Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Lateral and Longitudinal Control Analysis

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PRECURSOR SYSTEMS ANALYSES
OF
AUTOMATED HIGHWAY SYSTEMS

Activity Area D
Lateral and Longitudinal Control Analysis

Results of Research

Conducted By

Delco Systems Operations

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.

Lyle Saxton

Director, Office of Safety and Traffic Operations Research and Development

NOTICE

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16. Abstract This activity area report presents a preliminary control systems analysis of each of the Representative System Configurations (RSC's) in terms of expected performance, feasibility, complexity, affect on system safety, roadway capacity, driver involvement, operation, and maintainability. Communication systems and sensors are also discussed in their relation to vehicle control. Tradeoffs are presented for a variety of system configurations to emphasize the options available to the Automated Highway Systems (AHS) designer.		
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EXECUTIVE SUMMARY

The Automated Highway System (AHS) will reduce travel times, increase highway safety, reduce congestion, decrease the economic, physiological, and psychological costs of accidents, lessen the negative environmental impact of highway vehicles, and increase lane capacity. Lateral and longitudinal control system development will play an important role in this effort. Hardware and software performance capabilities will directly affect the achievement of each of the stated AHS goals.

Representative System Configurations (RSC's) are used in this report as a framework for discussions of various control-related concepts. A brief overview of the RSC's is presented in the Representative System Configuration section of this activity report. A detailed description can be found in the Contract Overview report.

Introduction

The prudent design and implementation of lateral and longitudinal control systems is critical to the success of the AHS. These systems must not only meet strict technical requirements, but must also be safe, reliable, economical, upgradable, maintainable, and acceptable to the general public. Key elements of these systems are described below. A brief overview of the issues and risks associated with each concept is presented as well.

System Configuration

The proper placement of vehicles on the roadway and their interaction with each other is a critical control design issue that will significantly affect overall safety, vehicle controllability, system cost, and highway capacity. Ideally, the system configuration design should allow for an increase in throughput if desired, while ensuring safe vehicle operation at all times. The amount of highway throughput available should also be controllable up to the maximum capacity level. Capacity gains should not be achieved at the expense of increased travel times.

In an AHS scenario, vehicles can be spaced on the roadway such that, assuming conservative values for operating parameters such as the deceleration level of an object or lead vehicle to be avoided (1.5 g), the deceleration capability of the following vehicle (0.3 g), and the system response delay (0.3 second), all vehicles should be able to avoid collisions with other vehicles. (Colliding with an object on the roadway remains an issue, as even an AHS cannot control everything.) This conservative vehicle spacing approach, while ensuring vehicle and occupant safety, reduces the potential capacity gains of an AHS. Using these conservative operating parameters, capacities of roughly 1,600 vehicles/h/lane are possible, but only at a low speed (20 km/h). At acceptable driving speeds (90 to 100 km/h), capacities on the order of 700 vehicles/h/lane are possible. Using more realistic values for these parameters (1.2 g, 0.6 g, and 0.3 second, respectively), capacities of 2,500 vehicles/h/lane are achievable at a speed of 40 km/h. At higher speeds (90 to 100 km/h), a capacity of roughly 1,800 vehicles/h/lane is achievable. Since current highways exhibit maximum capacities on the order of 2,000 vehicles/h/lane, these configurations do not meet the goal of increased capacity at normal highway speeds.

It is widely believed that safe AHS operation occurs either when vehicles are spaced as described above or when they are spaced very close to each other (about 1 m). The latter scenario is considered safe, since only relatively small collision velocities would potentially result from a collision between two vehicles when the lead vehicle executes a hard braking action. Unfortunately, very close vehicle spacings are generally not considered acceptable to the driving public. Also, the capacity levels they allow (6,000 vehicles/h/lane and beyond) are not only unnecessary but cannot be supported by the surrounding arterials. It would therefore be desirable to design a system that would allow higher capacities than 2,000 vehicles/h/lane, would be completely safe in terms of automated control, and would be acceptable to the AHS user.

The grouping of vehicles into units called platoons, which would include up to 20 vehicles, could achieve these goals. Platoons consisting of from 5 to 10 vehicles would be more realistic, even after the initial deployment phase. The intra-platoon spacings could vary over a range of 5 to 30 m depending on usage demands. During periods of low highway usage, vehicles could operate as single-vehicle platoons. Vehicle actions within a platoon would be coordinated such that all vehicles would begin the braking process and achieve essentially the same deceleration levels over time in response to a braking command from the platoon’s lead vehicle. The concept of coordinated braking is central to the notion of variable intra-platoon spacing.

Capacity levels well beyond the necessary and feasible range (2,000 to 6,000 vehicles/h/lane) can be achieved by configuring vehicles into platoons and coordinating all braking maneuvers. The coordinated braking concept is designed to reduce or eliminate the two critical factors involved in nonoptimal platoon braking performance: differences in decelerations between vehicles and time delays between the initiation of braking between vehicles.

In a coordinated braking scenario, the platoon lead vehicle would communicate a target platoon deceleration level based on the lowest braking performance capability of the vehicles in the platoon. All vehicles would then initiate braking at the same time. Control algorithms within each vehicle would ensure that the vehicle's deceleration was within some error tolerance of the target deceleration level at all times. As the conditions that initially prompted the braking maneuver change, the lead vehicle would issue appropriate target deceleration levels. This approach ensures no collisions between vehicles in a platoon and also achieves a high level of overall platoon braking performance. The issue of sensor, communication, and control system design is critical to the success of this approach.

The ability of a vehicle to predict or sense a malfunction that may cause loss of control or a high deceleration level in a timely manner is essential to vehicle and occupant safety. At moderate intra-platoon vehicle spacings, the potential exists for relatively large collision velocities if a vehicle decelerates at a high level unexpectedly due to a malfunction that is not predicted or sensed. However, the causes of this type of deceleration are few and the functionality generally exists to provide enough warning to the following vehicles to decelerate before a collision occurs. This will be an ongoing area for study and evaluation.

As the spacing between vehicles in a platoon decreases to achieve increased system capacity, the communication and control system complexity increases. Accurate control and reliable communication will be essential in the platoon system to guarantee safety for the driver and the vehicle. The costs associated with this type of system will be higher than those for a system where vehicles are widely spaced with little or no inter-vehicle interaction.

Lateral Control

The lateral control system will provide acceptable lane tracking performance as well as superior ride quality. The system will maintain lateral control of the vehicle under conditions of road curvature, slippery roads, side wind gusts, various levels of cornering stiffness and tire pressure, malfunctions (flat tire, communication loss), various vehicle loads and velocities, and a non-ideal reference system (missing or misaligned markers or lane lines).

Based on the potentially high cost or nonexistence of right-of-way and the need to provide increased capacity, it is very desirable in an AHS scenario to narrow the existing roadway widths. This will place added demands on the lateral control system to keep each vehicle's lateral error within an acceptable tolerance.

Representative System Configuration 1

Infrastructure-based communication and control systems will interrogate passing vehicles to determine their states (lateral components of position, velocity, and acceleration). These states can be derived from triangulation techniques and are used in conjunction with roadway maps and other necessary vehicle information to provide roadside controllers with adequate input information. Lateral control is maintained by the transmission of roadside control signals to AHS vehicles and subsequent steering actuations. Based on the complexity of this remote position control scheme, it is not considered a cost-effective, viable option for AHS lateral control.

Representative System Configuration 2

Magnetic markers will be used in this RSC as a lateral-control reference system. These markers will be placed beneath the surface of the road. Vehicles will be equipped with magnetometers to sense the lateral deviation of the vehicle with respect to the markers. The markers can be encoded with a positive or a negative polarity for the purpose of providing road curvature information or static highway information. This lateral control scheme is currently considered the leading technology to provide the greatest overall value to the AHS designer.

Representative System Configuration 3

Vision systems will be used to track lane lines and input a resulting lateral deviation to the vehicle-based lateral controllers for the purpose of lane control. An adequate reference system (lane lines) must be maintained for this concept to work effectively. For lateral control purposes, as well as other AHS functions, vision systems are a very promising technology. However, many advancements in this technology must be made prior to any practical implementation.

Longitudinal Control

The longitudinal control system will allow safe, smooth operation under conditions of potentially small vehicle separation distances, sub-optimal traction, various loads and velocities and roadway malfunctions (foreign objects, stalled vehicles, etc.). Issues and tradeoffs relating to longitudinal control are platoon size, vehicle speed, safe vehicle spacing, braking ability, communication resolution and rate, controller throughput and resolution, malfunction management, sensor accuracy and timing, and collision severity reduction.

Under conditions of heavy roadway demand, it may be desirable to form platoons of vehicles where the intra-platoon spacing is in the 1 to 10 m range. This spacing will place strict control demands on longitudinal controllers. They will be required to maintain adequate vehicle separations under nominal and emergency conditions.

Representative System Configuration 1

Infrastructure-based communication and control systems will interrogate passing vehicles to determine their vehicle states (longitudinal components of position, velocity, and acceleration). These states are derived from triangulation techniques and are used in conjunction with roadway maps and other necessary vehicle information to provide roadside controllers with adequate input information. Longitudinal control is maintained by the transmission of roadside control signals to AHS vehicles and subsequent throttle and brake actuations. Vehicle-based collision avoidance systems will function as backup longitudinal controllers in the event of a system malfunction. Based on the complexity of this remote position control method, it is not considered a cost-effective, viable option for AHS longitudinal control.

Representative System Configuration 2

Longitudinal range and range rates between vehicles in a platoon and between platoons will be derived from communication signals. This information, along with information communicated by the lead platoon vehicle and other appropriate vehicles, will be used by vehicle-based longitudinal controllers to maintain specified headways and perform longitudinal maneuvers. Vehicle velocity can be accurately derived from the magnetic reference system. Vehicle-based collision avoidance systems will function as backup longitudinal controllers in the event of a system malfunction. This longitudinal control concept offers the greatest performance-to-risk ratio of all the techniques considered.

Representative System Configuration 3

Classic time/slot controller systems utilize a traveling continuous wave as a reference for a vehicle-based control system. The vehicle control system, which is essentially a position servo controller, is designed to maintain its position relative to the pattern. The reference wave can be generated by a leaky transmission line embedded in the roadway.

In RSC 3, a slightly different approach to classical time/slot control is taken. Vehicle-based longitudinal controllers will receive desired space/time slot state information from the wayside and vehicle state information from on-board measurement systems. They will use this discrete information to control vehicle brake and throttle actuators to minimize longitudinal errors. On-board vision systems will function in a collision-avoidance mode by measuring headway and closing rate to preceding vehicles or objects. Time/slot control systems, though relatively safe, possess many performance limitations and are therefore not considered a high-value option for longitudinal control needs.

Collision Avoidance

The primary function of the collision-avoidance system in an AHS scenario is that of providing appropriate control input to the vehicle actuation systems to avoid vehicles or objects on the roadway. The secondary, though equally important, purpose of this system is to provide range and range rate information concerning preceding vehicles to the longitudinal control system (vehicle or infrastructure-based). These signals must be quite accurate at close vehicle spacings, when vehicles are within a platoon. They can be somewhat less accurate at large vehicle spacings, when a vehicle is a platoon leader.

Representative System Configuration 1

Radar-based sensors, such as microware radar and laser radar, can be used in collision avoidance systems. Microwave radar is fairly robust to environmental conditions such as rain, snow, fog, and mud. Laser radar does not generally perform well under these conditions. Both systems can detect objects at reasonably large ranges (150 m), but they may require more than an allowed amount of power to do so. At close vehicle spacings, both systems are capable of providing adequate range and range rate accuracies. Laser radar may suffer from some potential interference problems.

An advantage of laser radar is that the technology needed to enter full production with reasonable system performance currently exists. The same cannot be said for microwave radar. Cost-effective mass production of these systems may not be feasible for a few years.

Radar-based sensors are considered the leading technology in the field of collision avoidance. They will provide the best value to the AHS designer.

Representative System Configuration 2

See Representative System Configuration 1.

Representative System Configuration 3

The vision system that is used for lateral control can also be utilized for collision avoidance. The basic concept is analogous to the method a driver uses for this function. A driver will perceive the environment directly ahead of the vehicle, interpret the scene, decide on an appropriate action based on past experience, and respond with a control command. The vision system uses cameras to perceive the scene and a microprocessor to interpret this information, decide on a control action, and generate a control command.

Due to the large amount of information that must be processed and the difficulty in extracting and classifying pertinent information, vision systems generally require a significant amount of time to produce an output. Application specific hardware can be used to improve the speed of this process, but this can greatly increase the system cost. An advantage of vision-based collision avoidance systems is their wide field of view. Though vision systems possess great potential for meeting collision avoidance requirements in a cost-effective manner, many technological problems exist that must be overcome prior to any implementation.

Communication

The vehicle-vehicle, vehicle-roadside, and roadside-roadside communication requirements will be broadly defined for the purpose of identifying critical design issues for AHS information transfer. Rough measures of the complexity of the communication system will then be estimated. Looking at the communication system as a black box, the requirements will be partitioned into the following categories:

- Data rate (vehicle-to-roadside and roadside-to-vehicle).
- End-to-end communications delays.
- Allowable error rates.
- Communications access.
- Communications security.

These requirements will be examined as they relate to the operation of the communication system and the impacts that the communication approach will have on the AHS.

Representative System Configuration 1

The vehicle-roadside communication system is characterized by high transmission rates to support vehicle lateral and longitudinal control. Vehicle lateral and longitudinal states (position, velocity, and acceleration) can be derived from the communication signal. Communication links will allow wayside controllers to pass pertinent vehicle and control information between each other. There will be no vehicle-vehicle communication.

Representative System Configuration 2

Vehicle-vehicle and vehicle-roadside communication will be accomplished using the same hardware and software configuration. Transmission destinations will be defined by careful communication addressing. Vehicle-vehicle communication performance will be extremely important, since these transmissions support the control task. Range and range rate signals between vehicles in a platoon and between platoons will be derived from the communication signals. Vehicle maneuvers, such as platoon formation/separation and vehicle lane change, will be coordinated by the platoon leader. Thus, all maneuver instructions will be communicated from the roadside to the platoon leader.

Representative System Configuration 3

Roadside-vehicle transmissions at a relatively low frequency will support the longitudinal control effort. They will probably require more power than those for other RSC’s, due to the relatively large vehicle spacings and the desire to reduce the density of infrastructure-based communication systems. Vehicles will interrogate infrastructure-based transponder systems to obtain position updates. Communication links will allow wayside controllers to pass pertinent vehicle and control information between each other. There will be no vehicle-vehicle communication.

Combined Lateral and Longitudinal Control

It would be beneficial if the lateral control system worked in conjunction with the longitudinal control system, since this would improve overall control performance (especially in emergency situations), reduce vehicle and infrastructure costs, and simplify the system.

Combined control has been shown to allow vehicles to change lanes after traveling a shorter distance than those without this type of control. This capability will improve overall driver safety, as vehicles will potentially be able to do more than just decelerate to avoid objects in their paths.

Automatic Versus Manual Action

The role of the driver in the control of an AHS vehicle is an important consideration. Humans will probably always be superior to machines in their ability to recognize patterns in their environment and formulate appropriate actions based on their experiences. Machines, on the other hand, not only process information much faster than humans, but are not subject to the fatigue experienced by humans. They can also be programmed to perform flawlessly at all times, assuming an appropriate level of redundancy. The challenge is to utilize the capabilities of both the human and the machine while improving system safety and creating a comfortable driving experience. Allowing a driver to have control over certain vehicle functions may also alleviate the problem of liability to some degree.

Braking

It seems logical that the driver will slowly transfer control one function at a time to the automated system as the AHS deployment scenario unfolds. Once the AHS has reached a relatively mature state, there may still be some benefit for keeping the driver in the control loop. As was stated above, there are certain functions where a human will always be superior to a machine. In the case of vehicle braking, it seems reasonable to allow the driver to use this function. The motivating factor for this concept is that a human can classify objects and predict their actions much better than a machine can. Note, though, that driver actions would simply be in addition to existing primary automated control functions.

As an example, consider the case where a deer is standing on the side of the road. A human would be able to identify this object and predict that it may bound onto the roadway. An early braking reaction may help to avoid a collision. Safe coordinated braking will ensure following vehicle/platoon safety. Another example is that of a relatively small object on the roadway. This object may have fallen off a preceding vehicle. One of the challenges for collision avoidance systems is to detect and classify relatively small objects that are too large to safely ignore. These systems may never be able to produce the levels of detection and classification of which humans are capable. Here again, a braking maneuver initiated by the driver may help to avoid vehicle damage and occupant injury.

Steering

Vision systems that rely on passive lane markers for a lateral control reference are generally considered to function inappropriately under conditions of fog, rain, and especially snow. Unless these systems are developed to a point where they are able to maintain lane control based on infrastructure information or other visual clues, they will not function well under adverse weather conditions. Though humans also find it difficult to operate vehicles under these conditions, they have the ability to adapt to the nonoptimal environment by using infrastructure and other roadway visual clues to obtain an adequate lateral reference.

As an example, consider the case where the road is covered by snow. Drivers tend to continue on their way if their vehicles have reasonable traction capabilities (4WD, snow tires). They often create two unofficial lanes out of three. They simply follow the tire tracks of those who have gone before them and use visual clues from the infrastructure, such as barriers, trees, and other markings to guide them. In an AHS scenario, it may be desirable to allow the driver to steer the vehicle to maintain “lane” control, while the automated system performs the braking and throttle functions. It is assumed that vehicles will be equipped with some sort of traction control device. If the vehicle were to sense a lack of traction due to driver steering input, the automated steering system could limit the amount of steering to that which would not cause a loss of control. This limitation would allow the driver to maintain lane control while the vehicle maintains control with respect to the road. This, of course, places added demands on the driver during difficult driving conditions.

INTRODUCTION

Purpose

The purpose of this activity is to identify and assess the issues and risks associated with the lateral and longitudinal control of vehicles on an automated highway. The intent is not to design communication and control architectures for an AHS, but to discuss potential control requirements and the technologies that will meet these needs. The target time frame for an initial deployment of an AHS is 10 to 20 years into the future. In general, deployment issues will not be covered. However, certain issues relating to deployment will be raised in the discussions.

Organization

The activity has been divided into six task areas. The first task concerns the characterization of control situations such as entry/exit, merge/separate, and lane change for nominal and emergency situations. The second task discusses representative system-level and component-level AHS requirements. The third task identifies significant tradeoffs that result from various control approaches. The fourth task discusses issues relating to coordinated lateral and longitudinal control. The fifth task addresses the need and/or desirability of manual and automatic control. The sixth task defines the technology that is needed to implement a successful AHS. Comparisons are made to state-of-the-art technology. Also, each RSC is examined to determine whether its lateral and longitudinal control concepts meet these requirements. The material for Task 7, as defined in the Research Summary Report[1], is incorporated into the previous tasks and into the activity conclusion section. It is therefore not a standalone task report.

Issues

One of the primary goals of this effort is to discuss issues relating to automated vehicle control. A representative list of issues is defined in the Compendium of PSA’s. In general, the following issues will be discussed in detail:

- Lateral control system references, sensors, algorithms, locations, performances.
- Longitudinal control system references, sensors, algorithms, locations, performances.

- Vehicle configuration on the roadway — platoon (spacing within, between) vs. single unit.
- Role of the driver in the vehicle control system.
- Feasibility and performance of combined lateral and longitudinal control.
- Collision avoidance system capabilities and use as a longitudinal reference signal generator.
- Specific tradeoffs between:
  - Capacity and safety.
  - Lane widths and controllability.
  - Platoon size and controllability.
  - Deceleration techniques on steep grades.

In response to a request by the Federal Highway Administration (FHWA), special consideration was given to the issues surrounding the formation of vehicles into platoons. Task 3 discusses the majority of these issues, though the platoon concept is referred to throughout the report.

Approach

The approach taken in this activity was to uncover as many issues and risks associated with lateral and longitudinal control as possible. RSC's were defined to serve as a framework in which to discuss various system architectures. Within that framework, an emphasis was placed on discussing the attributes of various system control components, such as lateral control via magnetic markers, communication/ranging for longitudinal control, etc., and their possible interaction with other system components. Since Delco Systems Operations has an extensive automotive background, many of the issues relating to control are directly associated with current and planned vehicle components and performance capabilities.

The system and component level requirements provided in Task 2 are meant to serve as guidelines for eventual AHS requirements. Where possible, the guiding assumptions for these requirements are given. Quite often, a parameter range is stated for a specific requirement, rather than an absolute number, so as to allow a certain level of design flexibility.

Assumptions

In much of the analysis, worst-case parameters are used to determine requirement bounds. An example is the use of 160 km/h as the maximum operating speed. In terms of safe headway calculations, this value will result in rather large spacings between vehicles. When it is combined with worst-case deceleration and time delay values, unrealistic headway requirements result. Therefore, the reader should note where these types of values are used and apply an appropriate realism factor.

In general, requirements for an AHS in terms of lateral and longitudinal control are specified for systems that may exist in 10 to 20 years. Technologies that exist today are discussed, as well as technologies that may exist in the future.

REPRESENTATIVE SYSTEM CONFIGURATIONS

Design goals will be evaluated for three distinct Representative System Configurations. Table 1 defines the general attributes of each RSC. The Contract Overview report contains a full description of all RSC attributes. The roadway/infrastructure architectures for each RSC considered in this study are presented in figures 1 through 3. These diagrams depict basic hardware and communication schemes.

The components of each RSC are not necessarily meant to be considered only in the context of that RSC. To some extent, the RSC's are frameworks within which concepts such as vision-based steering systems and radar-based collision avoidance systems can be discussed. These systems may be applicable in more than one RSC. They may also be applicable to RSC's not discussed in this report.

Table 1. General RSC Attributes

Attribute	RSC 1 Infrastructure-Centered Platoon Control	RSC 2 Vehicle-Centered Platoon Control	RSC 3 Space/Time Slot Control
Coordination Unit	Small Platoon	Large Platoon	Single Vehicle Slot
Inter-Unit Control	Asynchronous	Asynchronous	Synchronous
Vehicle Class	Passenger and Light Truck	Passenger and Light Truck	Passenger, Light Truck, Heavy Truck and Transit
Lane Width	Normal	Narrow	Normal
Performance	Inclusive	High Performance	Inclusive
Vehicle/Roadway Interface	Rubber Tires	Rubber Tires	Rubber Tires
Propulsion	Internal Combustion Engine (ICE) and Electric With On - Board Source	ICE	ICE
Lateral Control	• Wayside Communication - Based Sensing • Wayside Electronic Map Reference • Wayside Control	• Vehicle Sensing of Magnetic Markers • Vehicle Control	• Vehicle Optical Lane Sensing • Vehicle Control
Longitudinal Control	• Wayside Communication - Based Sensing • Wayside Electronic Map Reference • Wayside Control Enhanced by Vehicle Collision Avoidance System	• Vehicle Communication - Based Sensing • Vehicle Control Enhanced by Vehicle Collision Avoidance System	• Wayside Generation of Vehicle State Requirements • Vehicle Control
Collision Avoidance	Vehicle Radar System	Vehicle Radar System	Vehicle Vision System
Longitudinal Position Location	Wayside Communication-Based Ranging	Vehicle Sensing of Coded Magnetic Markers	Vehicle Wheel Speed Sensing Enhanced by Wayside Tag System or GPS
Check-In Delay Time	Delay	No Delay	Delay
Unqualified Vehicle Entry Prevention	Physical Barrier	Electronic Barrier	Enforcement
Entry To Automated Lane	Dedicated Facility	Dedicated Facility	Normal Highway Lane
Driver Monitoring For Check-Out	Localized Roadway/Vehicle	Localized Roadway/Vehicle	Continuous In-Vehicle Monitoring
Traffic Management	Regional	Regional	Regional
Inter-Vehicle Control	Zone	Vehicle	Zone/Regional
Malfunction Management	Zone	Vehicle/Zone	Zone/Vehicle
Communications Vehicle To Vehicle	None	Vehicle Based Communications/Ranging	None
Communications Vehicle To Roadside	Two-Way Communication Tag	Same As Vehicle To Vehicle Or Public	Two-Way Communication Tag

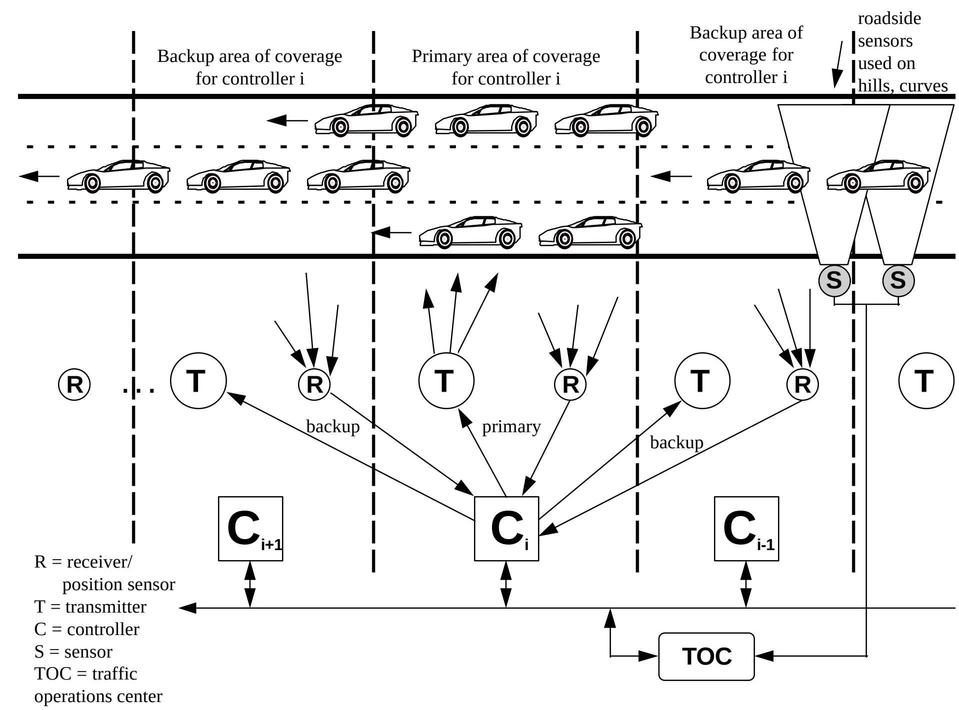


Figure 1. RSC 1 Roadway/Infrastructure Architecture

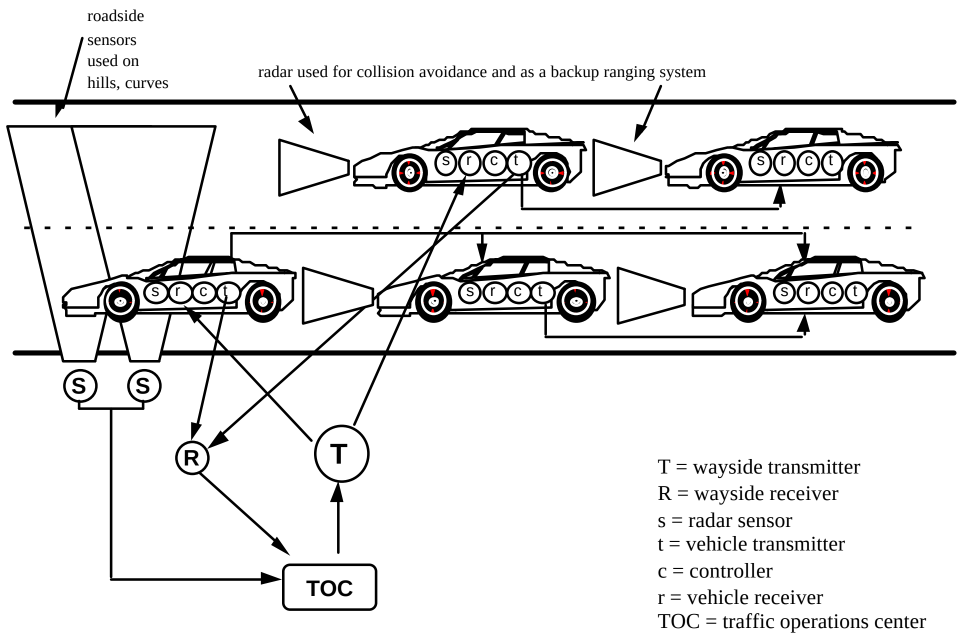


Figure 2. RSC 2 Roadway/Infrastructure Architecture

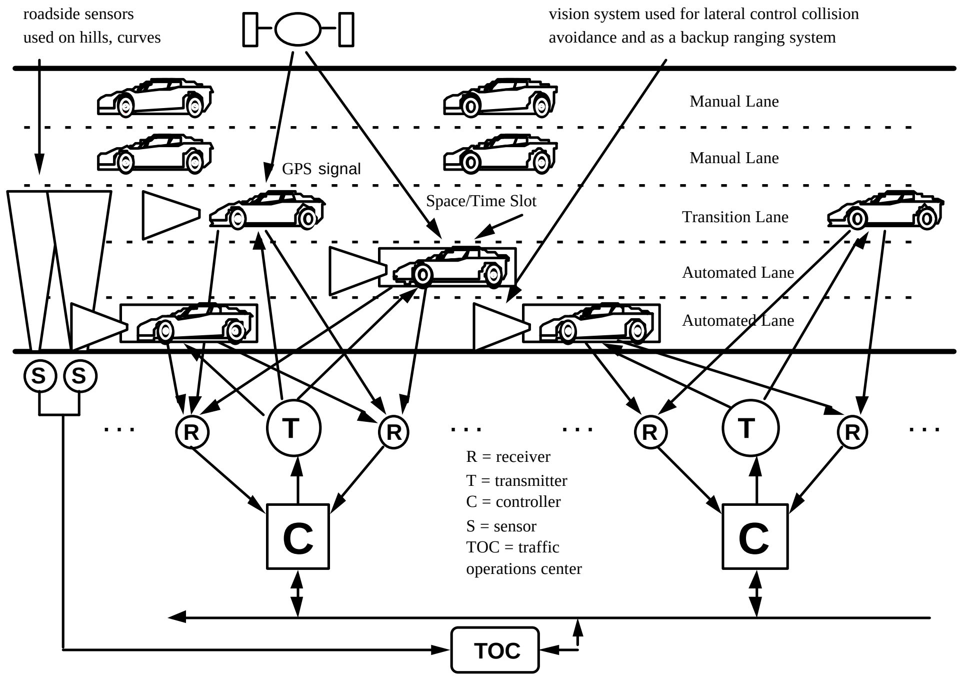


Figure 3. RSC 3 Roadway/Infrastructure Architecture

TECHNICAL DISCUSSION

Task 1. Typical Control Situations

Typical AHS platoon or time slot maneuvers will require some form of lateral and/or longitudinal control. These maneuvers are based on highway architecture assumptions. For RSC's 1 and 2, each vehicle will transition from a manually-controlled road to an automatically-controlled AHS road via a check-in area. The manual and automatic highway system will be segregated. The checkout operation will transition a vehicle from the automatically-controlled highway to a manually-controlled road. For RSC 3, a vehicle will enter a manually-controlled highway, maneuver into the transition lane, and request entry onto the AHS roadway. If permission is granted, the system will assume vehicle control and maneuver the vehicle into the designated space/time slot. The roadside system will maintain the vehicle in this or another appropriate slot until the vehicle reaches its desired exit.

AHS vehicles will utilize lateral and longitudinal control to safely and efficiently negotiate various roadway maneuvering tasks. Concepts such as roadway entry and exit, platoon merging and separation, headway maintenance, intersection merging, platoon or time slot lane change, and emergency handling are considered a core set of expected AHS maneuvers. Each maneuver will be characterized in terms of its control requirements for each RSC.

Roadway Entry

For all RSC's, vehicles entering an AHS roadway will be smoothly controlled such that performance goals are met without compromising ride comfort. All merge maneuvers into AHS traffic will occur collision-free and will minimize potential disturbances in the existing traffic flow. To the extent possible, vehicles will be maneuvered into appropriate platoons/slots such that overall traffic flow is optimized in terms of the number of required maneuvers, travel time, capacity constraints, etc.

Representative System Configuration 1

In this case, the wayside controller will accurately track each vehicle's position in order to control it in a platoon configuration while the platoon is operating on the transition roadway prior to entering a standard AHS lane. If multiple vehicles request entry at essentially the same time (determined by the check-in system), the system could begin lateral/longitudinal control at the entry station by organizing a platoon and moving it safely into the flow of AHS traffic. One or two wayside controller/transmitter/receiver systems may need to be dedicated to processing platoons entering the roadway. The wayside system will monitor the status of platoons currently on the AHS roadway and will maneuver them to allow space for oncoming platoons. Once the platoons have entered, control can be transferred normally to the next controller along the wayside.

The entry of either a single vehicle or a platoon onto the AHS roadway will be either via direct entry from the check-in transition lane to the AHS roadway or via the transition lane from the check-in station to another transition lane parallel to the roadway and then onto the roadway. The choice depends on the lateral control capabilities of the system, available right of way, and vehicle performance capabilities. The second option seems more reasonable for RSC 1, since vehicles with a variety of performance levels, including those with relatively low performance, will be considered. For this case, the extra parallel transition lane may be required for a platoon to reach appropriate merging speed when right of way is limited.

Representative System Configuration 2

For RSC 2, it would be difficult to form a platoon prior to entry into an AHS lane because of the lack of a check-in pause. Also, it is doubtful that the transition roadway between the check-in station and the main roadway would be long enough to assemble a number of AHS vehicles that checked in on the fly into standard platoons. It would seem more reasonable in the case of RSC 2 to allow individual vehicles to enter the AHS roadway under control of the Traffic Operations Center (TOC). The wayside system would receive information concerning the positions of platoons currently on the AHS roadway in the lane closest to the entry station and the position of the vehicles trying to enter the AHS roadway. This information would come from vehicles that utilized a position measurement system such as a discrete marker reference system. The TOC would process this information and command all appropriate vehicles currently on the road such that the entering vehicles could proceed safely. This could be accomplished by either platoon lane change, acceleration or deceleration.

Since RSC 2 allows only high performance vehicles, a more direct entry onto the roadway than that proposed for RSC 1 would seem reasonable and would cost less than building an extra transition lane for each entry point. However, a smooth lateral control transition into the first AHS lane remains a question. Since the vehicle-based lateral control measurement system senses magnets placed down the middle of the lane, there may be a control problem when a vehicle comes to an area where the two lines of magnets merge. It is conceivable, though, that the TOC could inform the vehicle's controller to expect this type of magnetic reference signal. The controller could then take the appropriate action to smoothly merge. Note that the method used to change lanes could also be employed here to preclude this potential problem (see lane change below).

Representative System Configuration 3

For RSC 3, the vehicle will manually enter the manually-controlled roadway and move into the transition lane. At this point, the driver can request entry into the adjacent AHS lane. The system will process this request and give approval when the driver and vehicle have satisfied all check-in requirements and a sufficient space/time slot has been located. Once approval is given to enter the nearest AHS lane, the system will assume lateral and longitudinal control of the vehicle and maneuver it into the most appropriate space/time slot. The AHS will control the vehicle while it is in the transition lane after the system has granted permission to the vehicle to enter the nearest AHS lane. In an AHS roadway of two or more lanes, vehicles already in an AHS lane may be moved over to accommodate newly arriving vehicles. Due to the capacity limitations of this system and the randomness of AHS entry requests, the ability of the system to accommodate user requests may be a problem.

Platoon Merging

A platoon can be composed of one or many vehicles. It may be merged at the front, middle, or back of another platoon. A merge maneuver is defined as the formation of one platoon from two or more separate platoons all in the same lane. If necessary, a platoon lane change can precede the merge. For RSC's 1 and 2, the TOC will determine the best place on the roadway to put individual vehicles based on destination, current flow conditions, local platoon sizes, and road conditions. During the merge maneuver, coordination will be necessary between both platoons to ensure vehicle safety during possible emergency braking maneuvers. Vehicle accelerations will also be limited to ensure ride comfort.

Platoon merging will generally take place to accommodate capacity demands. It is conceivable that in low traffic flow conditions, vehicles could travel in single-vehicle platoons. This concept is advantageous from a vehicle-safety standpoint. It may also be advantageous from a driver-acceptance viewpoint, but human factors studies need to be conducted to determine this. In high-density conditions, where the current platoon configurations are non-optimal, two multi-vehicle platoons may be required to merge. An example would be the merging of a 4-car platoon with a 3-car platoon either in an adjacent lane, or in front of or back of the 3-car platoon. This is a very realistic scenario, as the platoon configurations will be constantly changing (and therefore at times becoming non-optimal) as vehicles enter and exit the roadway.

<u>Representative System Configuration 1</u>

For RSC 1, both lateral and longitudinal control would be required to merge a platoon with a platoon. The lateral function is simply that of keeping the vehicles within the lane boundaries according to acceptable deviations. Once the vehicles are all in the same lane, the wayside controller will send longitudinal control signals to the lead vehicle in the trailing platoon so that it will be placed behind the last vehicle in the preceding platoon. Longitudinal control signals will also be sent to all other vehicles in the trailing platoon to maintain their intra-platoon distances.

<u>Representative System Configuration 2</u>

For RSC 2, the merging process is similar to that described for RSC 1. The TOC will command the vehicle controller in the trailing platoon to close the longitudinal gap between the two successive platoons. The lead vehicle in what used to be the trailing platoon will now undertake the vehicle following task by establishing intra-platoon communication with the preceding platoon. The other vehicles in the trailing platoon will maintain their intra-platoon spacings via the communication/ranging system. The lateral function is simply that of keeping the vehicles within the lane boundaries according to acceptable deviations. The wayside system uses input from the vehicle position measurement system to define the state (position, velocity, and acceleration) of each AHS vehicle in its jurisdiction. This information is used to safely maneuver and track all vehicles.

From a safety standpoint, it may be prudent to avoid merging two platoons in the same lane which are originally separated by a safe distance. The platoons would pass through the area of greatest potential impact velocity as they were merging. If a malfunction or other emergency condition occurred that required the application of full braking during this period, the potential for injury and damage would be quite high. A safer alternative to standard merging would be to command the trailing platoon to change lanes, decrease its effective distance from the lead platoon, then change lanes back into its original lane directly behind the lead platoon. If a 1 m intra-platoon gap is desired, the second lane change would bring the trailing platoon to within about 3 m. This lane change would be followed by a merge maneuver which would achieve the desired spacing. The approximate 3 m spacing would allow for any errors in longitudinal control signals due to differences in aerodynamic forces as the platoon changes lanes. Note, however, that intelligent control systems can be envisioned to coordinate multi-vehicle braking to alleviate the problem of a large velocity impact. Refer to the section concerning the platoon concept for more details.

Representative System Configuration 3

Platoon merging does not apply to RSC 3, since this RSC does not support platoons.

Platoon Separation

The lateral and longitudinal control methods for this maneuver are similar to those discussed for the merge maneuver. There are various reasons to separate either a single vehicle or a multi-vehicle platoon from a platoon. As each vehicle nears its destination, it must be maneuvered into the exiting lane. Assuming that the vehicle was in a platoon, this maneuver will require a separation operation. Also, a vehicle may experience a hardware degradation or failure and need to be maneuvered out of its platoon to the side of the road. Platoons may be separated or even dissolved by many separation operations if traffic density is relatively low, improving not only safety but driver acceptance and comfort as well.

