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A REVIEW OF RESEARCH RELATED TO AUTOMATED HIGHWAY SYSTEMS (AHS)*

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Abstract

Interest and research in Intelligent Vehicle/Highway Systems (IVHS) has increased dramatically in the last few years, especially since the passage of the Intermodal Surface Transportation Efficiency Act of 1991. New researchers are entering the field quickly, in part due to the recently awarded Federal Highway Administration Precursor System Analyses in Automated Highway Systems (AHS). While there are a number of good general reviews of IVHS, there appear to be no reviews that have focused on issues related to AHS. This literature survey fills that void. It provides a review of IVHS research with a focus on areas that are relevant to AHS. The review focuses on vehicle control, and other areas that are pertinent to it. The areas covered include: general AHS research; longitudinal, lateral, and combined vehicle control; sensors and alternative AHS vehicle types; communications requirements; system architectures; safety and fault tolerance; and human factors. A partial list of acronyms and abbreviations is included in an appendix. This review should be helpful to researchers attempting to quickly familiarize themselves with this field.

Contents

1 Introduction 1

2 General AHS Issues 5

3 Vehicle Control 15

4 Sensors & Vehicles 27

5 Communications 35

6 System Architecture 37

7 Safety & Fault Tolerance 41

8 Human Factors 49

9 Conclusion 53

References 55

Acronyms & Abbreviations

AASHTO: American Association of State Highway and Transportation Officials
AHMCT: Advanced Highway Maintenance and Construction Technology
AHS: Automated Highway System
AMTICS: Advanced Mobile Traffic Information and Communication System
ANSI: American National Standards Institute
APTS: Advanced Public Transportation Systems
ASCE: American Society of Civil Engineers
ASME: American Society of Mechanical Engineers
ATIS: Advanced Traveler Information Systems
ATMIS: Advanced Traffic Management and Information Systems
ATMS: Advanced Traffic Management Systems
ATT: Advanced Transportation Technology
AVC: Automatic Vehicle Classification
AVCS: Advanced Vehicle Control Systems
AVI: Automatic Vehicle Identification
AVL: Automated Vehicle Location
CVO: Commercial Vehicle Operations
CVSA: Commercial Vehicle Safety Alliance
DOT: Department of Transportation
DRIVE: Dedicated Road Infrastructure for Vehicle Safety in Europe
EPA: Environmental Protection Agency
FHWA: Federal Highway Administration
GPS: Global Positioning System
GT: Group Technology
HAR: Highway Advisory Radio
HOV: High Occupancy Vehicle
IB: Information Beacon
ICB: Individual Communication Beacon
IEEE: Institute of Electrical and Electronics Engineers
IPCS: Integrated Platoon Control System
IRRS: Intelligent Roadway Reference System
ISO: International Standards Organization
ISTEA: Intermodal Surface Transportation Efficiency Act of 1991
IVHS: Intelligent Vehicle/Highway Systems

LB: Location Beacon
NADS: National Advanced Driving Simulator
NAS: National Academy of Sciences
NASS: National Accident Sampling System
NHTSA: National Highway Traffic Safety Administration
NSF: National Science Foundation
PATH: Program on Advanced Technology for the Highway
PROMETHEUS: Program for European Traffic with Highest Efficiency and Unprecedented Safety
RACS: Road/Automobile Communication System
RDS: Radio Data System
RSC: Representative System Configuration
RTI: Road Transportation Informatics
RVC: Road-Vehicle Communications
TMC: Traffic Message Channel
TRB: Transportation Research Board
TRIADS: Trondheim Integrated Automatic Debiting System
VHD: Vehicle Hours of Delay
VHT: Vehicle Hours Traveled
VICS: Vehicle Information and Communication System
VMT: Vehicle Miles Traveled
V&V: Verification and Validation
WIM: Weigh-In-Motion

Chapter 1

Introduction

Roadway automation has been considered for at least the last fifty years. For example, the 1939 World's Fair had an exhibit called the 'Futurama' by General Motors, which contained many of the concepts still being considered today.[1] Intelligent Vehicle/Highway Systems (IVHS) related research was strong in the U.S. in the late 1960's and early 1970's, but waned with the reduction in the Federal Government's role in civilian technology development in the early 1980's.[2] Early efforts in route guidance in the U.S. motivated similar work in Japan and Europe; while U.S. activities lagged, the Japanese and Europeans increased their efforts. In the late 1980's, the recommendations of an informal group, Mobility 2000[3] a collection of interests from industry, Government, and academic institutions inspired the formation of the Intelligent Vehicle Highway Society of America, a nonprofit educational and scientific association. U.S. research in IVHS has recently accelerated, particularly in the wake of Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). The Federal Government, private industry, and academia are all showing renewed interest in various aspects of roadway automation research. In particular, the area of Automated Highway System (AHS) has received significant attention of late, due to the Federal Highway Administration's solicitation and funding of several "Precursor System Analyses of Automated Highway Systems." Additional motivation for AHS research, at least from a U.S. standpoint, includes:[1]

- Growth in congestion.
- Cost of new infrastructure.
- Public opposition to new construction.
- Pollution, greenhouse effects, and dependency on foreign oil.
- Advances in:
  - Sensing technologies.

- Computer hardware and software.
- Communication technologies.
- Control theory.

- Increased foreign competition in the automotive industry.
- Threat of the U.S. losing technological leadership in the world.

The AHS concept is summarized by Bishop and Alicandri:[4]

> The AHS vision can be summarized as a system of instrumented vehicles and highways that provide fully automated (i.e. "hands-off") operation at better levels of performance (safety, efficiency, comfort) than today; is practical, user-friendly, and financially affordable; is deployable in both urban and rural areas; and preserves the ability of instrumented vehicles to operate on non-instrumented roadways.
>
> To elaborate, it is essential that the AHS provide improved safety over existing highway travel and that this be the public's perception of the system, as well. In addition, highway capacity must be increased to alleviate congestion on urban freeways and overall efficiency should be increased for rural freeways, to enhance long distance, intercity travel. The system will be nothing more than a novelty unless the public embraces its use; therefore, the system must be easy to use, provide a smooth ride, provide a sense of safety and well being to the passengers in the vehicles, and, of course, be affordable to the driving public. While the operational environments of urban and rural freeways are quite different, service must be provided to travelers on both types of facilities, although the system configuration might possibly change between the two. Finally, a system which required such specialized vehicles that they are not usable on existing highways is clearly not practical; therefore, AHS-equipped vehicles must have the ability to move freely between automated and non-automated facilities.

Bishop and Alicandri[4] discuss the current status of the U.S. Department of Transportation AHS program. They then describe an ongoing human factors study, and introduce the AHS Precursor System Analyses, which cover a wide range of AHS issues using intensive studies. Finally, the status of the solicitation process for an AHS system developer is reviewed.

Roadway automation can mean many things   one definition[1] is:

> the application of communication and control technology to observe, guide and/or control the movement of vehicles in a traffic system (or to assist in the performance of those functions).

This is a very broad yet useful definition. The term "roadway automation" is seldom used these days, having been supplanted by the term Intelligent Vehicle/Highway Systems (IVHS), which was first used by Kan Chen from the University of Michigan. As noted in (3), IVHS is really a subset of Advanced Transportation Technology (ATT), which includes broader aspects of transportation technology including alternate fuels, alternate modal systems, and robotics for maintenance and construction. The researchers at the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center at the University of California Davis view the last aspect, robotics for maintenance and construction, as an integral and critical component of IVHS. Most AHS research to date indicates a need for faster, more precise, higher quality, and more cost-effective infrastructure construction and modification than is available using current techniques. In addition, the operation of an AHS may dictate different requirements for maintenance operations, which again may require more advanced methods. While a significant amount of work has been done in the various IVHS component technologies, there has been little research regarding implementation and deployment of an Automated Highway System. In particular, the current authors have seen no work in issues relating specifically to automated construction and maintenance of an AHS facility. This literature survey is a first step in a precursor study of applications of advanced highway maintenance and construction technology for use in Automated Highway System construction and maintenance. The major focus of this review is in areas that are deemed to have impact on the infrastructure, most notably Advanced Vehicle Control Systems (AVCS). However, it is important to note that successful deployment of AVCS is dependent on other IVHS areas, such as Advanced Traffic Management Systems (ATMS) and Advanced Traveler Information Systems (ATIS). It is possible to demonstrate the feasibility of vehicle control in isolation, but deployment will require established management, navigation and communication systems. As such, the focus is on Automated Highway Systems in general, and areas relevant to such an advanced system are reviewed.

The current authors view IVHS as a merging of communications, computers, displays, controls, electronics and information technology into vehicles and highways. The precise level of intelligence to be built into the vehicle and into highway or infrastructure is an open research issue at this time. The possible spectrum runs from an infrastructure-intensive system to a vehicle-intensive system. The distribution of intelligence may not have a single solution; rather it may have different answers based on the traffic characteristics of a given area.[5] The distribution choice will have considerable impact on system performance, investment and operating costs, flexibility, liability, and construction and maintenance.

Alternatively, IVHS can be viewed as a set of "integrated technologies, processes, and/or concepts which ... will help maximize the effectiveness and efficiency of the *existing* roadway network," rather than using the "traditional build-your-way-out-of-a-problem" approach to road transportation problems.[6] The traditional approach is now hitting a wall in many areas, as it is either physically or financially prohibitive to add additional lane capacity to the existing highway networks in many urban areas. This is a major motivating factor in the recent interest in IVHS.

This review is organized as follows. First, general AHS issues and research are examined in chapter 2. Chapter 3 presents some of the details of vehicle control research. Sensor requirements, and the impacts of alternative vehicle types are discussed in chapter 4. Next, the communication needs and technologies are examined in chapter 5. The important topics of safety and fault tolerance are reviewed in chapter 7. The related area of human factors is discussed in chapter 8. Conclusions are presented in chapter 9.

Chapter 2

General AHS Issues

The IVHS concept is not really new. In fact, the platooning concept was introduced as early as the 1939 World's Fair, and vehicle lateral control has been studied since the 1950's. However, it appears that research in a number of diverse areas has now reached the point where the individual components of the envisioned AHS are technically feasible. Integration into a complete system is another question, requiring further study and new results. This convergence of the component technologies has occurred at a fortuitous time, as Government interest, i.e. funding, in AHS and IVHS technology in general is at an all-time high, and appears reasonably assured in the future.

The Strategic Plan for Intelligent Vehicle-Highway Systems in the United States(7) is a fundamental document for IVHS research in the United States. This plan includes: goals and objectives for a National IVHS program; challenges to deployment and ways to resolve them; suggested roles for public, private, and academic participants; a course of action with associated milestones and operational tests; cost estimates; and a very useful glossary of IVHS terms and abbreviations that can save one from drowning in a sea of acronyms and abbreviations. The plan defines five functional areas within IVHS:

- Advanced Traffic Management Systems (ATMS).
- Advanced Traveler Information Systems (ATIS).
- Advanced Vehicle Control Systems (AVCS).
- Commercial Vehicle Operations (CVO).
- Advanced Public Transportation Systems (APTS).

For a detailed description of each of these functional areas, see (7). A recent addition to the functional areas is Advanced Rural Transportation Systems (ARTS), which is concerned with autonomous navigation systems, enhanced vision, Mayday signaling, etc.[2] As noted by others, e.g.,[8] these functional areas are a somewhat artificial structure imposed on the overall IVHS concept, especially when one looks at core IVHS technologies, which tend to cut across some or all of the functional areas. However,[7] is seminal within the IVHS literature, and an excellent starting reference for those pondering the possibility of IVHS research.

