longitudinal Collision/Safety Analysis", PATH Working Paper, UCB-ITS-PWP-93-2, June, 1993.

Summary: This paper develops a probabilistic model and a software tool for analyzing longitudinal collision/safety between two automated vehicles. The input parameters are the length of the gap between the two vehicles, the common speed prior to the failure, the reaction delay of the following vehicle and a bivariate joint distribution of the deceleration rates of the two vehicles. The output includes the probability of a collision and also the probability distribution of the relative speed at collision time.

We will use this model to compare the safety consequences associated with the platooning and “free-agent” vehicle-following rules. We will also demonstrate that the free-agent vehicle-following rule implemented with a potential technology of fast and accurate emergency deceleration, under some reasonable conditions, can virtually avoid collisions while offering a high freeway capacity previously thought possible only under the platooning rule.

Tsumura, Toshihiro, et. al., "A Method of Position and Attitude Measurement of Vehicle Using Fan Shaped Laser Beam and Corner Cube", IEEE-IEE VNIS, pp517-20, IEEE#0-7803-1235-X/93, 1993.

Summary: This paper proposes a method to measure the position and attitude of the vehicle on the road by use of laser transceivers on the vehicle and retro-reflecting targets on a side of the course. The laser transceivers emit fan shaped laser beams and detect the returned laser beams reflected by retro-

reflecting targets.

The time data when the laser beams return to the transmitter may depending on the movement of the vehicle. Then an on-board computer calculates the position and attitude from the time data. This paper reports the measurement principle and simulation results.

Tsumura, Toshihiro, et.al., "A Vehicle Position and Heading Measurement System Using Corner Cube and Laser Beam ", IEEE, 1988.

Summary: This paper proposes a method of vehicle position and heading measurement using a corner cube and laser beam system. The corner cube and laser beam system is to be used in conjunction with the dead-reckoning method. The dead reckoning position method estimates position and heading based only on on-board sensors such as odometers and is subject to large accumulated errors over long distances.

The corner cube and laser method reflects a laser beam off the corner cubes and measures the moved distance. Using the triangulation principle, the position and heading relative to the cubes is determined. This information is used to initialize the dead-reckoning method. The positioning algorithm is detailed in this report.

Experimental testing prove the laser and corner cube method to be an effective means of finding absolute position and heading information.

Varaiya, Pravin, "Smart Cars on Smart Roads: Problems of Control", PATH, PATH TECH MEMO 91-5, December, 1991.

Summary: Proponents of Intelligent Vehicle/highway System or IVHS see it as a new technology which will make a major change in highway transportation. Control, communication and computing technologies will be combined into an IVHS ystem that can significantly increase safety and highway capacity without new roads having to be built. This paper outlines key features of one highly automated IVHS system, shows how core driver decisions are improved, proposes a basic IVHS control system achitecture, and offers a design of some control subsystems. It also summarizes some experimental work. We hope that the paper will stimulate interest in IVHS among control engineers.

Vlcek, Charles, et.al., "GPS/Dead Reckoning for Vehicle Tracking in the “Urban Canyon”Environment", IEEE-IEE VNIS, ppA34-A41, IEEE#0-7803-1235-x/93l, 1993.

Summary: The latency of a solution for vehicle tracking is important to navigation system design. One second is generally accepted. A GPS/DR system can have a guaranteed latency less than 1 second. The redundancy of a GPS/DR system improves the system's integrity.

Velocity information for DR was extracted from the vehicle's odometer. GPS heading initialization was alternated with a rate gyro's output of instantaneous heading information.

The system incorporates a GPS receiver board, an antenna, a dead reckoning processor board, a gyro and an interface cable. A DR position filter, heading filter, odometer scale factor calibration, gyro scale factor calibration and gyro bias estimation are discussed.

Testing in urban areas, which tend to introduce many problems, revealed an accumulated DR error generally under 2% of the distance travelled. GPS errors from reflectewd signals were supressed, due to filtering.