Representative System Configurations 1 and 2

For RSC’s 1 and 2, the TOC will determine the need for a separation operation. If a vehicle in the middle of a platoon must exit, possibly all of the vehicles in the platoon, as well as other platoons, may be required to alter their speeds. The TOC will define an acceptable spacing around the exiting vehicle. This spacing will be a function of the ability of the longitudinal control system to maintain the desired intra-platoon spacings as the vehicle changes lanes to exit the platoon. The controller will ensure that this gap is established and maintained until the separation is completed. An example is as follows. If more than a minimum distance exists between a platoon and the preceding platoon, the vehicles in front of the exiting vehicle will increase their velocities to open up a space. Likewise, if more than a minimum distance exists between a platoon and the platoon following it, the vehicles behind the exiting vehicle will be required to decrease their speed to open another space. If only one or the other condition is true, then only one group of vehicles as well as the exiting vehicle will alter their speeds appropriately. There are, of course, many versions of this logic. If the lead vehicle, the tail vehicle, or a consecutive group of vehicles in a platoon must exit, similar control schemes will be used. Clearly, the TOC will be relied upon to coordinate and optimize the maneuvers.

Representative System Configuration 1

For RSC 1, the wayside controller will send longitudinal commands to the appropriate vehicles to carry out the maneuver. Lateral control will be maintained independent of the separation maneuver.

Representative System Configuration 2

For RSC 2, the TOC would command the vehicle-based controllers to execute the maneuvers. Lateral control will be maintained independent of the separation maneuver.

Representative System Configuration 3

Platoon separation does not apply to RSC 3, since this RSC does not support platoons.

Headway Maintenance

Representative System Configuration 1

For RSC 1, the TOC will determine appropriate inter-platoon and intra-platoon spacings as well as platoon velocities. The spacings will be a function of the number of vehicles in each platoon as well as their characteristics, the platoon velocity, and vehicle braking abilities. These braking abilities depend on vehicle hardware, communications delays, and road and tire conditions. The intra-platoon distances may be constant or variable, depending on eventual system performance. In RSC 1, the wayside controller will process communication signals to derive an estimate of range to each vehicle. Using this information and an electronic map of the roadway in its jurisdiction, the controller will command vehicles such that distances between platoons and within platoons will be maintained.

Representative System Configuration 2

For RSC 2, the TOC will determine appropriate inter-platoon spacings based on maintaining safe stopping distances. Each vehicle will determine an appropriate headway within a platoon. The type of headway policy (constant or variable) will be communicated to the lead vehicle in each platoon from the wayside TOC. Variable spacings will depend on vehicle characteristics, roadway qualities, and operating velocities. Communication between vehicles will be used to estimate the intra-platoon distances.

Representative System Configuration 3

The space/time slot controllers will define slot spacings and velocities for RSC 3. This information will be transmitted to each vehicle, which will maintain its position relative to the slot. Slot spacings will be a function of vehicle characteristics, such as current velocity and braking and acceleration capabilities. Vehicles will acquire position, velocity, and acceleration information using on-board measurement and communication systems. This information along with the slot location will determine the vehicle's longitudinal error. The vehicle controller will process this information and command the on-board actuation systems appropriately. An accurate measurement system, such as differential GPS or wayside tags, will correct any deviations in the state measurement system at regular intervals along the roadway (or as needed).

Merging Platoons/Slots at an Intersection

Representative System Configurations 1 and 2

For RSC's 1 and 2, the TOC will ensure that platoons can merge safely at roadway intersections. Representative interchanges are defined in figure 4. Other configurations, such as directional, scissor, trumpet, buttonhook, left side, etc., exhibit similar merge/separate control problems. Since the TOC knows the states of all AHS vehicles within its jurisdiction, it will be able to maneuver platoons prior to the intersection zone such that space will be available for the merging maneuver. It may be necessary to limit or restrict platoon configuration changes and alter platoon velocities within a certain range of the intersection to facilitate advanced space planning. A reasonable range may be 2 km. The lateral and longitudinal control aspects of the actual merge maneuver are the same as those described above in the roadway entry section.

Representative System Configuration 3

For RSC 3, the TOC will coordinate intersection merging maneuvers well in advance of the intersection. The management system will place strict destination request controls on AHS users

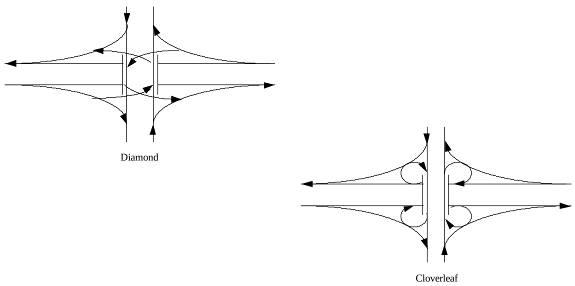


Figure 4. Typical Freeway Interchanges

so that once a destination has been entered into the system, changes can only be made when they don't affect intersection control management. The TOC will alter operating parameters in an attempt to accommodate all merging vehicles without a change in operating speed. Depending on the present state of the operating parameters, the reduction of slot velocities may increase lane capacity. Due to the relatively low traffic capacity supported by this RSC, the potential exists for lane backups prior to the intersection zone. These backups may affect the number of vehicles allowed to enter the AHS lanes from the transition lane.

Platoon/Slot Lane Change

One of the most significant factors reducing current highway capacity is the inefficient changes in speed generated by drivers. Once the highway becomes automated, this will no longer be a problem. At that point, the remaining major cause of traffic flow disruption leading to reduced capacity will be lane-change maneuvers. Therefore, control systems must be capable of performing these maneuvers efficiently. Lane-change maneuvers should be designed to provide ride comfort and avoid collisions.

For all RSC's, the TOC will track the positions of all vehicles over time. It will coordinate lane-change maneuvers to ensure that safe headways are maintained. The states (position, velocity, and acceleration) of vehicles in lane-change destination lanes will be considered prior to issuing a lane-change authorization. The system will choose to either maneuver vehicles in the destination lane to make room for new vehicles or wait for those vehicles to clear the area based on their present velocities.

Representative System Configuration 1

For RSC 1, the wayside TOC will communicate lane-change requests to the wayside controller to accommodate platoon destinations, improve traffic flow, give priority to emergency vehicles, and execute emergency maneuvering. The wayside controller will communicate lateral and longitudinal commands to the appropriate platoons to carry out the desired maneuver. The TOC will maneuver the platoon requiring a lane change only when the path is clear of other vehicles. Also, consideration must be given to emergency vehicles currently on the roadway and vehicles entering the roadway at an upcoming onramp. The wayside should synchronously control all the vehicles in the merging platoon to change lanes at an appropriate time; roughly the same control signal would be sent to each vehicle, depending on the specific actuation hardware and vehicle response for each vehicle in the platoon.

The lateral control system will be required to keep vehicles in each platoon aligned properly with the road. The zero error state for each vehicle would be the center of the target lane. The longitudinal control task during lane change will be essentially unchanged from that of controlling a platoon in steady-state mode (traveling in one lane). For the condition of high traffic density, where platoons of various sizes are separated by minimum headways, other platoons may be required to change their speeds to allow a platoon to merge into their lane. Note, though, that there are certainly ways of optimizing a given high-density situation to improve traffic flow. Examples are: consolidating fragmented platoons into optimal sizes, varying overall traffic speeds while maintaining safety margins, and maneuvering platoons to achieve a uniform density across all traffic lanes.

Representative System Configuration 2

For RSC 2, the lateral and longitudinal control system is located on the vehicle. Information is transmitted to and from the TOC. This system will communicate lane-change commands to the platoon’s lead vehicle for the same reasons described for RSC 1. The lead vehicle will then synchronously communicate the lane change command to the other vehicles in its platoon. The TOC must know the positions of all platoons in the immediate area in order to command a lane change. The vehicles in the platoon will carry out this lane change maneuver using on-board controllers, sensors, and actuators.

As an example, an operational lateral control system developed by PATH uses magnetic markers and magnetometers. The region of high magnetic resolution is within 25 cm of the center of the lane. Coarser resolution is achievable outside this range. The standard lane width is 366 cm. AHS lane widths will probably be in the 244 to 305 cm range. RSC 2 considers 244 cm lane widths. During lane changes, the vehicle controller would likely receive accurate marker position information only near the centers of each lane. The controller would operate in an open loop mode while the vehicle was in the “dead zone” between lane centers. PATH studies have shown no control degradation for vehicles outside the 25 cm high-accuracy range. The lateral controller only needs to know that the vehicle is “too far away from the lane center.” Though this system is capable of lane changes, it is desirable to maintain a lane deviation signal throughout the lane-change maneuver. Further refinements to this system may achieve this goal.

Longitudinal control for each vehicle in a platoon will be achieved by its communication/ranging system and commands from the TOC. This concept is the same as that for maintaining headway and intra-platoon distances during steady-state operation (traveling in one lane with no specific maneuvering).

For RSC 2, lateral deviation is measured with respect to magnetic markers placed in the center of each lane. Longitudinal deviation is derived from the intra-platoon communication signals. During a lane change, ranging information could become inaccurate. However, with the use of the lateral deviation signal, the true range to the preceding vehicle can be determined by the on-board computer. This concept applies to steady-state control as well.

Representative System Configuration 3

For RSC 3, the lane-change maneuver will be coordinated by the TOC. Once an empty slot in an adjacent lane has been located, the on-board controller will move the vehicle laterally into that slot. If traffic density is high, and all slots in the lane to which a vehicle must be moved are filled, the TOC may adjust the velocities of the slots (and therefore the velocities of the vehicles in the slots) in the adjacent lane. This adjustment will create a new slot for the vehicle to enter.

RSC 3 employs a vision-based lateral control system. The goal during lane change is to accurately detect the edges of the lane the vehicle is currently in as well as the edges of the lane the vehicle is merging to. The control algorithm will essentially steer the vehicle until the lane edge on one side of the vehicle has moved across the front of the vehicle and a new lane edge has appeared in the original lane edge position. Some current problems with such a system are the detection of the lane edge during bad weather or when the road is covered in snow, the relatively high cost of vision systems, and the relatively slow image processing time.

Exit from the Roadway

For all RSC's, the TOC will be designed to meet the destination requests of AHS vehicles. The system will maneuver vehicles that are nearing their destinations into the lane closest to the exit. This will, of course, entail some form of lane change or merge maneuver. The specific control methods for these maneuvers have been discussed for each RSC in the above sections.

Representative System Configuration 1

The control scheme for RSC 1 consists of a wayside controller/transceiver system and a vehicle transceiver/actuation system. A wayside controller will be responsible for maneuvering the vehicle from the highway onto the exit roadway. A separate controller may be required to process both entering and exiting AHS traffic. Based on the ability of the driver to resume manual control, the system will either transfer control to the driver or maneuver the vehicle into some form of holding area, where the vehicle will be stopped.

Representative System Configuration 2

The control method for RSC 2 consists of a wayside management/communication system and a vehicle sensor/controller/actuation system. The wayside will communicate the need for the vehicle to exit the roadway. The on-board controller will then maneuver the vehicle into the exit transition lane. The vehicle will follow the magnetic markers in this lane as the lane turns away from the AHS highway. The TOC must know the position of the vehicle on the roadway to properly command a transition from the AHS roadway to the exit lane. Again, some form of check-out procedure would take place and the results would be communicated to the vehicle. The controller would then either relinquish control or maneuver the vehicle into some form of holding area.

Representative System Configuration 3

For RSC 3, the TOC will maneuver the vehicle into the transition lane using commands from the space/time slot controller. This maneuver assumes that the driver has passed the check-out procedure. The controller will then return control to the driver, who will then exit the transition lane and merge into manually-controlled traffic. The vision-based collision avoidance system will longitudinally control the vehicle until the TOC returns control to the driver. This control is required since the wayside sensing system cannot track and control manually-driven vehicles entering the transition lane.

Emergency Maneuvers

Successful emergency maneuvers require appropriate sensing of the problem, decision-making logic, and vehicle operation. Since the majority of roadway problems are unforeseen, the sensing and decision functions are very difficult. Time delays may degrade performance as the decision logic processor may be located on the infrastructure. Also, communication to other platoons concerning the problem and the intended actions of the platoons directly involved complicates the issue. In the event of a system failure, the driver will be notified of the problem. During emergency situations, driver comfort will be sacrificed to achieve optimal maneuvering performance.

In the case of a lane hazard such as an object on the road or a stalled vehicle, the TOC will close that lane to all traffic except maintenance personnel. For all RSC's, collision avoidance radar with a range of around 350 m can be used to detect objects on the roadway. This value is based on a safe stopping distance under the conditions of a brick wall failure, 0.3 g braking, 0.3 second delay and an initial velocity of 160 km/h. Clearly, these assumptions are very conservative. Since the TOC constantly monitors the status of each AHS vehicle, it will be informed of vehicular malfunctions. The necessary evasive maneuvers will then be communicated to each AHS vehicle, and the problem lane can be closed. Where the roadway is designed with a large amount of curvature, or where it is built over a hill, sensors may need to be placed on the infrastructure to detect stalled vehicles or foreign objects. This is due to the fact that a radar or vision system placed on the front of a vehicle cannot "see" around curves, especially in an urban environment where buildings or other objects obstruct the view.

Reflecting objects placed strategically on the wayside may alleviate the sensing problem for radar systems.

Under the scenario of bad road or weather conditions caused by ice, oil, fog, rain, snow, wind, or potholes, the TOC will command a speed reduction or a lane closure. For all RSC’s, road condition sensors placed strategically along appropriate roadways may be able to adequately sense the presence of ice and communicate this information to the management system. Other problem conditions can be communicated to the management system by the drivers of AHS vehicles, vehicle-mounted sensors, or maintenance personnel. Also, feedback from vehicle systems to the TOC can be intelligently processed to determine whether these adverse conditions exist.

In the event of a loss of communication either from the wayside to AHS vehicles or between AHS vehicles, redundant transceiver systems will be used. For a complete loss of communication to occur from the wayside to AHS vehicles, multiple transmitters would have to fail. For RSC 2, a change of control algorithm from one that requires velocity and acceleration information from the lead vehicle to one that does not can temporarily alleviate the problem of a loss of lead vehicle communication. However, this is a non-ideal case and should be corrected as soon as possible. If the inter-platoon communication system used for headway maintenance fails, the collision avoidance system can be used.

In the event of a failure of a vehicle function, the driver will be alerted and the vehicle will be maneuvered off the AHS roadway or pulled over to the emergency lane as soon as possible. If the problem is only a degradation of performance, the driver will be informed and the vehicle may be allowed to continue. Platoons in the immediate area will be commanded to give more space than normal to the exiting vehicle. The driver may be required to operate some of the vehicle functions in the event of a complete subsystem failure. However, this is a very undesirable situation. For all RSC’s, the wayside may be able to sense the malfunction of a vehicle sensor or actuator, as it could constantly monitor these functions and compare their performance against historical or theoretical results.

Task 2. Sensor and Control Requirements

System-Level Requirements

System-level requirements are presented below to characterize the desired functionality of the AHS lateral and longitudinal control system. Specific values and a rationale are given to completely define a requirement whenever possible. The requirements and issues discussed are expected to be applicable to an AHS system 10 to 20 years from now.

Representative System Configuration 1

Actuation

All actuators will be electronically controlled. They will be capable of operating at external air temperatures from –60° C to +60° C.

A steering actuator will be used to convert control signals into steering motions appropriate to adequately steer the vehicle. This device will be characterized by dynamics that offer an appropriate level of response to control signals. The placement of the actuator along the steering mechanism will be a vehicle design feature. The ability to retrofit this piece of hardware will be taken into consideration during the design process. Clearly, the force needed to turn a vehicle's wheels decreases considerably as the vehicle's velocity increases. The actuator will therefore be designed to satisfy steering rate requirements at a variety of speeds.

The accuracy of the system will be the greater of ±0.1 degree at the tire/road interface or 4 percent of the steering angle. The steering rate saturation limit for a stationary vehicle on a dry asphalt road will be 20 deg/s or higher. These values result from PATH's test vehicle performance requirements.

Table 2 presents vehicle steering rates for a two-lane highway for various representative vehicle speeds, roadway superelevations, and curvature radii. These values were obtained from a highway design manual.[2] The steering actuation system must be able to produce vehicle rates in excess of those listed in the table. Expected AHS operating speeds on flat, straight roads may approach 160 km/h. Assuming that communication, control and vehicle systems can meet this specification, required vehicle turning rates may be larger than those given in the table. These concepts must all be considered during the design process.

Brake and throttle actuation systems will be employed in each vehicle. The braking system will be capable of at least 0.6 g deceleration levels for passenger cars under ideal road conditions. It is clearly advantageous from a control and safety perspective to require higher levels of braking, but this requirement may exclude too many vehicles from the AHS. Brake systems will exhibit no more than a 250 ms delay to reach their full braking force. These requirements are based mainly on the capabilities exhibited by modern vehicles.

Table 2. Representative Vehicle Steering Rates

Speed (km/h)	Superelevation (%)	Radius of Curvature (m)	Vehicle Steering Rate (deg/s)
48	8	79	9.7
48	2	582	1.32
96	2.3	1,747	0.87
96	5.1	699	2.2
96	7.8	436	3.52
113	8	582	3.08

To achieve an accurate and timely braking response, the control signal should enter the brake system as close to the brake pad/wheel interface as possible. The minimum brake actuator bandwidth should be 5 Hz.[] The throttle actuation system should be characterized by a minimum saturation rate of 400 deg/s and a minimum bandwidth of 5 Hz.[3] Brake pressure control accuracy equivalent to ±0.03 g on dry asphalt is required.

The throttle actuator will have a minimum saturation rate of 500 deg/s. Its accuracy will be better than ±0.5 degrees. The bandwidth will be at least 5 Hz. These values are based mainly on the results of PATH studies.

Measurement

The steering angle measurement system will be capable of accurately measuring steering wheel angle throughout the entire range of wheel motion.

Vehicle control algorithms require various input signals. Assuming that vehicle body translations and rotations, such as lateral and longitudinal position, velocity, and acceleration, and vehicle yaw rate are needed for the control effort, they must be measured. In general, the accuracies and ranges of the measurements will depend on the requirements of the control algorithm. Listed below are representative ranges and accuracies.

Lateral and longitudinal position measurements will be accurate to within 5 cm. Longitudinal velocity will be measured for a range of speeds from 0 to 160 km/h. Lateral velocity will be measured in the range ±5 m/s, since this range bounds controlled vehicle lateral motion. Lateral and longitudinal velocity will be accurate to within 0.05 m/s. These values are based on considerations of maximum vehicle velocities and vehicle size with respect to lane width and potentially small headways. The yaw rate measurement system will measure vehicle rates in excess of those given in table 2. The capability of measuring rates up to 30 deg/s should be adequate. The system will also be accurate to 5×10^{-2} deg/s. The lateral acceleration measurement system will measure accelerations up to ±10 m/s^2. It is doubtful that larger lateral accelerations will be imposed on a vehicle. It will be accurate to 5×10^{-2} m/s^2. This is based on the need for an accurate lateral acceleration measurement control input to guarantee ride comfort. The longitudinal acceleration measurement system will measure accelerations in the range –20 m/s^2 to 5 m/s^2. It will be accurate to 1×10^{-2} m/s^2. It is doubtful that a vehicle will experience decelerations in excess of 2 g (≅20 m/s^2) except during a collision. Since control algorithms will be designed to limit accelerations to within 0.2 g under steady-state conditions (for rider comfort), a measurement capability of 0.5 g is more than adequate.

Lateral Control

The infrastructure-based lateral control computer will process vehicle information to produce lateral control signals. These commands will be designed to steer each vehicle within an acceptable tolerance of the desired trajectory within or across lane boundaries. In the lane-keeping mode, the lateral controller will minimize the error with respect to either the center of the lane or lane boundaries. The lateral controller will limit the lateral error to within ±15 cm under nominal conditions and ±30 cm under 3σ conditions (wind gusts, pavement composition changes, uneven road surface, poor traction, low tire pressure, etc.) for vehicle speeds up to 160 km/h. These requirements assume that AHS vehicles have passed a reasonable check-in test and are in good working condition. On curved roads these requirements will also be in effect. It is expected that vehicle speeds, though, will be somewhat decreased to allow this level of tracking and to provide ride comfort.

In the lane-change mode, the controller will execute the lane change and resume lane tracking within the stated requirements in the new lane. Lane-change trajectories will be based on various vehicle and roadway parameters such as lane widths, vehicle velocity, lateral acceleration comfort limits, road curvature and superelevation, and desired lane-changing times. The controller will be capable of changing lanes while on a straight road within approximately 5 seconds of the lane-change command. Emergency lane changes will be completed within approximately 2 seconds of a command on straight roads, inducing lateral accelerations on the order of 1.85 m/s^2. Lane changing times on curved roadways will be a function of road curvature and vehicle speed and traction.

The wayside controller will transmit lateral state commands (desired steering angle and rate) to each AHS vehicle. Vehicle systems will be responsible for regulating on-board actuators to ensure that they remain stable and produce resulting vehicle motions consistent with the wayside commands.

Lateral control algorithms will be designed to minimize the need for high levels of processor throughput while optimizing performance. They will also be designed to provide ride comfort for the AHS user as well as rapid and safe responses to emergency commands. Ride quality can be quantified in terms of the vehicle's lateral acceleration and yaw acceleration. Therefore, a primary design consideration will be the trade-off between the tracking error and lateral acceleration. To ensure ride quality, lateral acceleration will be limited under normal operating conditions to ± 1.5 m/s^2. This limit is based on results from human factors studies concerning driver comfort levels. During emergency situations, ride comfort will be sacrificed to achieve optimal maneuvering performance.

Road curvature preview information will be provided to the lateral controller. The controller will use this information to minimize lateral position errors when the vehicle is turning. Preview information has been shown to improve the performance of lateral control algorithms in PATH simulations.[4] The initial use of preview information in lateral control algorithms was motivated by the work of Roland and Sheridan[5] and Donges.[6]

The lateral controller will provide effective operation over a wide range of environmental conditions, disturbance inputs and changing vehicle characteristics. Environmental conditions include wind, rain, ice, road surface and curvature, etc. Disturbance inputs include system noise, emergency maneuvering, maneuver requests (lane changes), etc. Lateral control commands will be generated such that all vehicles maintain an appropriate level of vehicle-roadway traction. These commands will also ensure vehicle stability at all times.

Controller logic can be categorized into distinct functions. Representative functions include steady-state lane-keeping, emergency handling (e.g. a vehicle has suffered a loss of tire pressure), normal lane changing, and emergency lane changing (e.g. collision avoidance). Different control algorithms may be required to meet the needs of each scenario. In this case, an intelligent function interrupt system can switch effectively between modes. Note, however, that an attempt should first be made to find a uniform control methodology that includes all of the control functionality.

Control signals will be generated and transmitted to each AHS vehicle at a frequency in the 40 to 50 Hz range. A control rate in this range should provide adequate control, since vehicle body dynamics are in the 1 to 2 Hz range.

Communication between wayside controllers is necessary to properly initialize each controller with incoming vehicle status as it enters its control zone. As vehicles are about to exit one controller’s zone into another’s, the first controller will transmit the necessary vehicle and controller state information as well as an appropriate level of control signal history to the next two controllers along the wayside. This assumes the need for triple redundancy between controllers, where controller i may be required to take over for controllers $i-1$ and $i+1$ in case they fail. Each controller will therefore be capable of controlling vehicles in the two adjacent control areas as well as in its primary area of control. This will allow failures in two adjacent controllers to occur without affecting system performance. This requirement necessitates two-way communication between the controllers.

Longitudinal Control

The longitudinal control computer will be part of the infrastructure. It will process vehicle information to produce a longitudinal control output signal that will maintain the desired AHS operating speed, the inter-platoon headway, and the intra-platoon spacing for all vehicles in a platoon. The controller must be capable of allowing a vehicle to overtake a platoon and merge smoothly with that platoon. It must also allow smooth, controlled separations to occur between vehicles and platoons. Disturbances to the intra-platoon spacings will not be allowed to propagate along the platoon.

The Traffic Operations Center (TOC) will define platoon headway distances. The commanded headways will be a function of the number and type of vehicles in each platoon, the platoon velocity, vehicle braking abilities, system reaction delays, and space required for lane-change maneuvers. Tradeoff analyses are presented in a subsequent section. Intra-platoon spacings between 1 m and 10 m will allow flexible traffic management while maintaining safety, reducing congestion, and increasing capacity. Larger headways may be required during the evolutionary stages of the AHS program.

Longitudinal control algorithms will be designed to minimize the need for high levels of processor throughput while optimizing performance. They will also be designed to provide ride comfort for the AHS user as well as rapid and safe responses to emergency commands. To achieve ride comfort, under steady-state conditions longitudinal acceleration and jerk will not exceed ± 2 m/s^2 and ± 2 m/s^3 respectively. These limits are based on results from human factors studies concerning driver comfort levels. During emergency situations, ride comfort will be sacrificed to achieve optimal maneuvering performance. The longitudinal controller will provide effective operation over a wide range of environmental conditions, disturbance inputs, and vehicle characteristics. Environmental conditions include wind, rain, ice, road surface and grade, etc. Disturbance inputs include system noise, emergency maneuvering, maneuver requests, etc. Longitudinal control commands will be generated such that all vehicles maintain an appropriate level of vehicle-roadway traction. These commands will also ensure vehicle stability at all times. Control logic will be designed to minimize throttle commands for the purposes of reducing vehicle emissions, increasing fuel economy, and promoting ride comfort.

For the relatively high speed and close vehicle following case, the longitudinal controller will be capable of maintaining vehicle speed within 1 percent of the desired speed. For lower speeds and greater spacings, this tolerance can be relaxed. Changes in speed will nominally be bounded by an acceleration level of ± 2 m/s^2 and a jerk level of ± 2 m/s^3 as discussed above.

The wayside controller will transmit lateral state commands (desired steering angle and rate) to each AHS vehicle. Vehicle systems will be responsible for regulating on-board actuators to ensure that they remain stable and produce vehicle motions consistent with the wayside commands.

Longitudinal controller logic can be categorized into distinct functions, such as headway maintenance, platoon merging and separating, interchange merging, and highway entry and exit. Different control algorithms may be required to meet the needs of each scenario. An intelligent function interrupt system can be used to switch effectively between modes. It is, however, more desirable to simply change filter parameters as opposed to switching between algorithms.

Control signals will be generated and transmitted to each AHS vehicle at a frequency in the 20 to 50 Hz range.

Communication between wayside controllers is necessary to properly initialize each controller with incoming vehicle status as it enters its control zone. As vehicles are about to exit one controller's zone into another's, the first controller will transmit the necessary vehicle and controller state information as well as an appropriate level of control signal history to the next controller along the wayside. Each controller will be capable of controlling vehicles in the two adjacent control areas as well as in its primary area of control. This will allow failures in two adjacent controllers to occur without affecting system performance. This requirement necessitates two-way communication between the controllers.

Controller Software

AHS software will be written in a standard high-level language. It will be generated in a structured, object-oriented format and will be well documented to minimize life-cycle costs. Independent validation and verification will be performed on all software. Verification will ensure that all specifications have been correctly translated into executable software. It will also guarantee the absence of infinite loops, unexecutable paths, equation overflow, etc. Validation will ensure the functionality of the software in a high fidelity simulation testbed. Field tests of the hardware/software product will be executed as a final step.

Collision Avoidance

Individual vehicles will be capable of detecting objects on the roadway such as vehicles or debris. The primary concerns of obstacle detection sensors include the following issues:

- Performance with respect to diverse targets and clutter.
- Frequency allocation, power, and licensing requirements.
- All-weather operation.

The collision avoidance system on the vehicle will be capable of detecting obstacles on the roadway such as stalled vehicles, rapidly decelerating vehicles, and foreign objects. The required detection range depends on the assumed values of a number of key vehicle system parameters. These parameters are the deceleration of a vehicle/object to be avoided, the detection time delay, the braking capability of the vehicle which must avoid the preceding vehicle/object, and the initial velocities and accelerations of the preceding vehicle/object and the following vehicle. For simplicity, one can assume that the initial accelerations are zero and that the initial velocities are equivalent. Table 3 depicts various combinations of these parameters and the resulting headways required to ensure no collisions between a vehicle and the vehicle/object it must avoid. Equation 1 was used to generate the headway values.

Table 3. Various Required Headways for a No-Collision Policy

	80 km/h	**100 km/h**	**120 km/h**	**140 km/h**	**160 km/h**
d1 = 2.0 g d2 = 0.3 g td = 0.5 s	83 m	125 m	177 m	238 m	308 m
d1 = 1.5 g d2 = 0.3 g td = 0.5 s	78 m	119 m	168 m	225 m	291 m
d1 = 1.5 g d2 = 0.6 g td = 0.5 s	36 m	53 m	73 m	97 m	123 m
d1 = 1.2 g d2 = 0.6 g td = 0.3 s	32 m	48 m	67 m	89 m	114 m
d1 = 1.0 g d2 = 0.6 g td = 0.3 s	23 m	35 m	48 m	63 m	81 m
d1 = 1.0 g d2 = 0.7 g td = 0.1 s	13 m	20 m	28 m	37 m	48 m

d1 = deceleration of the preceding vehicle/object
d2 = deceleration of the following vehicle
td = time delay for the following vehicle to achieve full braking force

$$Inter\text{-}platoon\ spacing = \frac{V^2}{2*B} - \frac{V^2}{2*F} + V*D + \frac{A*D^2}{2} \quad (1)$$

where: D = response delay
V = initial platoon velocity
A = initial platoon acceleration
B = platoon braking deceleration
F = preceding object/vehicle deceleration

It is clear from table 3 that headway requirements depend heavily on the assumption of specific values for a representative set of operational parameters. It therefore seems unreasonable to place a fixed range requirement on the collision avoidance system. For example, if a system designer wanted to ensure vehicle safety at most for the case of maximum preceding vehicle deceleration (brake-induced), following vehicle minimum deceleration (non-failure braking with somewhat worn tires, old brakes, and a slippery surface), and maximum time delay to reach full braking force, the parameters may be 1.2 g, 0.3 g, and 0.5 second, respectively. The resulting headway requirements for speeds from 80 to 160 km/h would range from 74 to 274 m. If the designer wanted to be even more conservative and “guarantee” a no-vehicle-collision policy for the case where the incident is a brick wall failure (possibly a bridge that fell down), the resulting headways would range from 95 to 358 m. If, on the other hand, the designer only wanted to ensure safety under reasonable or expected conditions, where the parameters may be 1.0 g, 0.6 g, and 0.3 second, the resulting headway requirements for speeds from 80 to 160 km/h would range from 23 to 81 m.

The collision avoidance system will also have the ability to resolve range and range rate estimates at distances greater than 0.5 m. This minimum range is based on the potential use of these sensors to aid the longitudinal position system by supplying intra-platoon distances.

The system will be capable of detecting objects a minimum of 7 cm above the roadway. Objects larger than this may cause damage to vehicles and may adversely affect vehicle control stability.

The collision avoidance system will also be used as a backup intra-platoon and inter-platoon ranging system. All of the requirements defined for the primary ranging system will also apply to the collision avoidance system.

Each vehicle’s on-board collision avoidance system will be able to override the steady-state lateral and/or longitudinal control commands generated by a wayside controller. The emergency commands will take precedence until the collision avoidance system relinquishes control back to the primary control system.

Wayside controllers will transmit information to vehicles concerning the roadway configuration directly ahead of each vehicle. This transmitted information will allow on-board collision avoidance systems to determine whether an obstacle is in a vehicle’s lane and should be avoided. This information will aid the system in identifying infrastructure-based objects.

The collision avoidance system (vehicle and infrastructure) will operate effectively on curved sections of roadway and on hills, where visibility is less than ideal. In this case, sensors may need to be placed on the infrastructure where the vehicle-based systems are rendered ineffective. These sensors will communicate emergency conditions to the TOC, which will then command AHS vehicles to maneuver appropriately.

Each vehicle will communicate wheel speed from its antilock brake sensor to the wayside. In the case of unforeseen braking by a platoon, this information will be used to command following platoon braking. This early warning system may decrease the normal time delay to acquire information which is used to command braking.

Communication

Typical communication scenarios are discussed in the following section. Included in the communication stream will be signals for vehicle control, driver requests, driver information, and diagnostic information. A representative example of specific data transmissions will be presented in the component requirements section of this task.

Vehicle-Roadside Communication

This communication will be relatively complicated, since control information must be transmitted to all vehicles at fairly high data rates. Vehicles will transmit information to the wayside to support lateral and longitudinal control processing. Vehicles will also transmit user requests and vehicle status. The infrastructure will transmit lateral and longitudinal control commands to each AHS vehicle in its jurisdiction at appropriate control rates. The infrastructure will also transmit information replies to AHS vehicles. Communication to support vehicle control tasks including emergency maneuvering will have the highest priority. Information transmissions will be processed as time permits. The system will be capable of satisfactory operation in adverse weather conditions. An appropriate level of redundancy will be built into the system.

Accident severity can generally be decreased when a parallel response delay is present as opposed to a serial response delay. Based on this concept, emergency maneuver commands will be transmitted to all appropriate vehicles at essentially the same time. In the case of an emergency braking maneuver, braking commands will be issued synchronously to all appropriate vehicles.

Communication Data Rate — RSC-Specific

The data rate is dependent on the amount of information that must be transferred and the time required for transmission. The amount of information transferred between the roadside and the vehicle will vary with each of the RSC's. Assumptions concerning message length and frequency are made to present a typical scenario. RSC 1 will require information transmitted from the roadside such as transmitter identification, diagnostic feedback, weather information, and road condition. This information is assumed to require no more than 100 bits and will be transmitted a maximum of 1 time per second. The maximum number of vehicles in a transmitter's zone is assumed to be 100. Vehicles will transmit user requests, such as destination changes, vehicle status, roadway status, and weather information. This information will be broadcast a maximum of 1 time per second to all vehicles and will be assumed to require no more than 150 bits. Vehicles will also transmit diagnostic information requiring about 100 bits at a frequency no greater than 10 Hz. The amount of diagnostic information transmitted can be reduced by sending only data that signifies a problem. A vehicle-based diagnostic system can filter the diagnostic signals and transmit only those requiring attention. The resulting maximum information transfer rate for non control-related data is:

$$((150\ bits + 100\ bits) * 1 Hz + 100\ bits * 10\ Hz) * 100\ vehicles = 125,000\ \ bits/second.$$

These transmissions will have lower priority than those for steady-state or emergency control. In addition to this representative bit rate, communication bandwidth will be required for message protocol.

This RSC will require additional information transfer between the vehicle and the roadside for the purpose of lateral and longitudinal position measurements and actuator commands. This information must be transferred at a relatively high rate in order to maintain the vehicle position. At the system level, the exact amount of information to be transferred between the wayside and the vehicle is not known. Therefore, as an upper bound, the amount of information for each controller which must be transferred is assumed to be 100 bits. The lateral controller, which operates in the 40 to 50 Hz range, will require a 4,000- to 5,000-bit per second transmission capability for one vehicle. The longitudinal controller, which operates in the 20 to 50 Hz range, will require a 2,000- to 5,000-bit per second communication capability for one vehicle. If the delay between reading vehicle sensors and commanding vehicle actuators is too large, transmission rates to and from the roadside can be increased. Using a 5 vehicle platoon, and assuming that each vehicle requires a separate communication path to the roadside, the vehicle-to-roadside communication system must support an information transfer rate of at most 50,000 bits per second. For a maximum of 100 vehicles in each zone, the largest data rate envisioned will be:

$$(100\ \mathit{bits} * 50\ \mathit{Hz} * 2) * 100\ \mathit{vehicles} + 125,000\ \mathit{bits/second} = 1,125,000\ \mathit{bits/second}.$$

These requirements will be further defined in the sections concerning component-level requirements.

Communication Data Rate — General

The bandwidth efficiency of the communication channel will be affected by the overhead associated with the coding scheme. Overhead includes such message fields as preambles required to allow message synchronization and error control coding. Depending on the transmit protocol selected, guard time between time slots may also be necessary. The length of the preamble is dependent on the type of modulation used and the characteristics of the propagation environment, which is affected by the transmit frequency. The preamble is generally designed to be long enough to defeat fades in a multipath environment and to allow a receiver sufficient time to lock onto the received signal when it is detected. The overhead associated with error coding depends on the method selected. Error correction requires a larger amount of additional bits than error detection. Extremely short losses in data integrity may be more compatible with error correction codes. Longer streams of corrupted data are often more compatible with error detection with repeat request, which adds additional overhead. The channel characteristics must be evaluated to determine the best coding scheme for defeating errors. Communication designs will take into account minimization of associated overhead.

The data rates described above are intended to be representative of a those found in an AHS. Many parameters affect the overall bit rate requirements. These include the number of vehicles allowed in a zone, the amount of messages to be transmitted, the bit allocation for each message, the use of data broadcast methods as opposed to individual vehicle addressing, communication overhead requirements, etc. Each of these issues, as well as others, must be considered in the context of the eventual AHS communication design.

End-to-End Communication Delays

End-to-end communication delays are critical in the infrastructure-centered RSC, since the vehicle position control loop includes the communication system. As stated above, the update rates of the control loops vary between 20 and 40 times per second, which yields a period of 25 to 50 milliseconds. In that time frame, the lateral and/or longitudinal measurement must be made by the sensors, the control information must be transferred through the communication system, and the actuator must be commanded to make the appropriate correction. If a second measurement is made before the actuator commands have a chance to take effect, an unstable control situation could result. The control algorithm can compensate for the communication delays as long as they are of predictable length and consume less than a certain percentage of the update period. The maximum percentage of the control cycle allowed for communication delays should be about 10 percent.

Communication Error Rates

Communication systems are susceptible to errors caused by interference or fading of the signal. The frequencies used, the antenna design, the transmit power, and the signal coding techniques are examples of design considerations which are used to defeat errors and increase the reliability of the communication system. Outside factors such as weather conditions and RF interference can also affect the reliability. Communication system errors fall into two broad categories: detected and undetected errors. Detected errors will be recognized by the communication system and will be treated in a specified manner depending on the coding scheme implementation. Although the information received in error is detected, the fact that the information is not received correctly will affect the performance. This is especially true when the information is part of a control loop, as the performance of the control algorithm is affected by the control information update rate. The communication system will be designed with an acceptable detected error rate.

Undetected errors are errors in the information that the communication system does not recognize. This erroneous information is assumed to be valid, which could cause serious problems in the system. Error detecting (e.g. cyclic redundancy check) and error correcting (e.g. Reed-Solomon coding) methods can be used to increase the reliability of the communication system and reduce the probability of undetected errors. Transmission algorithms such as Automatic Repeat Request (ARQ) may also be implemented to replace erroneous data. These techniques will reduce the probability of undetected errors to an acceptable level, but at the expense of communication bandwidth.

Communication Access

The method used to allow access to the communication system must be considered. Access methods are used to divide the time-bandwidth product among the participants. The number of vehicles which will be allowed to communicate concurrently with the roadside will affect the selection of the access method used in the communication system. The requirement for either broadcast or individual point-to-point links will also affect the access method.