Europe has strong IVHS research programs. IVHS is referred to as Road Transport Informatics (RTI) in Europe. McQueen and Catling[9] provide a review the development of IVHS in Europe. The Prometheus project, funded at several hundred million dollars, is run by the major European auto and electronics companies, and was initially an attempt to improve European car manufacturers competitiveness against the U.S. and Japan. It is noted that both General Motors and Ford are now involved in Prometheus, which has redirected the thrust of this project from boosting European competitiveness against the U.S. and Japan toward a joint effort by Europe and the United States to address the "continuing Japanese threat".[9] The Prometheus reports are not available to the public. DRIVE is another European project, which has more participation from academic and research institutions. Its goals are to guide Europe towards an "Integrated Road Transport Environment" (IRTE), with improved traffic efficiency and safety and reduced automobile environmental impact. Other European programs include Autoguide, which has reached at least the pilot program stage, EURO-SCOUT, the latest generation of the ALI-SCOUT system implemented in the Berlin LISB trial, and TARDIS, a project within the DRIVE program which concentrates on the establishment of common functional specifications for infrastructure-based systems, i.e. systems that are not completely vehicle-based but depend upon some communication between vehicles and roadside infrastructure.[9] It is interesting to note that in Europe a strong emphasis seems to be placed on navigation, guidance, and information systems, while in the United States, more emphasis seems to be placed on vehicle control, and the eventual deployment of a full Automated Highway System.

Australia is also actively involved in the IVHS field; indeed, some unique problems in this country led to ATMS applications as long as twenty years ago.[10] Australia is a large continent with a small, concentrated population and an extensive road network which is serviced from limited taxes. This has resulted in a system where urban traffic is carried by arterial road systems, and two-lane roads link cities. Urban traffic congestion was a major problem due this system, and as funds were not available for major construction, improvements to the traffic signal system were used to create extra capacity, resulting in the Sydney Co-ordinated Adaptive Traffic System (SCATS) traffic signal control system, one of the most advanced systems of its kind in the world. The advent of IVHS is seen in Australia as a means of combining existing technology with newly emerging technologies from North America, to the mutual benefit of both continents. The Roads and Traffic Authority (RTA) of New South Wales is cooperating with other Australian RTA's to set up an IVHS demonstration project in Oakland County, Michigan. This project will include the SCATS system, U.S. produced video detectors, and possibly the European ALI-SCOUT system. It represents a significant step forward in international cooperation in IVHS research. The maturity of the Australian systems in the area of ATMS should not be discounted by researchers and manufacturers in other countries.

The status of European and Japanese advanced highway systems is reported in (11). This report is of course dated at this time, but it does provide an outsiders view of the work being done in these areas. The authors discuss the European Prometheus project mentioned above. In Japan, the efforts of academia, industry, and government are being coordinated in a complex manner, with significant involvement of the Ministry of International Trade and Industry (MITI). The Japanese have demonstrated long-term commitment to AHS concepts for at least the last 20 years, with projects integrating a variety of communication, computing, and control technologies into a working system. Japan appears to be gearing up for the potential markets in the anticipated intelligent vehicle high-technology industry. For a more recent overview of global IVHS activities, see (2), which identifies the announcement of the European Prometheus and DRIVE programs, the Japanese AMTICS program, and "extensive prodding" by the California Department of Transportation (Caltrans) as major factors within the U.S. spurring the revival of research activities in advanced vehicle-highway technology. Reference[11] notes that mechanical and electronic lateral guidance systems are in operation in Furth and Essen, Germany, and Adeline, Australia. The authors were able to ride and observe both the Daimler-Benz mechanical and electronic guidance systems for laterally guided buses. They noted that the mechanical system provided a smoother ride, but the electronic system was judged adequate for future research, as well as being more flexible overall. This visit provided significant insights for the then-young Program on Advanced Technology for the Highway (PATH) program.

The Japanese approach to IVHS, as noted in (11), relies more heavily on vehicle intelligence, rather than infrastructure. In fact, the Japanese at the time of this report were studying Intelligent Vehicle Systems (IVS): note the explicit omission of 'Highway' from the phrase. Kanafani et al. believe this focus aims toward a commercial development strategy to design the next generation of automobiles. The Computer-controlled Vehicle System (CVS) developed in Japan in the 1970's focused more intelligence in the roadway. This system, costing about $20,000,000, was a fully automated personal rapid transit system involving a five km test loop and 75 passenger and freight vehicles, all tested at headways of one second and lower. Although it was the most advanced system at that time, it was never deployed. When asked why, a Japanese researcher indicated that the system was too expensive, the aerial structures required were visually intrusive, and the centralized control system may have been a mistake.

A more recent review of international field trials is given in (5). The OECD Road Transport Research Programme is meant to enhance the global scientific and technological network on road traffic issues between research institutions in Japan, Australia, Europe, and North America. Such an organization is needed to ensure that technology is transferred, and research efforts are not needlessly duplicated. The field trials, which focused on the area of road-vehicle communications (RVC), reviewed include:

- RACS, Road/Automobile Communication System (Tokyo).
- AMTICS, Advanced Mobile Traffic Information and Communication System (Osaka).
- LISB/ALI-SCOUT (Berlin).
- BEVEI/RDS-TMC, Radio Data System - Traffic Message Channel (German Rhine Corridor).
- TRIADS, Trondheim Integrated Automatic Debiting System (Trondheim, Norway).
- DUTCH RHINE CORRIDOR.
- WEGWIJS (Amsterdam).
- SEXTANT/CARMINAT (Paris-Rennes).
- INF-FLUX (Paris).
- AUTOMATIC DEBITING SYSTEMS (France).
- AUTOGUIDE DEMONSTRATOR (London).
- TRAFFICMASTER (M25 Motorway, UK).
- TRAVTEK (Orlando, Florida).
- ADVANTAGE I-75 (from Ontario to Florida).
- DIRECT I-94, Driver Information Radio Experimenting with Communication Technologies (Detroit, Michigan).
- ADVANCE, Advanced Driver and Vehicle Advisory Navigation Concept (Chicago, Illinois).
- HELP/CRESCENT, Heavy Vehicle Electronic License Plate Program (Western U.S., Canada).
- SMART CORRIDOR (Los Angeles, California).
- PATHFINDER (Los Angeles, California).
- FAST-TRAC, Forum for Advanced Safe Travel Through Traffic Routing and Advanced Control (Oakland County, Michigan).

- TEST SITE WEST SWEDEN (Gothenburg).
- ZELT (Toulouse).

Page 60 of[5] includes a matrix of current and planned system functions to be tested in field trials in OECD countries. This matrix details trials in fleet management, hazard warning, navigation, network traffic control, route guidance, and traffic demand management. With a cursory examination of this matrix, one can obtain a good idea about the components and the status of each of the above field trials. This document includes a discussion of the basic system functions considered in RVC, and discusses various issues in planning and implementing field tests. This reference also gives an alternative IVHS classification based upon information content. This is a useful addition to the current classification into ATMS, ATIS, AVCS, CVO, and APTS. As noted in (5), the field trials differed from normal field trials, as they occurred before basic research was completed. One major benefit of the field trials reviewed here is that they have initiated a cooperative process between industry and government; such cooperation is a key to eventual deployment and success of IVHS systems.

As noted in (5), RVC is one area where international standards are critical: vehicles should work on roads throughout the world, and the road-based equipment in a given country should accept and communicate with vehicles from other countries. This is just one area of IVHS in which international compatibility will be crucial. Without such compatibility, international traffic and trade will be obstructed, the costs of system introduction will be significantly increased, and the full benefits of these systems will not be reached. In addition, without compatibility, automobile manufacturers will be unlikely to pursue AHS technologies, as their markets will be restricted as a result. This is a difficult issue, as many existing programs are not aiming at such coordination. Many of the current programs have often treated their ideas as proprietary. Also, research in these areas is proceeding quickly, so that coordination is difficult even when researchers view such coordination as important. In light of these needs, such organizations as OECD, IVHS AMERICA, and other coordinating groups may be able to play an important role in assuring sufficient compatibility for deployed systems.

Until recently, IVHS research in the U.S. has been somewhat sporadic, subject to whims of Federal funding. However, since the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA), commitment to the IVHS concept and its eventual implementation at some level seems fairly strong, and the environment for useful research and development in this area appears ripe at this time. The ISTEA has had significant impact on the IVHS program.[12] As a result of this act, the U.S. Department of Transportation has established a major IVHS program. The program's foundation is a commitment to work closely in partnership with other public and private interests to achieve mutual program goals; the ISTEA provides support and funding for this partnership.

A major element of the ISTEA is the Intelligent Vehicle Highway Systems Act of 1991. This act established an IVHS program with approximately $660,000,000 authorized over a six year period.(12) This program established the Corridors Program, providing for operational testing under 'real world' conditions; these corridors will act as showcases and testbeds for IVHS technologies. This act also established IVHS AMERICA as an advisory committee for carrying out the IVHS program, and the availability of planning grants to state and local governments to study the feasibility and deployment of IVHS. In addition, demonstration of an Automated Highway System to serve as a prototype for future systems development is planned for 1997. The act also requires compatible standards and protocols, evaluation guidelines for IVHS operational tests, and establishment of an information clearinghouse.

Saxton and Schoene(12) discuss the FHWA IVHS research and development program, which includes the following areas:

- System analysis and system architecture.
- Transportation system analysis.
- Modeling and simulation.
- Databases and database management.
- Communications.
- Software.
- Safety and human factors.
- Institutional and legal issues.
- Socio-economic issues.
- Privacy as a design issue.

The FHWA is employing several approaches for conducting research: traditional R&D contracts, public/private/academic consortia, research institutes and universities, and the IVHS Innovations Deserving Exploratory Analysis (IDEA) program. The IVHS IDEA program, modeled after the Strategic Highway Research Program (SHRP) IDEA program, is meant to support the research of innovative ideas with potential applications to IVHS. Research under the IVHS IDEA program is conducted in two phases. The first phase funds initial feasibility studies of innovative concepts. The second phase selects the initial studies that may yield a prototype system or product.

Saxton and Shoene next discuss the status of key R&D programs, including traffic systems and tools, motorist information programs, and various operational test programs. Many of these details are discussed elsewhere in the current review.

Proponents of IVHS agree that a proper combination of control, communication, and computing technologies in the highway and the vehicle can assist driver decisions in ways that will increase highway capacity and safety without building more roads. However, according to (8), there is a wide range of opinion about the form of this "intelligence", due to variation in judgment about:

- Function the driving functions to be automated, and the degree of automation.
- Architecture the decomposition of functions into control tasks, and the assignment of tasks to subsystems.
- Design the division of intelligence between vehicle and infrastructure, and how technologies can be combined to implement this architecture.
- Evolution the timing of system development and deployment, and the extent to which the architecture can incorporate functions not originally planned for.
- Evaluation the effectiveness, costs, and benefits of various IVHS proposals.

Varaiya(8) addresses the first three aspects on this list. In this paper, the author focuses on capacity increases due to implementation of IVHS, and argues that, with respect to capacity increases alone, full automation is far superior to partial automation. This reference is discussed in detail in chapter 3.

Varaiya also breaks with the standard approach of classifying IVHS work into standard groups: ATIS, ATMS, AVCS, APTS, and CVO. This subdivision tends to be fairly artificial once one begins to investigate core IVHS technologies, which cut across most of these areas. The current authors agree that it is better from a technological classification to avoid pigeonholing research work into these areas; we will focus on developments as they relate to Automated Highway Systems in general, rather than on specific contributions to any one of the above groups.

Varaiya also gives a useful breakdown of IVHS design steps: functional specification, control system architecture, control system design, physical design, and communication system design For the details of these steps, see (8).

A study by Rockwell International Science Center(13) examines the potential payoffs from application of IVHS technologies. This reference provides a framework for systematic identification and evaluation of functions that may contribute to IVHS goals. The analysis shows significant capacity increases (factor of three) due to implementation of AHS concepts such as platooning and lateral control. In addition, this reference provides a good literature search regarding benefits analyses performed elsewhere. A software tool, the Decision Modeling System (DEMOS), was used for much of the analysis in this study, including sensitivity studies to estimate benefits of functions associated with modifying the speed-density-flow curves, representation of goal-action trees, safety analysis, and trade-offs in queue clearing at intersections.[14]

New technologies are also assessed by Garrison and Taff.[15] This reference includes an overview of the assessment process itself, i.e. the methodology and situations bearing on assessments, and what can be done to improve future assessments. As such, this report should be useful to anyone planning to assess new technologies, whether the technologies are related to IVHS or not. The report also includes an interesting evolution of traffic operations up to the current state, including the development of the interstate highway system. Garrison and Taff indicate that the current situation for the traffic manager considering application of new technology is different, due to the presence of “on the shelf” technologies that seem ready for application, including computers, sensors, communication devices, information system and control methodologies, traffic flow optimization techniques, pattern recognition techniques, etc. The authors refer to AHS conceptual studies as early as 1969;[16] however, the technology was not sufficiently developed at that time to implement such a concept. They also indicate that some of the technologies required for IVHS have been developed in maritime, rail, and other modal areas: one issue is the direct or modified application of this technology to the highways. Five areas are assessed: vehicle navigation and guidance, vehicle identification and classification, vehicle and guideway design, vehicle and guideway powering, and automated highway systems. The assessments are primarily literature based, consisting mainly of short, overview statements, with reference into the literature for those interested in more detailed information. The assessment of automated highway systems is clearly relevant to the current work. The interested reader is referred to[17] for further information.