Wemple, Elizabeth A., and May, Adolf D., "Improved Freeway Analysis Techniques: Flow Fundamentals for Freeway Lane Model", PATH Research Report, UCB-ITS-RR-91-5, June, 1991.

Summary: Currently the Institute of Transportation Studies (ITS) at the University of California is in the process of developing a freeway lane model which will predict flows by lane, and lane changes between lanes in the vicinity of ramp junctions and major weaves. To provide information for this model, ITS has studied certain characteristics of straight pipe sections of freeway (sections of freeway away from the influence of ramps) for three and four lane sites as described in this paper. These characteristics include lane distribution vs. flow, lane changing vs. flow, and speed vs. flow relationships for the two different sites.

Additionally, this research further demonstrates the difference between the estimated value of capacity of a freeway lane cited in the Highway Capacity Manual (HCM) and the approximate capacity measured at the two sites, and compares the speed-flow curves developed at these sites to the 1985 HCM curve and the JHK curve.

West, Thomas, "An Intelligent Roadway Reference System for Vehicle Lateral Guidance/Control"..

Summary: Recent studies have revealed that a lateral control system which uses only the vehicles deviation information can only track the reference in a compensatory mode. The sensing/reference system for automatic steering should possess an anticipatory capability for acquiring pertinent information on road geometry. This paper presents a discrete magnetic marker reference system to meet these requirements. Information processing for vehicle lateral position, along with road geometry information transmission and acquisition are described.

The reference system utilizes discrete magnetic markers, that may code one or more bits of information, installed in the center of the traffic lane. Vehicle borne equipment for acquiring information include a sensor, a computer, and an interface that links the sensor and computer. Magnetometer type sensors, which acquire signals even at zero vehicle speed, are implemented for signal acquisition.

The earth's magnetic field, which poses a problem, can be eliminated by measuring the magnetic field of the markers relative to the size of the earth's magnetic field.

By applying the set of rules derived in this paper, an algorithm was constructed to find each acquired signal, it's belonging subset and then transforms it to a lateral deviation value.

Both simulations and full-scale tests demonstrated that the algorithm is able to reliabley read the vehicle deviation independent of varitations in sensor height.

By strategically alternating the natural magnetic poles of the reference markers, two different binary codes can be represented (0,1), road geometry information can be previewed. The amount of information presented by the IRRS depends on the precision required. Initial studies indicate that an IRRS has the capacity to store information abount longitudinal vehicle position, lane recognition, speed limit, traffic sign information, etc.

Previous experiments show that environmental conditions have small effect on the system.

Williams, D.A, "Millimetre Wave RADARS for Automotive Applications", IEEE MTT-S International Microwave Symposium, Vol.2, p721-24, 0-7803-0612-0, 1992.

Summary: This paper discusses recent developments in RADAR technology specifically in the automotive area.

The concept of Intelligent Cruise Control (ICC) is introduced and the applicaiton of millimetre wave sensors is discussed. FMCW and Pulse Coded Radars are described and details of novel quasi-optical antennae and mixers are presented.

Wisloff, Tor E., and Andresen, Steinar, "Positioning and Traffic Information by Cellular Radio", IEEE-IEE VNIS, pp287-90, IEEE#0-7803-1235-X/93, 1993.

Summary: The Skinfakse concept (for service integrated distribution of mobile services) was introduced at the VNIS 92 conference in Oslo, Norway. In this paper we continue by examining Skinfakse to discern what additional information regarding the mobile user is deducible through evaluation of parameters related to the radio link. In particular, we will show that Skinfakse allows localization and gathering of statistical data for traffic monitoring as a fringe benefit of the Skinfakse structure. The paper focuses on GSM as the cellular infrastructure to form a commonly understood frame of reference, but the solutions of the paper are applicable to any digital cellular communication system realized in the Skinfakse structure.

Xu, Z., and Ioannou, P., "Modeling of the Brake Line Pressure to Tire Brake Force

Subsystem", Techinical Report to PATH and Ford Motor Co., No. 92-09-01, 1992.