Time-division techniques are a common access method used in shared communication systems. In a time-division system, the transmit times are divided into fixed length slots, called time slots. Each time slot is assigned to one user, who is allowed to transmit information in that specified time slot. The allocation of time slots to users will determine both the amount of data that each user can transmit and the rate at which each user is allowed to transmit. Frequency division is an access method which can also be used to share the time-bandwidth product. In a frequency-division system, the bandwidth is divided into a number of narrow bands. Each user is given one or more bands, which determine that users' data rate. Code division is another popular access method used in shared systems. In a code-division system, each user is assigned a unique diversity code which effectively gives the user a portion of the bandwidth. The code rate assigned to each determines that user's data rate. The selection of the access method affects the cost and complexity of the communication system, as well as the data rates and latency of the system.

Communication Security

The communication system must be designed to withstand interference from outside signals. A robust communication design will employ techniques such as signal spreading and forward error correction to minimize the effects of outside interference. These techniques will allow the receiver to filter out interfering signals in most cases. When the interference does cause errors, the communication system must recognize that fact and report the loss of data rather than passing on incorrect data. In those systems where the sender does not want the information to be intercepted by users other than the intended receiver, encryption of the information is usually performed.

Signal interference may be deliberate or accidental. It is anticipated that the interference to the AHS communication system will be predominately accidental and will occur from sources such as nearby microwave transmitters, high-power commercial transmitters, and other AHS users. Frequency-hopping, code-division, and time-division methods aid in the reduction of inadvertent interference. In addition, a carefully designed system approach to inter- and intra-platoon communication will eliminate most of the interference from other AHS users by appropriate allocation of bandwidth. Deliberate interference is possible but not likely.

Controller-to-Controller Communication

Each controller (e.g. C_i) will transmit vehicle control information to the next controller (C_{i+1}) in the direction of traffic flow. The information will consist of current and past vehicle states (position, velocity, acceleration), control system inputs (lateral deviation, desired headway, etc.), control system outputs (brake, throttle and steering commands), and controller intermediate states. In the case of a controller (C_i) failure, the previous controller will control the vehicles in the failed controller's zone. In the case of consecutive controller (C_i, C_{i+1}) failures, the previous controller (C_{i-1}) will control zone i and controller C_{i+2} will control zone i+1. For this case, controller C_{i-1} will communicate directly with controller C_{i+2}.

Representative System Configuration 2

Actuation

See Representative System Configuration 1.

Measurement

The steering angle measurement system will be capable of accurately measuring steering wheel angle throughout the entire range of wheel motion.

Vehicle control algorithms require various input signals. Assuming that vehicle body translations and rotations, such as lateral and longitudinal position, velocity, and acceleration, and vehicle yaw rate, are needed for the control effort, they must be measured. In general, the accuracies and ranges of the measurements will depend on the requirements of the control algorithm. Listed below are representative ranges and accuracies.

Since lane widths are assumed to be narrower in RSC 2 than those defined for RSC’s 1 and 3, the lateral measurement system accuracy will be increased to ±3 cm. Longitudinal velocity will be measured for a range of speeds from 0 to 160 km/h. Lateral velocity will be measured in the range ±5 m/s, since this range bounds controlled vehicle lateral motion. Longitudinal velocity will be accurate to within 0.05 m/s. Lateral velocity will be accurate to within 0.01 m/s. The longitudinal range and range rate measurement system will be accurate to within 5 percent of the actual range and range rate. The yaw rate measurement system will measure vehicle rates in excess of those given in table 2. The capability of measuring rates up to 30 deg/s should be adequate. The system will also be accurate to 5×10^{-2} deg/s. The lateral acceleration measurement system will measure accelerations up to ±10 m/s^2. It will be accurate to 5×10^{-2} m/s^2. The longitudinal acceleration measurement system will measure accelerations in the range –20 to +5 m/s^2. It will be accurate to 1×10^{-2} m/s^2.

Lateral Control

The lateral control computer will be vehicle-based. This approach will eliminate communication time delays with the infrastructure and between controllers on the wayside that are inherent in the RSC 1 approach. It is also a simpler approach from a flow and transition control standpoint; each RSC 1 controller will process signals from many vehicles, and the system will be required to smoothly transition control from one computer to the next. Vehicle systems will be responsible for regulating on-board actuators to ensure that they remain stable and produce resulting vehicle motions consistent with the wayside commands.

The lateral control computer will process vehicle information to produce lateral control signals. These commands will be designed to steer each vehicle within an acceptable tolerance of the desired trajectory within or across lane boundaries. In the lane-keeping mode, the lateral controller will minimize the error with respect to either the center of the lane or a lane boundary. Under normal operating conditions, this error will remain within ±8 cm for vehicle speeds up to 160 km/h. Under 3σ conditions, the error will be bounded by ±16 cm. This rather stringent requirement is necessary due to the assumption of narrow lane widths for this RSC — 244 cm and considering the maximum width of a passenger car to be 200 cm. In the lane-change mode, the controller will execute the lane change and resume lane tracking in the new lane. Lane-change trajectories will be based on various vehicle and roadway parameters such as lane widths, vehicle velocity, lateral acceleration comfort limits, road curvature and superelevation, and desired lane-changing times. The controller will command lane changes while on a straight road within approximately 4 seconds of the lane-change command. Emergency lane changes will be completed within approximately 2 seconds of a command on straight roads. Lane-changing times on curved roadways will be a function of road curvature and vehicle speed and traction.

Road curvature preview information will be provided to the lateral controller. The controller will use this information to minimize lateral position errors when the vehicle is turning. Preview information has been shown to improve the performance of lateral control algorithms in PATH simulations.

Lateral control algorithms will be designed to minimize the need for high levels of processor throughput while optimizing performance. They will also be designed to provide ride comfort for the AHS user as well as rapid and safe responses to emergency commands. Ride quality can be quantified in terms of the vehicle lateral acceleration and jerk. Therefore, a primary design consideration is the trade-off between the tracking error and lateral acceleration. To ensure ride quality, lateral acceleration will be limited under normal operating conditions to $\pm 1.5\ m/s^2$. During emergency situations, ride comfort will be sacrificed to achieve optimal maneuvering performance.

The lateral controller will provide effective operation over a wide range of environmental conditions, disturbance inputs and changing vehicle characteristics. Environmental conditions include wind, rain, ice, road surface and curvature, etc. Disturbance inputs include system noise, emergency maneuvering, maneuver requests (lane changes), etc. Lateral control commands will be generated such that all vehicles maintain an appropriate level of vehicle-roadway traction. These commands will also ensure vehicle stability at all times.

Controller logic can be categorized into distinct functions. Representative functions include steady-state lane-keeping, emergency handling (e.g. a vehicle has suffered a loss of tire pressure), normal lane-changing, and emergency lane-changing (e.g. collision avoidance). Different control algorithms may be required to meet the needs of each scenario. In this case, an intelligent function interrupt system will switch effectively between modes. Note, however, that an attempt should first be made to find a uniform control methodology that includes all of the control functionality.

The lateral controller hardware may also be used for the longitudinal control task. In addition, a coordinated lateral and longitudinal control system can be implemented in the vehicle controller hardware to optimize the overall control effort. This concept is discussed in a later section.

Control system outputs will be generated at least every 25 ms to adequately maintain a desired vehicle position with respect to lane boundaries.

Longitudinal Control

The longitudinal control computer will process communication and sensor information to produce a longitudinal control output signal that will maintain the desired AHS operating speed. The input signals include vehicle state information (position, velocity, acceleration, wheel speed, throttle angle, engine speed, etc.), information from other AHS vehicles (platoon lead vehicle velocity and acceleration, neighboring vehicle velocities, acceleration, ranges and range rates) and information from the TOC. The controller will also maintain the inter-platoon headway for platoon lead vehicles and the intra-platoon spacing for all vehicles in a platoon. The controller must be capable of allowing a vehicle to overtake a platoon and merge smoothly with that platoon. Disturbances to the intra-platoon spacings will not be allowed to propagate along the platoon.

The longitudinal control computer will be vehicle-based. This approach will eliminate communication time delays with the infrastructure and between controllers on the wayside that are inherent in the RSC 1 approach. It is also a simpler approach from a flow and transition control standpoint; each RSC 1 controller will process signals from many vehicles, and the system will be required to smoothly transition control from one computer to the next. Vehicle systems will be responsible for regulating on-board actuators to ensure that they remain stable and produce resulting vehicle motions consistent with the wayside commands.

The TOC will define platoon headway distances. The commanded headways will be a function of the number and type of vehicles in each platoon, the platoon velocity, vehicle braking abilities, system reaction delays, and space required for lane change maneuvers. Tradeoff analyses are presented in Task 3. Intra-platoon spacings between 1 and 10 m will allow flexible traffic management while maintaining safety, reducing congestion, and increasing capacity. Larger headways may be required during the evolutionary stages of the AHS program.

Longitudinal control algorithms will be designed to minimize the need for high levels of processor throughput while optimizing performance. They will also be designed to provide ride comfort for the AHS user as well as rapid and safe responses to emergency commands. To achieve ride comfort, longitudinal acceleration and jerk should not exceed $\pm 2 m/s^2$ and $\pm 2 m/s^3$, respectively. During emergency situations, ride comfort will be sacrificed to achieve optimal maneuvering performance. The longitudinal controller will provide effective operation over a wide range of environmental conditions, disturbance inputs, and vehicle characteristics. Environmental conditions include wind, rain, ice, road surface and grade, etc. Disturbance inputs include system noise, emergency maneuvering, maneuver requests, etc. Longitudinal control commands will be generated such that all vehicles maintain an appropriate level of vehicle-roadway traction. These commands will also ensure vehicle stability at all times. Control logic will be designed to minimize throttle commands for the purposes of reducing vehicle emissions, increasing fuel economy, and promoting ride comfort.

The longitudinal controller will be capable of maintaining vehicle speed within ±0.5 m/s of the desired speed. Changes in speed will be bounded by an acceleration level of $\pm 2\ m/s^2$ and a jerk level of $\pm 2\ m/s^3$ as discussed above.

Longitudinal controller logic can be categorized into distinct functions, such as headway maintenance, platoon merging and separating, interchange merging, and highway entry and exit. Different control algorithms may be required to meet the needs of each scenario. In this case, an intelligent function interrupt system will switch effectively between modes. Note, however, that an attempt should first be made to find a uniform control methodology that includes all of the control functionality.

Control signals will be generated and transmitted to each AHS vehicle at least every 50 ms. In general, the control frequency can range from 20 to 50 Hz.. Control frequencies in this range are about an order of magnitude faster than vehicle body dynamics.

Controller Software

See Representative System Configuration 1.

Collision Avoidance

See Representative System Configuration 1. Note that the collision avoidance system will override the on-board controller when necessary, and that the TOC will transmit roadway reference information to all vehicles. The discussion concerning wayside controllers does not apply to this RSC.

Communication

Vehicle-Roadside Communication

All vehicles will communicate with the wayside and with each other as necessary using the same communication hardware and software system. Platoon maneuver commands will be transmitted only between lead vehicles and the roadside. The communication system will be capable of satisfactory operation in adverse weather conditions. An appropriate level of redundancy will be designed into the system.

Vehicles will transmit user requests and vehicle diagnostic status information to the TOC. The diagnostic information will be the result of continuous on-board diagnostic analysis. The infrastructure will transmit information replies to AHS vehicles. It will also transmit control requirements to the platoon lead vehicle.

Communication Data Rate — RSC-Specific

The data rate for vehicle-vehicle transmission is dependent on the amount of information that must be transferred and the frequency of transmission. AHS user information from the roadside will require approximately 100 bits and will be transmitted a maximum of 1 time per second. Control signals, such as maneuver authorizations and target velocities, will require approximately 50 bits and will be transmitted at a frequency no higher than 1 Hz. Vehicles will transmit user requests, such as destination changes, vehicle status, roadway status, weather information and estimated time of arrival. This information will be broadcast a maximum of 1 time per second and will be approximately 150 bits in length. Vehicles will transmit diagnostic information requiring roughly 50 bits at a frequency no higher than 10 Hz. Vehicles will communicate their state (position, velocity, and acceleration) to the wayside. This information will require about 120 bits and will be transmitted once per second. Assuming a maximum of 100 vehicles in the transmitter's zone and a platoon size of 20, the resulting maximum information transfer rate is:

$$((150\ bits + 100\ bits) * 1\ Hz + 120\ bits * 1\ Hz + 50\ bits * 10\ Hz) * 100\ vehicles + 50\ bits * 1\ Hz * 5\ vehicles = 87{,}250\ bits/second.$$

These transmissions will have lower priority than those for steady-state or emergency control.

Communication Data Rate — General

See Representative System Configuration 1.

Vehicle-Vehicle Communication

Vehicles in a platoon will establish communication with all other vehicles in that platoon to support the lateral and longitudinal control tasks and transmit pertinent information. Vehicle-vehicle range and range rate information will be derived from intra-platoon communication signals. Each platoon lead vehicle will also communicate with the trailing vehicle in the preceding platoon. Inter-platoon range and range rate information will be derived from these signals. Braking signals can also be transmitted between platoons in this manner.

Communication Data Rate — RSC-Specific

The maximum vehicle-vehicle data rate can be defined based on the transmission of vehicle state information and control requirements within a platoon. Vehicle state information will require approximately 40 bits and will be transmitted at a frequency up to 50 Hz by each of the maximum of 20 platoon vehicles to support the longitudinal control function. Maneuver commands will require roughly 40 bits and will be transmitted when necessary while not exceeding a 1 Hz frequency during steady-state operation. Emergency maneuver commands will take precedence over all other commands. Inter-platoon communication will require approximately 30 bits and a frequency of 1 Hz. Therefore, the maximum vehicle-to-vehicle bit rate will be:

$$(40\ bits * 50\ Hz) * 20\ vehicles + (40\ bits + 30\ bits) * 1\ Hz * 1\ vehicle = 40{,}070\ bits/second.$$

Communication Data Rate — General

See Representative System Configuration 1.

Communication Error Rates

See Representative System Configuration 1.

Communication Access

See Representative System Configuration 1.

Communication Security

See Representative System Configuration 1.

Representative System Configuration 3

Actuation

See Representative System Configuration 1.

Measurement

The steering angle measurement system will be capable of accurately measuring steering wheel angle throughout the entire range of wheel motion.

Vehicle control algorithms require various input signals. Assuming that vehicle body translations and rotations, such as lateral and longitudinal position, velocity, and acceleration, and vehicle yaw rate, are needed for the control effort, they must be measured. In general, the accuracies and ranges of the measurements will depend on the requirements of the control algorithm. Listed below are representative ranges and accuracies.

Lateral and longitudinal position measurements will be accurate to within 5 cm of the true position. Lateral velocity will be measured in the range ±5 m/s, since this range bounds controlled vehicle lateral motion. Lateral velocity will be accurate to within 0.05 m/s. The yaw rate measurement system will measure vehicle rates in excess of those given in table 2. The capability of measuring rates up to 30 deg/s should be adequate. The system will also be accurate to 5×10^{-2} deg/s. The lateral acceleration measurement system will measure accelerations up to ±15 m/s^2. It will be accurate to 5×10^{-2} m/s^2. The longitudinal acceleration measurement system will measure accelerations in the range −20 to +5 m/s^2. It will be accurate to 1×10^{-2} m/s^2.

The vehicle-based measurement system will determine longitudinal velocity and position for any speed in the 0 to 160 km/h range. Velocity will be accurate to ±0.3 m/s. An infrastructure-based independent measurement system will provide exact vehicle position (±1 m) and velocity (±0.05 m/s) measurements to alleviate the inaccuracies of the on-board measurement system. The measurement updates will be spaced accordingly to ensure that vehicle-derived position errors are bounded by acceptable values. As an example, a vehicle traveling at 160 km/h with a 0.3 m/s velocity measurement error can accumulate 6.75 m of position error in 1 km. This level of accuracy may be considered acceptable for the time-slot case where vehicles are separated by significant distances (e.g. 121 m under conditions of 0.4 g lead vehicle deceleration, 0.3 g following vehicle braking, and 0.3 second response delay). The measurement system could then update the vehicle position at 1 km intervals. Clearly, the choice of update frequency depends on assumed conditions of failure deceleration, braking, and response delay. Note that conditions such as initial acceleration/deceleration values and time-varying decelerations will affect the safe headway as well. The contribution from these effects was not considered for the sake of simplicity.

Lateral Control

The lateral control computer will process vehicle information to produce lateral control signals. These commands will be designed to steer each vehicle within an acceptable tolerance of the desired trajectory within or across lane boundaries. In the lane-keeping mode, the lateral controller will minimize the error with respect to either the center of the lane or a lane boundary. The lateral controller will limit the lateral error to within ±15 cm under nominal conditions and ±30 cm under 3σ conditions for vehicle speeds up to 160 km/h. In the lane-change mode, the controller will execute the lane change and resume lane tracking in the new lane. Lane-change trajectories will be based on various vehicle and roadway parameters such as lane widths, vehicle velocity, lateral acceleration comfort limits, road curvature and superelevation, and desired lane-changing times. The controller will be capable of changing lanes while on a straight road within approximately 5 seconds of a lane-change command. Emergency lane changes will be completed within approximately 2 seconds of a command on straight roads. Lane-changing times on curved roadways will be a function of road curvature and vehicle speed and traction. The lateral control computer will be vehicle-based.

Lateral control algorithms will be designed to minimize the need for high levels of processor throughput while optimizing performance. They will also be designed to provide ride comfort for the AHS user as well as rapid and safe responses to emergency commands. Ride quality can be quantified in terms of the vehicle lateral acceleration and jerk. Therefore, a primary design consideration is the trade-off between the tracking error and lateral acceleration. To ensure ride quality, lateral acceleration will be limited under normal operating conditions to ± 1.5 m/sec^2. During emergency situations, ride comfort will be sacrificed to achieve optimal maneuvering performance.

Road curvature preview information will be provided to the lateral controller. The controller will use this information to minimize lateral position errors when the vehicle is turning. Preview information has been shown to improve the performance of lateral control algorithms in PATH simulations.

The lateral controller will provide effective operation over a wide range of environmental conditions, disturbance inputs, and changing vehicle characteristics. Environmental conditions include wind, rain, ice, road surface and curvature, etc. Disturbance inputs include system noise, emergency maneuvering, maneuver requests (lane changes), etc. Lateral control commands will be generated such that all vehicles maintain an appropriate level of vehicle-roadway traction. These commands will also ensure vehicle stability at all times. Separate controller logic may be required to maneuver a vehicle that has suffered a loss of tire pressure.

Controller logic can be categorized into distinct functions. Representative functions include steady-state lane-keeping, emergency handling (e.g. a vehicle has suffered a loss of tire pressure), normal lane-changing, and emergency lane-changing (e.g. collision avoidance).

Different control algorithms may be required to meet the needs of each scenario. In this case, an intelligent function interrupt system will switch effectively between modes. Note, however, that an attempt should first be made to find a uniform control methodology that includes all of the control functionality.

Vehicle systems will be responsible for regulating on-board actuators to ensure that they remain stable and produce vehicle motions consistent with the wayside commands. Control signals will be generated in the frequency range from 40 to 50 Hz. Control frequencies in this range are considered effective, since they are about an order of magnitude faster than vehicle body dynamics.

Longitudinal Control

The vehicle-based longitudinal control computer will generate control signals designed to minimize the errors between slot positions and vehicle positions. It will receive vehicle state information (position, velocity, acceleration, wheel speed, throttle angle, engine speed, etc.) provided by on-board measurement systems, as well as updates to these measurements provided by wayside systems and information provided by the TOC.

Longitudinal control algorithms will be designed to minimize the need for high levels of processor throughput while optimizing performance. They will also be designed to provide ride comfort for the AHS user as well as rapid and safe responses to emergency commands. To achieve ride comfort, longitudinal acceleration and jerk should not exceed ± 2 m/s^2 and ± 2 m/s^3. During emergency situations, ride comfort will be sacrificed to achieve optimal maneuvering performance.

The longitudinal controller will provide effective operation over a wide range of environmental conditions, disturbance inputs, and vehicle characteristics. Environmental conditions include wind, rain, ice, road surface and grade, etc. Disturbance inputs include system noise, emergency maneuvering, maneuver requests, etc. Longitudinal control commands will be generated such that all vehicles maintain an appropriate level of vehicle-roadway traction. These commands will also ensure vehicle stability at all times. Control logic will be designed to minimize throttle commands for the purposes of reducing vehicle emissions, increasing fuel economy, and promoting ride comfort.

The longitudinal controller will be capable of maintaining vehicle speed within ±0.5 m/s of the desired speed. Changes in speed will be bounded by an acceleration level of 2 m/s^2 and a jerk level of 2 m/s^3 as discussed above.

Longitudinal commands should be generated in the 20 to 50 Hz frequency range. Due to the “safe” (large) spacings between vehicles considered in this RSC, the bounded communications time delays, the maximum allowable operating velocities, and the inherent frequency of vehicle body dynamics, this control range seems reasonable.

Controller Software

See Representative System Configuration 1.

Time Slot Controller

The infrastructure-based time slot controllers will define all slot trajectories for given sections of roadway. They will determine the desired slot operational velocity based on capacity demands, vehicle capabilities, road surface conditions, weather conditions, etc.

Wayside controllers will communicate with each other and coordinate desired slot states to allow for continuous, smooth slot operation. Controllers will be appropriately spaced on the infrastructure to accommodate worst-case capacity demands. They will communicate with the TOC to coordinate entry/exit and lane change maneuvers.

Collision Avoidance

See Representative System Configuration 2.

Communication

Vehicles will transmit user requests, vehicle diagnostic status, and state information to the wayside. The infrastructure will transmit a desired slot state to each AHS vehicle in its jurisdiction at the appropriate control rate. The infrastructure will also transmit information replies, lateral maneuver commands, and state updates to AHS vehicles. Communication to support vehicle longitudinal control and emergency lane change commands will have the highest transmission priority. Information transmissions will be processed as time permits. The system will be capable of satisfactory operation in adverse weather conditions. An appropriate level of redundancy will be designed into the system.

Vehicle-Roadside Communication

Communication Data Rate — RSC-Specific

RSC 3 will require the roadside to transmit information concerning diagnostic feedback, weather information, road condition, and traffic conditions. This information will require approximately 100 bits and will be transmitted a maximum of 1 time per second. For this analysis, the maximum number of vehicles in a transmitter's zone will be 50. Due to the relatively low density of vehicles on the road for RSC 3, wayside transmitters must possess an adequate amount of power to cover their zone as well as the two adjacent zones. Vehicles will transmit user requests and vehicle state information to the roadside. This information will be transmitted a maximum of 1 time per second and will be roughly 150 bits in length. Vehicles will also transmit diagnostic information requiring roughly 100 bits at a frequency no larger than 10 Hz. The resulting maximum information transfer rate for non control-related data is:

$$(100\ bits * 1\ Hz + 150\ bits * 1\ Hz + 100\ bits * 10\ Hz) * 50\ vehicles = 62{,}500\ bits/second.$$

These transmissions will have lower priority than those for steady-state or emergency control.

Vehicles also require position updates periodically from the roadside. The roadside must have the capability to transmit up to 80 bits of data during a 100 ms time span. If 50 vehicles are supported by these transmissions at any one time, the resulting transmission rate is 40,000 bits per second.

This RSC will require additional information transfer from the roadside to the vehicle for the purpose of longitudinal control. This information must be transferred at a relatively high rate in order to maintain the vehicle position. The longitudinal controller, which is a 20 to 50 Hz vehicle-based system, requires state information concerning its specified time slot. This information will require approximately 50 bits and will be transmitted every second. Simulation studies will be needed to determine the effectiveness of updating slot states at this rate. Lateral maneuver commands will also be transmitted to each vehicle. This information will require about 20 bits and will be transmitted no more than 1 time per second. During an emergency, control maneuvering will have the highest communication priority. Assuming that each vehicle requires a separate communication path to the roadside, the vehicle-to-roadside communication system must support an information transfer rate of at most:

$$(50\ bits + 20\ bits) * 1\ Hz * 50\ vehicles + 62{,}500\ bits/second = 66{,}000\ bits/second\ .$$

These requirements will be further defined in the sections concerning component level requirements.

Communication Data Rate — General

See Representative System Configuration 1.

End-to-End Communication Delays

See Representative System Configuration 1.

Communication Error Rates

See Representative System Configuration 1.

Communication Access

See Representative System Configuration 1.

Communication Security

See Representative System Configuration 1.

Component-Level Requirements

Whereas system-level requirements specify overall lateral and longitudinal AHS goals, the requirements presented in the following section apply to specific implementations of those goals. Where firm requirements are not appropriate, implementation options will be discussed. Every effort was made to define component level requirements that would be applicable in 10 to 20 years, when the AHS will be deployed. In Task 6, current systems that meet AHS requirements and concept systems that could be designed to meet these requirements are described.

Representative System Configuration 1

Figure 5 shows the control and communication architecture for RSC 1. It is important to note that control inputs as well as TOC inputs and outputs are only meant to characterize the type of values to be used for the eventual AHS architecture. Though the quantities listed will probably be a part of the AHS, others may be present as well.

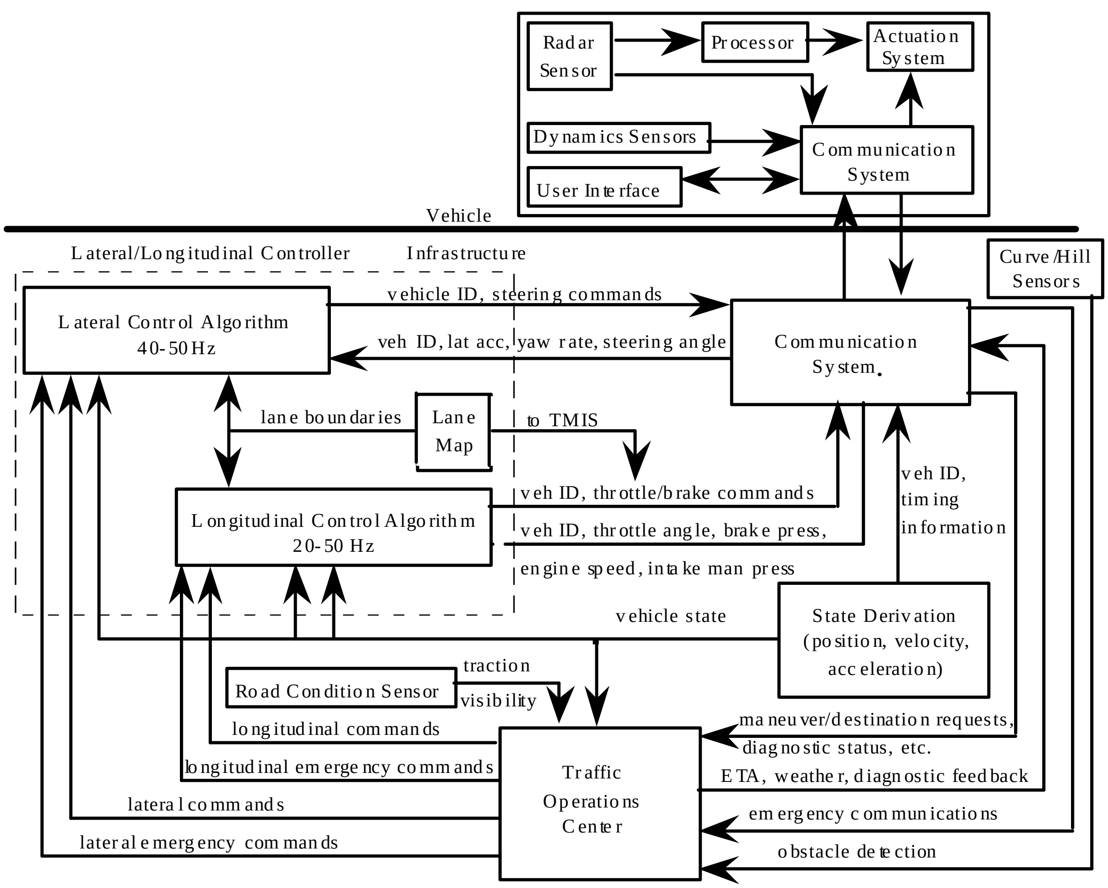


Figure 5. RSC 1 Communication/Control Architecture

Measurement

Potentiometers can be used for steering wheel angle measurement. They are relatively inexpensive, but are considered quite noisy. Steering wheel encoders can also be used. They are very accurate and are not prone to noise problems. However, currently they are rather expensive.

Lateral and Longitudinal Control

Wayside controllers will process vehicle state information (position, velocity, acceleration, yaw rate, etc.), wheel speed data, and TOC inputs to determine suitable control signals for each vehicle in their jurisdiction. Velocity and acceleration information can either be derived from the position information, or transmitted to the wayside from each vehicle. The latter would imply the use of acceleration sensors and a velocity measurement system in each vehicle. The former would imply the use of derivatives, which can be inaccurate due to noise.

Figure 6 shows a relationship between capacity, speed, and platoon size for certain parameters. This graph is based on the kinematic equation:

$$Capacity = 3{,}600 \times 0.8 \times \frac{N}{D + \frac{A * D^2}{2 * V} + \frac{V}{2 * B} - \frac{V}{2 * F} + \frac{N * L + (N - 1) * G}{V}} \tag{2}$$

where: N = number of vehicles in the platoon

D = response delay

V = initial platoon velocity

A = initial platoon acceleration

B = platoon braking deceleration

F = preceding object/vehicle deceleration

L = length of vehicle

G = inter-vehicle gap length

3,600 = seconds to hours conversion factor

0.8 = lane change, entry/exit factor to add realism

From figure 6, the maximum lane capacity for a 5-vehicle platoon under certain operating conditions is 3,415 vehicles/h when the platoon is traveling at a speed of 50 km/h. The capacity values are based on the conditions of no vehicle collisions for a 4.5 m vehicle length, a 1 m vehicle gap length, a lead vehicle (or object) deceleration of 2.0 g, a following vehicle braking level of 0.3 g, a time delay of 0.3 second, and a platoon length of 5 vehicles. Though these values are considered very conservative, they will be used at this stage of analysis for representative capacity estimations and controller demands. Further tradeoff analyses will be discussed in Task 3. Wayside controllers will be required to maintain headways resulting from such worst-case analyses at the expense of capacity.

Deceleration=2.0 g, Braking=0.3 g, Response Delay=0.3 s, Vehicle Length=4.5 m, Gap Length=1 m

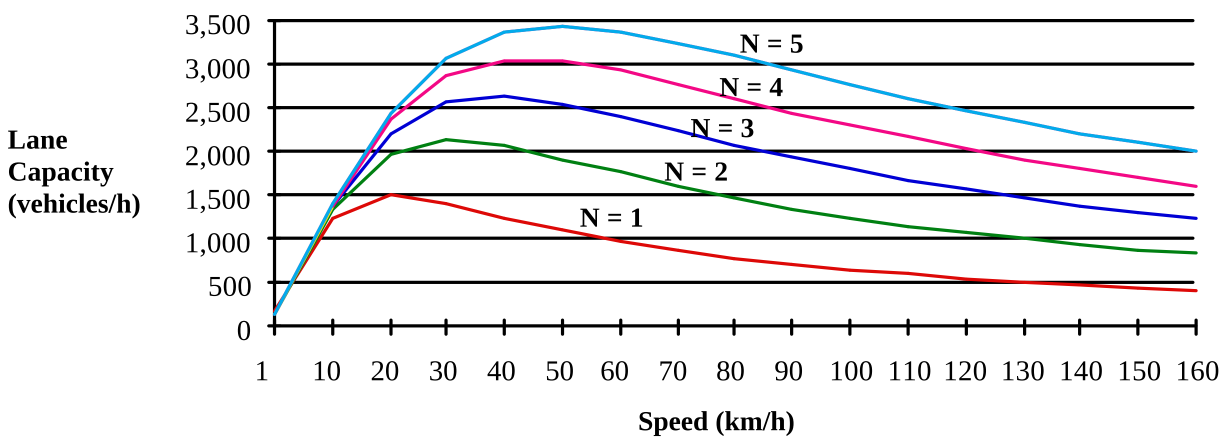


Figure 6. RSC 1 Representative Capacity Estimates With Respect to Time

The relationship between the number of vehicles per kilometer in one lane and the vehicle speed for the conditions described above is displayed in figure 7. These values are obtained by dividing the capacity results from above by vehicle velocity. Clearly, higher demand (in terms of vehicle capacity) on the wayside controllers occurs when vehicle speeds are very slow. For this case, though, control update rates can be relaxed from their 20 to 50 Hz steady-state values to ease the communication and control burden. For this analysis, the vehicle density occurring at 90 km/h will be used to determine the controller demand, since this is the minimum expected (i.e. acceptable) AHS operating speed. If maximum controller capacity is reached when the operating speed is 90 km/h, then if the speed decreases (and other operating parameters remain constant), platoon separation distances can be increased or platoon sizes decreased to reduce the demand on the controller. Another alternative is to employ time-headway intra-platoon spacing to reduce the capacity demand. This spacing method varies vehicle-vehicle distances as a function of velocity.

As an example, at 90 km/h, the lane capacity is 32 vehicles/km. Assume that each controller can support four lanes. Furthermore, if there are 10 controllers/km, then each controller would be required to process data from 32 vehicles/km/10 controllers/km $\times$ 3 control areas $\times$ 4 lanes = 39 vehicles. There are clearly a host of tradeoffs between the number and capability of infrastructure-based controller/communication systems, operating speeds, redundancy zones, and lane coverage.

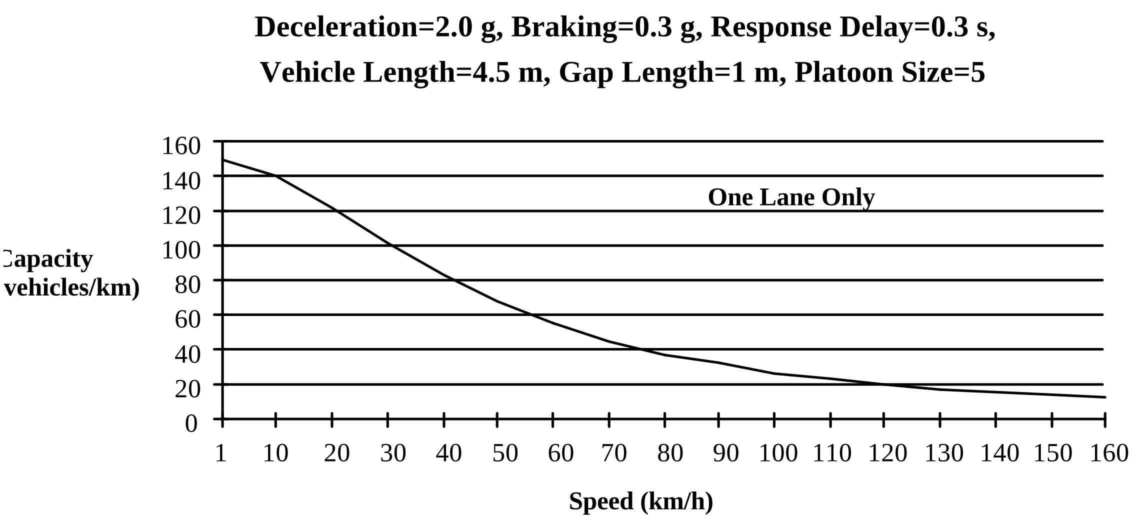


Figure 7. RSC 1 Representative Capacity Estimates With Respect to Distance

Each roadside controller will contain roadway reference information in the form of an electronic map which will be used along with vehicle state information to determine appropriate control signals. All lane boundaries and entry/exit lanes will be identified in the electronic map. These maps will contain only local information concerning the areas of primary and backup controller coverage. The roadway can be surveyed using the same infrastructure transmitter/receiver system that has been defined for providing vehicle state information.

Each electronic map will contain information for the controller's zone as well as those of the two adjacent controllers. These maps must be accurate to about 10 cm. Minor variations in lane lines can be ignored as long as the measurement and control systems reference the theoretical center of the lane. To support control cycles on the order of 20 to 50 Hz, data access times must be less than 5 ms.

Collision Avoidance

Radar sensor technology will be used in the collision avoidance system. The primary function of this system is to detect objects on the roadway that may impact vehicle safety. Distance measurements will be available to support the 20 to 50 Hz longitudinal control cycle. Radar-based systems will meet all federal regulatory mandates for allowed transmit power.

An infrastructure-based radar system will be placed on curved sections of roadway and on hills where the vehicle-based system is ineffective. It will provide measurements of vehicle positions and velocities for all AHS lanes to the traffic management system, which will then determine whether a problem exists in those areas. As an example, if the TOC loses communication with a vehicle on a curved section of roadway, it can obtain position and velocity information from the radar system and maneuver that vehicle and other AHS vehicles if necessary.

Radar sensor performance requirements determine the capability of a candidate technology for meeting longitudinal control parameters. A partial list of representative performance measures is given in table 4.

Table 4. Representative Radar Sensor Performance Measures

Target Detection Probability
False Alarm Probability
Range to Target Measurements Minimum Range Maximum Range Accuracy Unambiguous Range for Nearest Target in FOV
Relative Range Rate Closing Range Rate Opening Range Rate Range Rate Accuracy Unambiguous Range Rate
Target Bearing Measurements Azimuthal Coverage Number of Bearing Sectors Unambiguous Bearing
Number of Targets that can be Tracked
Minimum Target Cross-section

Communication

RSC 1 indicates that two-way communications will support the vehicle-to-roadside and roadside-to-vehicle links. The following paragraphs will discuss the requirements of the communications architecture consisting of a two-way infrastructure/vehicle link.

Roadside-to-Vehicle Communication

The communication system will provide roadside-to-vehicle and vehicle-to-roadside communication. Wayside transmitters will radiate signals over a predefined area of roadway (possibly a 300 m radius). Table 5 depicts a representative set of data that may be required by the vehicle.

Table 5. RSC 1 Roadside-to-Vehicle Communication Messages

Message Categories	Level 1 Description	Level 2 Description
Transmitter identification: 5 bits		
AHS user information: 48 bits	Vehicle identification: 7 bits	
	Diagnostic feedback: 10 bits	Tire pressure: 1 bit
		Fuel level: 1 bit
		Oil temperature: 1 bit
		Engine temperature: 1 bit
		Oil level: 1 bit
		Water level: 1 bit
		Steering actuator: 1 bit
		Brake actuator: 1 bit
		Throttle actuator: 1 bit
		Comm. system: 1 bit
	Weather information: 20 bits	
	ETA: 11 bits	
Lateral control signals: 19 bits	Vehicle identification: 7 bits	
	Steering angle command: 12 bits	
Longitudinal control signals: 31 bits	Vehicle identification: 7 bits	
	Throttle angle command: 12 bits	
	Brake pressure command: 12 bits	

The transmitter identification bit level indicates that no more than 32 transmitters are allowed to radiate to any one point on the road. This can certainly be altered as necessary. AHS user information should receive the lowest transmission priority to allow control signals in normal or emergency mode to have precedence. AHS users can receive information on current weather conditions, such as rain, sun, hail, fog, clouds, snow, high/low/current temperature, wind speed/direction, etc., along their selected route.

AHS user information will nominally be transmitted at a rate of 1 Hz. Lateral control signals are required to support a control rate of at least 40 Hz, while the longitudinal control signals are required to support at least a 20 Hz control rate.

Vehicle-to-Roadside Communication

Vehicle-based transceivers will reply to each signal by communicating the items listed in table 6 as appropriate.