Deakin[18] discusses the opportunities and constraints for the application of advanced highway technologies. She reviews the current technology and problems that have partially spurred the recent interest in IVHS technologies. Next, she overviews some of the technology options and applications being considered for advanced highways, and their potential markets and impacts. Finally, some of the barriers to the introduction of these technologies are discussed. This reference does not assess the technologies themselves; rather, it is meant as a guide to better understanding of the socio-economic and environmental context in which highway technologies may operate, and as a preliminary assessment of the opportunities and problems.

Shladover[1] discusses research needs in roadway automation technology within the following nine areas of an automated highway system: intelligent traffic signaling, traffic information systems, driver warning and assistance, automatic steering control, obstacle avoidance, automatic trip routing and scheduling, control of merging of streams of traffic, and transitions to and from automatic control. He examines each of these areas in terms of the data flow between seven components of the system: the vehicle being controlled (includes sensors and computers), the driver, the roadway, external objects, other vehicles and their drivers, wayside computers, and wayside traffic signals. Shladover views this information flow as a method of focusing on the technical issues that must be resolved to implement each of the nine automation functions. The author notes that coordination of the individual automation functions into a full Automated Highway System requires a focused plan using good system engineering principles. The plan should "proceed from the statement of needs to mathematical modeling and analysis, design and implementation of limited-scale experiments, and then multiple cycles of design refinement and testing before proceeding to public demonstrations of any substantial scale."(1) identifies many important yet unsolved issues that are critical for the eventual success of an Automated Highway System, and provides significant guidance for the new IVHS researcher.

Specific research needs in ATMS identified in(3) include: sensor improvements, better traffic flow models, and area-wide traffic control strategies that provide the best minute-by-minute traffic flow on the existing infrastructure. Such issues must be resolved for the foreseen benefits of Automated Highway System to be realized. ATMS sensor issues are briefly reviewed here, as they will have some impact on the AHS infrastructure; for other ATMS concerns, refer to (3), as well as numerous other references.

Harris(3) identifies many areas of required research in AVCS, which will form a critical part of an AHS. Near-term areas, in which substantial progress has been made since this workshop, include proximity sensing, lateral guidance sensing, and actuators and controllers. Long-term needs include study of vehicle dynamics, system dynamics, infrastructure support, safety criteria, standards and protocols, human factors, and other technologies. A number of institutional and societal issues are also identified, but will not be discussed here. Solutions to these institutional and societal problems, such as liability, are essential for the successful deployment of Automated Highway System, but are beyond the scope of this paper.

The Japanese are currently studying their next generation road traffic system, the Advanced Road Transportation System (not to be confused with Advanced Rural Transportation Systems), as well as an automated driving system, Super Expressway for Automated Driving 21 (SEAD 21).(19) These systems are intended to be high safety facilities which allow coexistence of automatic and manual cars, redundancy for safety, and cooperation between vehicles and roadways. The system as proposed appears quite impressive, and the Japanese plan to conduct initial field trials as early as 1995. IVHS researchers in the U.S. and Europe should pay attention to the progress being made here.

A comparative study of road transportation in the U.S. and Japan(6) indicates that IVHS should:

- Focus on regional needs, stress safety, and respond flexibly to uncertainty in accident trends to reduce the magnitude of the safety issue.

- Adapt to roadway architecture and traffic conditions, be perceived as effective and automatic, and handle any negative high-order system effects.
- Be compelling, receive Government support, and manage conflicting market trends to gain market penetration.

Reed notes that the potential safety benefit of eliminating alcohol from roadways appear to be greater than similar benefits of IVHS. Estimates here show that even a 50 percent reduction in roadway alcohol abuse would have a comparable safety benefit, although it seems difficult to quantify such factors.

Chapter 3

Vehicle Control

Vehicle control is at the core of the most advanced visions of IVHS. The long-term goal of IVHS is the implementation of an Automated Highway System (AHS), which will include completely "hands-off" driving in which vehicles are fully automatically controlled once they enter the system. Achieving this goal requires significant research in system modeling, lateral (steering) control, longitudinal (speed and headway) control, and combined lateral and longitudinal control of vehicles. Generally, control systems in an AHS will rely on vehicle-to-vehicle communication, as information regarding velocity and acceleration of other vehicles, in particular lead vehicles in groups or platoons, will be utilized in individual vehicle controllers, e.g.[(8),(20),(21)] In addition, vehicle-to-roadside communication will be needed to establish nominal speed settings for the entire group of vehicles.

Lateral Control

A variety of sensors have been proposed for use in lateral control of vehicles in an AHS, including discrete magnetic sensors (a.k.a. magnetic nails), embedded wires, and vision systems. For more details on the sensors relevant to AHS, see chapter 4. Here, we will consider the lateral control laws themselves, with only minimal reference to the sensors required for position measurement.

Hessburg and Tomizuka[(22)] report on a fuzzy rule-based controller for lateral vehicle guidance. For an introduction to fuzzy set theory, the foundation of fuzzy rule-based control systems, see (23),(24). A fuzzy rule-based controller is a natural method of lateral control based on human-type reasoning. Advantages include flexibility in the choice of inputs and outputs, and on-line or off-line training capability. The intuitive nature of fuzzy inference rules allow a control designer to make justified control design decisions while incorporating a good set of safety rules.

Hessburg and Tomizuka focus on achieving good tracking for a variety of roadway curves over a range of cornering stiffnesses and longitudinal vehicle speeds, using fuzzy rules based on human drivers' experience and knowledge, as obtained using a survey, heuristic and engineering judgment, and dynamic considerations. In cases of high road curvature, roadway information encoded into the discrete magnetic markers (see chapter 4 and [25]) is used to provide feedforward steering action. Parameter robustness and integral action rules are included to improve performance for variations in vehicle speed and road condition, and to eliminate steady-state error due to external disturbances such as cross winds. The fuzzy controller is simulated to demonstrate its performance and to show improvements in performance when rules are added to combat variations in system parameters and external disturbances. Results were good, and current investigations are being conducted to incorporate yaw rate as an additional linguistic variable to the fuzzy rules. Comparison of the performance of this controller and a control theoretic technique is presented in (26).

An alternative approach using neural networks for sensing and lateral control is presented in (27). This approach concentrates the intelligence in the vehicle, using the visual sensing approach discussed in (28), which is reviewed in chapter 4. This has the advantage that no infrastructure modification is required, but adds considerable cost and complexity to each individual vehicle. The results in this study are simulated; the feasibility of this approach would be greatly enhanced through some form of field demonstration. Kornhauser presents a detailed analysis of the neural network controller that explicitly defines the safe operational range of the system, which relates to the degree of confidence in the system. This is an essential step in the design of such a critical real-world application. The authors of the study indicate that the computational requirements of the present configuration are not large, so that given a sophisticated real-time visual preprocessor, the system could be prototyped. The need for the visual preprocessor indicates that this system may not be cost-effective for production purposes.

A significant lateral vehicle control experimental study for a full-scale automobile (a 1988 Toyota Celica Turbo All-Trac) is presented in (29). In this reference, the IRRS discussed in chapter 4 is used to implement and compare two control algorithms: a frequency shaped linear quadratic (FSLQ) control law, and a simple PID controller. In both cases, a deterministic preview controller is added. Due to the space limitations of the test track, only identifying numbers were encoded into the roadway, and these numbers were used to reference into an on-board database containing roadway information. Two vehicle dynamic models are used: a complex six degree-of-freedom nonlinear vehicle model which includes tire-road interaction, wind force, and suspension, to represent the vehicle as realistically as possible; and a simple model obtained by linearizing the complex model and retaining only lateral and yaw motions. The controllers were designed using the simple model. Performance measurements are based on lateral deviation and lateral acceleration. The components of the system include the discrete roadway reference system, on-vehicle magnetic sensing system, computer control system, and a hydraulic steering actuator. Additional sensor and measurement systems include a lateral accelerometer and yaw rate sensor, steering angle measurement, vehicle speed, and an independent lateral measurement system to verify the overall system performance and calibrate the magnetic reference/sensing system. Tests were done at relatively low vehicle speeds ($\leq$ 60 km/h) in a variety of conditions: nominal conditions with dry road and standard tire pressure, low tire pressure, wet roads, offset magnetic markers, missing markers, and increased vehicle loads. The following conclusions are based on the component and overall system experiments:

- The IRRS cooperative lateral control system produces good control response. Using the road geometry information, preview control reduces tracking error, and improves ride quality.
- Accuracy of the lateral measurement provides adequate precision and is robust to vehicle speed variation up to 60 km/h.
- The FSLQ algorithm provides better ride comfort than the PID algorithm, although both perform satisfactorily.
- The system performs satisfactorily under nominal and non-ideal conditions. Test data and passenger perceptions indicate good ride quality even when the vehicle went through a 74 m radius curve at 50 km/h.

The test results indicate a need for additional development of the components and full-scale experiments under adverse conditions and at higher speeds. For further details of the experimental setup and results, see (29).

Chira-Chavala et al. [30] examine issues related to implementation of lateral control systems in existing transitways. They discuss one possible evolutionary path from "steering assistance information systems (SAIS)" which are essentially warning systems, through partially automated lane-keeping systems, to eventual fully automated lateral control systems which will take over the tasks of lane keeping, lane changing, merging, and diverging. The focus is on deployment of systems that use discrete magnetic markers as the roadway reference system. Candidate facilities for early deployment include high-occupancy-vehicle (HOV) lanes separated from the freeway main lanes by permanent barriers, with controlled access and egress. Such lanes are known as transitways. The study assesses the safety and traffic impacts of each of the incremental steps in this evolutionary deployment process, and identifies human factors issues as well as possible approaches for addressing these issues. The systems considered for deployment are based mainly on those studied at PATH. Capacity increases due to reductions in lane-width requirements are discussed, as well as the impacts on capital costs and feasibility of future HOV facility construction.

Along with significant impacts on system safety and performance, factors such as response oscillation, acceleration, and jerk will have important effects on rider comfort, and thus on public acceptance of automatic vehicle control. Hayafune and Yoshida[31] consider the compatibility of vehicle controllability and rider comfort. As noted by these authors, much attention has been given to collision avoidance, system stability, and system feasibility, while comfort of the vehicle occupants has been largely ignored. These authors include rider comfort as one of the goals of the control system design. They focus on comfortable lane changes under automatic lateral control, although comfortable longitudinal control without safe headway considerations is also briefly investigated. Two lane change situations are considered: normal smooth lane changes, and emergency lane changes. Initial experiments were done with five drivers of varying skill levels to determine typical human responses in these situations; measurements included steering angle, yaw rate, lateral acceleration, longitudinal velocity, and lateral velocity. The authors select lateral acceleration and lateral jerk as benchmarks of riding comfort. Experiments indicate that humans are more sensitive to lateral jerk than acceleration. Based on the experimental data, an oval region on the jerk vs. acceleration curve is identified as acceptable, and used as a specification in the design of the controller. The controller design uses a transfer function between the steering angle input and the vehicle lateral displacement. The parameters used in the transfer function represent an ordinary compact car. Based on Bode plots and experiments, it is shown that for input frequencies up to 0.5 Hz, lateral acceleration is proportional to the steering angle input, and lateral jerk is proportional to the steering angle velocity input. Simulation results for a six degree of freedom vehicle model including cornering force nonlinearities show that the lateral control scheme proposed in this paper achieves compatibility between comfort and controllability. Additional experiments were performed on a steer-by-wire and drive-by-wire test vehicle. These experiments validate the conclusions made in the simulation, and show that a similar approach can be applied for comfortable acceleration and deceleration during longitudinal control, although the conditions for comfort here are more stringent.