Summary: On Order

Ygnace, Jean-Luc, et.al., "Vehicle Navigation and Route Guidance Technologies: Push and Pull Factors Assessment", PATH, UCB-ITS-PRR-90-2, May, 1990.

Summary: Scientific articles give evidence of research activities in the field of vehicle navigation technologies for at least the last twenty years and even more when considering some automated car prototypes shown in the late 1950's.

Today, as a result of the commercialization of some navigation devices and due to important research programs in Europe, japan, and the USA, it's fitting to investigate the push and pull factors affecting the implementation of these technologies. We will try to consider the global factors involved in this process.

This paper will examine:

1. Seclected technologies [without in-depth analysis of the numerous papers in this field. Such an in-depth analysis has also been presented by (Kanafani 1987, Gosling 19870].

2. Position of different economic and institutional partners and the complementary/conflicting strategies they develop;

3. Market evaluations and research programs.

Youcef-Toumi, K., et.al., "The Application of Time Delay Control to an Intelligent Cruise Control System", ACC, Vol.2, p1743-47, 0-7803-0211-7,1992 ACC/TA 13, 1992.

Summary: This paper focuses on the use of time delay control for longitudinal control and demonstration of it's advantages.

In the proposed system, a vehicle is equipped with a ranging sensor which measures the distance between itself and the preceeding vehicle. This distance is the control output of the system. The time delay controller uses past observation of the systems response and the control input to directly modify the control actions. This leads to a model independent controller whose algorithm can deal with large unpredictable system parameters and variations (ie. lead car acceleration or deceleration, changes in road condition, grade and wind). The dynamics of the lead vehicle is looked at as a time varying distrubance and can be effectively rejected.

A 1/5 scale model of an actual vehicle was controlled by the TDC algorithm to follow a generated position signal. Simulation and experimental results demonstrate smoothness of tracking action.

Several problems arose:

1 A necessary estimate of the control input gain, b, was found to be difficult. However, it was found to affect control action significantly.

2. The digital computer resolution is influential.

3. The output state, d, will have a steady state error if the leading vehicle has a constant velocity and a changing error when the velocity is changing. A suitable chosen sample time alleviates the problem.

Zanutta, Roberto, "Working Paper, Research Review of GPS for AHS Applications", SRI, November, 1993.

Summary: A brief overview of GPS is presented, followed by an explanation of these basic methods of determining the distance from the receiver to the satellites. These methods include: code tracking, code tracking with differential corrections, and carrier phase tracking. These methods provide RMS accuracy of 100-150m, 1-10m, and better than 10cm, respectively.

Code tracking, which matches the satellite pseudo random code to a similar code generated in the receiver, assumes ionosphere and troposphere delay, clock bias, multipath and ephemeris errors are insignificant. Differential GPS can be used to minimize these errors.

Differential GPS transmits corrections from a known location to compensate for the signal errors. Difficulties of DGPS, including additional hardware, correction degradation with distance, and the necessity of seeing at least four satellites by both the user and reference receiver, are not very difficult to overcome.

Carrier phase tracking, which provides the best positioning accuracy for GPS, is based on estimation of the number of carrier cycles to each satellite.The carrier cycle ambiguity problem and “fast” resolutions are discussed.

A bibliography of relevant research and articles is presented

Zhang, Wei-Bin, "A Roadway Information System for Vehicle Guidance/Control", Path Report No.912867..

Summary: This paper describes the principle of an intelligent roadway reference system (IRRS). The information capability of a discrete marker IRRS is discussed.

In the magnetic marker reference system, the natural poles of the magnetic markers are used to represent binary code. By strategically alternating the magnetic poles, information in a binary format is stored in a series of markers. The capability of an IRRS for acquiring dynamic information is limited. However, pertinent information, such as road characteristics, road information, position information, traffic sign information, may be provided by IRRS.