The allocation of 7 bits for the vehicle identification implies a maximum of 128 vehicles per controller. This can be altered as necessary. Maneuver requests can be generated by the user to exit the AHS at a different point than initially stated or to change lanes for any reason. The tire pressure message is divided into a required level and an actual level, since each vehicle has different pressure requirements. The lowest priority transmission is the AHS user requests. The diagnostic requests have a higher priority, but they are not to interfere with control signal inputs.

AHS user requests will be transmitted at a 1 Hz rate, while diagnostic status will be communicated at a 10 Hz rate. The latter rate supports the concept of predicting and/or detecting vehicle malfunctions. This will improve vehicle malfunction management and overall safety. Lateral control inputs are required to support a control rate of at least 40 Hz, while the longitudinal control inputs are required to support at least a 20 Hz control rate.

Each vehicle transceiver will receive information from multiple roadside processors. Each wayside controller will have one transmitter and receiver (transceiver) associated with it. The vehicle will be in the range of several roadside controllers at the same time, allowing hand-off of vehicle and/or platoon maneuver control to occur between controllers. Functions of the roadside transceiver may include processing of time delay information received from individual vehicles for determining position.

Controller-to-Controller Communication

Under normal operating conditions, each wayside controller will transmit information to the next controller in the direction of traffic flow for the purpose of coordinating vehicle control as vehicles travel from one controller zone to another. Under conditions where controllers fail, communication may be required between nonsequential controllers. Table 7 depicts a representative set of information that may need to be transmitted between controllers.

Table 6. RSC 1 Vehicle-to-Roadside Communication Messages

Message Categories	Level 1 Description	Level 2 Description
Transmitter identification: 5 bits		
AHS user requests: 70 bits	Vehicle identification: 7 bits	
	Maneuver request: 10 bits	
	Destination request: 50 bits	
	Information requests: 3 bits	Vehicle status: 1 bit
		Weather: 1 bit
		ETA: 1 bit
Diagnostic status: 76 bits	Vehicle identification: 7 bits	
	Tire pressure: 12 bits	
	Fuel level: 3 bits	
	Oil temperature: 1 bit	
	Engine temperature: 1 bit	
	Oil level: 1 bit	
	Water level: 1 bit	
	Steering actuator response: 12 bits	
	Brake actuator response: 12 bits	
	Throttle actuator response: 12 bits	
	Communication system: 4 bits	
	Collision avoidance sensor: 4 bits	
	Collision avoidance computer: 4 bits	
	Transceiver status: 2 bits	
Lateral control inputs: 43 bits	Vehicle identification: 7 bits	
	Lateral acceleration: 12 bits	
	Yaw Rate: 12 bits	
	Steering angle: 12 bits	
Long. control inputs: 103 bits	Vehicle identification: 7 bits	
	Throttle angle: 12 bits	
	Brake pressure: 12 bits	
	Engine speed: 12 bits	
	Intake manifold pressure: 12 bits	
	Wheel speed: 24 bits	
	Collision avoidance range: 12 bits	
	Collision avoidance range rate: 12 bits	

Table 7. RSC 1 Controller-to-Controller
Communication Messages

Message Categories
Controller identification: 5 bits
Vehicle identification: 7 bits
Controller states: 50 bits
Vehicle states: 50 bits

As an example of the vehicle handoff process, consider two control zones, i–1 and i, where zone i–1 precedes zone i in terms of traffic flow. As vehicles that are traveling in zone i–1 start to enter zone i, the controller for zone i–1 will identify itself and communicate the identifications of the vehicles that controller i must now process. This communication will take place every control cycle in time for controller i to use its communication-derived vehicle information to generate control signals without skipping a control cycle. Due to the requirement for controllers to have the capability to control vehicles in their adjacent zones, controllers will have a transceiver system that can communicate with those zones. Thus, when vehicles are in zone i–1, the controller for zone i will be receiving information from those vehicles.

For the case where a platoon is in two controller zones (i–1 and i), each controller will generate commands for the vehicles in its zone. The handoff process will be as stated above. Controller i will also receive vehicle state information from the vehicles in zone i–1 to be used for the control of vehicles in its zone. This will ensure that platoon headway requirements are always met. Note that communication from controller i to controller i-1 may be necessary to coordinate a platoon braking maneuver in response to an emergency situation.

Representative System Configuration 2

Figure 8 shows the control and communication architecture for RSC 2. It is important to note that control inputs as well as TOC inputs and outputs are only meant to characterize the type of values to be used for the eventual AHS architecture.

Measurement

See Representative System Configuration 1.

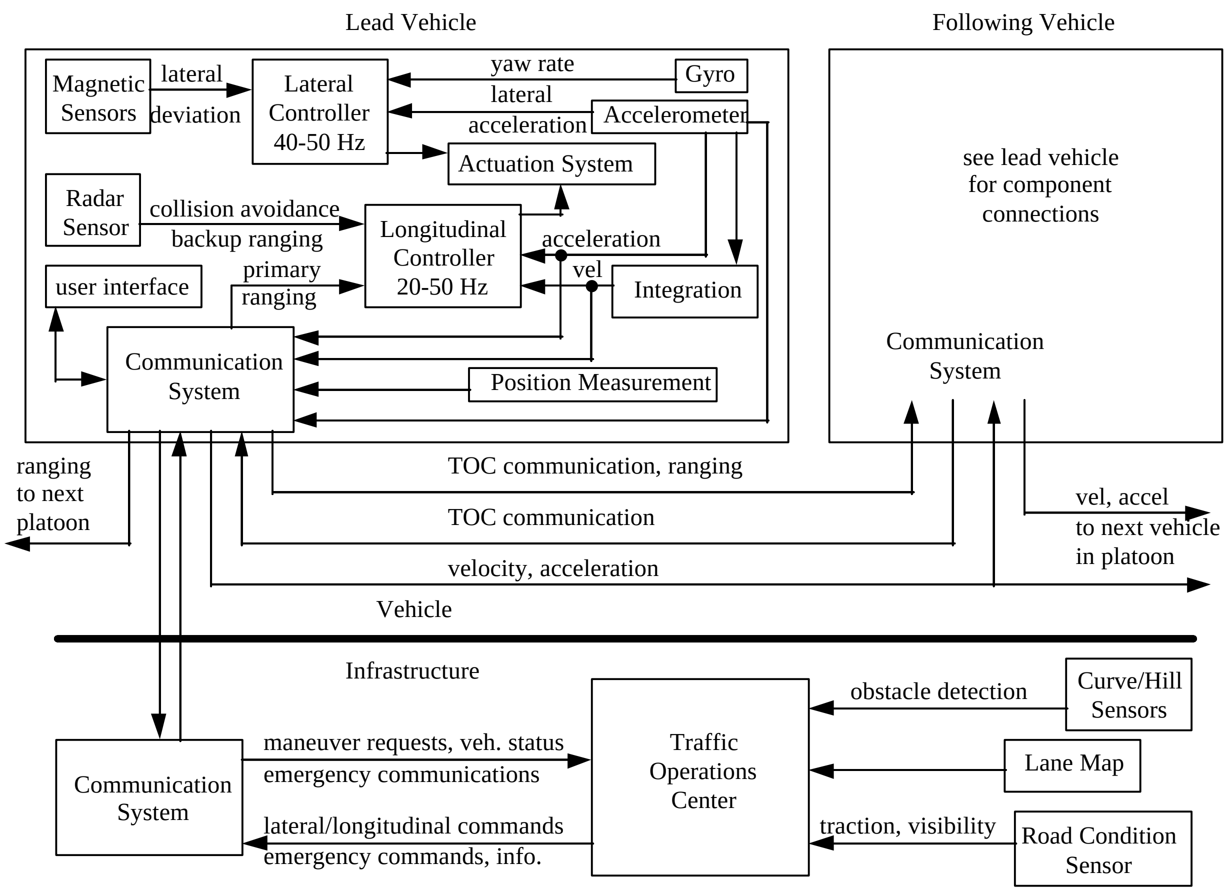


Figure 8. RSC 2 Communication/Control Architecture

Lateral Control

A magnetic marker system will be utilized for the lateral control task. Magnets will be embedded in the roadway in the center of each lane at least 4 cm below the surface to avoid damage from passing vehicles. These markers will be spaced appropriately to meet all lateral control requirements. Each magnet will have either a positive or a negative polarity. Magnetic field sensors will be placed on each AHS vehicle to measure the field produced by the markers. The system will be capable of providing a continuous lateral reference while vehicles operate on the AHS. The system will not be adversely affected by magnetic interference caused by the earth's magnetic field, high frequency magnetic noise generated by the vehicle’s engine system, spontaneous vertical movements of the vehicle, or roadway reinforcement material.

Longitudinal Control

The on-board longitudinal control processor will utilize on-board sensors as well as vehicle-vehicle communication to provide the necessary information required to solve control algorithms. The vehicle-vehicle communication system will serve as the primary provider of range and range rate information with respect to preceding vehicles. It will also transmit vehicle state information from one vehicle to another as required. The collision avoidance system will provide backup ranging information to be used if the primary system malfunctions. The requirements for both systems in terms of the accuracy and frequency of range and range rate signals are identical. Effective operation will exist at a range of vehicle spacings from 0.5 m to an upper bound which is dependent on vehicle operating and environmental assumptions (see RSC 1, Collision Avoidance System).

As mentioned previously, the lateral and longitudinal control hardware can be combined into one processor if desired. In fact, the two separate algorithms can be combined into one cohesive algorithm. Task 4 discusses the issue of combined control further.

Current platoon-based longitudinal control algorithms[7, 8, 9] use some combination of velocity and acceleration information from the lead vehicle, preceding vehicle, and on-board sensors, range and range rate information to the preceding vehicle, throttle angle, brake pressure, intake manifold pressure and temperature, and engine speed to generate appropriate control signals. An alternative algorithm[10] that does not rely on lead vehicle information has been shown to produce reasonable results. Depending on the type of communication system utilized, this approach in combination with the collision avoidance system may be used as a backup longitudinal controller in case of communication failure.

Longitudinal control functions will be coordinated as necessary to maintain intra-platoon spacings during nominal and steady-state operation. The communication system between vehicles will be utilized to transmit target decelerations and performance responses as appropriate. This concept is discussed in depth in Task 3.

This RSC assumes that vehicles can be grouped into moderately-sized platoons of 15 to 20 vehicles. It also assumes rather small intra-platoon spacings on the order of 1 to 10 m. In Task

3, these parameters are varied within the general framework of RSC 2 to determine resulting tradeoffs between highway capacity, control complexity, and communication complexity.

Position Reference

The TOC will contain roadway reference information in the form of an electronic map. This map will be used to determine exact locations of all AHS vehicles in the management system’s jurisdiction. All lane boundaries and entry/exit lanes will be identified. The map will be used as input to the flow control system. This system will attempt to optimize AHS traffic flow based on prevailing conditions. It will also manage vehicle maneuvers such as lane changes, entry/exit, and platoon formation/separation.

Discrete magnetic markers embedded in the roadway will be used for longitudinal position measurement as well as lateral control. These markers will contain longitudinal position information coded as a binary sequence. The markers will be coded with all appropriate preamble information. The position data will be accurate to less than a meter. During stretches of highway between entry points, the markers will be coded with position updates as opposed to absolute position. This will allow for more information (possibly other than position) to be coded into the markers as well. At each entry point, absolute position will be coded to ensure that each vehicle obtains an initial position correctly. An alternative to this approach is to require the check-in station to initialize each vehicle’s position and code only position updates into the markers.

AHS vehicles will possess multiple methods of determining their position on the roadway. Signals from these systems can be filtered to produce a “best estimate” of the true position.

Collision Avoidance

Laser radar technology will be considered for this RSC. Laser radar distance measurements will be available to support the 20 to 50 Hz longitudinal control cycle if necessary. However, the primary function of this system is to detect objects on the roadway that may impact vehicle safety. Laser radar-based systems will meet all federal regulatory mandates for allowed transmit power.

Communication

Several aspects of RSC 2 contribute to the definition of the communication system requirements. This RSC includes vehicle-based communication between vehicles in a platoon, with ranging included in the communication capabilities of the vehicle-vehicle system. An additional assumption states that information concerning roadway and traffic conditions is transferred from the vehicle to the wayside using the same technology as that used between vehicles. The transmission of information from the infrastructure to the vehicle will occur through publicly accessible bands. The following paragraphs will discuss the requirements of the communication architecture for the vehicle-to-vehicle, vehicle-to-roadside, and roadside-to-vehicle link capabilities specific to the configuration of the RSC.

Vehicle-to-Vehicle Communication

The data transfer requirements between vehicles within the platoon will entail high data rates to support frequent updates of control parameters. The communication system will also support the capability to allow the lead vehicle to transmit emergency maneuver information simultaneously to all vehicles within the platoon. This feature avoids propagation delays involved in relaying messages one vehicle at a time. It also supports synchronized braking, which will increase the safety of vehicles operating in a platoon configuration. Another advantage lies in eliminating the “slinky” effect documented in PATH research on this problem.

The process which ensures safe minimization of vehicle headway consists of four system-level requirements. The key requirements include position tracking accuracy, position update rate, safety, and reliability of the communication system. Conveying control information from the lead vehicle to many following platoon vehicles is best achieved using a group-directed approach. The safety aspect of ensuring error-free communication may be addressed through the network architecture chosen for the system. A multiple access scheme which assigns specific slots to participants for data transfer avoids the inevitable data collisions inherent in less sophisticated architectures.

AHS vehicles will maintain communication with each other for the purposes of transmitting information, requests, and commands as well as providing a reference for deriving inter-vehicle range. The lead vehicle in each platoon will synchronously communicate velocity and acceleration to each vehicle in the platoon. Intra-platoon distances and closing rates will be derived from communication signals transmitted between vehicles. Table 8 defines representative vehicle-to-vehicle communication messages.

The lead vehicle will be responsible for communicating maneuver commands from the wayside to vehicles in the platoon. All vehicles will broadcast state (velocity and acceleration) information and possibly brake commands. Nominally, only the lead vehicle will coordinate braking.

Table 8. RSC 2 Vehicle-to-Vehicle Communication Messages

Message Categories	**Level 1 Description**
Lead vehicle only: 15 bits	Maneuver command: 10 bits
	Vehicle identification: 5 bits
All vehicles: 31 bits	Velocity: 11 bits
	Acceleration: 12 bits
	Brake command: 8 bits

However, if another vehicle malfunctioned, the vehicle directly behind it will then act as a platoon leader for vehicles following it. Thus the original platoon will break into two platoons with two platoon leaders responsible for coordinated braking.

Roadside-to-Vehicle Communication

The communication system will also provide roadside-to-vehicle communication. Wayside transmitters will radiate signals over a predefined area of roadway. Representative signals are defined in table 9.

AHS user information will nominally be transmitted at a rate of 1 Hz. The TOC will communicate mainly with the lead vehicle in each platoon. It will communicate with the following vehicles only in an emergency where the lead vehicle has lost its communication ability. AHS users can receive information on current weather, such as rain, sun, hail, fog, clouds, snow, high/low/current temperature, wind speed/direction, etc., along their selected route. Maneuver authorizations or commands include lane changes, platoon formation or separation, and entry/exit. For these cases, the vehicle will perform the maneuvers by processing on-board control algorithms and commanding vehicle systems. The frequency of these transmissions is entirely dependent on current roadway operational status. However, these transmissions will be allowed to occur every second if necessary. During emergency situations, the time required to wait to send a maneuver signal will be no greater than 20 ms. The roadside will transmit a target velocity at a (possibly time-varying) frequency appropriate to support stable and optimal traffic flow.

Table 9. RSC 2 Roadside-to-Vehicle Communication Messages

Message Categories	Level 1 Description	Level 2 Description
AHS user information: 57 bits	Vehicle identification: 15 bits	
	Diagnostic feedback: 11 bits	Tire pressure: 1 bit
		Fuel level: 1 bit
		Oil temperature: 1 bit
		Engine temperature: 1 bit
		Oil level: 1 bit
		Water level: 1 bit
		Steering actuator: 1 bit
		Brake actuator: 1 bit
		Throttle actuator: 1 bit
		Magnetic sensing system: 1 bit
		Communication system: 1 bit
	Weather information: 20 bits	
	ETA: 11 bits	
Control requirements: 37 bits	Maneuver authorization/ command: 25 bits	
	Target velocity: 12 bits	

Vehicle-to-Roadside Communication

The communication system will also provide vehicle to wayside communication. These signals are presented in table 10. Signal types and their associated bit values are representative of information that will be communicated in an AHS.

AHS user requests will be transmitted at a 1 Hz rate, while diagnostic status will be communicated at a 10 Hz rate. The latter rate supports the concept of predicting and/or detecting vehicle malfunctions. This will improve vehicle malfunction management and overall safety.

The on-board diagnostic unit will receive input from various vehicle sensors. It will process this information to determine the vehicle health status. If an anomaly is detected, the unit will utilize

Table 10. RSC 2 Vehicle-to-Roadside Communication Messages

Message Categories	Level 1 Description	Level 2 Description
AHS user requests: 78 bits	Vehicle identification: 15 bits	
	Maneuver request: 10 bits	
	Destination request: 50 bits	
	Information requests: 3 bits	Vehicle status: 1 bit
		Weather: 1 bit
		ETA: 1 bit
Diagnostic status: 30 bits	Vehicle identification: 15 bits	
	Malfunctioning component: 6 bits	
	Level of severity: 9 bits	
Vehicle state: 111 bits	Vehicle identification: 15 bits	
	Position: 64 bits	Latitude: 24 bits
		Longitude: 24 bits
		Altitude: 16 bits
	Velocity: 8 bits	
	Acceleration: 8 bits	
	Steering angle: 8 bits	
	Steering rate: 8 bits	

the communication system to transmit the problem information to the wayside. The wayside will than determine an appropriate action for the vehicle, and if needed, for its platoon and other AHS vehicles in the vicinity. If immediate action is required, the diagnostic unit will direct an appropriate vehicle action, while coordinating this action with other platoon vehicles and the wayside.

Items that may require monitoring include:

- Steering, brake and throttle actuators (operating performance).
- Collision avoidance sensors, computer.
- Translational and rotational sensors.
- Communication system.
- Fuel level.
- Tire pressure.
- Oil temperature, pressure, level.
- Engine temperature, rpm.
- Water level.

Representative System Configuration 3

Figure 9 shows the control and communication architecture for RSC 3. It is important to note that control inputs as well as TOC inputs and outputs are only meant to characterize the type of values to be used for the eventual AHS architecture.

Measurement

See Representative System Configuration 1.

Lateral Control

The lateral control task will be accomplished by the use of a vision system. This system will acquire images of the roadway, process this data appropriately, and use it as input to the lateral controller. The controller will then solve control algorithms and command vehicle subsystems.

The system will be capable of maintaining a continuous lateral reference for the vehicle control system. It will also function effectively in a situation where an unauthorized vehicle moves in front of the AHS vehicle. Depending on the placement of the camera mount, the optical sensor may not be able to “see” the lanes lines. In this case, the system must use other visual clues for lateral control. The alternative would be to mount the optical sensors at a location on the vehicle where this form of lane intrusion would not cause a control problem.

Longitudinal Control

Wayside time slot controllers will define a desired slot state for each vehicle. The vehicle will be responsible for acquiring position, velocity, and acceleration information for each control cycle.

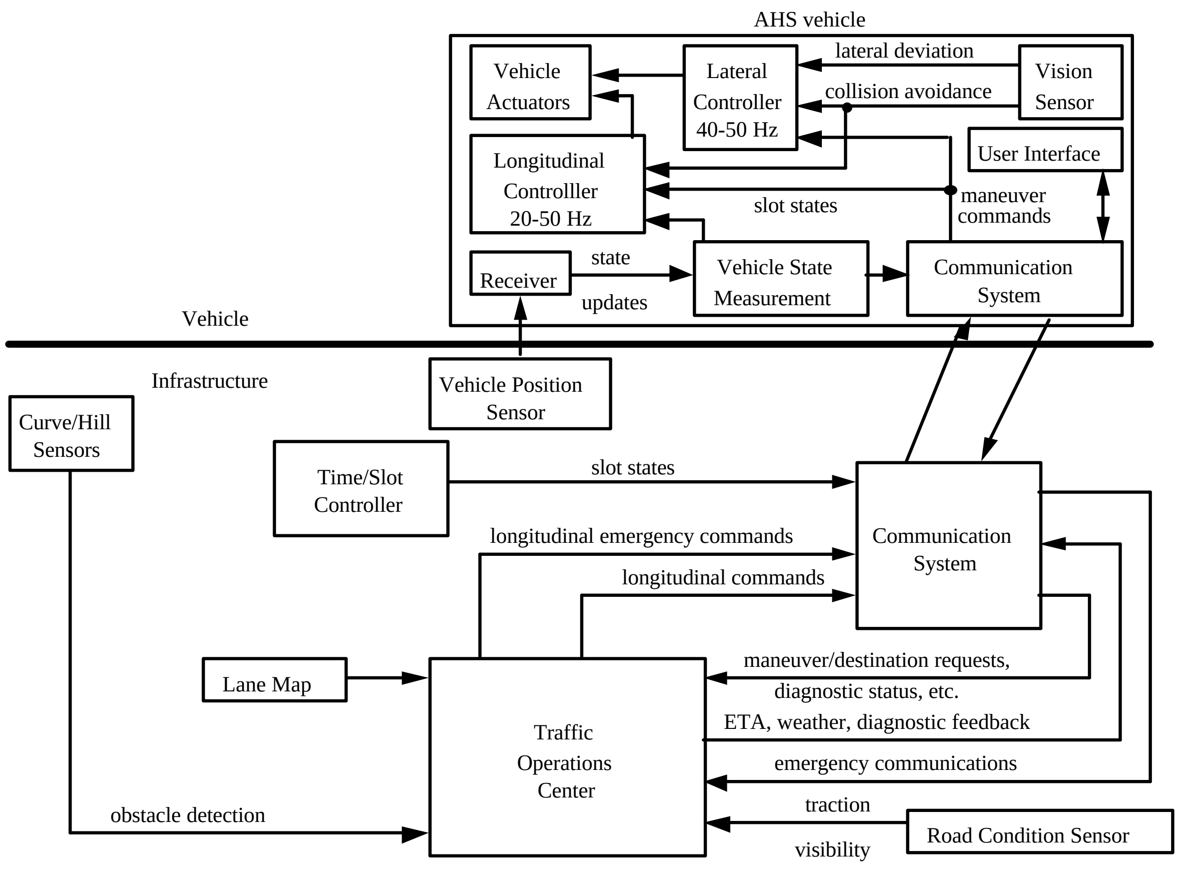


Figure 9. RSC 3 Communication/Control Architecture

The vehicle's on-board controller will solve control algorithms to minimize the error between the current slot state and the desired slot state, with an emphasis being placed on the position error. Due to the significant spacings between vehicles, longitudinal control outputs should be generated every 20 to 50 ms. It doesn't seem likely that a higher rate will be required for steady-state control.

Roadway map databases will provide the time slot control system with roadway information. This will allow the controller to properly define slot states to be communicated to AHS vehicles. Only the area in each controller's jurisdiction will be mapped and stored. Data access times will support the longitudinal control cycle (20 to 50 Hz).

Collision Avoidance

The vehicle-based vision system used for obtaining a lateral control reference signal will also be used to provide a collision avoidance reference signal. This signal will be processed by on-board computers to generate appropriate vehicle maneuvering commands. Due to the immense processing requirements for two-dimensional signals, application-specific hardware may need to be developed to meet these needs.

Position Location

Each AHS vehicle will supply its longitudinal controller with position, velocity, and acceleration information. The acceleration will either be obtained from an on-board accelerometer or will be derived from the wheel speed measurement system. Position and velocity can be obtained from the wheel speed system. Velocity can also be obtained from a microwave radar system.

A supplemental system, such as a global positioning or wayside tag system, will update the vehicle position and velocity under conditions where the on-board system is known to be deficient.

Communication

The approach to meeting communication requirements in the space/time slot control RSC is very similar to that defined for RSC 1. A two-way vehicle-roadside communication (VRC) system has been defined as the method for providing longitudinal control information to the vehicle and the vehicle-roadside data collection path. The primary difference in the two systems is in the addition of navigation dead reckoning as an input to the control loop. The features of the VRC system will be covered in Task 6.

The communication system will provide roadside-to-vehicle and vehicle-to-roadside communication. Roadside transmitters will radiate signals over a predefined area of roadway. Table 11 defines signal types and their associated bit values which are representative of information that will be communicated in an RSC 3 type of AHS scenario.

AHS user information will be transmitted at a 1 Hz rate. Lateral maneuver commands will be communicated every second to a vehicle if necessary. However, during emergency situations, the

Table 11. RSC 3 Roadside-to-Vehicle Communication Messages

Message Categories	Level 1 Description	Level 2 Description
AHS user information: 48 bits	Vehicle identification: 6 bits	
	Diagnostic feedback: 11 bits	Tire pressure: 1 bit
		Fuel level: 1 bit
		Oil temperature: 1 bit
		Engine temperature: 1 bit
		Oil level: 1 bit
		Water level: 1 bit
		Steering actuator: 1 bit
		Brake actuator: 1 bit
		Throttle actuator: 1 bit
		Communication system: 1 bit
		Vision system: 1 bit

	Weather information: 20 bits ETA: 11 bits	
Lateral maneuver commands: 11 bits	Vehicle identification: 6 bits Lane change: 5 bits	
Time slot control commands: 30 bits	Vehicle identification: 6 bits Time slot position: 8 bits Time slot velocity: 8 bits Time slot acceleration: 8 bits	
Vehicle state update (tag case): 51 bits	Vehicle identification: 6 bits Position: 45 bits	

time required to wait to send a maneuver signal will be no greater than 20 ms. Time slot control commands will be sent to each vehicle every 50 ms to support the longitudinal control rate. Thevehicle state update will be generated by a system that is separate from the primary vehicle-roadside communication system. This state update system will transmit information to vehicles when requested.

The vehicle-based communication system will transmit the information defined in table 12.

AHS user requests will be transmitted at a 1 Hz rate, while diagnostic status will be communicated at a 10 Hz rate. The latter rate supports the concept of predicting and/or detecting vehicle malfunctions. This will improve vehicle malfunction management and overall safety. Vehicle state information will be transferred at a 1 Hz rate.

In RSC 2, the vehicle was responsible for analyzing diagnostic data and transmitting its results, if significant, to the wayside TOC. In RSC 3, it is assumed that the analysis is provided by either the TOC or the roadside time slot controller. In the latter case, the processor would function in a multi-tasking mode. Clearly, the location of the diagnostic evaluation unit can be either in the vehicle or on the infrastructure.

Task 3. Tradeoff Issues and Analysis

Many tradeoffs between vehicle and operational parameters must be considered by AHS designers. AHS goals must be clearly defined and prioritized before any weightings can be placed on particular approaches. This section attempts to discuss some of the basic control performance tradeoffs involved in AHS design with an emphasis placed on the platoon concept. Other sections of this report present tradeoffs indirectly or discuss the tradeoffs listed below from a different perspective.

The Platoon Concept

It is very desirable to improve highway safety and increase potential capacity from their present levels. Note, however, that safety considerations as well as reduced travel times and a host of other potential AHS benefits overshadow the importance of increased capacity. Ideally, the AHS architecture should have the capability of increasing highway capacity on demand up to a certain capacity limit. One possible solution is to implement the vehicle platoon concept into the AHS architecture. Platoon sizes can range from one vehicle to possibly twenty vehicles. Platoons

Table 12. RSC 3 Vehicle-to-Roadside Communication Messages

Message Categories	Level 1 Description	Level 2 Description
AHS user requests: 35 bits	Vehicle identification: 6 bits	
	Maneuver request: 10 bits	
	Destination request: 16 bits	
	Information requests: 3 bits	Vehicle status: 1 bit
		Weather: 1 bit
		ETA: 1 bit
Diagnostic status: 89 bits	Vehicle identification: 6 bits	
	Tire pressure: 6 bits	
	Fuel level: 3 bits	
	Oil temperature: 1 bit	
	Engine temperature: 1 bit	
	Oil level: 1 bit	
	Water level: 1 bit	
	Steering actuator response: 12 bits	
	Brake actuator response: 12 bits	
	Throttle actuator response: 12 bits	
	Translational/rotational sensors: 20 bits	
	Vision sensor: 4 bits	
	Vision processor: 4 bits	
	Communication system: 4 bits	
	Transceiver: 2 bits	
Vehicle state information: 99 bits	Vehicle identification: 6 bits	
	Position: 45 bits	Latitude: 15 bits
		Longitude: 15 bits
		Altitude: 15 bits
	Velocity: 8 bits	
	Acceleration: 8 bits	
	Wheel speed: 16 bits	
	Steering angle: 8 bits	
	Steering rate: 8 bits	

consisting of more than twenty vehicles are currently viewed as being impractical and difficult to control. In the future, this may not be the case. Occupant and vehicle safety can be ensured through the use of well-designed cooperative communication and control systems. Highway capacity can be altered based on prevailing conditions by altering the platoon configuration (number of vehicles, spacing between vehicles) or operational velocity. The AHS design should consider an architecture that can accommodate a relatively large vehicle capacity (up to 6,000 vehicles/lane/hour). This capability will only be realized when needed and when practical.

Intra-Platoon Issues

Overall system safety can be maintained while highway capacity is increased when vehicles travel in platoon formation at appropriate vehicle spacings. Figure 10 shows the relationship between collision velocity and vehicle spacing for example values of lead vehicle deceleration (1.0 g), following vehicle braking (0.8 g), response delay (see chart), and initial velocity (130 km/h). Assuming these conditions, for vehicle spacings of 3 m, a collision would produce a velocity difference between vehicles of 12 to 20 km/h. Note that this is in the absence of a coordinated braking system. At a spacing of 1 m, the relative velocity between vehicles would be in the 7 to 16 km/h range. Note that vehicle manufacturers generally require airbags to deploy for frontal impacts beginning at 24 km/h and for frontal angle (30 degree) impacts beginning at 32 km/h. These are the speeds at which collisions have the potential to cause significant bodily injury. Frontal impacts at 14.5 km/h should not deploy the airbag.

Figure 10 depicts collision velocity for a moderate difference in deceleration between the failure condition and the following vehicle. Unfortunately, the potential exists for a greater disparity between decelerations. This in combination with 0.2 to 0.5 s response delays would increase the collision velocity considerably for all initial separations. However, the concept of coordinated braking can minimize the difference in decelerations by the use of adaptive control and can minimize response delays by using intelligently designed communication schemes.

Various problems can occur in an AHS requiring vehicles to perform emergency braking. This discussion concerns two significant safety issues involving platoons. The first is a case where the lead vehicle in a platoon either senses an upcoming hazard requiring braking (all RSC’s) or is commanded to brake by the infrastructure (RSC 1, 2) or another platoon (RSC

2). The second case is defined by a vehicle malfunction or other event within a platoon requiring certain vehicles to perform emergency braking. Clearly these two scenarios identify the potential for serious

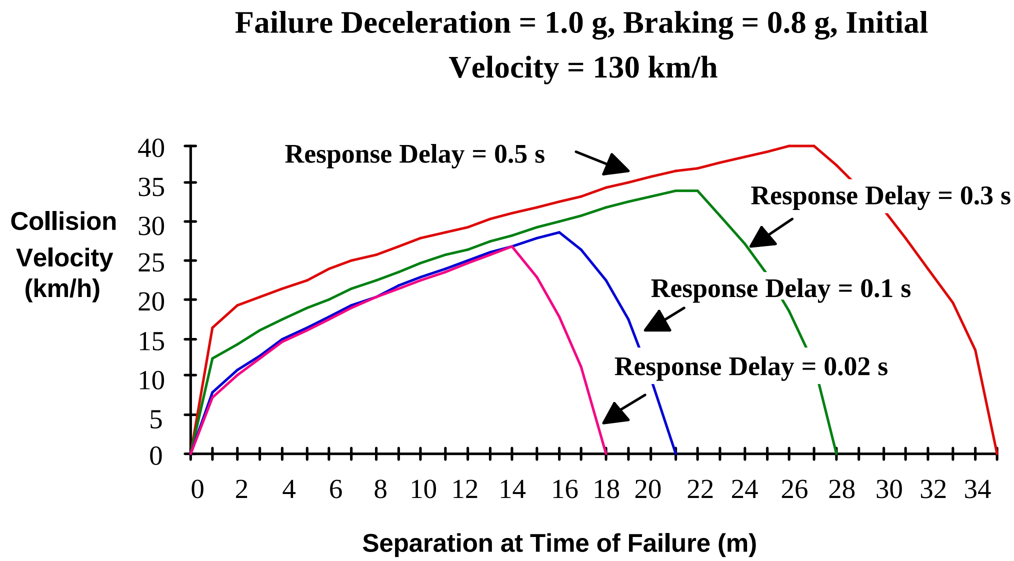


Figure 10. Potential Vehicle-to-Vehicle Collision Velocities

damage to vehicles and injury to their occupants if adequate platoon command and control is not maintained. The first safety concern is used as a framework to introduce a coordinated platoon braking system. A potential solution to the second issue will draw upon concepts from the coordinated system.

Coordinated Braking Control System

As vehicles merge into a platoon, they will communicate their performance capabilities to the current lead vehicle. The lead vehicle will then know the capabilities and limitations of all the platoon members. If these capabilities are somewhat time-varying, vehicles may be able to sense their changing performance abilities and communicate them to the lead vehicle in real-time. Once the lead vehicle determines the need for a braking maneuver, initial brake commands can be issued based on the braking capabilities of the vehicles in the platoon. Differences in deceleration rates between vehicles can be minimized by controlling vehicle brake and possibly throttle systems. The response delay can be decreased to an insignificant level by utilizing modern communications equipment in a coordinated manner. Figure 11 depicts a representative control system architecture to accomplish the task of optimally decelerating a platoon while avoiding intra-platoon collisions. This system is applicable to any RSC, as it does not specifically identify locations for measurement and control systems.

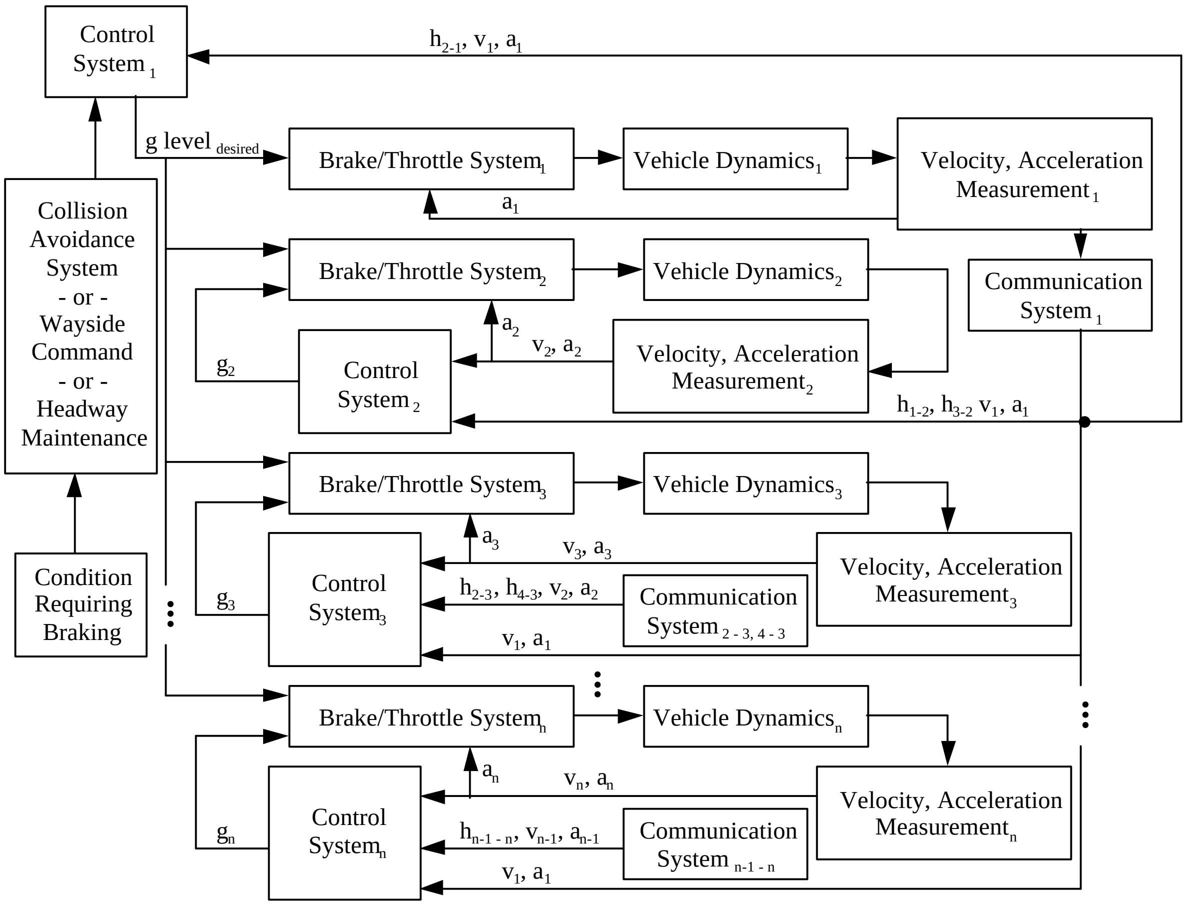


Figure 11. Representative Platoon Braking Control System

In figure 11, the platoon consists of *n* vehicles. The subscripts on velocity (v), acceleration (a), and deceleration level (g), and those inside the function boxes denote the vehicle number in the platoon. The lead vehicle is vehicle number 1, while the trailing vehicle is number n. In the communication boxes, “x-y” signifies a transfer of information from vehicle x to vehicle y via the communication system. The subscripts on headway (h) items indicate that range and possibly range rate information is transferred between vehicles. This information can be derived from the communication signal or obtained directly from the collision avoidance sensor.

The lead vehicle initially transmits braking commands in the form of desired g levels to all following vehicles for the purposes of avoiding a foreign object on the road, another AHS vehicle or platoon, etc. The following vehicles then brake simultaneously. Intelligent communication between vehicles can be used to attain this result (refer to the text associated with figure 12 for a discussion of this topic). This communication scheme can be achieved by requiring the lead vehicle to broadcast braking signals to all following vehicles. Each vehicle tries to attain the desired g level using an internal braking control system which is designed to drive the error between the desired g level and the measured acceleration to zero. Each vehicle must convert the desired g level into a brake signal based on vehicle characteristics, such as weight, tire conditions, brake system, engine inertia, etc. In the event that vehicles decelerate differently, control algorithms in each vehicle can adjust that vehicle's braking or acceleration. These algorithms can accept velocity and acceleration signals from the lead vehicle, preceding vehicle, possibly the following vehicle, and on-board measurement systems, as well as headway information from surrounding vehicles in the platoon.

This control scheme, which is designed to decelerate a platoon without causing intra-platoon collisions, presents a tradeoff. In the case where a platoon encounters an object on the roadway that cannot be avoided via a lane change (because adjacent lanes are occupied or there is not enough time to change lanes), emergency control systems will command braking actions. Furthermore, at the time of detection, assume that the platoon will not be able to brake effectively to avoid the object. If all vehicles brake according to their maximum capabilities, the platoon as a whole should stop in a shorter distance than if it used the control scheme described above with the communication system described below. The former method would potentially cause some intra-platoon collisions, but it would reduce the collision velocity between the platoon and the object more so than the controlled braking method. A possible solution to this tradeoff problem is to allow intra-platoon headways to decrease as a function of velocity to the point where all vehicles are very close together once the platoon has come to a complete stop. The initial headways could be in the 5 to 10 m range. Clearly this approach presents a more complex control problem.