Longitudinal Control

Longitudinal control is an important aspect of the envisioned AHS. One of the major concepts in this area is platooning, which is a formation of traveling vehicles which maintain close spacing at highway speeds. Platooning may double or triple highway capacity without the application of lateral control.[32] The general concept of a platoon requires inter-vehicle communication links to provide velocity and possibly acceleration information for the lead vehicle to each of the follower vehicles, as well as velocity and acceleration of the immediately preceding vehicle in the platoon. Inter-vehicle communication aids the stability of the platoon formation, as shown in (33), as well as several other references. Communication issues are discussed in more detail in chapter 5. Longitudinal control also requires headway sensing to provide vehicle separation as an input to the control system; possible sensors here include radar and laser range finding systems. Sensors applicable in longitudinal control are reviewed in chapter 4.

The performance of longitudinal control depends on variations in the response of vehicles in a group. For instance, Sheikholeslam and Desoer(33) show that when all vehicles in a platoon are identical, deviations in successive vehicle spacings can be decreased from the front to the back of a platoon in a manner such that the deviations do not exhibit oscillatory behavior. In this reference, the authors present a nonlinear model for the vehicle dynamics, including the effects of wind gusts and gravity. They quickly reduce the model to a linear one by assuming a flat roadway with no wind gusts, and by linearizing the effects of air resistance using a Taylor expansion. A linear control law is proposed for each vehicle in the platoon; the control law utilizes lead vehicle velocity and acceleration, along with a measure of the deviation of the vehicle from its desired separation from the vehicle in front of it. The acceleration term was not used in (32). The use of the lead vehicle acceleration and velocity illustrates the requirement for vehicle-to-vehicle communication; this communication must occur at a high rate relative to the time constants of the vehicle dynamics, which should not be a problem with existing communications technology. The behavior of this model and control law is simulated, and the results show that deviations of each vehicle are small, on the order of 0.25 m maximum deviation and 0.02 m steady-state for a change in lead vehicle velocity from an initial speed of 17.9 m/s (40 mi/h) to a final 32.0 m/s (72 mi/h) over a period of about 4 sec. Robustness to communication delays and sensor noise are also shown.

In the case of a platoon of non-identical vehicles, the situation is more complex, as each vehicle's deviation is influenced by the deviations of all vehicles in front of it. Elimination of these dependencies requires solution of a system of linear algebraic equations with more equations than unknowns, so that in general the dependencies cannot be eliminated.(33) The effects of this dependency on vehicle response were not examined in this reference, but it is feasible that they will lead to instability and/or oscillation in vehicle spacing. This is a critical issue, as the dynamics of two vehicles of the same manufacturer, model, and year may actually be quite different in practice.

Frank, Liu, and Liang(21) explicitly consider the case of non-identical vehicles. In this paper, the authors consider mixed vehicles cooperating on a highway. The vehicle dynamic model is nearly identical to the nonlinear version presented in (33), with the addition of time delay and force saturation in the propulsion system. While wind gusts are included in the initial model presented here, they are once again quickly eliminated from the analysis. The control scheme presented here combines three nested control loops for speed regulation, vehicle spacing control, and speed synchronization.

The speed regulator is a Proportional-Integral-Derivative (PID) controller. The authors use knowledge of the vehicle parameters to design the PID gains to cancel some of the system dynamics; as such, robustness considerations will be important here. The gains are also functions of the desired steady-state speed of the group of vehicles. The space controller accounts for changes in platoon configuration at any time. To reduce velocity oscillations and enhance rider comfort, smooth transitions are desired. To provide this, the closed-loop gain for all frequency ranges is kept below one. Frank et al. use a proportional controller with a crossover frequency of 0.2 rad/s for the space controller. The speed synchronizer receives the lead vehicle velocity command over a communication link. The modeled saturation in the propulsion unit is not included in the analysis and design of the controller, but the authors set a soft limit on the controller output signal to avoid hitting the hard power limit. This modification does not affect system stability, but temporarily decreases system bandwidth and increases errors.

One possible vehicle spacing policy is based on individual vehicle performance and platoon speed, i.e. larger vehicles and higher speeds requires greater headway. As an alternative spacing policy, constant headway time can be used, as is done in this reference. The control scheme is simulated for a fifteen vehicle platoon consisting of three significantly different vehicle types. One parameter, the driving coefficient or gain of the propulsion system, is kept equivalent in all the vehicles, which may be due to the dependence of the speed regulator parameters on this value. The first simulation investigates gravitational disturbances for a six percent grade, in which case maximum speed drop is less than four percent, and spacing is regulated smoothly. The second simulation models response when a vehicle leaves the platoon; transients in the vehicle spacing are smooth, and are less than five m, with the obvious exception of the vehicle behind the exiting vehicle. Note that the transients are greater than the one m intervehicle spacing proposed in other references, which raises serious doubts about the safety of spacings as low as one m. The final simulation is for a sudden decrease in the speed command; here again, the responses are good. Inclusion of vehicles with varying performance characteristics is an important aspect of this paper. Some of the important conclusions of this paper are:

- Platoon size must be limited to around 15 vehicles or less, and larger headways are required due to vehicle performance variations.
- Nonlinearities significantly affect the response of the platoon, and may determine safe headway. This is a critical conclusion, as many papers ignore the nonlinearities present in the real system in order to simplify the analysis.
- Emergency situations need further investigation before proper sensor specifications can be set. Again this is an important conclusion, as it appears that the current technology can provide adequate system performance under normal operating conditions, but it is unclear that the systems considered to date are sufficient under severe emergency situations. In particular, if a number of factors contribute to an emergency simultaneously, it is difficult to ensure safe degradation of the system performance. This indicates a need for more work in the area of fault tolerant design, as discussed in chapter 7 in this review.

The previous references require communication of lead vehicle information in longitudinal control implementation. Sheikholeslam and Desoer[34] provide a system-level study of a longitudinal controller that does not require this information. Such a controller is important given the possible loss of communication with the lead vehicle. The design objectives are formulated as a constrained optimization problem which is then solved to obtain the longitudinal control law without communication. Performance of this controller is compared with the standard controller using communication. Results show that without communication, performance is degraded, but the degradation is not "catastrophic." Comparisons of the controllers with and without communications show the following: implementation of the control without communications is less expensive; deviations in vehicle spacings increase from one vehicle to the next as one goes down the platoon; acceleration demands on the tail vehicle of the platoon are higher without communication; and control without communication does not suffer from the delays inherent when communications are used. Thus, there are distinct advantages to each approach. Sheikholeslam and Desoer do not propose this controller as a replacement to those that use communications; rather, this controller constitutes a backup system in the event that communications are lost.

Sheikholeslam and Desoer[35],[36] also discuss applications of decentralized adaptive control to lateral and longitudinal vehicle control.[35] provides sufficient conditions on the inputs and the parameter errors under which one can design a suitable local control law for the interconnection of nonlinear dynamic systems, such as in the longitudinal and lateral control of a platoon of vehicles. The authors show it is possible to meet the design objectives using a local, nonlinear adaptive control. The local nature of the proposed controller reduces computational costs while increasing reliability and flexibility; the adaptive property increases the robustness with respect to parameter uncertainty. In (36), another decentralized adaptive controller is proposed. This control law monotonically decreases vehicle spacing as one moves down the platoon. More significantly, deviations of the system states from equilibrium are bounded independently of parameter errors.

The above papers present simulation results for a platoon of vehicles using linear or nonlinear models for the vehicles. While this is an important aspect of the AHS research, in order for longitudinal control to be implemented in a real system, it is critical to test the designed control systems on real vehicles. Chang et al.[20] present experimental results for a vehicle platoon control system with a leader vehicle and a single follower vehicle. The system presented uses:

- Two Ford Lincoln Town Cars.
- 80386-based personal computers.
- Radar systems from VORAD (Vehicular Onboard Radar) Systems, Inc.
- Digital radio transceivers and communication interface boards.

- Data acquisition boards.
- Sensors to measure speed, acceleration, throttle angle, brake pressure, engine speed, engine intake manifold air pressure and temperature.
- Throttle and brake actuators.
- Data storage systems.

This system consists of essentially existing technology and components, which strengthens any conclusions regarding the feasibility of future application on the roadway. Cellular phone antennas and radio links using spread-spectrum digital radio transceivers provide inter-vehicle communication. The lead vehicle sends its time clock, speed, and acceleration to the following vehicle. This information is used by the follower vehicle control system to calculate throttle or brake commands. In this paper, only throttle actuation was used. Note that this initial experiment investigates only a two-car platoon. The control uses a modified sliding control method to compensate for the inherent nonlinearities in the automobile plant. Such controllers provide robustness to parameter uncertainties as well.(37) Throttle actuation is via a DC servomotor connected to the butterfly valve on the engine. The slow response of this throttle actuator is identified as one of the problem areas in the current experiment. Vehicle headway and closing rate between vehicles is provided by the radar signal.(38) As the current system uses the Doppler effect, absolute distance information cannot be obtained when the closing rate is very low. To overcome this, distance is estimated by integrating the closing rate signal; this approach cannot be used by itself in a practical situation, since the estimate will drift over time. The sensor and controller sampling time is 50 ms. A real-time operating system is used on the PC to perform control law calculation, communication, data acquisition, data transfer, data storage, and user interface operations. Additional routines are required for error handling, and as a final fail-safe feature the driver of the vehicle can override the automatic control at any time by applying the brake pedal, as in a normal cruise control system. Experiments are shown with the lead vehicle manually controlled and the follower vehicle automatically controlled in the longitudinal direction. Tests at speeds of 10 m/s and 25 m/s with acceleration and deceleration of the lead vehicle show good responses, although there is significant oscillation in the response of the follower vehicle, attributed to the previously mentioned slow throttle actuator. The slow-speed DC motor was replaced with a high-speed stepper motor, and the responses were significantly improved. These initial experiments lend credence to the eventual application of longitudinal control in an AHS. Experiments with more cars and on real highways are mentioned as future plans in the conclusion of this reference.

Combined Longitudinal & Lateral Control

Much of the control research to date has focused primarily on either lateral or longitudinal control, with little emphasis on combined systems. As the planned AHS of the future will not exhibit this kind of separation, research on an overall automated driving system combining both lateral and longitudinal control is vital. Investigations should include any coupling effects between the modes of control, as done in (39). This section presents some of the research that has been done in this area.

Varaiya[8] gives a structure for describing IVHS functions and their relation to driver decisions, sketches a fully automated IVHS system, and presents a four-layer hierarchical control architecture which breaks the design into more manageable units. After this, Varaiya lists the hardware needed to support this architecture, and describes some of the experimental work being done in this area in the PATH program at UC Berkeley.

The IVHS functions are divided into pre-trip, in-trip, and post-trip phases. Here the focus is on the in-trip phase: route choice, path planning, maneuvering, and regulation. Route choice can reduce travel time, and can be aided by both off-line information, such as maps, and on-line information, such as incidents or recurring congestion. Automating path planning can lead to additional improvements if instantaneous speeds are modified to avoid congestion. Maneuvering refers to the manner in which drivers change lanes, including entry and exit from the highway; this requires coordination of movement of neighboring vehicles to avoid accidents and congestion. Partially automated maneuvering can improve this function using a collision warning signal or a collision avoidance system to temporarily preempts driver action. Regulation concerns how the driver modifies speed and keeps in a lane. Regulation is the area of major focus of most IVHS research in the area of vehicle control.

Varaiya next illustrates the effect of platooning on vehicle capacity. Platooning, as mentioned before, refers to organizing traffic in tightly spaced groups. Varaiya gives a formula for calculating capacity C if traffic is organized into n car platoons:

$$C = \frac{n}{ns + (n-1)d + D} v \qquad (1)$$

where d is intra-platoon spacing, D is inter-platoon spacing, s is vehicle length, v is steady-state speed in m/min, and capacity C is measured in vehicles/lane/min.