The information capacity of an IRRS is measured by information space rather than transmission rate. It is shown that even if very strict precision requirements apply, an IRRS is still capable of storing static information using a reasonable amount of binary codes for highway application. A vehicle using cooperative IRRS, where on vehicle information storage exists in addition to discrete markers, uses fewer binary codes than an IRRS using only roadway information.

Zhang, Wei-Bin, and Parsons, Robert E., "An Intelligent Roadway Reference System for Vehicle Lateral Guidance/Control", Institute of Trans. Studies, University of CA, Berkley, CA 94720, and California Dept. of Transportation, Sacramento, CA 94274-0001..

Summary: An Intelligent Vehicle/highway System (IVHS) may require a multifunctional roadway reference system. This roadway referce system should help the vehicle locate its lateral and longitudinal position, and provide other information required for vehicle control. This reference system is defined as an Intelligent Roadway Reference System (IRRS).

The California Program on Advanced Technology for the Highway (PATH) is developing an IRRS, consisting of roadway reference and vehicle sensing elements which can transmit necessary information for vehicle lateral guidance/control. The reference system, passive discrete markers that may code one or more bits of inforation, is installed in the center of the traffic lane. An on-board sensing system acquires the information when the vehicle passes over the reference and determies the vehicle deviation and the upcoming road geometry. This sensing/reference system may also provide information for other IVHS functions.

Zhang, Xiwen, and Cremer, Michael, "Design of RTI System Architecture Methods and Examples", IEEE-IEE VNIS, pp277-80, IEEE#0-7803-1235-X/93, 1993.

Summary: This paper outlines an approach for designing RTI (Road Transport Informatics) system architecture by means of SDL (Specification and Description Language) which was applied within the framework of system architecture development activities of the German PRO-GEN, a subprogram of PROMETHEUS. To demonstrate the consistency and effectiveness of this approach, examples of a model architecture for an integrated interurban traffic management and information system are presented.

Author Available:

"Navigation (J, of ION)", Spring, 1992,April-March,1993.

Summary: Sp 92, description of Soviet GLONASS; system. Ap 93, p 22, list of IVHS applications of GPS, p 52 title "The GPS Observables", lists error sources and correction techniques. Mr 93, p 49 title "Using GPS to Determine Attitude of a Spacecraft;" discusses subject of single, double and triple difference techniques;, S/N ratios.

"Various", IEEE Position Location and Navigation Conference, 1982.

Summary: P 10, carier to noise (C/N) exceeds 36 dB Hz, is typically 48 dB Hz for coarse/acquisition (C/A) code. Acquisition possible in 25 seconds at 36 dB Hz. P22, analysis of differential GPS (DGPS). P 25, orbital radius is 26.561 Mm.

Navigation (J. of ION), 1980.

Summary: Spring, 27,1, zenith altitude; of GPS satellites is 10,900 nautical miles, inclination is 55 degrees. period is 12 hours, orbits are circular, satellites have 7.5 year life expectancy;, satellite clocks good to 2 parts in 1013. Summer, 27, 2, discussion of navigation equations, geometric dilution of precision (GDOP). Fall,27, 3, optimal processing, discussion of Kalman filtering;. Winter,27, 4, description of locating a Mississippi river barge by message relaying to a ground station in Schenectady;, NY via two satellites.

GPS and LORAN C Library Search..

Summary: Listing of numerous references to subject.

"Relative Navigation Offers Alternative to Differential GPS", Aviation Week and Space Technology, p50, November, 1992.

Summary: Simulation of a system that places a beacon and GPS set close to a place, e,g. runway, to which you wish to navigate. The beacon transmits its GPS position, satellite selection; (or pseudorange list;). Your own GPS fix, with a small agreed-on offset, so that you hit the runway rather than the beacon, becomes identical with that of the beacon to an accuracy of 1.7 m vertical, 0.72 m horizontal, if you use the same satellites and the beacon transmits new data every six seconds.

"France Conducts Dynamic GPS Tests", Aviation Week And Space Technology, p50, November, 1992.