Communications for Braking Control

The following communication approach is applicable to RSC 2, though variations can easily be applied to RSC's 1 and 3. Communication speed and coordination are very important to this braking concept. As an example, using a Time Division Multiple Access (TDMA) protocol, a platoon of twenty vehicles can allocate a 2 ms communication time slot to each vehicle. The remaining 5 time slots could be evenly spaced throughout the control cycle for use as contention slots (see the following paragraph for a definition). This will allow each vehicle one transmission opportunity every 50 ms to support a 20 Hz longitudinal control rate. Clearly, higher control frequencies can be accommodated by allocating less transmission bandwidth to each vehicle, increasing the communication rate capabilities, or decreasing the number of vehicles per platoon. During each of these time slots, modern communication equipment can transmit 160 to 320 bits.

During slot 1, for example, the lead vehicle will transmit (broadcast) information to the rest of the platoon, which will have their communication equipment in receive mode. During slot 2, vehicle 2 will transmit while all other vehicles are in receive mode. Addressing will ensure that the message is received by the appropriate vehicle(s). This process will continue for all vehicles in a platoon. Each vehicle's communication system will contain a very accurate clock to ensure exact transmit mode/receive mode switching times. Clearly, more communication bandwidth for steady-state and emergency control will exist for smaller sized platoons. This will be advantageous to the RSC 1 approach, as it is defined by small platoons (1 to 5 vehicles). RSC 2 allows larger platoons (up to 20 vehicles).

TDMA communication systems allow a reasonable amount of flexibility in their design. For example, the communication protocol can be designed to allocate larger time slots to those vehicles required to transmit greater amounts of data. The lead vehicle would be a good candidate for a larger time slot than the rest of the platoon. Also, non-dedicated contention slots can be added in the slot stream to allow any vehicle in the platoon to communicate emergency information. For example, one contention slot could be placed after every 5 slots to ensure that all vehicles have access to emergency communication without waiting for their next time slot to transmit. If the lead vehicle needed to command an emergency braking maneuver sometime during the 50 ms control cycle when it was in receive mode, it would wait until the next contention slot (10 ms worst case delay) to begin coordinated emergency braking. There is a possibility of the simultaneous use of the same contention slot by two or more vehicles, since any vehicle could transmit during this period. However, this is highly unlikely.

Maintaining similarity in vehicle deceleration profiles is critical to coordinated braking. Time delays resulting from lack of coordination could significantly affect system functionality. These delays include time for signal propagation through the air, the time required by each communication system to receive the entire data message, vehicle data bus delays, and brake system delays to the point of achieving desired deceleration levels.

Since signal propagation through the air requires about 3 ns/m, and a conservative estimate of platoon length for twenty vehicles is 300 m (vehicle length = 5.5 m, gap length = 10 m), the time required for a signal to reach the last vehicle in a platoon is roughly 0.9 µs. Based on the expected length of data signals and on the communication system's data rate, each receiver should require no more than the 2 ms (or more) allocated to the lead vehicle for transmission to obtain the transmitted message.

So far, this discussion has assumed that all data is transmitted either error-free or with correctable errors. Current radio communication technology cannot guarantee error-free transmission. However, the probability of communication errors is relatively low and can be negligible with the use of more sophisticated systems. During steady-state longitudinal control conditions, low probabilities of errors can be tolerated. During emergency conditions, data must be transmitted error-free. In this case, radios can switch to a high-power data priority mode to avoid interference and guarantee that emergency transmissions are received correctly by each vehicle receiver. The possibility of communication interference between platoons (traveling in the same direction or in opposite directions) can be addressed by the use of frequency or code allocations.

Current U.S. vehicle serial data links operate under 50 kilobaud. In the next 10 to 20 years, high speed links will be capable of 100 to 200 kilobaud. The various data buses that exist in present production vehicles can be differentiated by transmission speed, function, and level of message priority. For AHS vehicles, it may be necessary to require dedicated message buses for throttle, brake, and steering control. However, the worst-case time delay to wait for the data bus to clear is usually less than 1 ms for high-speed links. If this delay is tolerable, the cost of dedicated high-speed data links can be avoided. High-speed links can accept data from resident systems (radio receiver, engine controller, transmission controller, etc.) every 5 ms. This update cycle time is short enough to support expected control update times on the order of 20 ms or greater. Current dedicated medium speed links (10 kilobaud) can accept data every 25 ms. This performance will not be adequate for AHS purposes.

Assuming that a brake command requires two bytes of data, then six total bytes of data must be sent from the receiver to the brake controller (four bytes are required for protocol overhead). At a baud rate of 200 k, less than 1 ms is required to convert the data into the proper transmission format, send the data two or three times to ensure receipt, and decode the transmitted message at the brake controller. Therefore, for a dedicated bus, the transmission delay will be less than 1 ms.

A delay of up to 8 ms can occur between the time a braking signal arrives at the brake controller and the time the brake system is ready to act on that command. This is due to the requirement that the antilock brake system (ABS) complete its control cycle prior to accepting new commands.

The brake system uses the transmitted signals to ultimately decelerate the vehicle. Variations in brake systems can be characterized by known and unknown components. The known component is composed of ideal brake system performance capabilities, vehicle loading, and recent historical braking performance. These factors affect a vehicle's ability to decelerate as a function of time. Performance capabilities (g level versus time) will change for a braking system during its lifetime and will differ between braking systems. This information can be communicated to the platoon leader by a vehicle when it enters a platoon. This will allow the lead vehicle to intelligently plan a coordinated braking maneuver based on the known capabilities of each of the platoon's members.

Unfortunately, there is also an unknown component of brake system performance. This component is composed of any type of unforeseen system malfunction or change to the system's performance capabilities. As an example, braking performance is significantly affected by the degree of brake pad burnishment. Until new brake pads become appropriately burnished, braking performance will be non-optimal. This situation can exist after new pads have been installed in a used vehicle. Unknown braking performance has the potential to create deceleration variations within the platoon. However, since the control system for vehicle i commands vehicle i and receives input from vehicles $i-1$ and $i+1$, as discussed above, it can be expected to alleviate this problem. For the purposes of this discussion, since brake system variations over one control cycle (50 ms) are difficult to quantify, assume an effective worst case delay of 12 ms to ensure coordination of all platoon braking systems.

The total time required from the point where the lead vehicle is ready to begin transmission of emergency braking commands to the point where platoon braking begins (and brake system differences are taken into account) is roughly 2 ms (lead vehicle transmission time to all vehicles) + 1 ms (data bus delays) + 8 ms (wait for ABS control cycle) + 12 ms (brake system performance delay) = 23 ms. Thus the lead vehicle would define a specific clock time to begin vehicle braking in its communication to all vehicles based on this worst case delay. This should ensure a reasonable level of coordinated braking within a platoon to avoid intra-platoon collisions during emergency braking maneuvers.

This braking coordination system requires the platoon to delay braking by at most 10 ms (delay for a contention slot) + 23 ms (various system delays) = 33 ms. This delay is considered negligible, since, at a maximum velocity of 160 km/h, vehicles travel less than 1.5 m in a 33 ms period.

Figure 12 illustrates a representative time line of one complete communication/control cycle for a vehicle-centered system. Initially, the lead vehicle broadcasts desired brake commands as well

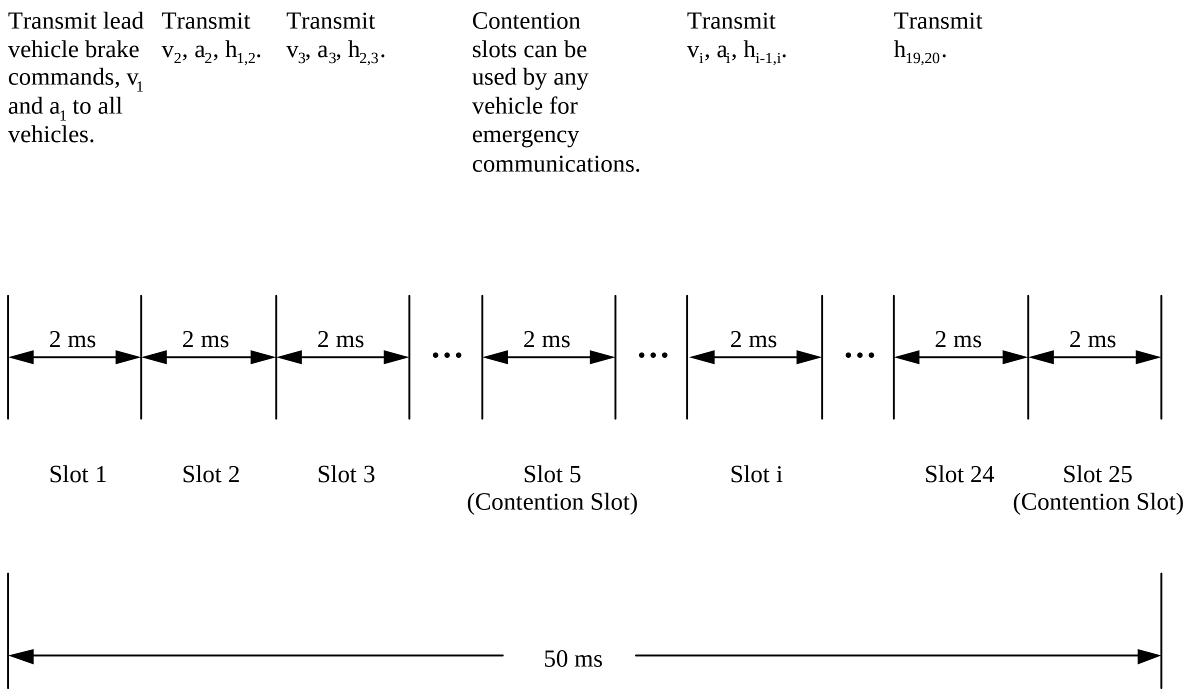


Figure 12. RSC 2 Representative Platoon Braking Communication Timeline

as its velocity and acceleration to all following vehicles during its time slot. In an emergency situation, the lead vehicle would wait for the next available contention slot (or its own dedicated time slot) to transmit the time to begin braking and the desired braking levels. All vehicles would then carry out the desired g level braking commands at the appropriate times.

Vehicle 2 would transmit its derived headway from vehicle 1 to all platoon vehicles. Only vehicle 1 would use this information. This would allow the control system of vehicle 1 to react to the motions of vehicle 2. Note that other information, such as the velocity and acceleration of vehicle 2, could be transmitted for use by vehicle 1. Next, vehicle 2 would use its time slot to transmit its velocity and acceleration for use by vehicle 3, which would then determine the headway between vehicle 2 and itself from the communication signal. It is unlikely that the maximum allowable bit rate will be required to transmit this information. Vehicle 3 would then transmit headway information for use by vehicle 2. This process would continue for all platoon vehicles. Once a vehicle has obtained velocity and acceleration information from the lead vehicle, the preceding vehicle, and itself, as well as range and range rate information between neighboring vehicles and a desired platoon g level, it can calculate a new desired g level for its braking system. This g level should meet the requirements of optimal platoon braking and allow the maintenance of a minimum headway between a vehicle and its predecessor.

Note that communication designs based on IR systems do not support broadcast methods and therefore introduce finite information delays as data passes from one vehicle to the next. However, assuming that the total time delay for signals to reach the last vehicle in a platoon was acceptable, coordinated braking control schemes using this form of communication can be envisioned.

Communications equipment would be required to switch between transmit and receive in a fraction of the 2 ms time slot. Technically, fast switching times on the order of 100 μs are feasible, but they tend to increase the cost of the communications equipment. Typical switching times are on the order of 500 μs.

When coordinated braking is employed in the platoon, it should be possible to avoid intra-platoon collisions entirely. Figure 13 emphasizes the idea that coordinated braking can indeed

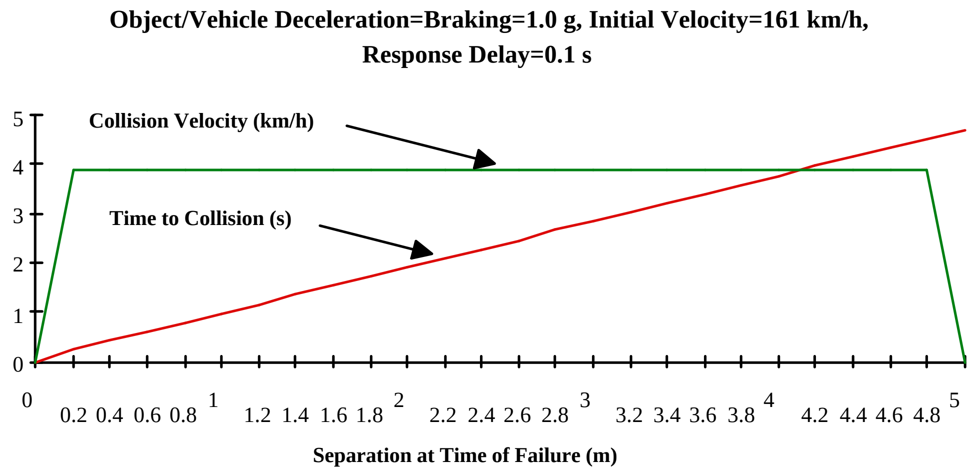


Figure 13. Time to Collision for Uniform Braking

avoid collisions among vehicles, since the time to collision is relatively long, even at close vehicle spacings. In figure 13, only the difference in braking levels has been optimized by a coordinated braking scenario. The response delay still exists for illustration purposes. For example, at 1 m spacings, for vehicles decelerating at 1.0 g, and an initial conservative response delay of 0.1 s, roughly 1 second will pass before the vehicles collide. During this time, intelligent control algorithms can adjust vehicle braking and acceleration levels to maintain adequate headways. This figure also shows the tolerance for some delay in the initiation of braking between vehicles.

Intra-Platoon Disturbance

The previous discussion sections considered the case of stopping a fully functioning platoon while avoiding intra-platoon collisions. The following discussion concerns the situation where a disturbance (malfunction of a vehicle in the platoon or in another platoon) causes localized braking within a platoon. Examples of vehicle malfunctions include tire blowouts, structural failures, engine failures, etc. Some of these malfunction conditions, namely structural failures, cannot be predicted or sensed by vehicle collision avoidance systems in time to avoid intra-platoon collisions. However, other problems can be sensed and following vehicles can take appropriate action.

Tire blowouts have the potential to cause significant disturbances in the lateral and longitudinal control system. If uncompensated, they may cause an AHS vehicle to momentarily veer into another lane. Fortunately, tire manufacturers are developing tires designed to function properly under conditions of no internal air pressure (blowouts).[11] If these tires become standard equipment in the next 10 to 20 years, concerns over vehicle control under the condition of a blown-out tire will be alleviated.

In the case of a tire blowout, the tire pressure sensing system will communicate a required braking condition to the following vehicles in a platoon and to any following platoons that may be affected by this malfunction. By the time an AHS which supports platoon operations is deployed, it is conceivable that tire pressure sensing systems could be mandatory equipment on all vehicles. Since a tire blowout will not cause a large deceleration of the affected vehicle, the following vehicle should be able to coordinate braking to avoid collisions of any type.

The pressure sensing system would initially send a braking command through the vehicle's data link to its transmitter. The transmitter would wait for the next available contention time slot to communicate this information to the following vehicles in the platoon and possibly to other platoons. Based on calculated worst-case system time delays (as discussed above), the malfunctioning vehicle would identify a clock cycle to begin emergency braking. The following vehicles would then initially brake at maximum levels. Based on feedback from the communication system and the collision avoidance system, which calculate range and range rate, the following vehicles could then either continue to brake at maximum levels or reduce braking. Once the failed vehicle has been maneuvered out of the lane, the fractured platoon can either re-form or continue to separate to establish and maintain a minimum safe headway.

In the case of a vehicle in a platoon experiencing a structural failure, it will be very difficult for the following vehicles to react in a manner that will avoid any type of collision. Structural failures include vehicle components becoming detached from the vehicle or load bearing members breaking. Under these conditions, the vehicle can decelerate, or an item from the vehicle can obstruct the following vehicle's path. The vehicle following the malfunctioning vehicle must rely on its collision avoidance system to detect the problem and determine an appropriate action. However, at intra-platoon spacings of 1 to 10 m, this will be very difficult.

It is conceivable that the control system, and other diagnostic systems, could identify a potential problem before it starts to decelerate the vehicle. They would compare the current vehicle state to expected states derived from historical data to conclude that the vehicle was not functioning correctly. The vehicle could be removed from the platoon prior to experiencing any effects of the malfunction. An example is the scenario where a part of the steering mechanism starts to lose its load-bearing capability. This problem could be detected by comparing steering responses with expected values for that particular vehicle. Before the component completely fails, and possibly causes the vehicle to decelerate or lose control, the control system could detect the potential problem and remove the vehicle from the platoon.

Engine failures can usually be predicted by various sensors in a vehicle. The vehicle experiencing an engine problem could be removed from a platoon prior to the onset of any serious effects. Even if an engine were allowed to fail completely, the resulting deceleration would be small and would not adversely affect the following vehicles.

Collision Dynamics

In the event of a vehicle or system malfunction, intra-platoon collisions may occur. Therefore, platoon "buckling" must be considered. Since not all vehicle front and rear ends align with each other, and since failure conditions are largely unpredictable and potentially uncontrollable, collisions may result in significant angular differences between vehicle headings. During vehicle braking, a pitching moment results. As the braking force, and thus the deceleration of the vehicle, increases, the vehicle will pitch forward with a greater pitch angle. This forward pitch will misalign a vehicle's front bumper with the lead vehicle's rear bumper. The case of a platoon encountering an emergency braking condition due to a malfunction on a curve is a good example of this potential problem. Furthermore, nonhomogeneous traction (e.g. scattered icy spots, oil spills) will complicate this issue by creating significantly different operating conditions between vehicles. Though control systems can be designed to compensate for unforeseen forces acting on the vehicle, intra-platoon collision forces and vehicle interactions may be strong enough to render the lateral control system ineffective. At the point where the control system cannot keep vehicles in their lanes in an acceptable orientation and at a controlled speed, the potential exists for vehicles to cross lanes and collide into other AHS vehicles or roadway barriers. Clearly this scenario is very detrimental to system safety and must be avoided.

Inter-Platoon Issues

To minimize required headways between platoons, and thus increase capacity, response delays must be minimized. A platoon could be required to communicate severe braking levels not only internally, but to following platoons operating within a certain headway as well. Another method is to communicate the output from the wheel speed sensors, which are standard equipment on antilock braking systems, to a following platoon. This concept should provide the following platoon with braking information much earlier than it could derive that information itself from its collision avoidance system. The use of coordinated braking will allow inter-platoon spacings to be defined solely on the basis of required maneuver space. Spacings on the order of 300 to 400 m defined for large response delays and large differentials between deceleration levels will no longer be necessary.

Safety

Safety issues must be considered from the viewpoints of all vehicles in a platoon. Consider the case of a 20-vehicle platoon, where maximum lead vehicle braking will not stop the platoon from impacting an object with relatively large mass on the roadway. Also, assume that intra-platoon collisions are not allowed to distribute the impending relative velocity difference among the vehicles in the platoon. Here, the lead vehicle will suffer a frontal collision with a much greater force than that created if it was acting independently, due to the mass of the 19 trailing vehicles. The last vehicle in the platoon will receive the least amount of damage. This analysis is rather pessimistic, since some or all vehicles in a platoon could change lanes to either avoid a collision or reduce the severity of an unavoidable collision.

Control Stability

Longitudinal control stability for relatively long platoons is a safety issue. Longitudinal control algorithms are designed to maintain the desired intra-platoon spacing. However, errors in spacing can propagate down the platoon and cause the last vehicle to continuously make significant headway corrections. This concept is referred to as the “slinky” effect. Instabilities could lead to intra-platoon collisions, especially between the last few vehicles in a closely spaced platoon. Researchers have simulated 15-vehicle platoons with 1 m spacings and have shown bounded acceleration corrections and headway errors for all vehicles. These results have yet to be proven in a realistic test, where all system nonlinearities and noise will have an effect on the control system.

Aerodynamics and Emissions

Researchers at the University of Southern California have conducted wind tunnel tests to determine the aerodynamic drag coefficients of vehicles operating in a platoon at 2 to 3 m spacings.[12] All vehicles in a platoon benefit aerodynamically from small intra-platoon spacings. Their results showed a 38 percent reduction in the average platoon aerodynamic drag. This approximately equates to a 24 percent increase in mileage as well as reduced emissions. Maintaining small spacings between vehicles is not expected to require a significant amount of throttle and brake use. Even under poor conditions, the use of throttle and brake systems in an AHS scenario should be less than their use during current driving situations.

Headway Alternatives

It is worthwhile to note that if a communication and control system, such as the one described above, could be designed to meet the requirements of headway maintenance during braking, intra-platoon spacing variations would not pose a significant safety risk. The control system could guarantee that intra-platoon collisions would not occur during any level of emergency braking when the platoon (or a portion thereof) is required to brake as a unit. It could not guarantee that vehicles in a platoon would not collide with a preceding vehicle of the same platoon that experienced a malfunction. This category of malfunction includes the case where another vehicle changes lanes and sideswipes the platoon. However, assuming that the majority of vehicle failures can be sensed in time to alert following vehicles, adequate coordinated braking could be commanded to isolate the following vehicles (and platoons) from the malfunctioning vehicle.

Based on the assumption of adequate vehicle component and system sensors and relatively small communication delays, instead of defining constant headways of 1 m (using the argument of low collision velocity), headways of 3 m, 5 m, 10 m, etc. could be employed. Clearly greater headway would decrease potential capacity, but levels of safety would remain high. Since the attainment of extreme levels of capacity is a very minor goal of AHS design, this is not considered a negative tradeoff. The use of larger headways would also address the potential problem of user acceptance of close headways. Requirements on the accuracy and responsiveness of sensor, communication, and control systems could be relaxed as well.

Figures 14 through 16 present capacity estimates for specific vehicle performance capabilities as a function of varying intra-platoon gap size (10 to 30 m). Figure 14 shows that very reasonable capacity levels can be attained assuming rather conservative vehicle performance parameters and a 10 m vehicle-to-vehicle gap length. At speeds below 40 km/h, single-vehicle configurations actually result in higher capacity than multi-vehicle platoon configurations. Figures 15 and 16 also display this phenomenon. In figure 16, even with 30 m inter-vehicle spacings, a 20-vehicle platoon can still achieve capacities in excess of 3,000 vehicles/h/lane for speeds in excess of 140 km/h. When considering the many tradeoffs of AHS designs (human factors, highway capacity, arterial capacity, control/communication complexity, etc.), the 5-vehicle platoon operating with the parameters of figure 14 (namely a 10 m vehicle-to-vehicle gap) seems like a very reasonable

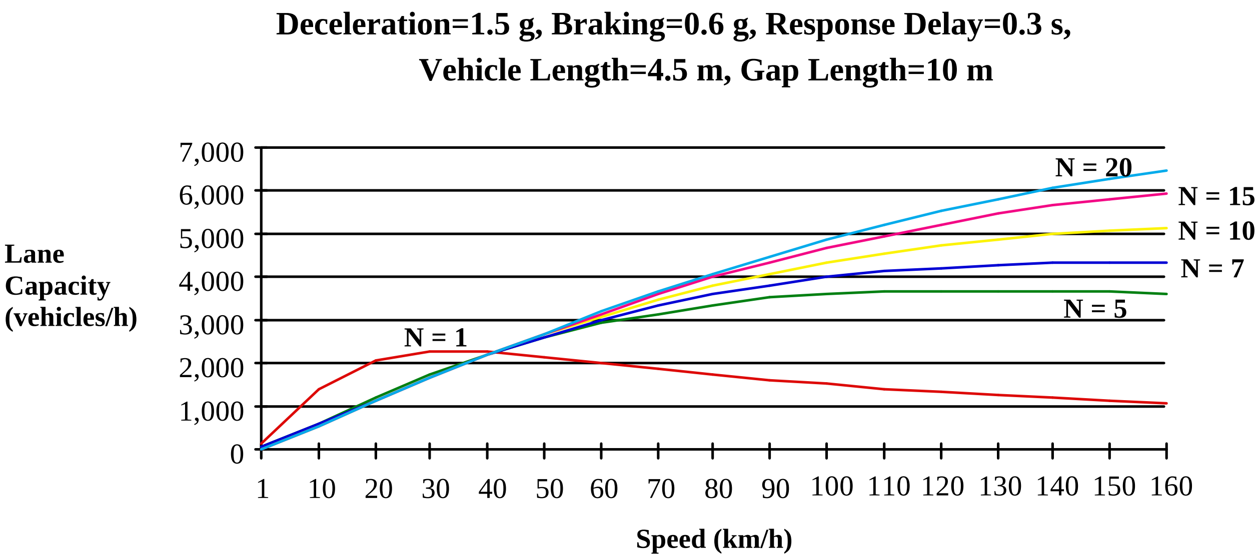


Figure 14. Capacity Estimate for Intra-Platoon Gaps of 10 m

compromise. Here, capacities approaching 4,000 vehicles/h/lane are achievable at a variety of speeds, and vehicles are spaced comfortably.

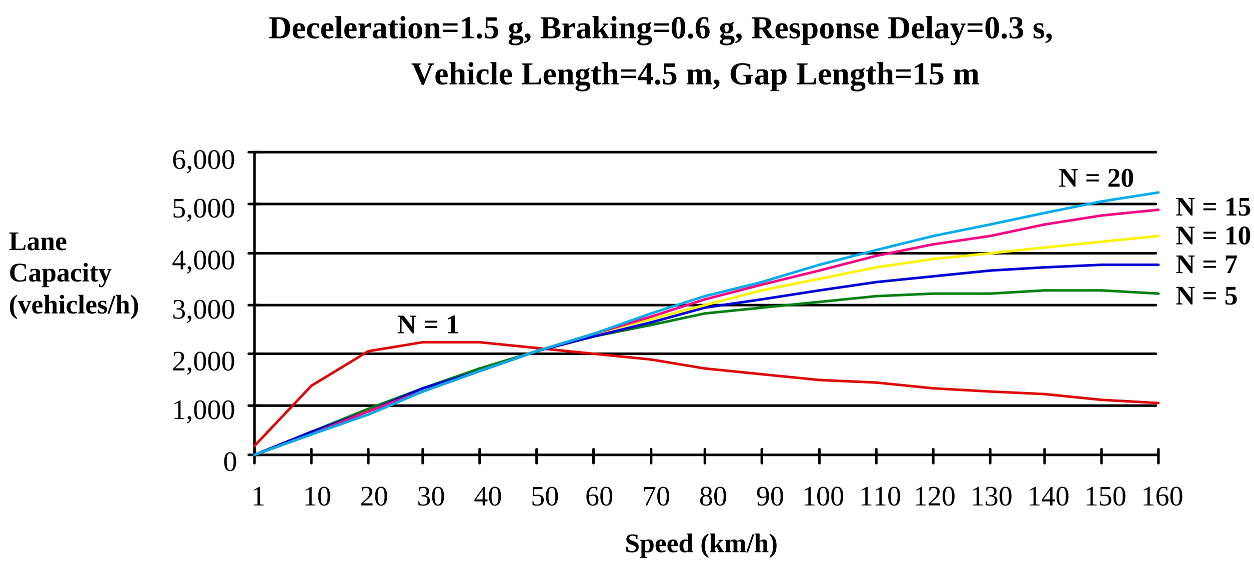


Figure 15. Capacity Estimate for Intra-Platoon Gaps of 15 m

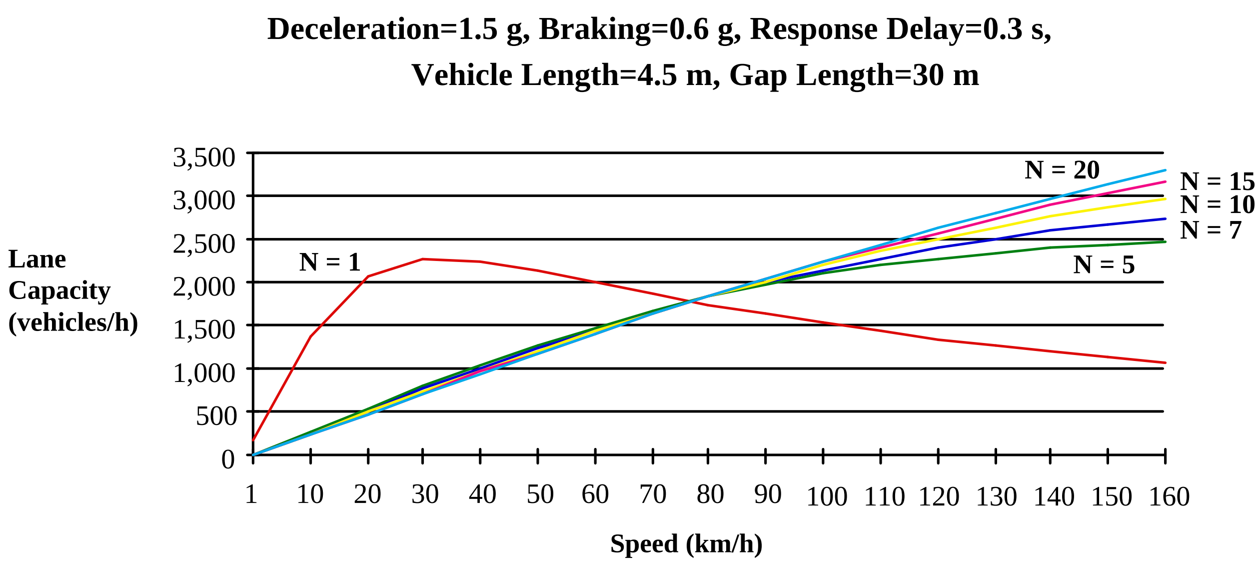


Figure 16. Capacity Estimate for Intra-Platoon Gaps of 30 m

As intra-platoon headways increase, the need for high levels of control signal accuracy and high update rates decreases. The larger variations allowed between vehicles (e.g. 10 m spacing ±0.5 m as opposed to 10 m spacing ±0.1 m) will result in the need for a lower data-rate communication system, a less accurate sensor system, and a slower control loop. With more room for error between vehicles, the overall communication and control system would be able to tolerate reduced levels of performance compared to those for a system operating at 1 m intra-platoon spacings. As the level of performance decreases, the cost of both the communication system and the control system decreases. With sufficiently large spacings, the communication system can be completely eliminated from the control loop (with the control system relying only on the sensor inputs) allowing for a much simpler design of the longitudinal control system.

When intra-platoon spacings are defined in the 5 to 10 m range, the initial coordinated braking delay needed to guarantee simultaneous brake application of all coordinated vehicles could be reduced significantly. In this case, the lead coordinating vehicle would transmit the braking signal to all following vehicles and begin braking after a slight delay (wait for a contention slot). The following vehicles would begin braking when they received and processed their braking signals. Clearly, delays would exist in the start of braking between vehicles along the platoon. There would be, however, 5 to 10 m of space to travel before any vehicle-to-vehicle collisions occurred. As an example, a vehicle traveling at 160 km/h covers approximately 1.1 m in 25 ms. This time delay is used here as an approximate worst-case delay from the time the lead vehicle sends the braking signal to the time the trailing vehicle's brakes begin to respond (see above). This concept reduces the effect of the tradeoff between lead vehicle collision velocity and intra-platoon collisions discussed above.

Operating platoons with 5 to 10 m spacings will reduce roadway capacity from that achievable with smaller spacings. Also, if a vehicle in the middle of a platoon exhibits a malfunction that cannot be predicted or detected in the amount of time necessary for the following vehicles to coordinate braking, intra-platoon collisions could occur. It is assumed that a vehicle cannot decelerate at a level greater than that achievable by its braking system. Vehicles within a platoon will only be allowed to brake at the level achievable by the worst performing vehicle in that platoon.

Figure 17 shows collision velocities for two vehicles in a platoon, where both vehicles decelerate at a 1.0 g level, and the onset of braking by the following vehicle occurs after various response delays. If a vehicle initiated braking without first coordinating the braking function with other platoon vehicles (possibly caused by collision-avoidance false detection), braking information could be communicated to the following vehicles to initiate their braking functions. The delay for this case would probably be less than 50 ms, and would not result in collisions for separations greater than 3 m. Other vehicle malfunctions, such as a flat or blown tire or an engine failure, can produce moderate decelerations (probably less than 1 g). At 5 to

10 m spacings, the following vehicle should be able to detect this deceleration and apply an appropriate amount of braking to avoid a collision.

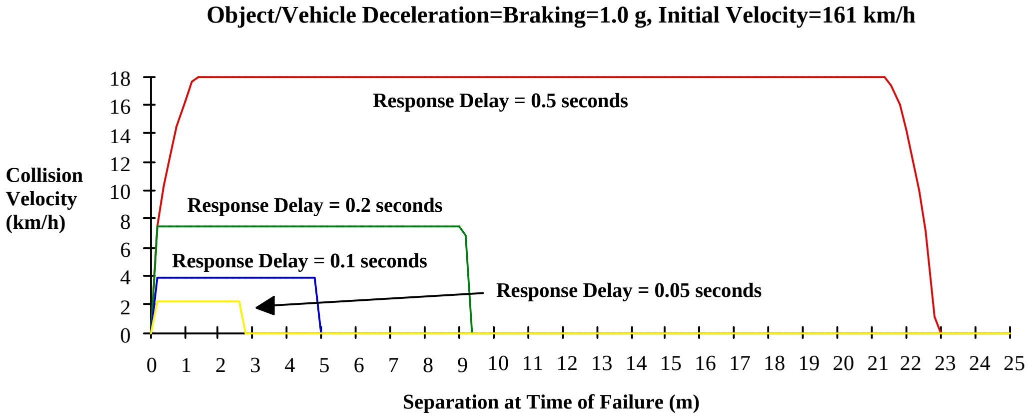


Figure 17. Effect of Response Delay on Collision Velocity

Another alternative is to define intra-platoon spacings based on each vehicle's performance characteristics. Each vehicle has a certain stopping capability based on its brake system, vehicle weight, tires, etc. In this scenario, higher-performance vehicles could follow vehicles closer than lower performing vehicles could. This would still ensure safety via a coordinated braking approach and it would improve capacity over a system that required uniform conservative headways.

Platoon Alternatives

The discussion concerning vehicle placement on the highway has been concerned so far with grouping vehicles into units called platoons and requiring moderate spacings between these platoons. With the use of localized coordinated braking, vehicles can operate at spacings on the order of 15 to 30 m. Each vehicle would coordinate its braking function with the following vehicle(s) as necessary. There would be no need for inter-platoon gaps for safety or maneuvering purposes. This approach has the advantage of not requiring relatively close vehicle spacings (possibly 1 to 10 m) as in the platoon concept. It will also allow lane changes to occur after a vehicle travels a maximum of one vehicle length (plus a safe spacing ≅5 m) in either longitudinal direction. The new localized vehicle spacing, which could initially be as small as 6 m, could be increased by repositioning vehicles in the same lane as necessary. This separation would still be considered safe due to the use of coordinated braking. In a platoon situation, where the number of vehicles can approach 20, a vehicle directly adjacent to the vehicle in the middle of a 20-vehicle platoon would have to travel half the length of the platoon to change lanes. Clearly, this alternative approach would improve vehicle maneuverability.

In the early deployment stages of an AHS, large capacity gains are not required. Also, public acceptance (and enthusiasm) is mandatory. Close vehicle spacings are therefore not needed or desired. Vehicles that are deployed 15 to 30 m apart that use localized coordinated braking methods can meet AHS safety, control, and capacity requirements.

The alternative to forming platoons in the absence of a coordinated braking system is to establish large vehicle spacings such that a safe operating environment exists. Motivating factors for this type of system could be lack of user acceptance for close vehicle spacings, concerns for safety in a platoon, lack of congestion on the roadway (rural consideration), insufficient technology to meet platoon control requirements, or the potentially high cost of meeting platoon requirements. Clearly, larger vehicle spacings are somewhat advantageous in terms of perceived vehicle safety and control complexity when compared to the platoon concept, but the decreased levels of capacity significantly detract from the benefits.

Capacity

Analysis of the lateral and longitudinal control functions reveals an interdependent relationship between various characteristic parameters. Examples include roadway capacity, vehicle speed, vehicle braking, communication delays, and hardware delays. This section describes the tradeoffs between these parameters and attempts to characterize an optimal system when appropriate.

Inter-platoon distances required to meet a no-collision policy are heavily dependent on vehicle/object deceleration and the deceleration capabilities of the following vehicles. The distances are dependent to a much lesser extent on reaction/communication time delays. Various graphs are presented below to illustrate these points as they relate to highway capacity. In many situations though, optimal lane capacity may not be a firm requirement. For these cases, vehicle speed may be increased to reduce travel time, or reduced to allow smaller headways. The equation used to generate capacity values is discussed in the RSC 1 component level requirements section of Task 2.

Current highway capacity is on the order of 2,000 vehicles/lane/hour. Automated highway system improvements over the present system, such as precise maneuvering, lack of rubbernecking, constant system attentiveness, and high performance control, will undoubtedly lead to increased highway capacity. From a very narrowly-focused point of view, control system designers can envision capacities two to four times the current capacity with the use of modern control hardware and software. There is, however, a serious concern as to whether the highway arterials can support an increase in capacity. It is therefore necessary for designers to develop a system with a fairly high vehicle capacity potential and a method of altering traffic flow to meet a desired capacity level.

Figure 18 displays a graph of lane capacity as a function of speed for an optimistic failure scenario (failed vehicle/object stops at 0.5 g, following vehicle brakes at 0.4 g, and the delay time to apply the brakes is 0.1 s). For this case, optimistic implies a relatively small difference between deceleration levels and a relatively small response delay. According to this graph, lane capacity is optimized by the highest possible operating speed. Assuming more conservative parameter values (failed vehicle stops at 0.9 g, following vehicle brakes at 0.4 g, and the time delay is 0.3 s), figure 19 shows that lane capacity peaks for a 20-vehicle platoon at 140 km/h. Capacity also peaks for a 15-vehicle platoon at 120 km/h. Capacity decreases by only 10 percent for the 20-vehicle platoon between the speeds of 100 and 160 km/h. To bound the problem from a conservative standpoint, figure 20 shows a brick wall failure (failed vehicle/object is at rest on the roadway), vehicle braking of 0.3 g, and a time delay of 0.5 s. These values can be used in a worst-case analysis, since 0.3 g represents a rather poor vehicle braking capability (wet pavement) and response delays are expected to be bounded by about 0.5 seconds. Here, capacity peaks at 6,300 vehicles/h at an operating speed of about 88 km/h for the 20-vehicle platoon. Again, there is only a modest decrease in capacity as vehicle speed increases.

The time delay is a function of the malfunction detection and vehicle actuation systems. For example, RSC 1 employs a radar system to detect objects on the roadway. The radar scans the road to determine whether a collision is impending. If so, emergency routines will be executed to generate braking and/or steering commands. These commands are then transmitted to the appropriate vehicle actuation systems, which require a finite amount of time to produce a vehicle response. There clearly exists a time delay between the onset of the failure incident and the start of emergency handling by the affected vehicles.