Varaiya next gives a conceptual overview of a network of automated, interconnected highways. First, a vehicle route is selected once its destination is known. This route consists of a connected sequence of highway segments. As a vehicle travels along a given highway, it announces its designated exit gate for that segment of its route. In response, the system plans a path by which the vehicle can eventually reach the desired exit, where it may move onto another segment of highway, based on the above overall route. Once the paths along the highway are assigned, the vehicle creates a real-time plan approximating this path, and executes a trajectory conforming to the plan.

At this point, Varaiya describes a four-layer hierarchical control architecture to achieve this vision of an IVHS network. This architecture is summarized briefly here, but is discussed further in chapter 6. The layers of the architecture, starting at the top, are: network, link, planning, and regulation. The network layer assigns a route to each vehicle as it enters the system. The link layer assigns each vehicle a path which balances traffic for all lanes and assigns a target speed for each section of highway to smooth flow, prevent congestion, and adapt to incidents. The link layer may also assign the target platoon size. The planning and regulation layers exist in each individual vehicle. The planning layer creates a plan which approximates the desired path. The regulation layer controls the vehicle trajectory so that it conforms to this plan. Below the regulation layer, the physical layer provides sensor data and responds actuator signals.(40) The regulation layer must implement five feedback control laws in order to accomplish the tasks selected by the planning layer:

- Follower spacing control, typically decomposed into longitudinal and lateral control.
- Leader tracking target speed.
- Accelerate to merge.
- Decelerate to split.
- Free agent change lane.

As noted by Varaiya,(8) communication between the planning and regulation layers is fairly simple: the planning layer sends a command, and the regulation layer returns a reply once it successfully completes the command. A richer interface may be required: the planning layer could pass multiple parameters to the regulation layer, which could then return 'success' or various kinds of 'errors' and 'exceptions'. Varaiya indicates that the theory of control of such systems is not yet developed. In addition, he notes the absence of published research concerning the last three types of control laws in the regulation layer. Finally, he identifies a need for research as to how the regulation layer should gracefully switch from one control law to another. These represent open research issues whose solution may be vital to the implementation of a full AHS.

The design in(8) is a balance between a fully centralized control system in which a single controller determines the position of every vehicle, and a system in which every vehicle is viewed as autonomous, navigating in an unstructured environment. Through the platooning concept, the weaknesses of both of these approaches are avoided as most of the information and control is distributed among individual vehicles, and uncertainties are reduced by coordinating the movement of neighboring vehicles.

The control design presented in[8] needs hardware both in the infrastructure and the vehicle. Roadside monitors will measure traffic flow and speed, and the link layer will calculate vehicle paths based on this information. Such measurements can be made with loop detectors, ultrasonic sensors, or vision systems. Information may be communicated by infra-red beacons, variable message signs, or broadcast radio. The vehicles need a longitudinal sensor to measure distance and relative speed to the vehicle in front of it. Such sensors may be based on radar, ultrasound, or vision. To facilitate lane changes, the vehicle must have sensors that locate vehicles on the side within a range of about 30 m. Varaiya does not mention any form of sensing for lateral control during follower spacing control, but clearly this will be required for the system described. To facilitate planning and regulation, communications between vehicles may use broadcast or cellular radio, infrared beacons, or communication through a roadside station. For companies that provide such IVHS-related products, see (41). For more details on the design of this controller, see (8).

Further details of the planning layer (referred to here as the platoon layer) of this architecture can be found in (42). The platoon layer's plan can always be constructed as a sequence of three elementary maneuvers called merge, split, and change lane. To accomplish these maneuvers safely, the platoon layer controller coordinates its actions with those of its neighbors. The protocol for negotiation between neighboring vehicles when planning one of these elemental maneuvers is specified in two stages. In the first stage, the protocol is described as an informal state machine, with one machine per vehicle. In the second stage, these state machines are specified in a formal language called COSPAN, short for coordination-specification analysis, which is then used to verify that the protocol machines work correctly. Also specified are path planning supervisor machines which invoke the elementary protocols to produce the correct sequence of maneuvers conforming to the assigned path. To simplify the overall design, a platoon is allowed to perform only one maneuver at a time. This restriction means that the machines must be coordinated so that when a platoon receives two or more maneuver requests, one and only one request is granted. A coordination method that grants at least one request is said to be deadlock-free, and one in which at most one request is granted is said to achieve mutual exclusion. Here, deadlock is prevented by enforcing a priority among requests, and mutual exclusion is achieved by using a single busy flag for all machines. Hsu et al.[42] present the formal specification and verification for each of the elementary platoon maneuvers. Formal specification and verification is important in system development, as it provides a method of detecting and correcting design mistakes in a complex system.[43]

Sheikholeslam and Desoer[39] provide a system-level study of the combined longitudinal and lateral control of a platoon of vehicles. The authors developed detailed kinematic and combined longitudinal and lateral dynamic models of each vehicle in a platoon, including nonlinearities. A nonlinear control law is presented which maintains a close spacing between successive vehicles and keeps all vehicles close to the center of the lane while following a lead vehicle on a curved highway. The proposed controller is similar to the computed-torque control laws used in robotics, as it attempts to cancel nonlinearities due to road geometry, engine dynamics, and longitudinal and lateral vehicle dynamics. With exact cancellation, the closed-loop dynamics are exponentially stable. Note that this requires either estimates or measurements of the nonlinearities to be cancelled. The measurements required include: longitudinal and lateral velocity and acceleration measurements, yaw rate, front steering angle, lateral deviation, and headway deviation. As in most other systems, communication of the lead vehicle's velocity and acceleration is required for each of the follower vehicles. Simulation results show that the proposed control law performs well for roads with suitably large radius of curvature under nominal operation.

Chapter 4

Sensors & Vehicles

Sensor technology will have a critical role in AHS operation and safety. Sensors will be needed for lateral position, longitudinal speed, yaw rate, headway, etc. for vehicle control. Other sensors will be required to provide flow and incident information for management purposes. If one considers CVO, then additional sensors are required for automatic vehicle identification, weigh-in-motion, etc. In this chapter, the sensor issues related to control are reviewed. Sensors for traffic management are also reviewed, but in a more cursory manner. Finally, alternative vehicle types and their impact on the AHS scenario are discussed

Sensors

A variety of sensors have been proposed for vehicle position sensing in an AHS. These sensors will play a critical part in an AHS, especially in the area of control. Some of the technologies proposed for lateral control include wire guiding, discrete magnetic markers (a.k.a. "magnetic nails"), and vehicle-based vision systems. Each of these systems has certain advantages, but the trends in the IVHS community indicate a bias away from wire guiding. Wire guiding has been demonstrated as technically feasible on test tracks,[(44),(45)] but there are many reasons that such a system is not feasible in practice; mainly, the approach requires significant additional capital investment in highway infrastructure. Use of a wire guiding system requires embedding a cable along each highway lane, so that a significant portion of the "intelligence" of the AHS is built into the infrastructure. Such a system must be fully deployed before automated vehicles can operate, and the vehicles can only operate in areas where deployment occurs.[(28)] This means that there is really no evolutionary path for such a system. An evolutionary approach to implementation of AHS is viewed as a critical aspect of any proposed system. In addition, major concerns have been expressed about the physical reliability of a wire-guided system,[(3)] particularly regarding consequences when a wire breaks. This is an important issue in terms of both safety and maintainability. Vision-based sensing has shown significant promise in recent years, as shown for example in the CMU NavLab experiments, but may be prohibitively expensive. Because of these difficult issues, recent work has moved in the direction of some form of discrete marker system.

Many sensing technologies have been proposed, simulated, and/or implemented for vehicle lateral control, including electromagnetic, magnetic, optical, radar, acoustic, and video sensing techniques. Most systems using these techniques can obtain relatively accurate measurement of a vehicle's deviation from the lane centerline. However, recent studies have indicated that predictive action is helpful, if not necessary, in many automated driving situations, particularly in areas of higher road curvature. As such, a position sensor system which can also provide information about the upcoming road characteristics is quite useful.(25)

The use of discrete markers(46) is an area that has received much attention and shows great promise for lateral control sensing and other IVHS functions, as the discrete markers can be used to store road characteristics, which allows predictive action in the lateral controller. In this approach, discrete markers are embedded in the center of the lane to designate the desired vehicle path. Markers types that have been considered include optical reflectors, magnetic markers, and other objects capable of storing at least one bit of information. Experiments and research at PATH have focused on the use of permanent magnetic markers, here and in the literature often referred to as magnetic nails. There are several advantages in the use of discrete magnetic markers. Magnetic markers are passive devices that produce a magnetic field which is relatively insensitive to environmental conditions. The life cycle of permanent magnets is comparable to that of highways, so they should not need any maintenance once they are installed. Finally, such a sensor system can be installed in existing highway infrastructure, providing an evolutionary path to an eventual AHS. This form of discrete marker system possesses both sensing and communications capability. Vehicles equipped with a magnetic field sensor can sense their distance from the centerline of the lane, and use this as an error signal in a lateral feedback control loop. The magnetic sensors, Hall-effect magnetometer probes, sample both the vertical and horizontal components of the field, and an algorithm has been developed to ensure that the sensor's lateral measurement is independent of the vehicle's vertical motion.(25) This fixed reference system can also provide an accurate estimate of the vehicle longitudinal speed. Additionally, information can be conveyed from the infrastructure to the vehicle by using the magnetic poles as binary digits. In this way, a sequence of markers can form a digital "word" that conveys information about curvature, access, egress, highway number, number of lanes, etc. Because of the ability of this system to store and convey information, the authors refer to it as an Intelligent Roadway Reference System (IRRS).

Zhang et al.(46) next investigate IVHS information needs and information capacity of an IRRS. They divide IVHS information into dynamic and static. Static refers to time independent information, such as roadway characteristics. Dynamic, i.e. time-dependent, information includes state information of the controlled vehicle, information on adjacent vehicles, incident information, etc. The IRRS will be capable of providing mainly static information, although it can provide vehicle lateral position and longitudinal speed, and can also be used to help coordinate certain dynamic information. The static information needed by an IVHS which may be encoded by an IRRS includes:

- Road information: geometry, access, ending point of automated lane, highway number, number of lanes, lane width.
- Position information: mileage post, lane number.
- Traffic sign information: stop signs, yield signs.
- Other information: rest areas, etc.

An important factor in an IRRS is an efficient representation method to decrease the number of bits needed, so that information is conveyed using minimal roadway space. Zhang et al. discuss two approaches: a full roadway information source in which all data is encoded in the road, and a cooperative IRRS in which indexing information is encoded in the road, and this information is used to reference into an in-vehicle information source, such as a roadway database. Clearly, each of these approaches has associated advantages and disadvantages in terms of road bits and vehicle intelligence required. The authors consider a typical example curve on a real roadway, and shows that very precise road characteristic information can be encoded in a space of about 50 m using a marker separation of 1 m. This space includes necessary header and error correction code, which will be critical for fault tolerance and error recovery.