Summary: French GPS (Sextant Avionique; Topstar) good for 50 G and 10 km/s. DGPS; flight tests within 50 km of reference had horizontal accuracy of 1.3 m and vertical of 1.5 m. Reference was a laser tracker.

"GPS Attitude Sensing Tested", Aviation Week and Space Technology, p52, November, 1992.

Summary: Using Trimble; TANS Vector attitude receiver and 486 laptop aboard a Piper Dakota aircraft, Stanford University measured attitude to 0.1 degree accuracy and wing flexing, an indicator of vertical acceleration, to 1.4 mm. Even when only two satellites were in view, e.g. during 45 degree banking, there was no loss of attitude lock.

"Navsys Develops Low-Cost Sensor", Aviation Week and Space Technology, p52, November, 1992.

Summary: A system called Tidgit ;is described that could be used to transmit a compressed (65 kbps) description of the GPS signal received at a remote station, e.g. a radio sonde to permit its location with respect to a base station.

"ION GPS", The Institute of Navigation, 1993.

Summary: Listing of proceedings at a conference held 22 to 24 Sp 93 in Salt Lake City. Papers include several related to IVHS, including one on GPS antenna placement on cars;.

"GPS, Navtech Seminars & Book and Software Store, 1993/94 Catalog", Navtech Seminars 2775 S. Quincy Street, Suite 610 Arlington, VA 22206, 1993,1994.

Summary: Lists, among others, several books; useful to the understanding of GPS.

"GPS World Newletter", GPS World, Box 10460, Eugene, OR, 97440-2460, February, 1993.

Summary: INMARSAT to test coverage area vs accuracy of Wide Area DGPS; (WADGPS;) using its geostationary comm sat as a relay. Anticipated coverage is such that six ground reference GPS stations would provide for the Eastern Atlantic Ocean. Sextant; P-code receiver; better than 5 m. Future Instrument Landing System to be GPS based, not Microwave Landing System.

"Navtech 1993 Catalog", Navtech, Arlington, VA, 1993.

Summary: Older version of catalog described elsewhere.

"GPS World, 4", GPS World, Eugene, OR, April, 1993.

Summary: Articles on Automatic Vehicle Location;, Fleet Monitoring. There is also one of a series of articles ("Innovation: The GPS Observables") that explain concepts like pseudorange; and phase measurement; in a fashion suitable for a non-specialist.

"Magellan GPS Brain", Magellan Systems Corporation, 960 Overland Ct., San Dimas, CA, 91773, (714) 394-5000, Fx 394 7050, Mike Brower, 394 5015..

Summary: OEM board with five channels. Four continuously track while one multiplexes through other visible satellites for ephemerides and selection. Two G, 950 MPH. RF input -135 to -110 dBm. One serial port (RS-232, RS 422, NMEA or TTL compatible). DGPS-ready;.

"Turnkey DGPS Systems", MAGNAVOX Electronic Ssytems Company, 2829 Maricopa Street, Torrance, CA 90503, (310) 618-1200, Fx 618 7001..

Summary: Introductory brochure on the process of interconnecting Magnavox; (and other's) components to assemble a DGPS;. EDAC; refers to error detection and correction. Brochure holds data sheets for MX 9012 Reference station; and MX 9212 Navigator. These are 12- channel, L1; (1575.42 MHz), C/A; code receivers with a Costas threshold; of -143 dBm.

"GPS, 6-Channel Parallel Receiver, LSmart Bracket Mounting Kit", Motorola Automotive and Industrial Electronics Group, 4000 Commercial Avenue, Northbrook, IL 60062, (800) 421-2477, Fx (708) 205-2890..

Summary: 6-channel, L1;, C/A code; (1.023 MHz chip rate), carrier-aided tracking, 1000 knot, 4 G receiver. The data sheet is accompanied by another for a mounting kit.

"Various", Trimble, 645 North Mary Avenue, Sunnyvale, CA 94088-3642, (800) 827-8000, (408) 481-8000, Fx 481-6057..