For the case of platoon braking in RSC 2, the brake signals can be transmitted to the following platoon directly to avoid braking detection delays. Since inter-vehicle communication is not considered for RSC’s 1 and 3, this braking information would be transmitted to the appropriate vehicles via the wayside. This would introduce an extra delay in the overall response time.

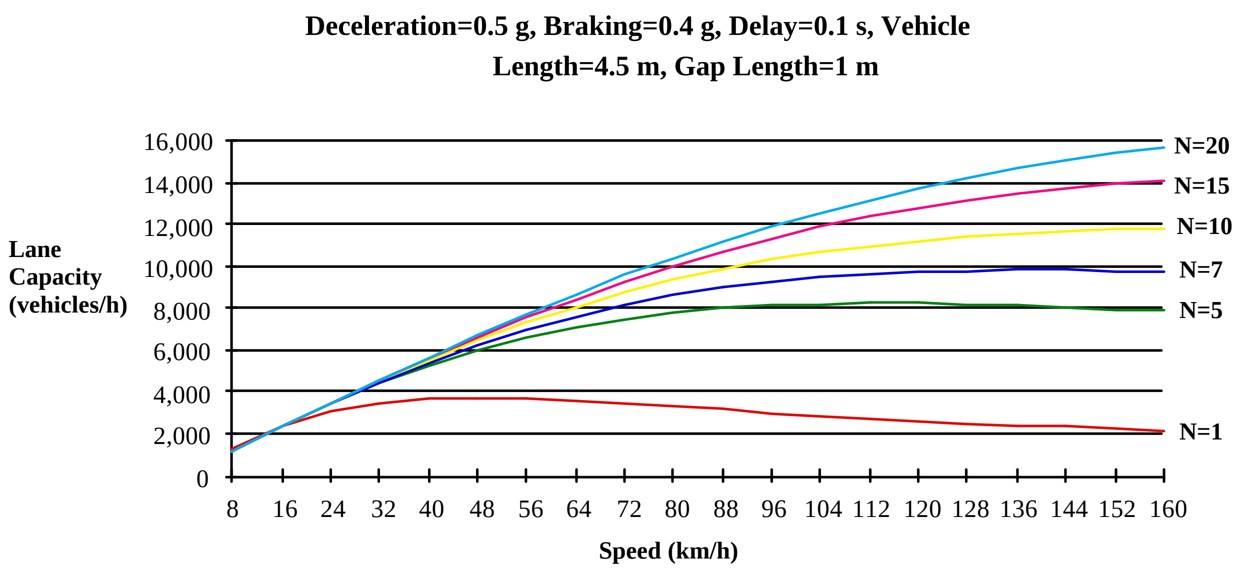


Figure 18. Capacity Evaluation #1

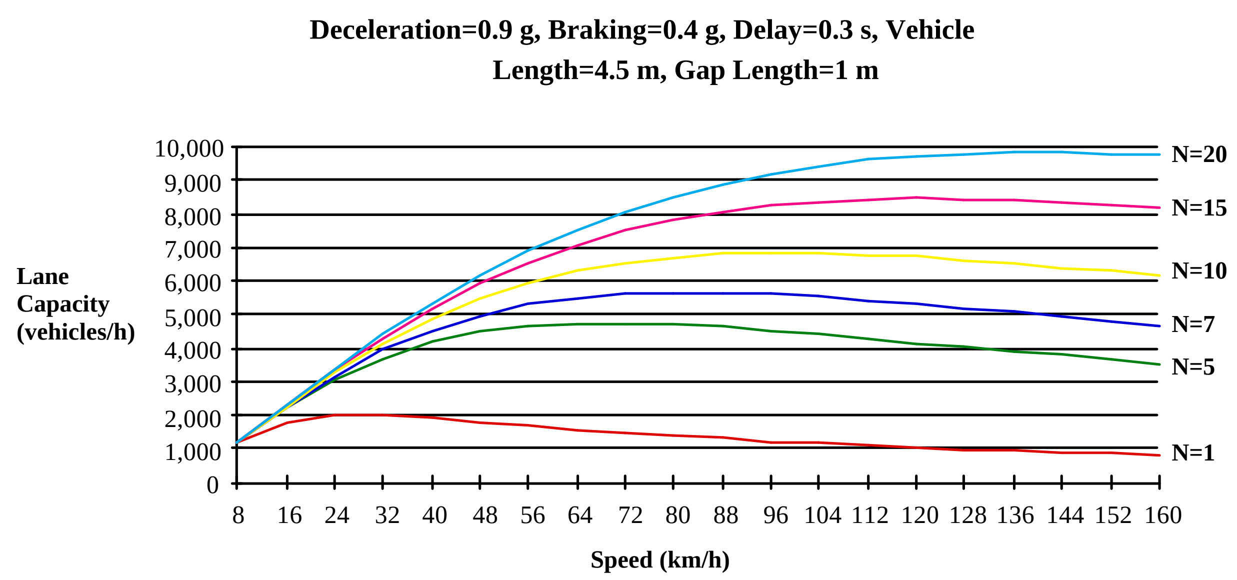


Figure 19. Capacity Evaluation #2

Brick Wall Failure, Braking=0.3 g, Delay=0.5 s, Vehicle Length=4.5 m, Gap Length=1 m

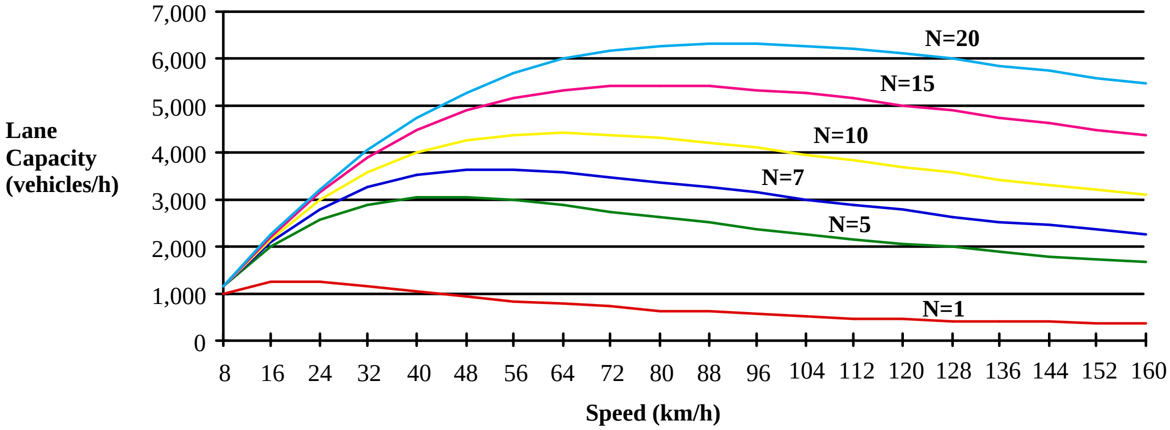


Figure 20. Capacity Evaluation #3

A vehicle's braking ability depends on many things, such as brake actuator response, tire wear, vehicle mass, type of road surface, and road surface conditions. A 0.3 g level is considered modest for dry pavement, achievable on wet pavement, and overly optimistic on snow or ice. Since the Traffic Operations Center (TOC) will vary the operating speed depending on road surface conditions, this braking level is considered appropriate for a worst-case analysis. Also, the check-in controller will ensure that all vehicles entering the AHS meet minimum braking requirements.

It is desirable from a capacity standpoint to design headway criteria that assumes very optimistic braking and response delay conditions. Whether or not this capacity is utilized will remain an operational issue. However, since not all incidents that result in a vehicle/object deceleration are predicted or controlled by the AHS, the headway policy must cope with extreme deceleration levels. Fortunately, as figure 21 shows, the capacity decreases only slightly as vehicle/object deceleration levels increase past the 1 g point. It is also clear that capacity depends less on increased operational speed as the headway policy assumes a more conservative value for vehicle/object deceleration.

Highway Grades

The case of a platoon descending a long and gradual grade presents a deceleration tradeoff. The control system (vehicle or infrastructure based) can choose to either use the brake system or engine inertia (with or without a gear shift) to slow the vehicles. The continued use of the braking system will wear down the brake pads and the system in general. Lowering the gear can result in a discontinuous longitudinal deceleration and may therefore be unwarranted in a platoon situation. In general, the use of engine inertia (drop throttle) without shifting down provides little longitudinal deceleration. The effectiveness of each of these methods of deceleration will vary from vehicle to vehicle. Clearly, this will be a control design issue for the AHS.

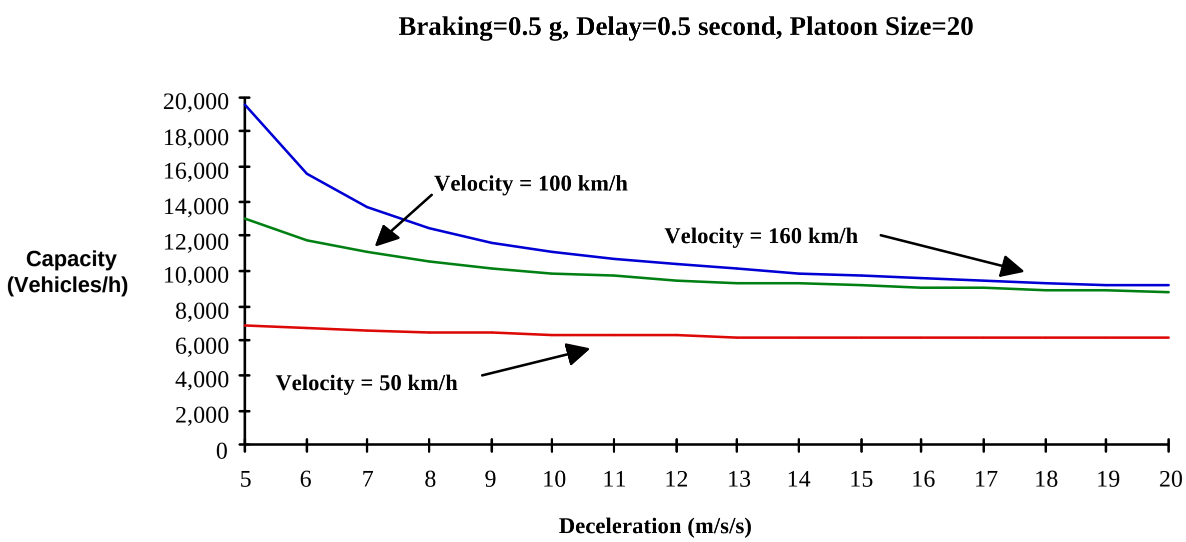


Figure 21. Capacity Evaluation #4

The case of a vehicle or a platoon of vehicles ascending a grade also presents some tradeoff issues. Assuming AHS operating speeds of greater than 130 km/h, vehicles will generally need to downshift on grades to maintain the operating speed. This action will increase vehicle emissions and reduce fuel economy. It will also decrease travel time slightly. From a control standpoint, it would be easier to require vehicles to maintain a specified speed regardless of terrain. However, this seems non-optimal and should be avoided in order to promote lower emissions and less engine strain.

Lane Widths

The definition of RSC 2 states the use of lane widths narrower than those implemented on current roadways. For example, the lanes could be narrowed from 366cm to 244cm. This narrowing would impose strict lateral control performance requirements. It would also allow space for more lanes, a dedicated emergency lane, or infrastructure equipment.

Lateral and Longitudinal Control System Comparisons

Various lateral and longitudinal control methodologies have been considered in this study. Each has favorable and unfavorable qualities. A qualitative measure has been used to compare these different strategies for a variety of operating conditions and requirements. Table 13 displays these results for lateral control technology.

The use of cooperative ranging in RSC 1 for lateral control is analyzed in table 13 for various infrastructure, vehicle system, performance, and miscellaneous issues. In terms of deployment cost, the cooperative ranging method is considered problematic due to the excessive and complex infrastructure electronics content. However, the existing roadways would suffer little, if any, down time during the deployment phase. The maintenance complexity and frequency are acceptable due to the quality and reliability of communication equipment. Overall life-cycle cost is considered unsatisfactory due to the excessive deployment costs. Costs associated with vandalism and sabotage may be a factor. Reliability is a strong point for individual components, and for the system as well, especially when consideration is given to the redundant layers of operation. This system is fully compatible with the existing road.

In the cooperative ranging case, the vehicle system is the vehicle transceiver. Cooperative ranging cannot be implemented using simple passive transponders such as backscatter devices. The primary implication of this is the necessity to provide power to the active vehicle units. Modern vehicle transceivers are very inexpensive and can be mounted on the vehicle or built into the vehicle body. The requirement for batteries or line power limits the installation options, since the active units cannot be simply embedded. It would seem ideal to place the transponder in the body of the vehicle. This is a trivial task with active transponders, as they are implemented in a simple credit-card format that is placed on the windshield or dash in toll applications. Active transponders can also be embedded in the body of the vehicle during the manufacturing process. Transceivers require little maintenance, if any, and their life cycle cost is minimal. The cooperative ranging system is capable of effective operation when the sensor targets (vehicle transceivers) are not in a direct line of sight or are mounted at various positions on each AHS vehicle. The cooperative ranging approach puts a greater portion of the instrumentation required into the vehicle as compared with roadside radar.

Table 13. Lateral Control Technology Evaluation

Lateral Control Technology Evaluation	RSC 1	RSC 2	RSC 3
5 = desirable, ... , 1 = unacceptable	Cooperative Ranging to Roadside Controllers	Vehicle Sensors with Discrete Lane Markers	Vision System with Roadway Lane Markers
Infrastructure:			
Deployment cost	2	3	5
Maintenance complexity	4	5	5
Maintenance frequency	4	5	4
Life cycle cost	3	4	5
Reliability	5	5	4
Compatibility with existing road	5	3	5
Vehicle system:			
Added cost to vehicle	5	4	2
Maintenance complexity	5	5	3
Maintenance frequency	5	5	3
Life-cycle cost	5	5	2
Reliability	5	5	4
Retrofit capability	4	5	4
Robustness to non-ideal sensor targets	5	4	4
Performance – hardware/software:			
Measurement accuracy	4	5	4
Computational requirements	5	5	2
Ride comfort	4	5	4
Performance degradation due to:			
Bad weather	5	5	1
Poor road surface conditions	5	5	1
Road maintenance	5	4	5
Interference from other sources	3	4	3
Acquisition of curvature preview information	5	5	3
Lane-changing capability	5	4	5
Suitability for multiple lanes	5	5	5

The addition of range measurement functionality to the transponders will increase the size and cost of the units. The accuracies in clock synchronization necessary to achieve AHS position resolution add complexity to the transponder, which directly leads to additional cost. The cost may also increase to support data reliability requirements for vehicle control. Beacons for toll applications may interrogate a transponder several times if necessary until a message is received error-free. Data must be transferred correctly during each control cycle to support velocity and acceleration information updates for AHS. Implementation of error correction is an effective option, with resulting increases in complexity.

The lateral control task can be accomplished effectively using communication/ranging systems with the capability to track vehicles to within 10 cm. The ranging computation is straightforward and does not require an excessive amount of processing power. Ride comfort is also considered acceptable, with some possible degradation due to delays in the wayside control signal reaching the vehicle. Weather, road surface conditions, and road maintenance do not adversely affect the control capabilities of communication-based position guidance. Adequate control signals can be generated, even in cases of roadway maintenance, through implementation of map-following algorithms in the wayside controllers. Map-following data bases provide the wayside controller with an accurate map of the lanes in its jurisdiction and contain preview information on all aspects of road curvature. Interference between many closely spaced users can be avoided in an RF communication system through multiple access protocol designs, which are ideal for providing specific time, code, or frequency assignments for individual transceiver transfers. This system should be able to command lane-change trajectories with sufficient accuracy.

Communication with vehicles in multiple lanes and in non-line-of-sight trajectories are a requirement for the roadside transceiver. One approach to meeting these needs is through spread spectrum modulation techniques, which may be used to mitigate the effects of multiple users through code and frequency diversity. Existing systems developed for tolling and commercial vehicle load tracking and fee payment have been demonstrated in open road configurations in which the wayside transceiver is placed at the side of the road and is capable of communicating across four lanes of traffic moving at speeds up to 160 km/h.

RSC 2 considers the use of vehicle sensors and discrete magnetic markers for lateral control. The process of placing magnetic markers in the roadway is considered cumbersome and would require lane closures during the deployment phase. However, once installed, the magnetic markers are expected to function at least as long as the roadway. If maintenance is required, the affected lanes must be closed. This is considered acceptable. The overall life cycle cost will be relatively low and acceptable. Passive magnetic markers are very reliable, since there are no moving parts and they do not require power. Magnetic markers do require installation and are therefore not compatible with the existing road.

The cost of adding magnetometers to AHS vehicles is considered acceptable, since these devices are fairly inexpensive. These units are quite desirable from a maintenance, reliability, and life-cycle cost standpoint. For the most part, retrofitting vehicles doesn't seem to be much of a problem, since these devices are small and should fit under the front bumper of most vehicles. Misaligned or missing markers seem to have little effect on lateral control capabilities, though more testing needs to be done in this area, especially under stressful performance conditions.

Measurement accuracy is very good near the center of the lane. More work needs to be done to ensure valid measurements during the lane change process. Data processing algorithms are fairly straightforward and do not require extreme amounts of processing time. There are no significant problems concerning ride comfort. Weather and road surface conditions should not affect the performance of this system. Performance during periods of road maintenance may degrade slightly due to the potential for misplacing temporary markers in detour lanes. Interference from sources such as the earth's magnetic field or steel roadway reinforcements can either be compensated for in processing algorithms or should have a negligible effect on performance. The discrete marker system can encode curvature preview information adequately. To date, lane changes have not been tested. However, the system should provide an adequate amount of information to carry out this maneuver successfully. Finally, this system is very well suited for multiple lanes, as there will be no interference between markers in adjacent lanes.

Considering RSC 3, the vision system concept is very desirable from an infrastructure deployment standpoint. The only effort would be to repaint existing lane markers as needed. The maintenance complexity is very low, since a lane painting mechanism is already in place. The frequency of maintenance would be only slightly higher than that experienced today. The reliability of passive lane markers is very high. Therefore, overall life cycle costs are considered very desirable.

The vision sensor is expected to add moderate cost to the vehicle, especially since two cameras may be needed for stereoscopic vision. The vision system processor, on the other hand, will probably add considerable cost due to the very high demands on the application specific hardware. Due to the complex nature of vision systems, maintenance aspects are unsatisfactory. Reliability is acceptable, but overall life-cycle costs are a problem for this system. Non-ideal targets, such as faded or missing lane markers, shouldn't cause any significant problems for the lane detection system.

Vision systems have shown reasonable measurement accuracy in rather controlled field tests. However, image processing on a large amount of data requires significant computational power. Ride comfort should be acceptable to the user. Inclement weather conditions, such as ice or snow on the road, camera blooming, lane occlusion, shadows, low sun angles, etc., may render the vision system ineffective. Other conditions such as fog or heavy rain will also be very detrimental to performance. Certain vision systems process features from an image in much the same way a human extracts features. Currently this technology is immature, but in the future it may be advanced enough to alleviate at least some of the problems associated with bad weather conditions. Theoretically, if a human can drive safely in bad weather (i.e. can extract critical features such as lane or road boundaries and parts of the infrastructure), then a vision system should be able to also. Road maintenance should not interfere with lateral control, as temporary lane markers can be painted on detour lanes. In general, interference is not a problem, though bright sunlight or low sun angles may hinder performance slightly.

Vision systems have the advantage of looking at the entire field of view in front of the vehicle. They can therefore process curvature preview information to improve the performance of the lateral controller. Again, since the system can view adjacent lanes in addition to the current lane, the lane changing capability is very desirable. Finally, this system is well suited for multiple lanes.

The use of cooperative ranging for longitudinal control is analyzed in table 14 for various infrastructure, vehicle system, performance, and miscellaneous issues. Reference the text for table 13 (RSC 1) for a discussion of specific issues.

RSC 2 employs a communication/ranging method for longitudinal control. This system does not impact the infrastructure. The cost of adding a communication system to each vehicle can be rather high in the short term. Vehicle-vehicle links based on spread spectrum modulation are ideally suited for providing reliable mobile communications in addition to ranging capabilities. Existing technology slated for deployment in the BART train tracking system allows vehicle positions to be easily determined. The high initial cost for combined communication/ranging capability will be driven by the position accuracies required, which are directly related to the complexity of the processing requirements. Other spread spectrum radios exist that may meet

Table 14. Longitudinal Control Technology Evaluation

Longitudinal Control Technology Evaluation	**RSC 1**	**RSC 2**	**RSC 3**	**RSC 3**
5 = desirable, ... , 1 = unacceptable	Cooperative Ranging to Roadside Controllers	Vehicle-Based Communication/ Ranging	Vehicle Control and Wheel Speed Measurement	Vehicle Control and Microwave Measurement
Infrastructure:				
Deployment cost	2	5	3	3
Maintenance complexity	3	5	4	4
Maintenance frequency	3	5	4	4
Life-cycle cost	2	5	3	3
Reliability	4	5	5	5
Compatibility with existing road	5	5	5	5
Vehicle system:				
Added cost to vehicle	5	3	4	4
Maintenance complexity	5	4	5	4
Maintenance frequency	5	4	5	5
Life-cycle cost	5	3	5	4
Reliability	5	4	5	5
Retrofit capability	4	3	5	4
Performance – hardware/software:				
Measurement accuracy	4	5	5	4
Signal acquisition time	5	5	5	5
Ride comfort	4	4	4	4
Performance degradation due to:				
Bad weather	5	5	5	5
Poor road surface conditions	5	5	3	5
Road maintenance	5	5	4	4
Interference from other sources	3	3	5	5
Suitability for multiple lanes	5	5	5	5

early AHS data rate and user capacity requirements, with longer term development costs that can be prorated over the development cycle of the full system deployment.

For RSC 3, a roadside communication and control system is expected to have a high deployment cost. However, the overall life cycle cost should be acceptable. Costs associated with vandalism and sabotage may be a factor. Maintenance complexity and frequency will be similar to that for the RSC 1 system. A higher rating was given here due to the lower density of roadside time/slot controller stations. The reliability of the system electronics should be quite high. This system is compatible with the existing road.

Since standard antilock braking systems incorporate a wheel speed sensor which is capable of position and velocity measurement, this component will not add cost to the vehicle. The maintenance complexity and frequency are reasonable. Since the reliability is also quite high, the overall life-cycle cost will be low.

Under nominal operating conditions, the wheel speed system has an acceptable level of measurement accuracy. This system should produce reasonable ride comfort. Bad weather shouldn't affect the transmission of required slot states from the wayside to the vehicle. Ice or water on the road will adversely affect the performance of the wheel speed system. Road maintenance is considered acceptable. Spread spectrum communication techniques alleviate the problem of interference. This system can function on a multi-lane roadway, but this is not the ideal operating condition.

The microwave velocity measurement system would add a reasonable amount of cost to the vehicle. Maintenance considerations are acceptable. With a high system reliability, the overall life-cycle cost is acceptable. Required mounting tolerances make this system's retrofit capability unsatisfactory. The hardware and software performance aspects of the microwave system are acceptable. Poor weather and road surface conditions should not affect performance adversely.

Task 4. Coordinated Lateral and Longitudinal Control

In most instances, lateral and longitudinal control can be considered separate control problems. Effective control systems have been developed and proven via simulation and test. However, performance improvements can be expected through the coordination of the lateral and longitudinal control functions, especially during emergency maneuvers. In fact, it may be necessary to coordinate these functions during emergency conditions to produce a desired level of vehicle performance. Since safety concerns are a significant part of any AHS design, the concept of integrating these two vehicle control functions should be thoroughly investigated.

Coordinated Acceleration and Steering

The coordinated use of acceleration and steering functions can improve the overall performance of AHS vehicles. During a lane-change maneuver, where a vehicle is exiting a platoon, the vehicle will experience significantly increased aerodynamic forces (up to 60 percent).[12] Halfway through the maneuver, the forces will be present while the vehicle must still maintain its required spacing in the platoon. Assuming small intra-platoon spacings, the longitudinal control system may not be able to optimally compensate for these forces. In this case, it makes sense to precede the lateral maneuver with increased throttle action, the level of which would depend on vehicle acceleration dynamics, platoon operating speed, relative wind speed, and vehicle body characteristics. Note that the time delay inherent in the engine system required to produce an acceleration is greater that required to brake a vehicle. For intra-platoon spacings of 1 m, vehicles may be required to separate to 3 to 5 m spacings before a lane change can occur. An alternative is to simply execute the lane change slowly to allow the longitudinal control system time to react to changing disturbance conditions. Research into aerodynamic effects has been conducted for a platoon of vehicles spaced 2 to 3 m apart. This study did not consider vehicles traveling closer together or leaving the platoon.

Coordinated Braking and Four-Wheel Steering

The simultaneous and coordinated use of a vehicle's braking system and its four-wheel steering (4WS) system has been shown to be superior to an uncoordinated approach using a 2WS system and a braking system during emergency maneuvers. Most production vehicles steer using only the front two wheels. Vehicles employing 4WS have been developed, but consumer acceptance has been quite low. There are, however, a number of features concerning four-wheel steering systems that make them very applicable to an AHS control design. Simulation work has shown that 4WS systems are superior to 2WS system in terms of lateral displacement capability, achievable yaw rate (without experiencing spinout), and sideslip angle. Coordinated braking and 4WS is particularly useful as part of a collision avoidance system. In many cases, it may be necessary to change lanes to avoid an obstacle, since maximum braking may not stop the vehicle/platoon in time.

Vehicle dynamic behavior under various driving conditions depends heavily on the forces acting on the tires at the tire/road interface. The combination of braking and turning increases the demand for both longitudinal and lateral tire forces. Current vehicle systems fail to coordinate braking and steering maneuvers and thus limit the desired force distribution. Therefore, it is expected that coordinated braking and 4WS should increase the stability and performance of an automatic lateral motion controlled vehicle.

Researchers at Clemson University have developed a Slip Control Braking System (SCBS) which is designed to maintain pre-specified slip values for both the front and rear wheels.[13] These slip values are a function of the front wheel steering angle. The SCBS is based on the sliding mode control method. This system, when combined with a 4WS system provides superior performance over 4WS and an antilock braking system (ABS).

Simulation results show that coordination of the SCBS and 4WS systems allows a vehicle to improve its yaw rate response, its lateral displacement as a function of longitudinal distance traveled, and its sideslip angle response when compared to a vehicle with ABS and a 2WS system. In a simulation, at an initial speed of 88.5 km/h, a large step in brake torque (3,252 Nm) was commanded together with a step in front wheel steering angle. The value of tire-to-road adhesion was 0.85. The average yaw rate response for the SCBS/4WS system was 27 deg/s. Systems employing ABS and 4WS performed in the 9 to 20 deg/s range on average. A system with conventional front wheel steering and standard brakes was not able to maintain control for any reasonable yaw rate. The SCBS/4WS system achieved a peak sideslip angle of 18 deg, while the other systems peaked at between 5 and 9 deg. More importantly, from the standpoint of collision avoidance, the SCBS/4WS system was able to change lanes (lateral displacement of 3.66 m) while traveling only 27.43 m in the longitudinal direction. Other systems required between 30.5 m and 36.6 m. Note, however, that even though the SCBS/4WS system was able to turn sharper than other systems, its resulting stopping distance was larger than those of other systems by about 3.05 to 4.57 m.

System robustness was investigated by increasing the vehicle loading (+272 kg) and decreasing the road adhesion coefficient (–0.35). The control laws used for the previous testing were used for this scenario as well. A step in the front-wheel steering angle of 10 deg was commanded simultaneously with a step in brake torque of 3,252 Nm. Results of this test showed that all systems except the SCBS/4WS system failed to maintain control during the braking/steering maneuver. The SCBS/4WS system was able to change lanes (lateral displacement of 3.66 m) while traveling only 39.6 m in the longitudinal direction.

The SCBS/4WS system requires the longitudinal component of velocity, longitudinal acceleration, wheel angular velocity and yaw rate as inputs. These quantities should be readily available from vehicle sensors, since other control functions require them as well.

Issues concerning this system include defining sensor and actuator requirements and resolving the tradeoff between stopping performance, maneuverability, and stability during emergency maneuvers.

Researchers at General Motors have used a robust servomechanism design to effectively coordinate brake torques and rear steering angle.[14] Though this system assumes some interaction with a human driver, the results are still valid for an AHS system. They have shown that the integration of braking and steering can improve a vehicle's directional stability, path tracking, and performance robustness to vehicle parameter variations.

Researchers at PATH have investigated the use of combined lateral and longitudinal control. They concluded that for normal platoon operations, the combined control system did not outperform existing decoupled systems. Their research did not cover topics related to emergency maneuvers.

Task 5. Automatic Versus Manual Action

It is desirable to design an AHS that does not rely on manual operation for any of the primary or backup control functions. This is consistent with the AHS goal of relieving the driver of the fatigue, stress, and workload associated with manual driving. However, there may be cases early in the deployment phase where the superior abilities of the human driver compared with those of the automated system could be used to increase safety. It may also be possible to allow the driver to obtain some level of maneuvering control over the vehicle while the system maintains collision avoidance control functions.

The concept of including the driver in the control loop stems from various reasons. System and operating costs for a fail-safe AHS may be unacceptable. The inclusion of the driver in the control process may alleviate some liability issues and ease a driver's anxiety caused by lack of direct vehicle control. Also, humans possess powerful sensing and decision-making capabilities that can potentially be used in the control loop to enhance system performance.

A comparison between driver and automated system response times and control accuracies will be made to determine the difference in performance capabilities. A test program will also be defined which could be conducted to more accurately determine the manual response capabilities. Finally, an evaluation of the need and desirability for manual control in an AHS environment will be discussed for each of the standard control functions.

Driver Reaction Times

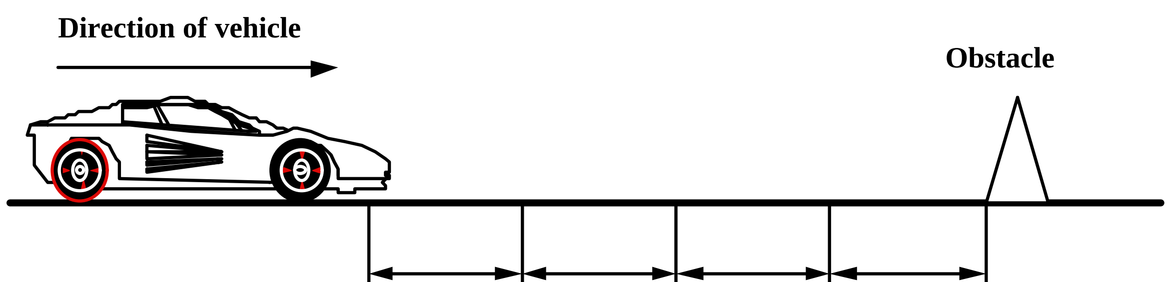
A research study conducted by the University of Michigan Transportation Research Institute and General Motors Research Laboratories identified eighteen categories of traffic accidents.[15] The five most common accident scenarios that accounted for approximately two-thirds of all vehicle accidents will be discussed. Information concerning driver detection of a potential collision and braking reaction time to avoid the collision will be presented. Approximately 20 percent of the accidents investigated occurred with vehicles traveling in the same direction. Specifically, 77 percent of these involved rear end collisions, while 23 percent involved sideswipes from passing vehicles or vehicle lane changes. Another accident scenario encompassing 14.5 percent of all accidents involved a single car hitting an animal (44 percent), hitting a fixed object (32 percent), hitting a parked car (12 percent), or overturning (8 percent).

The process that a driver goes through to avoid a potential collision or accident is shown in figure 22. In this collision/accident avoidance process, the driver needs to 1) perceive/recognize the potential of the accident or collision, 2) interpret the situation, 3) make a decision regarding an appropriate action, and 4) react by braking or steering. In figure 22, reaction times for drivers of all ages to apply full brake pressure to the brake pedal are shown as a function of the driving population. The data for this figure as well as figures 23 and 24 and table 15 comes from a review of the literature for both simulator and vehicle driving/braking research over the past twenty years.[16, 17] The average driver (50^{th} percentile) will perform the perception, interpretation/recognition, decision and reaction process in about 2.1 seconds. For the 99^{th} percentile driver, reaction time (full braking) will require about 4.1 seconds.

Figure 23 shows brake reaction results obtained from ten subjects of unspecified ages driving a simulator along a 10 km segment of road. The subjects were unexpectedly confronted with a pedestrian walking out of a roadside building onto the roadway. These data support other research findings indicating initial brake contact of from 0.8 seconds to greater than 2.4

seconds for full pressure. Table 15 shows mean, standard deviation, and the 85th percentile brake contact

Reaction Time = Perceive + Interpret + Decide + Respond



	Perceive	Interpret	Decide	Respond	**Total Time**
50th Percentile	0.29 s	0.40 s	0.50 s	0.85 s	2.04 s
75th Percentile	0.29 s	0.45 s	0.75 s	1.11 s	2.60 s
85th Percentile	0.29 s	0.50 s	0.85 s	1.24 s	2.88 s
90th Percentile	0.29 s	0.55 s	0.90 s	1.42 s	3.16 s
95th Percentile	0.29 s	0.60 s	0.95 s	1.63 s	3.47 s
99th Percentile	0.29 s	0.65 s	1.00 s	2.16 s	4.10 s

Figure 22. Driver Collision Avoidance Reaction Times

response times measured for 100 drivers confronted with the onset of a yellow light at several intersections. Notice that during nighttime driving, mean response times were slightly faster than those obtained during daylight hours at the same intersection.

Figure 24 shows simple reaction time for age groups. In this study, drivers were required to remove their foot from the accelerator and make brake contact after the onset of a red light mounted on the dash. Drivers were in a non-moving vehicle and had no other tasks to perform. A total of 1,422 measurements were made across the age groups. As noted, drivers between the age of 60 to 70 were up to 25 percent slower than younger drivers for making initial brake contact. The accuracy of the measurement was 0.10 seconds.

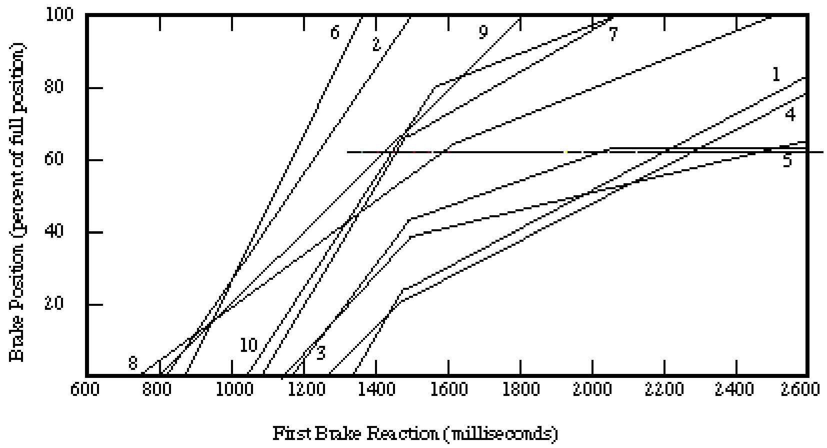


Figure 23. Driver Braking Reaction Time

Table 15. Driver Braking Reaction Time at Intersections

Intersection Approach	**Mean Time (s)**	**Standard Deviation**	**85th Percentile Response Time (s)**
University Drive	1.28	0.82	2.0
Southern Avenue (day)	1.49	0.62	1.9
Southern Avenue (night)	1.43	0.73	2.0
U.S. 60	1.38	0.60	2.1
First Avenue	1.24	0.51	1.8
Sixth Street	1.55	0.70	2.0
Broadway Boulevard (day)	1.16	0.48	1.5
Broadway Boulevard (night)	1.09	0.44	1.5
All approaches	1.30	0.60	1.8

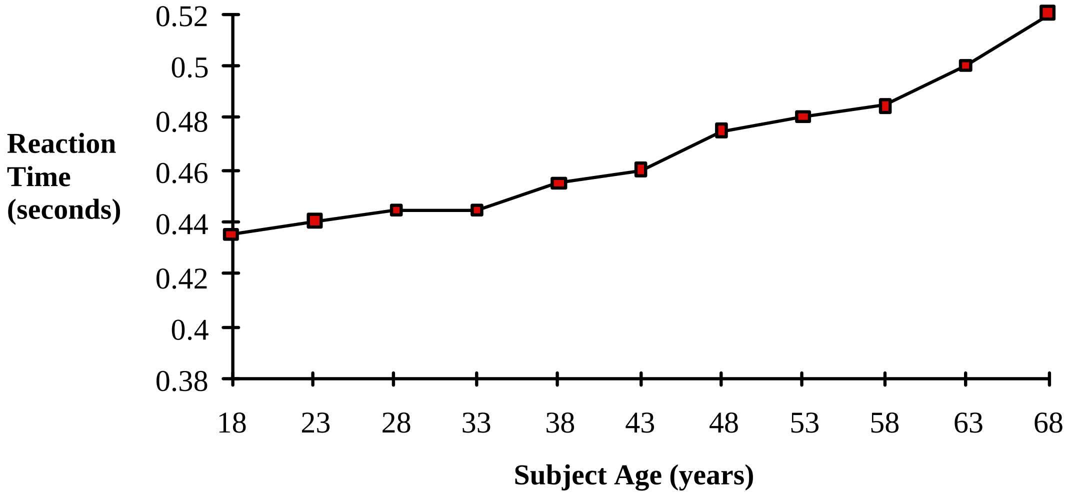


Figure 24. Driver Braking Reaction Time as a Function of Age

In another study, perception/reaction time was measured for older and younger drivers. Drivers operated their own vehicles on an actual roadway, under normal and relaxed conditions. Subjects were informed that they were participating in a study related to judging road quality. At a point during the drive, a large trash barrel was remotely released from behind a bush adjacent to the road and rolled towards the driver's path. Although the fastest observed perception reaction time favored the younger driver, there were no differences in central tendency (mean 1.5 s) between groups of drivers or upper percentile values (85 percentile = 1.9 sec.) among age groups. Although these times are quite fast, the conditions under which the study was conducted may not be realistic of normal driving situations with heavier traffic conditions, multiple lanes, and other-directional traffic. Nearly all the drivers (87 percent) made a vehicle maneuver in response to the barrel. Of these, 43 percent made a steering change and brake contact. Thirty-six percent of the drivers only made a steering change while 8 percent of the drivers applied brakes only and did not make a steering change.

Methodologies for Manual Driving Response Measurements

A number of simulator research studies have been conducted where driver steering variability under a variety of workload and driving conditions has been measured to as little as 2.5_cm. Braking response from initial contact to full pressure is another measure that can be obtained in the simulator. Speed variation to tenths of miles, driver eye tracking, and fixation times can be accurately recorded. Interaction with controls, i.e. workload and driver stress, can also be measured.

Driving Simulators

Honeywell and Iowa University are planning and conducting a number of driver simulations in the Iowa simulator. Many of the issues they are addressing relate to specific AHS automated and manual driving tasks, scenarios, and human factors issues.

Typical Accident Scenarios

Figures 25 through 29 below describe the five most common accident scenarios along with the percentage of the different accident types within each scenario. A general description and accident cause related to driver perception, interpretation, decision, and response to the potential accident are discussed within each scenario.