The use of vision for lateral vehicle control has been discussed in a number of papers. There are several drawbacks to this approach, including processing required and variable performance of vision systems under poor lighting and weather conditions. Kornhauser(28) presents work on a flexible simulation environment for constructing, training, and testing a variety of neural network control architectures for closed-loop vision-based lateral control. The simulator was developed on a Silicon Graphics Iris 4D system, and is composed of five major modules: road design, vehicle dynamics, image processing, neural network design and training, and autonomous driving simulation. According to Kornhauser, neural networks may be applicable in vision-based automatic lateral control because they are good classifiers of seemingly unrelated data. Correlating the driver's view image with steering decisions is an approach to automated driving which requires a relationship between image data and physical parameters such as yaw angle and displacement from the lane centerline. One can do this with a neural network, but the better approach is to "train" the network to relate the image to the steering angle. The neural network controller designs considered in(28) are open-loop systems in which the image is input and the steering command is output, and an alternative design in which the controller determines a trajectory over the next n time steps, and feeds back future values of that trajectory. The input is then the current image and a feedback of the anticipated steering commands for time steps two through n, which provides some memory of previous views and smooths responses to image disturbances. The author considers two neural network structures: standard back-propagation, and the Adaptive Resonance Theory (ART) architecture of Carpenter and Grossberg.[(47),(48)] Image data is preprocessed to extract edges, which then form a reduced input space to the neural network, which cannot handle the amount of pixel data in the raw image. The data representation is further reduced using *a priori* information about anticipated road edge behavior and a simple "stepping stone" representation, a form of chain code.[(49)] The network is trained, i.e. the values of the coefficients are set, using a set of input images and output steering commands. Training is done using a human teacher approach, wherein a human operator views the simulated roadway and steers the vehicle toward the centerline. The instantaneous offset, yaw angle, and steering angle are stored, and are later used as the benchmark to train the neural network. Based on intermediate results, Kornhauser prefers the ART approach over back-propagation, as back-propagation tends to forget previous training trials. However, at the time this reference appeared, successful training of an ART network had not yet been achieved. Additional tests are planned by the Kornhauser. Further application of this system to the lateral control of a simulated autonomous road vehicle is presented in (27), which is discussed in chapter 3. Performance of the system is robust with respect to initial vehicle position and heading, vehicle velocity, road curvature, and temporal update interval.

Several systems have been proposed for headway sensing for use in either driver warning systems or longitudinal control. Chang[(20)] presents experimental results for a longitudinal control experiment using front-mounted radar. The main drawback of this system is that it uses the Doppler effect, so that absolute distance information cannot be obtained when closing rates between vehicles are low. Microwave radar sensors perform very well in fog, heavy rain, and other low visibility conditions, but they are prohibitively expensive.[(50)] In this reference, the authors propose a laser radar system using a laser diode. This is a much cheaper system, although it does not handle low visibility conditions very well. Such a system can be quite effective in the role of preventing serious accidents. The system works by measuring the time for the laser beam to travel to the vehicle ahead and reflect back, which allows the distance to be calculated. Within a few dozen meters, the rear panel of the vehicle ahead provides sufficient reflectivity for the laser, but beyond that distance a retro-reflector must be used. The unit provides a continuous display of the distance to objects ahead, and when a dangerous situation arises, sounds an audio warning. Fail-safe features of this unit include a filter to eliminate signals received from small particles, a dust detector to alert the driver when the lens dust cover is too dirty, and internal system checks. Such measures are important in any sensing system used in AHS, as it is important to know when sensors are functioning reliably; this approach will provide higher levels of safety as well as public confidence. The system has provisions to reduce the number of false alarms: at low speeds, the sensor is disabled to avoid excessive warnings due to congestion; simple repetitive patterns are identified and ignored to avoid warnings when traversing a curve; and if the relative speed sensed is greater than the sensing vehicle's speed, the system assumes that this is due to detection of an oncoming vehicle in the opposite lane, again avoiding a false warning. The issue of false alarms is a very important consideration in AHS, as excess false alarms will lead to public rejection of the system, as well as failure of the driver to believe in the system when the alarms are not false. This is a difficult area, as it is also critical to identify all dangerous situations and provide warnings. Satisfying both criteria constitutes a fine balancing act. Due to the low cost of the components and the provision for suppression of false alarms, the system presented in[50] appears to be a practical and effective system.

ATMS, an important component of an AHS, requires reliable, robust, and easily maintained sensors to detect traffic stream characteristics. Labell et al.[51] discuss current sensing technology. One widely used devices is the inductive loop detector (ILD), along with other detectors embedded in the pavement, such as magnetic detectors and magnetometers. These devices exhibit high failure rates resulting from incorrect installation, poor maintenance, pavement failures, and unrelated maintenance work. Installation and repair of such embedded devices requires potentially hazardous lane closures, which adds to congestion. Finally, there is some concern about the effects on pavement integrity when using embedded sensors.

Alternative detectors are discussed in (51). These technologies can be installed and maintained without lane closures, and provide the same data, with higher reliability. Infra-red detectors have been tested in Texas and California; ultrasonic detectors are widely used in Japan; radar detectors have been used in Germany for freeway surveillance; microwave detectors are commonly used in England at pedestrian crossings; and image processing systems are being developed in the United States, Europe, Australia, and Japan. For references and further discussion on these devices, see (51).

Vehicles

Here, we will focus specifically on vehicle research as it impacts AHS implementation and overall highway infrastructure. Clearly, much of the work in sensors and other areas could be included, but specific research in these areas has been discussed elsewhere in this review.

The so-called "lean vehicle" is one concept which would have a major impact on AHS implementation and highway infrastructure.[52] For an overview of the lean vehicle concept and general discussion of various benefits, see that reference. Here, we will highlight the issues that are most relevant to AHS infrastructure. One criterion for a lean vehicle is a low tare (empty) weight relative to work. Reduced vehicle weight (and presumably size) is of great interest for AHS application. The example lean vehicle considered in this reference is the GM Lean Machine, which is about 3 m long, 1 m wide, with a mass of about 200 kg. For an overview of the Lean Machine development and driving characteristics, see.[53] Here, the characteristics of reduced weight and size will have the most impact on an AHS. One block to transition of current commercial and private fleets to lean vehicles is the massive existing infrastructure that is designed for heavy vehicles. However, when considering a radical new system such as an AHS, the benefits of design for, or at least provisions for, lean vehicles should not be overlooked. As Garrison and Pitstick put it, "IVHS technologies might be used as building blocks for a lean vehicle system." These authors discuss several benefits of lean vehicles for parking, and present alternatives to the currently accepted parking concepts once lean vehicles are introduced; such benefits are critical in certain urban areas. However, the major interest here is in how lean vehicles could be incorporated into an AHS concept.

By designing for the presence of lean vehicles from scratch, it is possible to devise facilities that take advantage of the small size and performance of these vehicles. One major benefit would be higher capacity of roadways under various conditions. Based merely on a decrease in the length of the vehicle, an increase in capacity of as much as 18 percent is possible with lean vehicles.[52] Longitudinal control can be used to reduce headways between the vehicles for even greater capacity increases. Estimates show that a 1.8 m wide lane should be sufficient for operation of a lean vehicle at most speeds, so that it will be quite possible to drive two lean vehicles side-by-side in one standard 3.6 m lane. Here, use of lateral control could allow side-by-side driving in bottlenecks where lateral spacing is limited, presenting an opportunity for introducing IVHS technologies into a specific market niche. Capacity gains due to the use of lean vehicles depend on the proportion of lean vehicles to standard vehicles. In the extreme case of a stream of all lean vehicles of the size of the GM Lean Machine, the capacity would be more than double that of a stream of all standard vehicles.

The facilities which can benefit most by application of lean vehicles are arterials and freeways. Bottleneck areas, such as bridges, tunnels, and viaducts could be the first areas of application of special lean vehicle lanes. Potential, but expensive, solutions include stacked lanes in tunnels and outrigger lanes on viaducts and bridges. These solutions are possible due to the reduced size and weight of the lean vehicles, so that, for example, lightweight outrigger structures can be cantilevered from existing structures. It is in such areas that innovative application of advanced highway construction and maintenance technologies can lead to reduced overall system cost. Some existing bridges, such as the Golden Gate Bridge in San Francisco, California, have room within the structure beneath the roadway which could be used for special lean vehicle lanes, which may be less expensive than an outrigger lane solution. In addition, existing roadway shoulders, which are not strong enough for standard vehicle traffic, should be more than sufficient to support the lighter lean vehicle traffic, so that investment in additional infrastructure for support of lean machines could be minimal. Another option is to construct elevated exclusive lean vehicle viaducts over existing roadways. Again, this option appears expensive, but possible application of light-weight prefabricated structures could reduce this cost. Standardized structures could enable economies of scale in the production of road facilities. This is a concept that should be utilized more in general roadway construction design. For more information on the impacts of lean vehicles on an AHS, see (52),(54),(55).

Chapter 5

Communications

Reference[5] considers field trials related to road-vehicle communications (RVC). RVC is a critical aspect of AHS. Vehicles need to be identified, speeds must be communicated to platoon leaders, actions need to be coordinated, and traffic flow must be managed from a high level. All of this indicates a strong need for RVC. In addition, there will be a need for vehicle-vehicle communication. For example, in a platoon, the velocity and acceleration information of the lead vehicle must be communicated to each of the follower vehicles in order for good overall performance, and maneuver requests from follower vehicles must be communicated to the leader. Additionally, coordination between groups of vehicles and between individual vehicles requires some level of vehicle-vehicle communication.

One can consider the ranging device, whether microwave radar or laser range finder, used in longitudinal control to be a simple form of communication. This type of system can be used for collision warning or for complete longitudinal control of headway. More precise control can be obtained using full duplex communication, so that lead vehicle information can be communicated to the follower vehicles. Networking represents a higher level of communication, in which traffic and hazard information detected by one group of vehicles can be communicated to other vehicles approaching a site.

There are a variety of methods for road-vehicle communications.[5] For example, simple inductive loops can be used for communication with one vehicle at a time, possibly for use in vehicle identification. Line-of-sight (LOS) transmission can be achieved with infra-red signals between a roadside beacon and a detector on the vehicle. Such a system may be able to provide an estimate of vehicle position, in addition to communicating other information. Another LOS approach uses microwave beams. This form of transmission has been used for communication in platooning tests. For general roadside-to-vehicle communication, radio frequency transmission may be best. Highway Advisory Radio (HAR) is a typical example. Cellular radio is useful for two-way communication. Wide area communication can be achieved with conventional FM broadcasting, as in the Traffic Message Channel

(TMC) standard being drawn up within the European DRIVE program. For areas which are relatively insensitive to cost, satellite communication systems can be used for wide area communication.

Chapter 6

System Architecture

The system architecture selected for deployment of an AHS is a very important issue. The architecture will have serious implications regarding performance, capacity, robustness, and safety. While this is a critical issue, it appears that little work has been done regarding a complete IVHS or AHS system architecture. The main responsibility in the U.S. for coordinating work in this area lies with the IVHS AMERICA System Architecture Group.[56]

Varaiya and Shladover[40] present an overall system architecture combining ATMS, ATIS, and AVCS. The architectures presented consist of a five layer hierarchy for ATMS and ATIS, and a separate five layer hierarchy for AVCS. These architectures are parallel and compatible, so that work can be done on the easier (ATMS/ATIS) architecture in a manner that allows extensions to the features of AVCS once the details of a fully automated system are determined. While the concept of an evolutionary deployment is explicitly omitted from (40), this parallelism and extensibility of the architectures appears to leave such a path open. The tasks to be accomplished in each architecture are spread across four dimensions: function   ranges from regulating and stabilizing individual vehicles to adapting traffic flows to changing demands; time scale   varies from under 1 sec. for vehicle control to hours for network flow optimization; spatial scope   varies from an individual vehicle to the entire network; information span   ranges from information regarding a single vehicle to information that spans the entire system. The hierarchical formulation yields a structured, modular approach for the following reasons: it resolves the four dimensions of difference in tasks; each layer presents a standard reference model to the layer above it, so that the reference model serves as an open systems architecture for IVHS; and communications takes place only between adjacent layers and between peer layers, which aids in specifying the communications required to for the system. The work presented here focuses on full automation, including platooning for high capacity improvements. However, the possibility of partial automation, in which the driver remains in control of the vehicle, with the system providing route and path planning, is also considered; the impacts of partial automation on the proposed architecture are discussed. The organization of traffic is presented; further details of this can be found in (8),(42), and are also discussed in chapter 3. The management and control tasks are divided into the following four areas, ranging from system-wide impact down to a single vehicle: route flow and control, path and congestion control, trajectory and path planning, and feedback control. The overall system architecture is discussed next. The hierarchical structure resolves the differences in dimensions of the various tasks; moving down the hierarchy, frequency of decisions increases, spatial scope reduces, and information span is more localized. The architecture is decentralized: each control task's logic is placed where the relevant information is available. This is an important issue, as previous systems, such as the Japanese Computer-controlled Vehicle System, have failed in part because they were overly centralized.[11] A decentralized approach can increase robustness, minimize design change impacts, and reduce communication cost and delay. Decisions at each layer of the hierarchy are based on either commands from above or information from below, which facilitates modular design. The importance of an open systems architecture is emphasized here. The analogy to current computer networks illustrates the benefits of an open architecture: equipment conforming to standards will work with any other conforming equipment, although the equipment designs may be proprietary and different. With an open IVHS architecture, similar benefits may be achieved. Without one, equipment on different vehicles on different highways will be incompatible, more expensive, and less productive.[40] Development of such an open systems architecture will require the active participation of at least transportation agencies, automobile manufacturers, and control and communications equipment developers. IVHS AMERICA appears to be a good forum for coordination of such activities.