Summary: 1. Ensign; and Ensign XL Marine Navigation System. Three channel GPS receiver tracks up to 9 satellites, 2 G, 650 MPH, less than 2 minute acquisition 5 hours on 4 AA cells, weighs 400 gm. XL is DGPS-ready.

2. Placer; GPS 300. Vehicle-mount, 6-channel GPS sensor for L1; band and C/A; code. Output is in a Trimble-specific, RS-232; format based on printable ASCII characters. Operates on 9 to 28 Volts (2 Watts) operating and 5 to 7 V, 0.5 mW in standby. A DGPS-ready; version is available.

3. Placer GPS/DR. This unit is similar to Item 2, except that it

consumes 4.5 W at between 10 and 32 V, contains a solid-state, piezoelectric gyro; and accepts input from the pulse odometer and back-up light of the vehicle. With these inputs it dead-reckon;s with 3 to 5 percent accuracy for up to 10 km if satellite navigation is not available.

4. SVeeSix Series. This is a series of components, including a 6-channel, L1;, C/A; GPS receiver designed for incorporation into other systems. Various features, e.g. port;s, can be configured to an OEM's requirements. This is probably the basis for the Placer systems (Items 2 and 3 above).

5. SVeeSix-CM is a credit card size;, 6-channel, 5 V, 1.5 W GPS receiver board that is probably the basis for the Ensign systems.

6. GPS Pathfinder Professional. This is a mapping/surveying system for acquiring a geographic data base;. One to five meter accuracy is obtained by parking a reference receiver at a base point and recording GPS offset as a function of time while the surveyor records GPS position and time at various places, e.g. oil or gas wells. Records are stored in a data logger and corrected later by reference to the base point records.

7. StarView is a tracking and display station that permits a fleet operator to keep track of vehicles and to record fleet movements. It is not explained whether and how this system relates to GPS.

"Magellan GPS Brain", Magellan..

Summary: See other Magellan entry.

"GPS, Magellan 5-Channel Technology", Magellan..

Summary: See other Magellan entry. Two detailed data sheets on receiver and power supply/digital boards of Magellan set.

"PONS, Parachute Offset Navigation System", Magnavox..

Summary: This brochure is a description of a full military L1, L2, C/A and P manpack GPS Navigator Set. Procured under US Army Contract DAAD05-85-C-9031, the unit is described as having been tested at YPG (Yuma) and being in engineering test. The number 788 appears on the cover of this undated document, suggesting that it may have been issued in July 1988.

"Global Positioning System", Donna R. Bell, Sales Manager, GPS Core, GPS Business Unit, Automotive and Industrial Electronics Group, 4000 Commercial Avenue, Northbrook, IL 60062. (708) 205 3892 Fx (708) 205 2890..

Summary: The Motorola; receiver is a 6-channel, L1, C/A code device organized to track 6 satellites at a time with an active antenna. Output is via a Motorola specific protocol, but NMEA 0183 Version 2.0 is available, as well as a RS-232 interface. There is a vague reference to differential systems, but no mention of an input port.

"Trimble Advanced Navigation Sensor (TANS)", Trimble, 645 North Mary Avenue, Sunnyvale, CA 94088-3642, (800) 827-8000, (408) 481-8000, Fx 481-6057, 1988.

Summary: 1. System Definition and Program User's Guide. Designed for an evaluation system comprising an IBM PC, Epson printer and TANS, this is a 1988 publication, possibly slightly out of date.

2. GPS Receiver Specification and User's Manual. Also a 1988 publication, this provides a detailed description of the plentiful information that can be derived from the GPS signal and how one manufacturer makes it available. Sensitivity is -163 dBm.

"GYROSTAR™, Piezoelectric Vibrating Gyroscope", muRata Erie, Smyrna, GA..

Summary: This manual and enclosed data sheets describe a device ($300 in sample quantities, $80 in 100,000) that is probably the basis of the Trimble Pacer GPS/DR dead reckoning heading sensor. The piezoelectric gyro; is a rate sensor and its output must be integrated.

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