Same-Direction, Non Intersection Accidents (19.3 percent)

Rear-End Collisions (77 Percent)

Rear-end collisions account for 77 percent of all non-intersection accidents where the vehicles are traveling in the same direction. The primary problem is the action time required for braking. A secondary problem is the interpretation time due to the driver's difficulty in knowing whether the vehicle ahead is slowing or stopping.

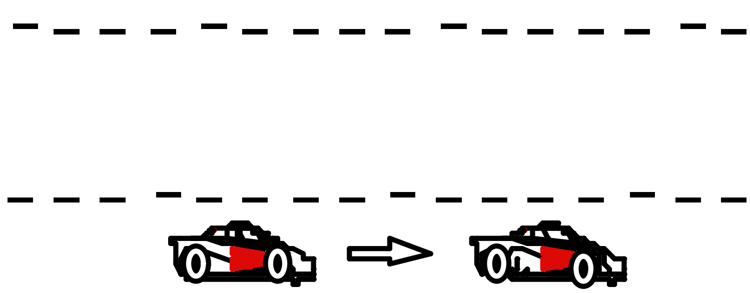


Figure 25. Rear-End Collisions

Sideswipe Collisions (23 Percent)

Sideswipe collisions account for 23 percent of all non-intersection accidents where the vehicles are traveling in the same direction. The primary problem in lane-keeping and lane-changing scenarios is perception. Leaving a lane inappropriately can be prevented if the driver knows that the other vehicle is about to leave the lane or that another vehicle is in the lane which the driver intends to enter.

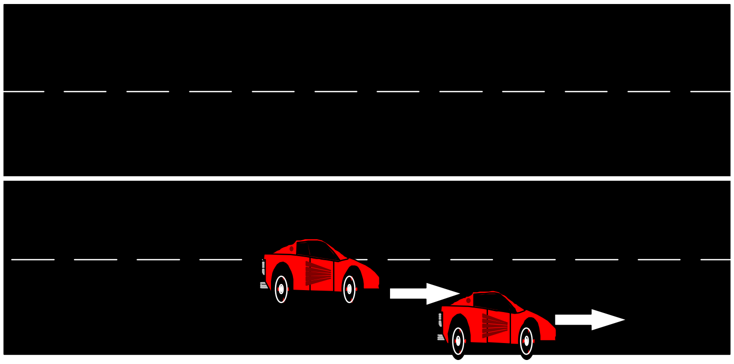


Figure 26. Sideswipe Collisions

Single-Vehicle, Non-Intersection Accidents (14.5 Percent)

Collision With an Animal (44 Percent)

Hitting an animal is the cause of 44 percent of all single-vehicle non-intersection accidents. The primary problem in this scenario is reaction time. Once the driver sees the animal, an evasive maneuver (braking and/or steering) must be made to prevent an impact.

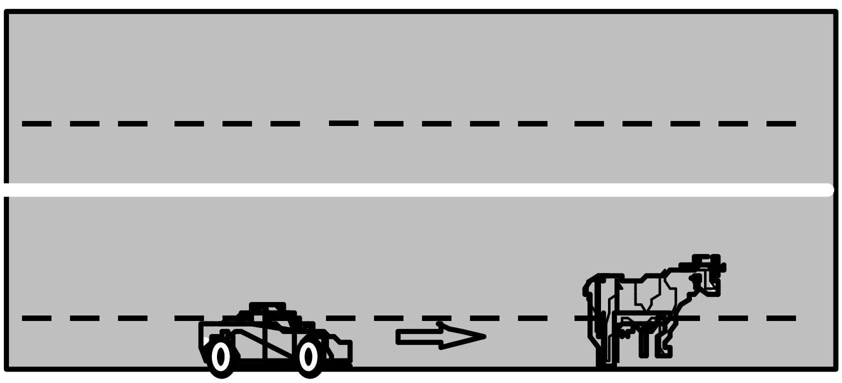


Figure 27. Collision With an Animal

Collision With a Fixed Object (32 Percent)

Hitting a fixed object is the cause of 32 percent of all single-vehicle non-intersection accidents. The primary problem in this scenario is driver perception of the object. Due to a variety of reasons, the driver fails to see the object on the road.

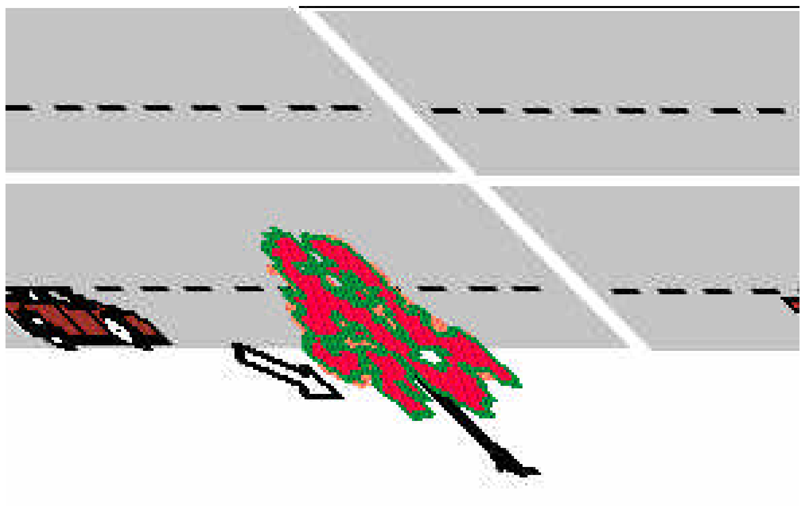


Figure 28. Collision With a Fixed Object

Overturned Vehicle (8 Percent)

Overturned vehicles account for 8 percent of all single vehicle non-intersection accidents. The primary problems are speed perception and the driver's inability to react in a timely manner. Due to a variety of reasons, the driver fails to perceive and react to dangerous road conditions.

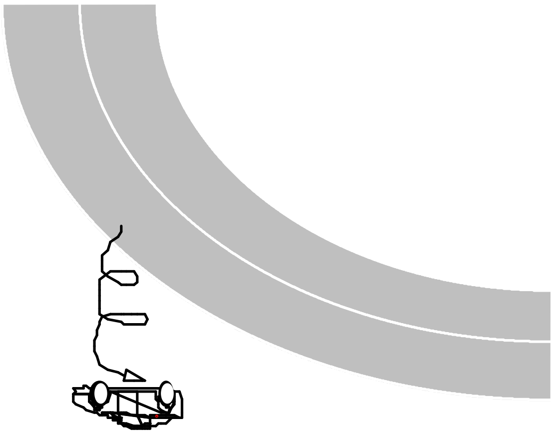


Figure 29. Overturned Vehicle

Automated System Response Times

Each AHS vehicle will be equipped with a collision avoidance system, which will be comprised of a sensor and a processor. Vehicles will also contain an internal communication system as well as actuation systems for the braking, accelerating, and steering functions. The automated system response time for an AHS vehicle is defined by the time required for the collision avoidance and actuation system to perceive an obstacle on the roadway, interpret the nature of the obstacle, decide on an appropriate response, and carry out that response by applying full braking force. The definition of full brake force will be equivalent to that used for the manual response time, i.e. the time required to apply full brake pressure to the brake pedal. The two types of collision avoidance systems described in the three RSC's are radar and vision systems.

Radar System

Forward-looking radar-based collision avoidance systems consist of a sensing module and a processing device. The goal of these systems is to correctly distinguish obstacles on the roadway to be avoided from objects on or off the roadway that can be ignored. This presents a very difficult data acquisition and object classification problem.

The response time for an automated system should be equal to or better than the response time for drivers as presented in a preceding section. In that time the system must gather object data, process that data in a rather complex algorithm, compare results with those from previous cycles, and decide the proper control response. In order to allow noisy data, such as multipath signals, to be filtered out and discarded, several sets of object data need to be gathered and processed before the final control decision is reached. Also, because highways curve, data must be gathered from several segments of the highway ahead. A prototype of such a collision avoidance system was recently developed by General Motors.[18]

Restrictions are imposed on radar-based systems by the Federal Communications Commission (FCC) (Part 15 standard) for characteristics such as peak power density, band width, and frequency.

Radar-based collision avoidance systems planned for use in automobiles in the near future will be designed to only detect objects the size of vehicles or motorcycles. This is due to the difficulty in classifying smaller objects, i.e. a box or a tire on the road, in a cost-effective manner. There is also a question of liability surrounding these systems. Eventually, though, as system costs decrease and the liability issue is solved, fully-functioning systems should be brought to market. While these systems have clear advantages over human operators in terms of object detection and data processing times, the drivers can classify objects much better than automated systems can. It is doubtful whether automated systems will ever be able to exhibit the fine classification detail of which humans are capable. As an example, if a driver saw a cardboard box lying on the road that was clearly empty, the driver would probably not risk a lane change to avoid it. Rather the driver would continue on, knowing that the box would probably not damage the vehicle. An automated system, however, would probably try to avoid contacting the box by executing a lane change or a braking maneuver. While these maneuvers are not detrimental to occupant safety, they are not optimal in this particular situation.

Vision System

Vision systems have tremendous potential concerning their application to the concept of obstacle detection, evaluation, and resulting vehicle action. They perceive their environment in roughly the same manner as humans do. Their wide field of view, like that of humans, allows them to gather all pertinent information from their surroundings. Currently, these systems are only in a research and development state with limited prototype testing occurring on actual vehicles. Efforts are focused on developing more efficient algorithms to process the large amount of 2-dimensional data that is captured by the system's cameras. Improvements in the ASIC design field in terms of processing speed and efficiency will undoubtedly enhance the performance and applicability of these systems.

The challenge of accurately extracting obstacle information from a scene is still the subject of much research. However, the information needed to perceive obstacles on the roadway does exist and is given to the processor for evaluation. It is simply a matter of developing algorithms that can hopefully process this information with the same level of classification and prediction performance as that of humans.

In terms of response time delays, vision systems can generally produce an output signal 5 times per second. This again depends heavily on existing hardware performance. Since processor speeds have generally doubled about every 18 months, in 10 to 20 years, ASIC's may be 6 to 13 times faster than those used today. The 5 Hz output frequency also depends on the level of algorithm sophistication, which directly leads to a higher performance system capable of accurately detecting obstacles and issuing appropriate vehicle maneuver commands.

Manual/Automatic Control Evaluation

Based on calculated response times for drivers and for the automated system and on statistics concerning typical accident scenarios, recommendations are presented below as to the need and/or desirability of automated control and manual control.

One possibility is to allow the vehicle operator to override only failed automated control functions. In this case, the automated system would contain fault detection logic to inform the driver of a malfunction condition. An audio system could be used to inform the driver. Visual information could also be displayed on the driver interface screen.

It seems reasonable to assume that the driver will be properly positioned in the driver's seat. The AHS should require this, as air-bag systems will not perform optimally if passengers are not properly seated. If the AHS assigns a meaningful role for the driver, then the driver should remain alert at all times. Assuming these conditions, the driver would be ready to assume control of a failed automated function.

Lateral Control

Current research into vehicle lateral control has produced systems which are capable of maintaining lane control for a variety of normal and adverse operating conditions. However, current technology, as applied to a variety of lateral control systems, does not meet every performance and safety requirement.

Magnetic Marker System

The magnetic marker system has been shown to perform well under a variety of conditions. Assuming sufficient vehicle and infrastructure-based redundancy, it is difficult to imagine a scenario where driver intervention could improve either the safety aspects or the performance of this system.

Barring independent backup systems, or assuming the failure of these systems, if the sensing system failed or the roadway reference markers were damaged or deliberately sabotaged, the system would suffer serious performance degradations. In these extreme and unlikely situations, driver control would possibly improve the vehicle's lane-keeping ability. The driver's stress level would also be increased, due to the requirement of constant roadway monitoring. Note that for RSC 2, where narrow (244 cm) lane widths are assumed, the driver would have difficulty maintaining a lane under conditions of high vehicle speed and road curvatures. This is especially true if the driver was operating in a “hands off” AHS environment for some time and had lost the “look and feel” of the road.

Vision System

Another type of lateral control system is based on lane vision. As in the previous example, barring any independent backup systems, or assuming the failure of those systems, driver intervention could possibly reduce the degradation of system lateral control during failure conditions. However, it would also place undue stress on the driver. Again, the need for human intervention is unlikely, as redundancy must be designed into all aspects of the AHS.

Vision systems can identify lane boundaries or objects either on the roadside or on the road for the purposes of lane-keeping, headway measurement, and collision avoidance with moderate accuracy. Unfortunately, current vision systems are susceptible to poor weather and lighting conditions. Also, the headway and collision avoidance performance levels do not currently meet AHS requirements.

During inclement weather, the ability of the system to produce accurate information generally degrades to the point where safe driving may be impossible. This may be true even if the Traffic Operations Center (TOC) reduces maximum speeds and alters other parameters to increase safety. Lane markers can be obscured by snow and rain causing the system to erroneously identify lane boundaries and possibly fail to meet the lane keeping requirement. At some point in the process, temporary driver intervention may improve overall system performance.

Unregulated speed and overreaction to temporary loss of control are common mistakes that drivers make when operating on slippery roads. The automated system would clearly solve the former problem. In the latter case, a driver could be required to take control of the vehicle when the lateral control reference system becomes inadequate. The control system could assist the driver by regulating the steering function. In the case of momentary loss of steering control (e.g. back wheels slide out on icy road), many drivers steer in the wrong direction or overreact by steering or braking too hard. The control system could use vehicle body rate and wheel traction information to essentially keep the vehicle headed in the right direction by applying an appropriate amount of throttle, brake, and/or steering control. The driver would then make appropriate steering corrections to return the vehicle to its lane once it is stabilized. In the case of steering assist, the automated system would override the driver until the vehicle was again under control.

Though the possibility of vehicle attitude control loss exists on slippery roads, modern traction control/ABS systems generally alleviate this concern. These systems are able to prevent loss of attitude control by measuring the traction of each wheel and applying appropriate amounts of braking force. The application of possibly different brake forces to each wheel allows the vehicle to stabilize its attitude. Decreasing vehicle velocity will inherently improve overall traction.

The advantage of computer-based systems over humans is their increased computational speed and constant attentiveness. Humans can generally perceive their environment and make appropriate decisions much better than state-of-the-art computer-based vision systems. In the future, vision data processing algorithms may evolve to become more proficient at some decision-making tasks than humans.

Vision Enhancement System

Infrared imaging has provided the military with vision at night for decades. Recent advances in the commercialization of infrared night vision technology is making its use feasible for a variety of commercial automotive, trucking, and security applications. As an automotive night vision enhancement system, infrared images could be displayed to the driver permitting the previewing of potential hazardous situations well beyond the range of existing headlights (both low and high beams). This type of information could be used by the driver to supplement the view through the windshield, rather than as a replacement for normal vision. Strategically mounted low cost commercial infrared cameras could provide other safety benefits to AHS as a means of monitoring traffic flow and potential problem areas in total darkness. Infrared image information may also be used by the automated vision system to aid in the detection of lane lines or other visual clues.

Vision Enhancement Systems (VES) have been actively developed for the past several years. The Dallas Police Department has recently installed VES in their police cars for use on nighttime patrol. The VES has been tremendously successful in providing the police the ability to conduct nighttime searches in remote, dark areas.

Longitudinal Control

Brake Control

Under steady-state control conditions, manual braking intervention will not be needed. Due to the potentially small headways assumed for RSC's 1 and 2, manual braking would be detrimental to system performance. The longitudinal control systems for these RSC's will be designed to maintain adequate vehicle spacing under all conditions. However, manual intervention for avoiding potential collisions may be useful.

Collision avoidance systems should be designed to function properly when obstacles are clearly present on the roadway. However, they may have some difficulty detecting and/or predicting the actions of objects that do not pose an immediate threat. An example of this is an animal on the side of the road. The collision avoidance system (radar or optical) may not be able to identify this as a potential problem, since it intentionally ignores or cannot specifically identify such objects. In this case, the driver could apply the brakes to slow the vehicle (or platoon of vehicles). This braking would reduce the potential for a high-speed collision and may even avoid the collision entirely. It is the driver's ability to recognize objects and predict potential behavior based on years of experience that can be used to improve AHS safety.

Another example is that of a relatively small object on the roadway that may have fallen off a preceding vehicle. It is a challenge for collision avoidance systems to detect and classify relatively small objects that are too large to safely ignore. These systems may never be able to produce the levels of detection and classification of which humans are capable. Here again, a braking maneuver initiated by the driver may help to avoid vehicle damage. By possibly initiating a braking maneuver earlier than a collision avoidance system could, the driver allows the collision avoidance system, once it detects and classifies the object, to effect a lane change in a shorter distance than if it operated without driver control intervention. This seems like a win-win situation, since the driver can only improve overall system safety by initiating braking control (see the section below on the coordinated braking concept).

Though drivers may be allowed to activate the brakes, most would become confident in the system's abilities and would not maintain the vigilance necessary to react faster than the system would.

Unwarranted use of the brake system would be deterred by the social pressure of conformity imposed by the other drivers affected by this action. The fear of embarrassment or perceived stupidity would serve to regulate the manual use of a vehicle's brake system.

If a driver is allowed to brake at any time, then coordinated braking must always be active. Coordinated braking ensures that all following vehicles (especially those in a tightly spaced platoon) will be able to brake at roughly the same deceleration level and at the same time as the lead vehicle to avoid vehicle collisions. A constraint can be imposed such that only the lead driver in a platoon can manually apply the brakes. This will alleviate some accidental brake applications.

Allowing drivers to manually apply the brakes may also alleviate some of the liability concerns associated with AHS. An example would be the case of collision avoidance, since the driver would have some control of the vehicle.

Throttle Control

It doesn't seem advantageous to allow a driver to control the throttle for any conceivable situation. In fact, the driver may abuse this freedom to reach a destination faster. Since most problems encountered on a road can be resolved by either the steering or braking functions, the added complication of allowing the driver to control acceleration seems unnecessary. Though it can be argued that a driver could accelerate to avoid a potential accident that the automated system did not recognize, the relatively slow acceleration response of vehicles (as opposed to braking and steering responses) would hinder the effectiveness of this maneuver.

Driver Preference

It may be desirable to design an automated system that would allow the driver to obtain control over the steering, brake, and throttle functions at any time. Reasons for this include the possibility of increased public acceptance of the system, a liability shift from system operators to individuals (at least in part), and increased system safety. It is unreasonable to expect or allow a driver to regain complete control over the vehicle under adverse control conditions, such as those encountered at high speeds in a tightly-packed platoon. It is also potentially dangerous to the safety of the driver and other AHS users. Therefore, the system could be designed to allow drivers some level of maneuvering control while the underlying control system maintained safe vehicle lateral and longitudinal spacings to avoid collisions.

As an example of this scenario, if a driver wanted to exit the AHS prematurely, the driver could make an attempt to steer to the rightmost lane. If the path was clear, the system would allow this maneuver. However, if the path was obstructed by another AHS vehicle or object, the system would not allow the maneuver. Notification could be made to the driver via the driver interface system.

While the driver has partial control of the vehicle, the system will constantly monitor driver actions to ensure that they fall within specified AHS operating guidelines. As an example, the driver would not be allowed to maneuver into an adjacent uncrowded lane for the purposes of increasing operating velocity.

The automated system should notify the driver when it has some level of control over the vehicle and when the driver has some input to vehicle control. This notification could be accomplished by the use of small lights on a driver interface module and/or an audio message system.

Task 6. Technology Requirements, Issues, and Risks

The purpose of this section is to present current and future system performance capabilities for the systems described in Task 2. The issues and risks associated with each type of technology that conceivably meets the system and component level requirements for an AHS will be discussed. Relevant research results will also be presented.

Representative System Configuration 1

Actuation

Some modern passenger cars can achieve deceleration levels in excess of 1 g on dry, high-performance pavement. Braking capabilities in the 0.7 to 0.9 g range are more common. On wet pavement, vehicles are generally capable of a 0.3 g braking level. Current brake systems are capable of reaching full brake force in 250 ms. The two major factors that determine the time delay are the lag time to move the brake fluid and the softness of the brake calipers when the application begins. Softness refers to the feel that is experienced by the driver. It translates into a shallow compliance curve during initial pressure increase. It is possible to reduce the delay time, perhaps as low as 100 ms, by redesigning the system to make the calipers stiffer. Unfortunately, this would make the braking action feel unpleasant to the driver, especially during manual control on non-AHS roads. It would also potentially cause some noise and would definitely raise the brake system cost substantially.

By the time an AHS is deployed, all vehicles equipped to drive on the AHS should contain antilock braking systems. These systems will utilize either electric motors or solenoid valves. Control signals can be easily and efficiently tied into either component.

Steer-by-wire systems are being investigated by a number of automotive component manufacturers, but their widespread inclusion into mainstream vehicles by the time an AHS is deployed remains a question. This system would provide easy access to the steering function through electronic signals. There would be no need for an additional actuation device to drive the steering mechanism.

Measurement

The technology currently exists to track vehicles within a 250 m range with a precision of 1 cm to 10 cm using interferometry techniques.[19] It is reasonable to assume that the use of more sophisticated communication techniques could improve this performance and guarantee reliability as well. See the communication section below for a discussion of vehicle state measurement capabilities.

Another method of determining vehicle position, velocity, and acceleration measurements uses radar ranging techniques. A roadside radar can accurately determine the position of numerous targets by converting the time delay of the echo signal received from each target into a distance measurement and pinpointing the location relative to the radar. Resolution to a fraction of a meter is practical. Ranging accuracy to within 1 cm can be obtained using microwave radar operating at 70 GHz. The echo from a moving target produces a frequency shift due to the Doppler effect, which produces the relative velocity measurement. Relative velocity can also be determined from the rate of change of the range. In the same sense, the rate of change of velocity can be computed, yielding the acceleration of a target.

The radar ranging technique for determining vehicle position, velocity, and acceleration requires multiple range measurements for determining each velocity and acceleration data point. In addition, the task remains to accurately identify and track specific vehicles in order to control the maneuvers of individual vehicles. Other issues include discrimination of targets from unwanted echoes such as surface clutter due to objects on the ground and volume clutter caused by rain. Advanced techniques incorporating pulsed Doppler radar or moving target indication (MTI) may be employed to improve the performance of the radar at the expense of increased complexity and cost. The digital signal processing techniques used in MTI and pulsed Doppler are becoming increasingly cost-effective as reliable, small, and inexpensive integrated circuits continue to evolve.

The most difficult issues with the radar ranging implementation concern the transfer of information to the vehicle to provide control and along the infrastructure to provide continuity between sensors. A single radar with 100 vehicles within its range may be capable of accurate tracking, but at some point vehicles will move out of range and additional vehicles will come into range. The coordination of the vehicle control information must include an identifier which is unique to individual vehicles. This is true in the case of transmission of control information back to the vehicle as well. Existing ranging radars do not have the capability of uniquely identifying targets and passing target information to another radar without the addition of auxiliary communication. The efficacy of implementing radar ranging may be outweighed by the added complexity of infrastructure-to-vehicle communication and radar processor-to-radar processor communication.

For AHS purposes, angular rate sensors are capable of measuring rates from ±30 deg/s to ±1,000 deg/s. Accuracies of 0.05 deg/s are possible. Many devices exhibit effective operating frequencies from DC to 50 Hz. Since automotive operation will probably result in frequencies from DC to 5 Hz, some signal filtering will be beneficial.

Typical vehicle accelerations will exhibit relatively low frequencies. Accelerometers should possess a low frequency operating range. Higher frequencies due to vibration and other noise sources may need to be filtered prior to any control processing.

Strain gage accelerometers are capable of measuring DC to low frequency signals. Devices capable of ±5 g and ±10 g ranges in a 0 to 250 Hz frequency range are available. The resolution of these units easily meets the estimated milli-g requirement. Operating temperatures are in the –40°C to 93°C range, which is quite reasonable for automotive operations.

Lateral and Longitudinal Control

Wayside controllers will have access to roadway reference information. Accurate mapping techniques, such as via the use of GPS or interferometry techniques, can be used to guarantee accuracies of roadway boundaries within 10 cm. Map data can be stored in processor memory as a look-up table. It can also be stored in high speed random access memory (RAM). Either of these methods, or other similar methods, will allow fast access to relevant data. Reference the communication section for a discussion of the process used to determine vehicle state information.

Controller Software

Object-oriented programming techniques will promote the maintainability and reliability of the software and ease the transfer of application programs across different generations of system software and hardware operating systems. Object-oriented programs have many favorable attributes. An example is code reusability, which will minimize life-cycle costs. Programs coded in low-level (assembly) language are harder to modify. In an evolving AHS environment, costs associated with software development and maintenance may exceed hardware development costs. High-level coding will minimize costs, time, and development errors.

The importance of clearly written, well documented, structured code cannot be emphasized enough. Lessons learned from a variety of military programs, where the software design, development, and test cycle dominated the program cost and schedule, should be considered in the front-end planning of the AHS. Clearly defined software requirements are absolutely essential for the success of the AHS.

Collision Avoidance

One approach to providing an obstacle detection capability is forward-looking radar (FLR). Microwave Doppler-based FLR technology makes it possible to detect objects within 100 m. Tradeoffs between target detection accuracy and signal power exist throughout the target detection range. Current implementations can detect objects falling from preceding vehicles. Detection of objects at greater ranges is possible, but the required power levels would exceed Federal Communications Commission (FCC), Occupational Safety and Health (OSHA), and Federal Highway Administration (FHA) allowable limits. Typical scanning radars operate at

76 GHz. The high operating frequency leads to smaller antennas and improves the signal return performance from small targets.

High resolution is obtained using narrow beam scanning techniques. Switched beam or fixed beam approaches have a wider beam width and cannot achieve the degree of resolution demonstrated by the scanning FLR. The scanning FLR uses a more focused beam which is electronically steered to survey the entire field of view rather than relying on one or two wide beams.

Multiple targets in the field of view will require tracking through time and space to eliminate roadway targets from adjacent infrastructure targets. Glint and multiple reflections can cause occasional problems.

Microwave radar is capable of detecting objects 7 cm above the road, though intensive data processing may be needed. At close vehicle spacings, it is capable of 0.05 m resolution using interpolation techniques. In this case, range and range rate measurements require high levels of frequency stabilization and timing accuracy.

In general, microwave radar seems fairly robust. These systems operate quite well under adverse environmental conditions such as snow, rain, ice, or mud. For rainfall conditions above 16 mm per hour, radar performance degrades, but rather slowly. Scintillation is considered a common problem among radar systems. The effective scattering center appears to move, producing “target noise” otherwise known as glint.

Many of the difficult problems associated with AHS functionality demands on collision avoidance systems, such as range detection, roadside object clutter rejection, and multiple target tracking, can be solved by allowing various targets to be cooperative. Passive reflectors can be placed on the backs of AHS vehicles to allow interrogating signals to acquire a stable and well defined target. These reflectors can also be placed on roadside objects, such as sign posts and support structures. This would allow on-board collision avoidance systems to easily distinguish between roadway and roadside targets.

Current collision avoidance system product development is driven by cost/safety tradeoffs. These systems are therefore designed to only detect nonstationary vehicles. Small objects or objects that are not moving will generally not be detected. As these systems evolve, more functionality will probably be added.

Communication

The vehicle-roadside communication (VRC) link is a bidirectional path similar to the poll-response method used for electronic toll and traffic management technologies. One implementation of this infrastructure-based system supports both open-road and lane-based strategies. This implementation has the advantage of being applicable to toll plaza installations as well as multilane data collection and transfer to moving vehicles from the roadside. Existing VRC designs support up to 8 lanes of traffic moving at speeds up to 160 km/h with vehicle spacings of 8 m. This design can be modified to accept smaller vehicle spacings. The current range of this system is 30.5 m. This range can be increased with a more powerful system.

The VRC protocol is based on a time division multiple access (TDMA) scheme which permits multiple vehicle transponders to simultaneously request permission to perform a transmission. The infrastructure unit then assigns specific, dedicated message slots within a frame structure. The safe operation of closely-spaced vehicles in a platoon configuration depends on receiving accurate, timely control information. A limit of one unit transmission per time slot ensures that vehicle-to-roadside information is transmitted unambiguously and conflict-free at a pre-determined time. The TDMA protocol also permits a roadside station to act as a master and interrogate many vehicles at one time. The two-way communication provided by the VRC technology allows the link to support vehicle-to-roadside requests for entry/exit and lane change coordination as well as collection of vehicle sensor data necessary for closing the lateral and longitudinal control loops.

The VRC data rate is currently 500 kbps. This rate was defined based on the needs of the application and on cost considerations. It would be possible to build a 5 Mbps system today, but the cost would be much higher than that for the 500 kbps system. There are expectations that communication technology will improve dramatically in the near future in the same manner as computing technology improved in the 1980's. In 10 to 20 years, one could easily predict that the cost of a 5 Mbps VRC link would be much lower than the cost of a 500 kbps VRC link today. The size will likely be much smaller and the reliability of the communications much higher.

The time slot architecture of the VRC is capable of supporting a 50 Hz update rate for a 20-vehicle platoon. The radio frequency (RF) carrier is 915 MHz, falling in the band designated by the FCC for unlicensed mobile radio messaging. Reliability of the link is enhanced through the use of error detection such as cyclic redundancy checking (CRC) to retransmit data and guarantee reception of data with no undetected errors. The VRC approach meets the requirements of high data rate, capability to support safe vehicle headway maintenance, and reliability.

The VRC architecture can also support position, velocity, and acceleration measurements. In order for the infrastructure to determine each vehicle's position, it must have the ability to measure the time it takes a signal to travel from the roadside beacon to the vehicle and back. This propagation time can then be translated into a distance measurement between the beacon and the VRC using simple triangulation techniques. Similarly, multiple measurements of distance can be used to determine velocity and acceleration.

The common concept of a VRC system is a small, inexpensive transceiver. When functions such as range measurements are added to the VRC system, size and cost will increase. Since RF signals travel approximately 20 cm every nanosecond (10^{-9} seconds), in order for a VRC system to measure distances in centimeters, it must have a clock accurate to fractions of a nanosecond. That clock can be synchronized to a fraction of a nanosecond with the beacon clock. These requirements add to the complexity of the VRC system, which leads directly to additional cost.

Data reliability is another requirement which can lead to more expensive VRC equipment. When used for toll collection or weigh station functions, the VRC can operate with relatively poor data reliability. The beacon can interrogate the VRC multiple times until the data is received without error. Simple CRC codes can be used for error detection. When the VRC technology is used to exchange vehicle state (position, velocity and acceleration) information for a control cycle, the data must be correctly received for each cycle (20 to 50 Hz rate). Forward error correcting may need to be employed. Hardware designs which compensate for multipath and fading may also be required. These design considerations will add complexity to the VRC system, resulting in higher costs.

Regional Communication

Each of the RSC's will require some method for collecting and disseminating information regionally. The TOC may collect data concerning traffic flow, environmental conditions, and traveler trip plans. The TOC may disseminate information including route guidance, emergency notifications, and check-in validation. The TOC may also be involved in coordinating platoon assignments.

Infrastructure intensive configurations like RSC 1 may require a fiber-optic or conventional cable backbone for carrying control information between roadside processors located as frequently as 100 m intervals. The medium chosen to transport the data will depend on the availability of capacity on the existing electronic infrastructure as well as the distances that must be instrumented. Fiber-optic cable currently being installed will contain sufficient capacity to support a wide variety of users, but may not coincide with the proposed AHS routes. Conventional telephone lines or cable television lines are also an option with more limited capacity. The cost of trenching and installing cable dedicated to AHS may be prohibitive to implementing an infrastructure-based RSC.

Infrared communication, which relies on a clear line of sight between the transmitting and receiving systems, can also be considered for controller-to-controller communication. The clear advantage of this approach is the relative ease of installation. However, adverse environmental effects from lens obstructions, fog, dust, and snow must be considered.

The roadside processors must also be linked to the TOC. This may be accomplished via landline systems such as fiber-optic or telephone cable. An alternative method involving low earth orbit (LEO) satellites connecting local cells similar to proposed personal communication systems (PCS's) is also conceivable. Each TOC may operate a base station which can transfer data via satellite. The PCS-style satellite solution can support the data rate requirements of AHS control signals, and the cost would be traded off against wired solutions.

Representative System Configuration 2

Actuation

See Representative System Configuration 1.

Measurement

PATH experiments using magnetic markers for lateral control have shown a maximum lateral sensing error of 1.5 cm with 1 cm standard deviation.[4] This is well within the stated requirement of 3 cm.

Discrete magnetic markers embedded in the roadway can be used for longitudinal position measurement as well as lateral control. These markers can be coded with roadway position information which each vehicle can read via its onboard magnetometers. Each magnet is capable of storing 1 bit of information. The coded sequence would consist of some header codes to initialize and uniquely identify the message followed by the position information. Error detection codes could be placed at the end of the message as well. Repeated messages could be coded to ensure a correct transfer of information to the vehicle.

The length of road required to transmit the information is determined by the distance between markers and the desired accuracy of the transmitted information. PATH studies consider marker spacings of 1 m adequate to laterally control a vehicle. Clearly, a decreased spacing would increase the information volume/accuracy and would continue to support the control effort. However, implementation costs would increase as well.

Full length information sequences would need to be placed near AHS access facilities to properly initialize each vehicle. On long stretches of road with no access facilities, position differences with respect to the previous position, which are much shorter than a full position message, could be coded. This compression would allow for fixed traveler information messages to be communicated to vehicles, position information accuracy to be increased, and/or increased levels of error detection and correction. The use of data compression is advantageous because road curvature information must also be coded in the magnetic markers.

Another advantage of using coded magnetic markers is the ability to derive an estimate of vehicle velocity from the changes in magnetic field. As a vehicle passes over a magnetic marker, the vertical component of the magnetic field peaks. Since the spacing between each magnet is fixed, the time intervals between each successive signal peak can be used to estimate the vehicle's speed. PATH researchers have used three successive time intervals to increase estimation accuracy.[4] These velocity measurements can be integrated by the vehicle control computer to estimate longitudinal position. To complete the calculation, vehicle steering rates can be integrated, or steering commands summed to provide an estimate of lateral position. Acceleration information can also be derived from magnetic marker readings.

Lateral Control

PATH studies show that a magnetic marker reference system can be used to successfully guide a vehicle under off-nominal conditions at speeds of 50 to 60 km/h through turns (much tighter than those found on open highways) with a maximum lateral deviation of ±20 cm.[4] Higher speeds are certainly possible, but further work in this area needs to be done.

Permanent magnetic markers offer the advantage of being completely passive, which eliminates concerns about potential failures. Maintenance requirements are quite negligible as well. Magnets can be designed to function beyond the lifespan of existing roadways. They are also relatively inexpensive.

In PATH studies, the magnetic markers were placed at 1 m intervals along the roadway. It is conceivable that the distance between markers could be increased. However, further tests must be completed before this can be termed feasible. The range of the magnetic marker sensor system is ±50 cm. This is tolerable, since the effective control range under off-nominal conditions is ± 20 cm. However, since it is desirable to have a continuous lane reference during lane changing, the range of the magnetic sensing system may need to be increased.

The Frequency Shaped Linear Quadratic (FSLQ) optimal control approach was used to develop the lateral control algorithm since requirements for tracking error and lateral acceleration are not uniform over the entire frequency range. The controller produced steering angle commands every 25 ms.

The control algorithm used preview information about the upcoming road geometry (radius, superelevation, and curve start and end points), which was found to be very beneficial. The preview information was coded into the magnetic markers by alternating the magnetic polarities.

Four Hall-effect magnetometer probes were used to sense the magnetic field. The probes were placed 15 cm above the roadway surface on the front bumper of a vehicle. Two probes measuring vertical and horizontal components of the magnetic field were centered along the bumper, while the other two measuring the vertical component were placed 30 cm to either side of the center of the bumper.

The relationship between the lateral displacement of the sensor and the measurement of the magnetic field was determined by experiment. An algorithm was then developed based on this relationship which determined the magnetic field of the marker and used a look-up table for translating the magnetic field measurement into values for the vehicle's lateral displacement.

The system was analyzed under off-nominal conditions: low tire pressure (30 percent), slippery road, offset magnetic markers (±2 cm), missing magnetic markers, and increased vehicle load (+227 kg). For all cases, the system performed within the ±20 cm lateral displacement bound.

The system has not yet been tested at the maximum speeds expected for an AHS system (150 to 160 km/h) nor with external force loading. The system must be able to adequately control the lateral deviation of the vehicle (±16 cm) at these speeds through realistic turns (>1,000 m) and under various off-nominal conditions (described above). Note that it is reasonable to assume that the Traffic Operations Center (TOC) will reduce vehicle speeds when certain off-nominal conditions exist.

PATH comments that ride quality around curves can be improved by developing a low-cost technology to install markers on a path with a fixed radius of curvature. Tests on different road surfaces and tests using wind gust disturbances need to be completed to fully characterize the system. Lane merging techniques have not yet been investigated.

Magnetic interference due to the earth's magnetic field, high-frequency magnetic noise generated by the vehicle's engine system, and spontaneous vertical movements of the vehicle do not seem to degrade the performance of the magnetic marker reference system. Other environmental conditions such as water, ice, snow, etc. have minimal interference effects on the system.

Longitudinal Control

For RSC 2, the communication system can be used to provide the on-board controller with range and range rate signals. Reference the RSC 2 Communication section below for a discussion on the capabilities of a communication system to provide cooperative target position and velocity information.

Lead vehicle information is not an absolute requirement for platoon stability. PATH researchers have shown that an algorithm which does not communicate lead vehicle information to the remaining vehicles in a platoon can achieve satisfactory, though non-optimal results.[20] A simulation of a 15-vehicle platoon under certain conditions showed that vehicle deviations from their assigned positions were less than 0.08 m and that they “decrease to zero reasonably fast and do not exhibit too much oscillatory behavior.” In the event of a loss of intra-platoon communication, this type of a longitudinal control algorithm could be used effectively for a short period of time. In this case, vehicle spacing could be increased by the TOC to allow more room for spacing deviations.

Position Reference

The TOC will access local roadway information stored in electronic maps to perform maneuver management and flow tasks. Lanes can be mapped by moving a GPS receiver along lane boundaries while recording position information at appropriate intervals. Since traffic management systems will be less frequent than the wayside controllers discussed in RSC 1, they will cover a wider range of AHS roadways. However, the amount of information that must be stored is still relatively small. Storage devices such as RAM or compact disk read-only memory (CD-ROM) can be used to ensure appropriate levels of data storage and access time. When detours are required for road maintenance, updates to the roadway maps must be made.

An alternative to wayside map storage is to place the electronic maps in the vehicle. There are currently about 72,000 km of interstate roads in the country. After full AHS deployment, these roads may be completely automated. Assuming another 88,000 km of potential AHS roadway (intra-state), electronic maps must accurately characterize approximately 160,000 km of AHS roadway. Since lane-keeping and longitudinal control functions are autonomous for RSC 2, the purpose of the electronic map is to provide a reference which will be used for maneuver management. Therefore, sub-meter accuracy may be required.

Controller Software

See Representative System Configuration 1.

Collision Avoidance

Collision avoidance sensors can be based on laser radar technology. Laser radar is capable of detecting objects 7 cm above the road. It can also operate at relatively close spacings between vehicles. Its effective range (up to 90 m, or up to 210 m) usually depends on internal current amplification levels.[21] This system, however, performs poorly in adverse conditions including snow, rain, ice, or mud. The maximum range can decrease by as much as 30 percent during rainy conditions. Its performance is also degraded by a reduction in the optical power of the received light pulse due to vehicle exhaust emissions.