An interesting aspect in the consideration of AHS system architectures is the impact of alternative vehicle types on the overall architecture. Pitstick and Garrison[55] consider the effects of the use of lean vehicles on the system. Potential impacts of these vehicles on the AHS architecture are discussed in chapter 4.

Hall[57] discusses the time benefits and capacity increases available through the application of highway automation. In this reference, Hall addresses various forms of travel delay, and how they can be reduced through automation. The relevance to system architecture is in the various highway automation scenarios presented: the mini-highway, the bottleneck bridge, the high-speed highway, the express highway, and the automated corridor. Hall discusses each of these scenarios in terms of their potential application and time benefits. None of these scenarios constitute a system architecture in the sense of (40), but they do yield interesting concepts for consideration in the design of an AHS.

Tsao et al.[58] discuss design options for a fully automated AHS, and propose six AHS operating scenarios featuring variations in design options critical to the human factors of AHS operations. Four dimensions of an AHS design are identified and discussed: separation of traffic; transitions between manual and automated driving;

normal automated driving; and failures and emergency responses. There are several design issues within each of these areas; for further details, see (58). Once these dimensions were identified, six possible scenarios were selected, based on their potential impacts on human factors issues: segregated highway (without mixing automated and manual traffic) with platooning; segregated highway with free-agent vehicle-following; shared highway (with dedicated automated lanes) with barriers and platooning; shared highway with barriers and free-agent vehicle-following; shared highway without barriers under platooning; and shared highway without barriers under free-agent vehicle-following. These scenarios provide a useful framework in designing the physical layout of an AHS.

Chapter 7

Safety & Fault Tolerance

Without question, the most important issues that need to be resolved in IVHS relate to safety. At this time solutions exist or can be found for most of the technical problems in vehicle control, traffic management, information systems, and communications. However, unless the safety of the overall system can be verified, the envisioned Automated Highway System will never be deployed. Safety and fault tolerance issues have been investigated by a number of IVHS researchers, but this appears to be an area where much additional work is needed.

Reference[56] is an excellent starting point for any IVHS researcher concerned with safety and human factors, and all IVHS researchers should fundamentally be concerned with safety, whether the systems they are studying are designed specifically to improve safety or not. The effects, positive or negative, of any IVHS technology on safety must be seriously studied and documented before that technology can be considered for deployment. This reference considers the four functional areas first identified by Mobility 2000: ATMS, ATIS, CVO, and AVCS. The groups that studied each area identify the safety and human factors issues relating to it, and make recommendations for continuing work needed for safe development of IVHS systems. In general, more questions are raised than answered, and further detailed study is required to assess the safety of all areas of IVHS, but this reference is an excellent foundation, providing a framework for future work. Readers interested in ATMS, ATIS, and CVO safety issues should refer to (56): we will focus on the conclusions and questions raised regarding AVCS safety, as this forms the heart of an AHS.

The AVCS group, led by A. Hitchcock, raises many interesting issues regarding safety and human factors. The group notes that focusing on a single aspect of AVCS, such as just the technology, will obscure important safety issues. Other viewpoints, including the environments in which devices operate, the drivers, the behavior the devices influence, and the safety issues and accidents that they address, yield a variety of perspectives and aid in identifying safety and human factors issues. The group considers safety issues for a variety of AVCS technologies;

for their views, see (56). In the specific area of Automated Highway System the group notes that in other branches of engineering, such as nuclear, chemical, and aerospace, techniques have been developed which enable the design of safety-critical systems to be approached in a systematic way. Variations of these techniques, known by such names as "hazard analysis," "hazard and operability study," etc., are applicable in IVHS. The importance of requirements specifications is emphasized, as well as the need for a system architecture which is modular, with safety-critical systems clearly defined, and with precisely defined interfaces between components.

One issue which is often overlooked by researchers working on individual systems, deemed safe in isolation, is the possibility of undesirable interaction of systems. It is well known in the control literature that two systems that are stable in isolation may become unstable when coupled to each other.[(59),(60)] An example cited in[(56)] concerns two devices which try to maintain vehicles at constant lateral spacing using side range sensing. If the devices (including the vehicles) have different dynamics, it is possible that one or both of the vehicles may become unstable, possibly resulting in a collision. Such interactions are difficult to anticipate, and certainly some interactions will not be considered until they are noticed in practice. The technique of configuration management, used in aerospace, is recommended as a partial solution to this problem. The current authors are investigating the application of passivity concepts to deal with such situations.

Two general technical policies regarding safety are proposed in[(56)] for all future studies:

- Identify safety-critical subsystems, and apply formal design, verification, and validation techniques. These designs should be modular, with rigorously defined interfaces and access protocols.
- When considering a full AHS, hazard analysis procedures should be applied. Protocols and procedures must be defined in a standard manner.

Mathews[(61)] identifies a "safety conflict": cars have become safer, partly in response to Government and industry standards, but due to human error, fatality levels remain high. This reference reviews factors that create safety conflicts, identifies and forecasts technology challenges that lie ahead in the effort to aid vehicle operators to significantly reduce collisions that cause deaths and serious injuries, and conveys a vision of the necessary improvements, i.e. a road map of the technology progression and timetable required to accomplish the implementation of collision avoidance in vehicles. The author concludes that the ultimate solution to accomplish a major reduction in deaths and injuries lies in technology, essentially the AHS vision.

Furukawa[(62)] approaches the automobile safety question from an interesting perspective: the instinctive ability of humans and animals to sense and avoid dangers, an ability which is impaired when driving a car. Furukawa feels that building this instinctive function into automobiles as a form of intelligent technology is a good approach to improve safety. He introduces the "Mutual Safety Concept," which considers the safety of all road users, including automobiles, motorcycles, bicycles, and pedestrians. Three abilities are identified as enhancing mutual safety: the ability to sense danger, the ability to communicate with other transportation elements, and the ability to adapt to changing road and traffic conditions. The technical requirements for these abilities are then examined. Several practical technologies that provide a portion of these abilities are discussed. This approach may have significant merit in an eventual AHS.

McLellan et al.[63] discuss the role of vehicle chassis subsystems in active safety, including Antilock Brake Systems (ABS) and Traction Control, also known as Acceleration Slip Regulation (ASR). Future subsystems are also discussed, including: closed-loop rear wheel steering, controlled dampers, drive torque control, and active load distribution. The role of the driver in controlling the vehicle and driver actions that can be emulated in hardware are also discussed. This reference uses the friction circle representation of the boundary of maximal longitudinal and lateral force that the tire/axle/vehicle can exert. Four key areas are identified that need further progress in order for interactive vehicle control to be realized: sensor development, including accelerometers and yaw rate sensors; actuator efficiency; high rate communication between several closed-loop chassis systems; and the control and diagnostic approach governing the interaction of active systems. Interactive vehicle control includes the driver in the feedback loop, so that the overall dynamics are not well defined. As a result, new control techniques, such as neural networks, may play an important role in such a system.

Novak[64] provides guidelines to allow design engineers to incorporate diagnostics into various safety systems. The four general guidelines are:

- Before a controller issues a fault code and disables a system, verify that the fault condition is a true fault.
- Determine severity of each system fault condition. Is it necessary to disable the complete safety system due to that fault?
- For each fault condition, determine how to disable the system.
- Determine what information can be attained from the controller about the fault condition. What information can be provided to a service technician.

The inclusion of system diagnostics is treated here in terms of how it will assist development, manufacturing, and service areas in the automotive industry. However, from a general safety standpoint, the inclusion of diagnostics in IVHS systems, particularly safety-critical systems, is a very important issue. Such diagnostics can aid in the area of fault tolerance, and can be used to verify the integrity of critical systems before problems arise. As noted by Hitchcock,[65] safety-critical subsystems that are used only in infrequent emergencies will require the most diagnostics. In addition, as the complexity of vehicles increases due to the inclusion of IVHS technologies, providing a relatively simple means of diagnostics will be imperative. This is already being identified as a problem area by automobile service people who have to contend with a confusing array of electronic systems in today's vehicles, especially in the engine.

Evaluation of the potential safety impacts of an AVCS device is a difficult, often expensive task. Hitchcock(66) investigates the possibility of using the National Accident Sampling System (NASS) raw data files in evaluating the effectiveness of devices. Seven advisory AVCS devices are examined in the study: forward night vision, forward object detection, blind spot warning, red light warning, vehicle status indicator, driver status indicator, and rollover threshold warning. The purpose of the study was to ascertain whether the NASS raw data would be useful in the evaluation, not the actual evaluation of these devices. To protect the privacy of individuals documented in the database, the records used in this study are significantly modified by removing both the Police Accident Record and the words used by the driver to describe the accident. According to Hitchcock, such information is likely to improve the ability to evaluate the effectiveness of devices using NASS data, but even without this data, he concludes that NASS raw data is useful for evaluating AVCS devices in some circumstances. Further study seems warranted in this area.

Hitchcock(67) provides an informal discussion of IVHS standards and safety issues. In this reference, he identifies three areas pertinent to safety in IVHS design evaluation: hazard analysis and safety-critical subsystems; design, verification, and validation of safety-critical software; and configuration management. A distinguishing feature of IVHS relative to other safety-critical applications is that in IVHS, there will be multiple ownership of vehicles and roadside equipment; this will have significant effects on standards and certification of compliance with the standards. Most industries, with the notable exception of highway transportation, begin considering system safety using hazard analysis. Such an approach should be applied to proposed AHS to reduce the likelihood of catastrophic accidents. Safety-critical subsystems must be identified, so that they are not redesigned without considering the impacts on safety. The possibility of redesign emphasizes the need for modularity in the overall design. Software must be verified as conforming to its specification, and validated that the specification is actually what is wanted. Formal verification methods have made great advances in the last few years, and it appears possible to use these techniques to mathematically prove if a system conforms to specification. Validation is more difficult, but the use of formal methods can reveal some errors, as they force specifications to be written rigorously. The possibility of adverse interactions between otherwise functional subsystems is also identified as a serious potential problem in an AHS. A possible solution to such a problem lies in configuration management, but Hitchcock indicates that this issue is not as urgent as the previous issues.

Further considerations on the analysis of IVHS safety are presented in (43). The first question raised here regards how to specify a safety criterion for an automated freeway. Given such a specification, is it possible to design an automated freeway which prevents casualties if the criterion is satisfied? As designers are subject to error themselves, it is also important to ask how one can demonstrate that a design does what the first question requires. Hitchcock presents solutions to these problems. The design method is complete specification, and the verification technique is fault tree analysis. These techniques are used in other fields as well. One side benefit of this study is the indication that there do exist designs for automated freeways which are safe. Another conclusion is that in designing an AHS, it is vital to have two teams, equal in status: one concerned with design, and the other with verification. In such work, both teams must define everything with mathematical precision, and any decision logic must be recorded carefully. While it is shown that it is possible to design an automated freeway which conforms to reasonable safety criteria, it is also noted that no such system will be absolutely safe there must be trade-offs between safety and economics. This reference provides a useful design methodology to improve the safety of an AHS design; however, Hitchcock notes that the managerial organization and techniques required to implement these techniques are not in place in highway and automobile engineering. A significant conclusion relative to AHS is that safety considerations will constrain design considerably. For example, Hitchcock concludes that automated lanes must be separated by fences, with gaps to permit lane changing. This conclusion is not accepted by all researchers in the AHS community, but any design which refutes it should do so with full and formal consideration of the safety implications.