Laser radar relies heavily on the light reflectivity of objects, and the sensors have a narrow field of view. Lasers have been shown to perform poorly when they are required to detect dark, freshly waxed vehicles. The laser beam essentially bounces off the vehicle without returning enough signal energy for an accurate detection. Allowable laser power may also be an issue if the system is required to detect objects at moderate ranges. Interference from other laser radar units may cause a problem, especially with two-way traffic.

An advantage of laser radar is that it uses technology that is currently available. Since it operates at such a high frequency, the laser infrared beam can be shaped into almost a perfect square. This reduces false targeting of roadside objects. A microwave radar beam has more of a trapezoidal shape in addition to side lobes, which produce more secondary reflected signals.

One of the significant complaints concerning laser technology is that it cannot “see” through fog. Proponents of these systems argue that this phenomenon is beneficial in that AHS controllers will not be able to operate at normal velocities in this type of environment. There may also be a tremendous liability burden imposed on the system if it were to experience a failure after allowing high speed operation during foggy conditions.

The comment concerning the usefulness of cooperating targets discussed in the RSC 1 Collision Avoidance System section applies here as well.

Communication

Three basic types of communications links are available, including point-to-point, broadcast, and group addressed. The characteristics of each methodology determine the best fit approach to the particular communication paths described in RSC 2.

One candidate technology which meets the high update rate requirements is spread-spectrum radio using a TDMA protocol. TDMA provides the benefit of assigning unique time slots to individual vehicles, allowing vital control information to be transmitted reliably and conflict-free. The spread spectrum waveform is also capable of providing range resolution and interference rejection. Direct sequence spread spectrum systems modulate the data signal with a wideband high rate spreading code. The higher rate or bandwidth of the spreading signal is referred to as the chip rate. A chip is the period of the chip rate. The lower rate information signal carries the data message bits. Current spread spectrum systems support 20 Hz update rates and range resolutions on the order of 10 cm.

A significant factor in determining link path reliability in the mobile environment is the effect of multipath on signal strength. Multipath occurs when there exists one or more reflected paths in addition to the direct signal path from the transmitter to the receiver. Shadowing of antennas by nearby reflectors (adjacent cars) can result in rapid fading and peaking of the input signal as direct and reflected signals cancel and reinforce one another. Spread spectrum modulation is inherently resistant to multipath signal variations because signals which are delayed by more than one code chip are treated as an uncorrelated input. As the code chip rate increases, the system becomes less susceptible to multipath problems. As an example, the reflected signal path must be less than 200 ft different from the direct path to have any effect on signals spread using 5 Mcps (million chips per second) codes.

The direct sequence spread spectrum waveform also offers enhanced interference rejection. The measure of interference rejection is made in terms of the system's processing gain developed by spreading and despreading the message signal. At the transmitter, the higher rate chipping signal modulates the data into a wide spectrum. At the receiver, despreading is accomplished by correlating the received signal with a local reference spreading code. The desired and interfering components are compared with the reference, and the desired signal collapses into its original baseband width while the unmatched input (noise) is spread in bandwidth and reduced in amplitude. A filter then selects only the desired narrowband signal. The spread spectrum receiver recovers the desired signal while suppressing the effects of all other inputs.

The ranging technique used in spread spectrum modulation relies on the fixed rate of propagation of the RF signal. Signaling waveforms are a function of time, and differences observed at the receiver relative to the transmitted signal correspond directly to the distance between them. The reflected signal will display a time shift in the synchronization of the spreading code that is related to the distance traveled by the signal. An unmodulated carrier is delayed the same amount as a spread spectrum signal traveling the same distance. However, the spread spectrum waveform has the advantage that its phase is easily resolvable. The basic measure of resolution is the length of one code chip. The higher the chip rate which spreads the signal bandwidth, the greater the measurement resolution capability.

Direct sequence spread spectrum systems are currently capable of a higher resolution than that exhibited by frequency-hopping systems because existing technology does not support hopping rates fast enough to match the resolution of direct sequence techniques. The direct sequence code phase shift modulates the carrier, while the information channel is unaffected and may be employed concurrently. The advantage to this approach is that data transfer and ranging can be accomplished using one communication link without increasing hardware or system bandwidth. Existing technology supports resolution in range measurements to 0.001 chip periods. In order to achieve ranging accuracies to within 10 cm, the chip frequency must be on the order of 3 MHz. The radio selected for the BART train control communication uses a chip rate of 20 MHz. The 3 MHz spreading rate is therefore well within the capability of existing technology. The ranging capabilities of spread spectrum signals are not limited by the data rates or chip rates, in general. The accuracies and frequent update rates required for vehicle control will require much more powerful signal processing and filtering capabilities than are implemented for other applications. These advances will rely on the speed and size and power consumption of the DSP integrated circuits.

The effective range of spread spectrum systems is a function of both the transmit power and the line of sight distances between each unit. For AHS, distances in the range of 0.5 m to possibly 200 m must be measured. Assuming the use of spread spectrum radios in the FCC approved unlicensed band, a maximum of 1 watt transmit power coupled with typical receiver sensitivities roughly yields effective ranges of 1,000 m. When the line of sight path is reduced due to tall vehicles or curves and grades in the roadway, the range will be reduced. A spread spectrum system can be effective for ranging within a platoon, where a signal travels from one vehicle to a following vehicle spaced roughly 1 to 10 m apart. When using a spread spectrum radio to range between platoons, the same restrictions which apply to vehicle radars apply to the radio. That is, if there is a good line of sight from the last vehicle in a platoon to the first vehicle in the next platoon, radio ranging is well within the required limits of AHS.

Vehicle-to-Vehicle Communication

Inter-platoon communication can be used to disseminate global or zone information to nearby platoons in addition to providing headway information. This information may include hazards and malfunctions detected by a platoon, platoon speed information, or congestion information. This information transfer can be accomplished either directly from a vehicle in one platoon to a vehicle in another platoon, or from one platoon leader to another platoon leader. The information can also be sent from a vehicle in one platoon to the roadside to a vehicle in another platoon.

The vehicle-roadside communication link integral to this RSC provides one solution for the relay of inter-platoon information. This approach has the advantage of allowing platoon coordination to be passed between wayside management systems as the individual platoons travel along the highway. The issue of establishing communication with only the platoon leader or any vehicle in the platoon may depend on the type of information contained in the messages relayed between platoons. Examples are emergency braking or lane change maneuvers. The optimum transfer of emergency information may be to all vehicles within the platoon, while less time-critical data may be transferred only to the platoon leader.

Selection of a slotted architecture for the vehicle-vehicle link will require slot assignments to support inter-platoon as well as intra-platoon communications. Packet protocols are often considered candidates for this application, but this approach does not guarantee communication without collisions. The slot architecture can be designed to accommodate a set quantity of nearby platoons without collisions by providing a unique time for each participant to communicate. Packet architectures can be subject to variable and unpredictable relay times, which are not compatible with the vehicle control loop requirements.

Techniques for mitigating inter-platoon interference using spread spectrum communication include implementation of multiple independent RF networks, established using either frequency diversity for TDMA systems, or code diversity for CDMA systems. In either case, participants on each network operate independently from participants on all other networks. A large number of intra-platoon communication nets can be established in the same area, with little concern for interference between platoons. A global frequency or code may be established for platoon-to-platoon communication. Each vehicle (or just the platoon leader, in some architectures) would then periodically switch to the global platoon-to-platoon frequency/code and either listen or transmit.

Roadside-to-Vehicle Communication

The roadside-to-vehicle link is a one-to-many communication path. A broadcast architecture is sufficient to meet the requirements of one-way communication advisory messages. The Radio Broadcast Data System (RBDS) is a relatively low cost alternative, with RBDS compatible radios currently commercially available. Major US market coverage of FM stations broadcasting RBDS is expected to occur near the end of 1994. The use of a commercial broadcast system has several advantages over an AHS specific system.

First, existing commercial infrastructures provide the necessary coverage area, reducing the cost for implementing roadside-vehicle infrastructure. Second, consumer demand exists for broadcast receivers in the marketplace providing a potential boost for the speed of implementation. The incremental cost of adding the RBDS circuitry to a commercial receiver is lower than the cost of a stand-alone AHS specific receiver for roadside to vehicle communication. Another advantage lies in the existence of currently available RBDS products, reducing the time-to-market factor for deployment in new vehicles. Finally, additional radio frequency allocation for AHS applications is eliminated as an issue through the use of broadcast subcarriers.

The RBDS was originally designed to display information on and exert control over the vehicle radio. The basic implementation permits control information contained in the subcarrier message to interrupt the user selected CD or cassette function and turn the radio on to traffic information broadcasts. The widespread availability, low hardware cost, and robustness of the transmission technology provides a proven method for achieving reliable low data throughput.

Vehicle-to-Roadside Communication

The vehicle-to-roadside link is a many-to-one communication path. The definition of RSC 2 dictates the use of the inter-platoon communication system to support the vehicle to roadside path. The time division multiple access scheme provides a time-ordered, synchronous approach to the network access problem. The TDMA technique allows vehicles to be assigned time slots within which communication with the wayside station will occur. Limiting one unit transmission per time slot ensures that vehicle-to-roadside information is transmitted unambiguously and conflict-free. The TDMA protocol permits a roadside station to act as a master and interrogate many vehicles at one time. This feature is beneficial in providing check-in/check-out capability in open road configurations such as RSC 2 in which vehicles do not have to slow down when passing through entry/exit plazas.

Regional Communication

RSC 2 will require a relatively small amount of infrastructure backbone to support regional communication. The TOC will be required to transfer information to roadside communication systems spaced at intervals on the order of 1 to 10 km. This configuration is also compatible with a satellite-based PCS approach. Another wireless approach could be implemented using radio networks on land. The roadside systems can both be linked in a wide area RF network (WAN) to the TOC. This approach would require evaluating the propagation characteristics of the available modulation techniques as well as the message protocols for their compatibility with the AHS control requirements. It is expected that a landline approach to connecting roadside communication systems in a vehicle-based RSC would not be cost effective since the locations that must be linked are spaced at rather large intervals.

Representative System Configuration 3

Actuation

See Representative System Configuration 1.

Measurement

Vehicle velocity measurements can be obtained either by processing wheel pulse information or by using a microwave radar. Wheel speed sensors on the undriven wheels of a vehicle are used to measure distance traveled and velocity. They are required equipment in an antilock braking system. Since these systems should be standard equipment on vehicles by the time an AHS system is deployed, position and velocity measurements can be obtained from existing hardware. This idea makes the wheel speed sensor option very attractive. Under ideal conditions, position and velocity measurement accuracies are very high. However, measurement degradations are caused by computational errors, wheel slip, and inaccuracies in the estimation of tire radius. Tire radius can be altered under driving conditions by vehicle speed, tire pressure, vehicle load, and vehicle drive torque.

The position accuracy of this system is difficult to quantify. As vehicle and roadway parameters change, the system will exhibit varying levels of accuracy. Fortunately, RSC 3 does not require high levels of longitudinal position measurement accuracy. Tests using a wheel speed sensor system under varying 3σ conditions can be executed to determine the distance required between position updates from the wayside. Velocity estimates seem to be accurate enough to be used successfully in the control loop.

Wheel speed sensors typically consist of a toothed pulse ring and an inductive wheel speed pickup. As the wheel rotates, the pulse ring produces a signal whose frequency is proportional to the wheel speed. Calibration of this system can be performed by integrating the system's velocity signals from one infrastructure position measurement location to the next and comparing this estimation of distance traveled to the known roadway distance between infrastructure measurements. One drawback of this system is its poor performance on slippery surfaces. In this case, accuracy will be less than desirable.

Wheel speed sensors on each of the four wheels have been shown to exhibit a 0.3 to 0.4 percent difference between each other, which translates into roughly a 0.3 to 0.4 percent error in position estimation. This accuracy range includes a case where one of the tires is inflated to only 57 percent of the pressure of the other tires. Though these numbers are only approximate and can vary in magnitude under different conditions, they represent the basic navigation capabilities of an autonomous wheel speed sensor system. Assuming these errors, if a vehicle traveled 10 km, the system would be bounded by measurement readings between 9.97 and 10.03 km. There would be up to a ±30 m error. For this accuracy, wayside updates could be provided to vehicles every 5 km for a ±15 m maximum error accumulation. This accuracy would be sufficient for the RSC 3 scenario.

With the addition of a map matching system, similar to the type used in modern automobile navigation systems, and coarse updates from GPS satellites, under ideal conditions the resulting position errors remain bounded by about 6.1 m. This level of accuracy is sufficient for the navigation needs of the RSC 3 configuration. However, this type of system will exhibit larger errors for conditions of non-powered vehicle movement and travel on inclined, slippery, unmapped, banked, or long, straight roadways. The addition of very accurate, independent measurements is needed to update the primary measurement system. System limitations will dictate the frequency of updates, which will surely vary with time, distance traveled, and current location.

A microwave radar can also be used to estimate vehicle velocity. The radar is mounted on a vehicle at some angle (usually 45 degrees) with respect to the road surface. The received signal consists of various velocity (Doppler shift) components generated by the horizontal and vertical translation of the moving vehicle. The vertical component results from road surface topographical features that provide upward or downward forces on the vehicle. Simple geometry and the inclusion of Doppler effects isolates the horizontal component, which is the desired measurement. Microwave velocity sensing, being noncontact, is not affected by mechanical movement resulting from ground contact or parts wear, as is the case with current speedometer linkages. Electronic measurement is based on the road surface passing the sensor's antenna and not on the rotational speed of a wheel, which can vary with sliding or bouncing on slippery or rough roads. Also, mechanical speed error can result from needle bushing, cable, or tire tread wear or use of nonstandard tire size.

A reasonably extensive research effort was recently performed concerning the performance capabilities of a 4-axis microwave radar velocity sensing system. The goal of this project was to accurately measure vehicle ground speed, heading, and attitude without the sensitivity to powertrain gearing, tire variations (size, wear, pressure), load, traction, or wheel lockup. The study was limited by rather inaccurate machining of the sensor mounting holes. Further refinements in the system could be expected to improve performance.

Tests were conducted for vehicle speeds in the range of 48 to 256 km/h. Longitudinal velocity was measured to an accuracy of ±2.7 percent on a concrete roadway and ±1.7 percent on asphalt. Though the accuracy of transverse velocity and heading velocity was not specifically measured, results showed reasonable operation for both. Vehicle pitch angle was measured to an accuracy of ±0.25 degrees over the range ±32 degrees. Heading angle was measured to an accuracy of ±0.14 degrees over the range ±32 degrees.

Two systems with the capability to provide accurate position updates are the Global Positioning System (GPS) and a wayside tag system.

Global Positioning System

A well-known option to solving the position location problem is the use of GPS. This system is operated by the U.S. Department of Defense in conjunction with the U.S. Coast Guard. GPS is a radio-navigation system that employs RF transmitters in 24 satellites in 6 orbital planes at altitudes of approximately 20,187 km above the earth's surface. GPS receivers use signals from the satellites to calculate the latitude, longitude and altitude of a specific position. GPS receivers are providing accuracies 10 to 100 times better than ground-based Loran, Omega, and VOR/DME TACAN.

For complete and continuous global coverage, GPS requires 21 satellites and three spares circling the earth once every 12 hours. The satellite configuration guarantees that a GPS receiver located anywhere on earth can receive RF signals from at least four satellites 24 hours a day.

Conventional two-way radio-navigation systems determine distance by measuring the time of arrival or phase difference between a transmitted signal and a received echo signal. GPS determines position by transmitting information on two L-band carrier frequencies from the satellite to a ground-based receiver. The satellites modulate the carriers with two pseudo-random noise (PRN) waveforms. The PRN waveform modulating the L1 carrier is the Coarse/Acquisition (C/A) code, also known as the civilian code. The other PRN waveform modulating the L2 carrier is the Precise (or protected) code, which the military uses for greater resolution (also known as the P code).

The P code was designed to provide the military with more resolution than an adversary by turning off the Selective Availability (S/A) feature and degrading the resolution to that of the C/A code alone. GPS receivers achieve greater accuracy using a technique referred to as carrier phase GPS. This technique tracks the carrier phase of the L1 frequency and is capable of position accuracy to a fraction of the carrier wavelength of 19 cm. Carrier phase GPS techniques effectively cancel the effects of S/A, so availability of the P code is not critical to achieving the level of resolution necessary for longitudinal control of vehicles. Mobile GPS receivers pick up satellite signals in tandem with signals from a reference receiver at a known fixed position, a technique which results in accuracy within a centimeter.

A key issue in the availability of GPS is the funding of operating costs, which are currently born by the federal government. The maintenance cost includes replacement of satellites which have expected lifespans of 7.5 years. GPS is currently under the control of the Department of Defense, which implies that technical changes can be made, causing compatibility problems.

GPS receivers are commercially available in a variety of formats, including units small enough to be handheld. The price of GPS integrated circuits is rapidly dropping, causing multiple channel receivers capable of tracking as many as eight satellites to become more common. Multi-channel receivers have greater accuracy because single channel models lose phase-tracking information while breaking and re-acquiring lock with several satellites. Differential GPS is currently a viable option for fleet management of commercial vehicles, and applications for private vehicle location are becoming prevalent.

Current GPS systems using differential carrier phase measurements have provided position accuracies of less than 3 cm and velocity accuracies of less than 1 cm/s. These results meet the position location requirements of the AHS. However, there are issues that remain unresolved, such as the need for additional hardware and potentially long initialization times. The latter issue arises whenever a lock on a satellite has been lost. If high accuracies are required (position to within 3 cm) and pseudolites (pseudo-satellites, discussed below) are not available, the time delay could range from 10 to 15 minutes. In the future, this acquisition time is expected to be in the 0.5 to 3 s range. If lower accuracies are desired (position within 1 m), code-based GPS can be utilized. Code-based signals require an initialization time of no more than 10 seconds.

In areas where adequate satellite coverage does not exist, such as near tall buildings, under trees, beneath overpasses, inside tunnels, near mountains, etc., pseudolites can be implemented to quickly resolve the cycle ambiguity problem associated with differential carrier phase tracking, the most accurate of the GPS position estimation technologies. Two pseudolites and differential correction algorithms are needed to provide full cycle ambiguity resolution.

Pseudolites are ground-based transmitters that use the same GPS signal structure with a different pseudo-random code than satellite-based systems. They can be used to compensate for various gaps in GPS signal coverage. Pseudolites that use the same frequency as satellites have a limited range of operation due to what's known as the "near-far" problem. When a GPS receiver is within a specified distance of a pseudolite, the pseudolite will jam the satellite signals. When the receiver is outside an area of given radius from the pseudolite, the signal will be too weak to be received properly. The effective near-far ratio of a C/A code (single frequency commercial receiver) is 10:1, i.e. within 1 unit of distance the pseudolite causes jamming, while at distances greater than 10 times this, the signal is very weak. Pseudolites that use non-GPS frequencies have been developed, but current receivers cannot receive these signals. New, protected frequency allocations must also be created for signal transmission.

Various schemes have been designed to combat the problem of urban blockage due to tall buildings. As an example, one hybrid GPS design[22] uses a receiver to monitor available satellites, taking position information from the three with the best geometry. The other receiver simultaneously collects all other GPS data. This design allows the system to access up to eight GPS satellites, the maximum available at any one time, and minimize the risk of urban blockage. If the tracking lock is lost on one of the satellites used for positioning, the system inserts position data from the satellite with the next best geometry.

Carrier phase GPS also provides attitude information (accurate to 0.1 deg) and time. The former can be used in conjunction with the lane sensing system to improve lateral control accuracy. It is well known that vision systems currently have trouble tracking lane boundaries during inclement weather (rain, snow, etc.). The attitude information provided by GPS in conjunction with the roadway map database and past vehicle states could alleviate some of the shortfalls of vision systems.

GPS may be required to update the exact vehicle position and velocity under conditions where the on-board system is known to be deficient. This requirement should alleviate the problem of continuous operation near obstructions. Also, there is more room for position error in the time slot case than there is for the case of closely spaced platoons.

An alternative to low-frequency GPS updates is to use a GPS/Inertial Reference Unit (IRU) system to provide vehicle state information. Current carrier phase GPS is capable of 10 Hz update rates which are probably too low for longitudinal control purposes, especially during emergency maneuvers. However, an IRU can be integrated into the system to provide state information between GPS measurement updates. Typical IRU’s produce outputs in the 50 to 100 Hz range.

Wayside Tags

Vehicle position measurements can be achieved by utilizing wayside transponders which transmit their absolute positions in an appropriate reference frame (latitude/longitude, x/y, etc.). Vehicles will continually interrogate these transponders to determine their exact positions on the roadway. This information will be used to correct position errors for longitudinal control purposes. It will also be communicated to the TOC, which will keep a map of all the AHS vehicles in its jurisdiction for the purposes of maneuver and flow management.

Wayside tags can be placed in areas where the on-board navigation system is known to be deficient. As vehicle navigation systems improve and overcome some of their limitations, certain wayside tag systems will no longer be necessary. They can therefore be moved to positions on new AHS roads.

Each wayside tag will consist of an active transponder which obtains its energy from the interrogating signal. The tag will be designed to transmit its coordinates upon interrogation. Power from the infrastructure will not be required.

<u>Lateral Control</u>

Vision systems can be used to optically track lane boundaries and preceding vehicles for the purposes of vehicle lateral control. These systems generally require extensive data preprocessing to extract pertinent information. Due to the excessive amount of information to process from multiple frames of two-dimensional data, this preprocessing task can be very time consuming. Overall frame rates on the order of 5 Hz are common. This rate is considered too slow for effective lateral control at expected AHS speeds. However, it is reasonable to predict that by the time an AHS system is deployed (10 to 20 years), application specific hardware and preprocessing algorithms will be improved to the point where speed is no longer an issue. At this time, though, cost may still be a critical issue.

Vision system performance in inclement weather is also a very critical performance issue. Current system algorithms have a difficult time extracting features when the field of view is obstructed by rain, snow, fog, etc. The extraction of lane line information can become quite difficult under conditions of low sun angles, where light reflects off the road surface. Night driving can also pose a difficult lane-line extraction problem.

An advantage of vision systems is their wide field of view. Not only can they be used to optically track lane lines, but they can be used to determine distance and range rate with respect to preceding vehicles, and the velocities of the preceding vehicles as well. The wide field of view can also be used to detect vehicle cut-ins from a neighboring lane. This information can be used to avoid a side impact collision. Assuming the cost of such systems decreases and intelligent algorithms are developed to process the immense amount of data available, these systems have great potential, since they mimic a human’s method of environment perception. Vision systems can also be applied to lateral control functions in a platoon scenario. In this case, the system would track the rear end of the preceding vehicle in a vehicle following mode. Clearly, thorough coordination between vehicles would be required to ensure that vehicles would not follow malfunctioning vehicles into collisions or any other dangerous event.

Princeton researchers have simulated a roadway lateral control system.[23] This system captures simulated road image data, preprocesses it, and then uses this data to train an Adaptive Resonance Theory Neural Network. Training samples are taken from a simulation where a user guides a vehicle along a road. Various initial orientations of the vehicle with respect to the lane are used to train the network. The system is still very experimental, and the simulation makes many simplifying assumptions. However, the performance is quite good. A ten-fold robustness to velocity is observed when the vehicle tests on velocities ten times those used during training. This shows the network's ability to "scale up" to conditions outside the training set. Note that lateral control systems that are based on neural networks will perform only as well as the performance inherent in their training data. If a driver possesses bad driving habits, and the resulting driving data is used to train a neural network, the network performance will mimic these habits to some extent.

Researchers from the Institute for Microelectronics and Daimler-Benz have developed a fully operational vision-based lateral control system.[24] Steering response data was collected for a manually-controlled vehicle (human driver) as it negotiated various typical driving scenarios. In a parallel operation, a vision-based system optically determined the yaw angle, road curvature, lateral deviation, and weighted time averages of road curvature and lateral deviation. These five quantities were used to train a multi-layer feedforward neural network which employed the backpropagation-of-errors training method. A desired output (driver response) is associated with each set of inputs. The network learned the input-output relationships for the temporal data. The real-time image processing system evaluated 12.5 images per second and computed the relevant parameters in less than 80 ms. Though this is currently too slow for an AHS system, especially if lane widths are reduced, processing times will certainly decrease in the future.

The neural network performed well in a simulated environment, where it exhibited a maximum lateral deviation of 16 cm. In a highway test comparison to a conventional proportional, integral, derivative (PID) controller, the neural network exhibited a maximum lateral deviation of 20 cm (average of about 8 cm), while the PID controller showed a maximum of 40 cm (average of about 20 cm).

Carnegie Mellon University researchers have also developed a vision-based lateral control system using a neural network engine.[25] The neural network trains in about 4 minutes by observing a human driver. One problem with this method is that the training data will not fully characterize normal driving scenes as observed by the optical system. If the training data does not include the condition of a roadside guard rail or a car passing on the right, the network may react inappropriately. However, by introducing structured noise into the training set, test runs of up to 21 miles of unassisted driving have been achieved. This structured noise simulates expected driving scenes such as roadside configuration changes, image intensity changes, vehicles passing on the right or left, approaching a preceding vehicle, etc.

Researchers at PATH have developed a stereoscopic vision system.[26] After adjusting for the difference in left and right camera fields of view (disparity), all features below the ground plane disappear, leaving only objects of interest, such as vehicles and infrastructure content. Typical range accuracies lie in the 2 to 3 m range. They decrease with the square of the distance to the object. Where the vision system can “see” enough of the side view of a preceding vehicle, range estimates to the front and back of that vehicle can be obtained. Vision systems can provide road curvature preview information to the lateral control system. Preview information has been shown to improve the ride quality and overall control system performance.

One of the tradeoffs with stereoscopic vision systems is the separation of the two cameras versus the processing requirements. As the distance between the cameras increases, the depth perception also increases. Unfortunately, the amount of processing required also increases. This adds to an already relatively slow data processing time.

Researchers at Matsushita have used vision processing techniques to develop a lane line recognition system.[27] The frame rate for this transputer-based system is 30 Hz. Results for daytime, twilight, and nighttime driving were quite reasonable, with accuracies nearing 100 percent for most cases. The case of vehicle operation during the rain at night, though, resulted in accuracies of only 12 percent. Recent unpublished work by the authors shows that most of the accuracies listed in the referenced work have been somewhat improved, except for the rainy nighttime case. As is usually the case for such systems, the presence of snow on the road greatly degraded system performance. Also, their present system no longer has difficulty detecting lane lines while executing a lane change maneuver. Their current work is focused on using their system for headway measurement and vehicle/obstacle detection.

<u>Longitudinal Control</u>

Researchers at the University of Iceland have used robust design methods to design vehicle point follower controllers.[28] Simulation results show that large signal commands used for entry-merging maneuvers produce errors bounded by ±1 m, while small signal commands used for small move-up maneuvers generate errors bounded by ±0.4 m. Perturbations to quantities related to the propulsion system and its interaction with the roadway interface and to the tire-roadway interface were used to determine the robustness of the controller design. This parameter variation was not taken into account in the design process. However, results showed reasonable performance. Future work is expected to improve the robustness feature of the controller to the point where it is insensitive to system parameters.

<u>Controller Software</u>

See Representative System Configuration 1.

<u>Collision Avoidance</u>

Researchers at the Institute for Neuroinformation have developed a vision system that uses edge detection techniques and the inherent symmetry of the rear of preceding vehicles to follow cars and identify foreign objects in the present lane or in adjacent lanes. The class of objects that can be identified includes vehicles of all sizes as well as trucks and conventional trailers. Range estimates can be derived from the image data. Though the identification process requires 1 to 2 seconds, most of the algorithm can be executed in parallel to increase throughput.

Researchers at the National Institute of Standards and Technology[29] are using optical flow techniques to identify discrete objects on a roadway and the corresponding terrain slopes. Vision systems based on optical flow methods have certain advantages over other vision systems in terms of their simplicity, speed, and robustness. In terms of simplicity, only one component of the optical flow is needed. Information such as road or terrain model, specific knowledge of vehicle or camera motion, or knowledge of the coordinate transformation between the camera and the ground is not required. Discrete objects are detected using only a straight line. Therefore, since these lines can be processed in parallel, computational requirements are low. The error sources involved in this method are reduced to a minimum, since the only required information is one component of the optical flow.

This optical flow technique does not require the direct calculation of distance to the object. Instead, the ratio of distance to speed determines the time to collision which can be used for avoidance maneuvers. Due to the passive nature of the sensing equipment, radiation concerns are eliminated and sensing costs are reduced.

Testing was performed to identify bumps and potholes in the roadway. The slopes of these objects were also estimated. Excellent results were obtained for discrete object identification and slope determination even after noise was introduced into the system. The estimation of the size of an object and its slope can be used by an intelligent algorithm to determine whether to avoid the object or to simply ignore it. In many cases, the latter may be a more optimal solution.

Communication

A major difference between RSC 1 and RSC 3 is the density of traffic in the automated lanes. Fewer cars must be accommodated with the point following architecture of RSC 3 than must be accommodated with the platoon architecture of RSC 1. Since the VRC has the capacity to accommodate the traffic capacity of RSC 1, it can easily accommodate the traffic capacity of RSC 3. It may also be possible to allocate more communication time slots to each vehicle in RSC 3, thus increasing the data rate to every vehicle.

Enabling Technologies

Neural networks

Due to the complex parameterization and the nonlinear system dynamics of vehicles, the development of a controller by conventional system-theoretical methods is very difficult. Furthermore, effort must be expended by experts to develop such systems for each new type of vehicle. To alleviate these problems, neural networks can be used to learn measured human driving data without knowledge of the physical vehicle parameters. In essence, the conventional vehicle modeling step is completely bypassed and the controller development effort is significantly reduced. The use of “good” data which characterizes the ranges of the system is of utmost importance to network development.

Issues surrounding the use of neural networks include the lack of formal stability proofs and a lack of complete understanding of the method used by the network to arrive at its decisions.

As is the case for any intelligent algorithm, the ability to generalize, i.e. perform well on data not used during training (calibration), must be sufficiently proven. Note, though, that neural research is a relatively new field and tremendous progress has been made towards satisfying these issues. Also, extensive testing with closed-loop simulations can sufficiently answer the stability question.

Fuzzy control

Fuzzy logic is a powerful problem-solving technique with widespread applicability, especially in the areas of control and decision making. It has the ability to draw conclusions and generate responses based on vague, ambiguous, qualitative, incomplete, or imprecise information. In this respect, fuzzy-based systems have a reasoning ability similar to that of humans. In fact, the behavior of a fuzzy system is represented in a very simple and natural way. This allows quick construction of understandable, maintainable, and robust systems. In addition, a fuzzy approach generally requires less memory and computing power than conventional methods, thereby permitting smaller and less expensive systems.

Researchers at PATH have developed a fuzzy lateral control algorithm. The motivation for a fuzzy-rule-based controller to steer a vehicle arises from its capability to process steering decisions using “if, then” rules which are similar to the method of reasoning used when humans operate a vehicle. The flexibility of a fuzzy-rule-based controller allows for a variety of system inputs to be manipulated in an efficient manner. Furthermore, rules based on human decision-making can be complemented with rules based on control theoretic techniques intended to enhance performance and robustness characteristics of the closed loop system. In addition, fuzzy rules provide an effective means of handling imprecise measurements and estimates.

The fuzzy controller developed by PATH uses lateral error, yaw angle error, yaw rate error, longitudinal velocity, steering angle, change in lateral error, and sum of lateral errors as inputs. The three types of fuzzy rules are feedback, preview, and gain scheduling. The feedback rules are analogous to the concepts used in a classical proportional, integral, and derivative (PID) controller. The preview rules attempt to capture and process information concerning the future geometry of the roadway. The gain scheduling rules are used to incorporate vehicle velocity into the final control signal. An example would be a more aggressive steering command at a low velocity on dry pavement than at a high velocity on slippery pavement.

The goal of this investigation was not to improve on the tracking of the previously developed PID or frequency shaped linear quadratic (FSLQ) controllers, but to show that a controller based on an implicit model of the vehicle can perform as well as the PID and FSLQ controllers, which were designed from an explicit mathematical model of the vehicle.

Simulation results show that the fuzzy controller makes use of each of the three sets of rules to achieve an appropriate tracking solution. The system tracked to within 15 cm on a curve with a 650 m radius at a vehicle velocity of 30 m/s. Similar results were obtained for various curve and velocity combinations. The performance results of the fuzzy controller were virtually identical to those obtained from previous PID and FSLQ tests for a variety of vehicle velocities.

Four-Wheel Steering (4WS)

Researchers from Nissan Motors and The National Defense Academy of Japan have analyzed the effects of vehicle dynamics on the stability of an automatic lateral motion controlled vehicle equipped with a 4WS system.[30] The 4WS system was configured around model following control theory.

Simulations were performed by introducing a crosswind on vehicles traveling at 180 km/h. The 4WS system proved superior to the 2WS system in responsiveness and stability. The 2WS system exhibited oscillations and instabilities as a result of the crosswind and increased control gain. In general, the 4WS system was able to track its lane much better than the 2WS system under adverse conditions. This capability is very important to an AHS control system.

Researchers at Fiat have analyzed the fault tolerant aspects of 4WS systems.[31] It is clearly important to design automotive control systems which can detect a fault and recover from it. The result should be the same functionality or a degraded system functionality. In any case, enough functionality should remain to operate the vehicle safely. A worst case fault on a 4WS system might require the complete disabling of the rear steering, leaving only the front steering active.

A master-slave architecture utilizing independent processors and redundant sensors and actuators was designed to perform the task of detecting and correcting faults. Results showed that this system performed quite well.

CONCLUSIONS

The emphasis of the lateral and longitudinal control analysis work was on defining significant issues and risks associated with vehicle control. Reference was made to numerous research results that described the state-of-the-art in vehicle control technology. These concepts were applied to representative system configurations which formed a basis for system comparison and critique. This conclusion section identifies the key points that result from the six task areas of this report.

Vehicle platooning is a very feasible concept for an AHS. The choice of the intra-platoon spacing parameter presents a challenge, as there is a perceived tradeoff between capacity and safety. Close vehicle spacings (1 m) may result in many low-velocity collisions, while larger spacings (5 to 20 m) may result in fewer collisions (possibly none under reasonable assumptions), but with relatively high collision velocities. The concept of a coordinated platoon has been presented in Task 3 to address the intra-platoon collision issue. In theory, an adaptive control system in conjunction with accurate and timely vehicle-vehicle communication should be able maintain intra-platoon vehicle spacings under a variety of maneuver conditions. One significant question that remains is the likelihood of nonpredictable vehicle/roadway malfunctions that could cause a vehicle in a platoon to decelerate at a relatively high level. The coordinated braking scheme would potentially have difficulty responding to this malfunction in a manner that maintained all intra-platoon spacings. In general, the greatest deceleration a vehicle can achieve under reasonable roadway conditions is through the use of its brakes. Vehicle-specific malfunctions should not be able to cause a larger braking deceleration rate. It is suggested, though, that a more thorough study be performed to investigate this issue, as it is central to the feasibility of variable intra-platoon spacings.

In the event of a serious vehicle malfunction, a loss of lane control, or an intentional maximum braking maneuver, intra-platoon collisions in a closely-spaced platoon may result. In this case, it is important to understand the nature of the resulting collision dynamics. These dynamics are the physical interactions and resulting body motions between vehicles. Based on the results of this study, lateral and longitudinal controllers can be tested to ensure that they are able to maintain vehicle attitude control while the platoon brakes. Note that vehicle front and rear ends may not generally align well. At the time of a collision, the platoon may also be undergoing a turning maneuver, which would slightly misalign each vehicle with respect to surrounding vehicles. Individual vehicles would probably also brake before any collision.

This would result in a vehicle

that is pitched forward with respect to the previous vehicle, which if braking is also pitched forward.

In the area of vehicle control algorithms, reasonable advancements in headway maintenance control systems for platooning vehicles have been made. Also, good lane-keeping algorithms which produce acceptable performance levels have been developed. However, robust lane changing and platoon/vehicle merging algorithms that will provide ride comfort while meeting AHS requirements are still needed.

The remote servo control approach of RSC 1 will be very difficult and probably costly to implement. Accurate vehicle position measurements will be difficult and costly to obtain from the wayside-based communication system. Therefore, a vehicle-based approach, such as RSC 2, is considered a more practical and realizable solution.

The issue of whether a driver should be involved in either the steady-state control or the emergency control of a vehicle is very complicated and depends to a great extent on the performance levels of automated control systems at the time of an AHS deployment. If these systems perform all of their functions flawlessly with redundant capabilities, there will be no need for driver intervention. However, this is a highly unlikely case, as machines will probably always have some trouble with certain tasks. Thus, drivers may be needed to fulfill some critical functions, since they will probably always be able to perform tasks, such as perception, classification, and prediction, with greater skill than machines.

One of the challenges of an AHS is to arrive at an appropriate marriage of automated action and driver action as they apply to vehicle control. In the early deployment stages, the driver will probably have more control input than at later stages. There must be no confusion as to the role of the driver and the functions that the driver is expected to perform. In a case where both the driver and the automated system can have shared control over the vehicle, the driver must be alerted in a clear and concise manner. An example of this is a case where the driver has a high-level steering responsibility while the automated system maintains vehicle traction and performs the longitudinal control function.

In terms of response times to detect and interpret objects on the roadway and respond appropriately, automated systems seem superior to drivers. However, drivers currently (and may always) possess a much greater skill in classifying these objects and determining appropriate maneuvering actions. Unfortunately, drivers require a fair amount of time to process their sensory information. Therefore, assuming a relatively controlled driving environment (no vehicles carrying loose loads allowed on the AHS, reasonably segregated AHS lanes, good vehicle lateral and longitudinal control performance, etc.), automated collision avoidance systems may perform adequately.

In order to develop, test, and analyze vehicle control algorithms, communication systems, and vehicle maneuvers, a comprehensive AHS simulation encompassing basic vehicle dynamics, vehicle interactions with other vehicles and with the roadway, multiple lanes (possibly mixed traffic), entry/exit lanes, various roadway configurations, and environmental effects (wind, rain, icy roads, etc.) must be developed. The simulation will serve as a testbed to develop flow/maneuver optimization, platoon control, and merge/separate, lane-change, and entry/exit algorithms, and to understand the effects of various vehicle maneuvers. It will also help to determine the best mix of infrastructure and vehicle-based functionality.

The ability of communication systems to be able to guarantee error-free transmissions in the presence of electromagnetic interference from such sources as AHS vehicle-roadside communication systems, AHS vehicle-vehicle (intra and inter-platoon) communication systems, and non-AHS signals is critical to the success of communication-based control systems. It is also important from a data transmission viewpoint as well. Various methods have been described to counteract the effects of interference, such as the use of spread spectrum techniques, the proper choice of overall communication bandwidth, and the use of specific transmission frequencies and message coding methods.

Sensor, communication, and control design needs to be as flexible as possible in a given roadway operational environment, since it is difficult to predict the transportation needs of the country in 5 to 10 years after a design is completed. To achieve this goal, system software should be carefully developed in a well documented, object-oriented manner to allow for various operational conditions. System hardware should also be designed to meet all expected performance requirements.

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