Hitchcock[(68)] presents an example specification of an automated freeway. Hitchcock intended this reference in part as an example of applying formal language and specification techniques in the AHS field. The specification follows along the lines of the architecture presented in (40), adding a sixth layer, based on the law, at the top of the hierarchy. Hitchcock concentrates on the link, platoon, and regulatory layers. The safety-critical subsystems are identified as the platoon, regulatory, and physical layers. This specification lists several modes of operation, including the 'natural mode', which is identified as useful during construction and maintenance operations. The specification provided is rather detailed, including flowcharts for roadside controller operations and detailed module specifications.

The techniques discussed in[(43)] are applied in a fault tree analysis of the above specification.[(65)] This reference demonstrates that Hitchcock's specification and safety analysis works, at least in its qualitative stage. The safety criterion used here is that three near-simultaneous independent failures must occur to cause a high relative velocity collision between platoons. Hitchcock identifies several hazards, where a hazard is defined as "a precursor to a condition in which one further failure could lead to a catastrophe." The fault tree concept is reviewed, and applied to Hitchcock's specification. The analysis identified four design faults, one error in the hazard specification, and the omission of some details in system messages, demonstrating that the fault tree analysis is applicable and useful in checking an AHS design. In addition, the analysis identified the functions and sensors that are used only in rare emergencies. This is an important issue from a system maintenance viewpoint. Maintenance of the sensors in an AHS is very important; in particular, systems which are seldom used must have regular maintenance and self-checking. Hitchcock strongly recommends that some form of hazards analysis and a standard verification and validation process be adopted by the IVHS design community.

Varaiya(8) briefly considers safety when discussing capacity increases possible with platooning. He indicates a potential fourfold increase in highway capacity using 20 vehicle platoons with inter-vehicle spacing of 1 m at highway speeds. While this appears technically feasible based on current research, he questions, as do others, whether such a platoon is safe. In a superficial discussion, it is indicated that an inter-platoon spacing of 60 m should allow enough time for the lead vehicle in the rear platoon to decelerate to avoid an accident if the front platoon suddenly decelerates. For collisions within the platoon, in an extreme case, "safe" impacts will occur even if the vehicles are under full automatic control so that they can decelerate immediately. According to Varaiya, experimental evidence indicates that such controllers can be built, but he does raise several interesting questions regarding safety:

- Why is relative speed on impact the correct measure of impact severity?
- What happens if, upon impact, a vehicle enters an adjacent lane?
- What about failures?

As Varaiya notes, such questions are not sufficiently answered at this time, and in the opinion of the current authors, represent critical issues in IVHS research that must be solved.

Varaiya gives a specific set of restrictions on platoon operations which are designed to maintain safety:

- Only leaders and free agents can initiate maneuvers; followers always maintain platoon formation.
- A leader carries out a maximum of one maneuver at a time.
- A leader coordinates maneuvers with the leaders of neighboring platoons.
- The leader executes maneuvers only after coordinated agreement is reached.

Various studies have been done to ascertain the acceptable minimum longitudinal spacing under automatic vehicle control. Such a number is important for design considerations, and for estimating capacity increase due to automation. The conventional wisdom is that to achieve significant gains in capacity, some form of platooning is required. However, Tsao and Hall(69) provide a probabilistic model and software tool for longitudinal collision and safety analysis, and demonstrate that free-agent (i.e. no platoon) vehicle-following under some conditions can virtually avoid collisions, while offering high capacity. Thus, it may be possible to achieve high levels of safety and capacity without the use of platooning. The use of a probabilistic model is important, as variations in vehicle deceleration and failure detection time may invalidate a deterministic approach. The input parameters used in this study are the spacing between the vehicles, the common speed prior to failure, the deterministic reaction delay of the following vehicle, and a bivariate joint distribution of the deceleration rates of the two vehicles. The bivariate distribution permits correlation between the two random deceleration rates due to common driving conditions. According to this study, the merits of any vehicle-following rule, in terms of collision probability and collision speed, depend heavily on the accuracy of the braking system. Tsao and Hall conclude that if low-relative-speed collisions are unsafe, and fast and accurate emergency deceleration becomes feasible, the free-agent rule may actually be safer than platooning.

Tongue et al.(70) describe a reduced-order vehicle model used to simulate platoon collision dynamics. The high order model presented in(71) was reduced using a least-squares technique, resulting in a nonlinear numerical reduced-order model. Comparison plots for the throttle force in both models showed that the reduced order model closely approximates the full model response. Another asset of this reference is the inclusion of an annotated bibliography.

Hsu et al.(42) recommend future research in the areas of safety and fault tolerance. This reference develops a set of formal specifications for elementary platoon maneuvers, which are then verified as correct. However, the proposed design assumes perfect communication and synchronization. In a practical system, errors will arise, and the protocols must address this. The elementary maneuvers are sufficient for normal operating conditions, but must be augmented to deal with vehicle failures, obstacles, and accidents. It is important to note that no design will be able to anticipate all possible failure modes, so that using a design methodology that is inherently fault tolerant is an important consideration.(72)

The Rockwell benefits study(13) also discusses safety issues involved in an AHS. This study includes cursory review of literature that indicates that an AHS would have to be between 10 and 20 times safer than the current highway system to be acceptable to the general public, e.g.(73) These observations are based on public expectations for airline safety and reactions to airplane accidents. Hitchcock(43) points out that when platoons crash, news coverage will be intense due to numerous vehicles being involved, so that even if such crashes are rare, the public perception of risk will be high. As also pointed out in (73), "automated steering and braking systems will have more parts and more failure modes than nonautomated systems. Overall, we will probably have fewer accidents caused by human failure and more caused by mechanical failure. It is unclear if the result would be fewer accidents."

The Rockwell study characterizes these concerns as judgments of the individual authors, and concludes that there is little basis for careful evaluation in these works. The current authors feel that these concerns should not be lightly dismissed, and that thorough attention must be given to the safety and fault tolerance issues involved in a system as complex and potentially dangerous as an AHS.

Chapter 8

Human Factors

Human factors research is another very important area for an Automated Highway System. In an advanced system such as an AHS, the driver will be confronted with significantly more information, and possibly more controls, than are currently used in vehicles. Other problems may arise that have no counterpart in current driving situations. For example, in a system that uses complete automation during some segments of a trip, safe transition from automated driving back to manual driving is a difficult issue. Concerns such as driver information overload and driver attention fall under human factors research. Human factors issues are intimately tied to the safety of an AHS.

Reference[56] reviews both safety and human factors considerations in ATMS, ATIS, CVO, and AVCS. Here, some of the relevant conclusions regarding AVCS will be discussed. In this reference, it is noted that current estimates of the benefits of IVHS technologies seem reasonable, but these benefits are realizable only if the technologies consider human factors and driver capabilities for the full range of drivers, and if institutional and societal barriers can be overcome. Thus, consideration of human, societal, and institutional factors is a critical area of IVHS research. The AVCS group in[56] recommend that human factors 'centers of excellence' be formed at several universities in order to fill the current lack of experts on safety and human factors in the IVHS field.

The issue of drivers accepting devices which either tell them what to do or take control away from them is nontrivial. Other potential problems include: reserving lanes specifically for AVCS-equipped vehicles, which may lead to problems similar to those encountered currently when implementing HOV lanes; privacy issues related to devices such as smart cards for charging tolls; and "platooning claustrophobia," for lack of a better term, when following distances are severely reduced at high speeds using longitudinal control and lanes are narrowed due to lateral control. Each of these problems may lead to public reaction against the deployment of IVHS technologies. Further societal and institutional issues, such as liability, responsibility, etc., are discussed in this reference, but will not be presented here.

As noted in (3), the privacy issue for vehicles equipped with electronic identification is important. It is unnecessary to track individual vehicles in the system, except at points which require individual billing, e.g. automatic toll collection. Guidelines are required so that state and local governments can collect, process, and distribute information effectively, yet still respect individual privacy.

As an example, Longfoot[10] discusses vehicle tagging, which is part of the Australian Automatic Network Travel Time System (ANTTS), a system designed to provide measurements of link speed and travel time over an entire network. This system allows traffic managers to effectively pin-point troublespots for both immediate action and future planning and reporting. Such a system has the potential for invasion of privacy, due to the ability to locate individual vehicles within the network. The view in Australia appears to be that systems with some privacy implications which provide demonstrable public good may gain limited acceptance, but such systems must respect privacy.[10]

Farber[74] discusses human factors issues in vehicle control and display systems. A number of concerns are raised, including: traditional human engineering details such as the size, type, location, and visibility of controls and displays; systems level design concerns relating to the logical and operational characteristics of the man-machine interface; and human factors testing and validation of the man-machine interface, including driver/system performance measures, workload measurement, and the use of simulators and on-road testing. The traditional issue of information overload is mentioned, with the concern that excess information will distract the driver from essential driving tasks. There are concerns that advanced safety systems may lead to a false sense of security, actually increasing risk. The focus of this reference is on the human factors aspects relating to the driver and the vehicle, mainly in the area of ATIS. Here, human factors encompasses traditional human engineering design, performance, and safety issues, and also incorporates marketability and driver acceptance of IVHS features. One significant problem identified is lack of room in the instrument panel. Solutions to this problem steering wheel-mounted controls, heads-up displays, and integrated multi-level displays all have their own associated problems. Also, complex controls and displays can overwhelm the driver, or distract attention for extended periods of time. Various other issues are identified, including the need for better measures of system performance from a human factors standpoint, design approaches for human factors, and research methods and simulations. The interested reader is referred to (74).

Tsao et al.[58] discuss design options for a fully automated AHS, and propose six AHS operating scenarios featuring variations in design options critical to human factors in AHS operations. The majority of this reference discusses the design options and scenarios; for further discussion, refer to chapter 6. See[75] for a more extensive discussion of the human factors issues related to the proposed scenarios.

Part 2 of[30] examines human factors issues related to lateral control. One important question is how to study these issues using documented research methods. Some approaches include simulations, surveys, and expert opinions. Human factors areas considered include acceptability and public confidence, displays and warnings, driver skill, and attentiveness. The most important issues identified in[30] are:

- Acceptance and public confidence:
  - Will the public accept the system? Do people want the system?
  - How will drivers react to false alarms? What is an acceptable false alarm rate?
  - How will drivers deal with system failures?
- Displays and warnings:
  - How much information should be given to the driver in normal and emergency situations?
  - How much information can the driver absorb?
  - What is the most effective display and/or warning?
  - Will an alarm prompt panic or corrective action?
  - How will the driver know whether the system is activated or not?
  - For what situations should a warning come on, and how much time will the driver be given to react?
- Driver Skill:
  - What is the combined reaction time of the driver and system to an emergency?
  - If the system fails, can large quantities of vehicles operate in narrower lanes without automatic guidance?
  - If the control system fails, can the driver take over lateral control?
  - How extreme is the change in the driver's performance level when the system is activated?
- Attentiveness:
  - What is the effect on driver vigilance?
  - Does the driver need to be awake? How should the system react to a sleeping driver?
  - What is the necessary attentiveness to react to a warning?

A more extensive list is given in (30). This reference also gives a discussion of existing driver simulation systems, which are listed here:

- The Atari Driving Simulator.
- The Daimler-Benz Driving Simulator.
- The Hughes Driving Simulator.
- The Iowa Driving Simulator.
- The Mazda Dynamic Driving Simulator.
- The Systems Technology Institute Driving Simulator.
- The University of Michigan Transportation Research Institute Driving Simulator.
- The Vag-och Trafik-Institutet (VTI) Simulator.
- The Virginia Polytechnic Institute Simulator.

The reader is referred to[30] for more discussion on the current status of knowledge and research for these and other human factors questions and issues.

Chapter 9

Conclusion

This survey has identified some of the important research areas related to the design and eventual deployment of an Automated Highway System. Some of the significant research in relevant areas has been reviewed. This document will serve as a guide in future AHS work at the Advanced Highway Maintenance and Construction Technology Research Center. In particular, it represents an important initial step in our current research on "A Precursor System Analysis of Automated Construction, Maintenance, and Operational Requirements for Automated Highway Systems (AHS)." While much of the technology applicable to an AHS has been identified in at least a preliminary fashion, little work has been done on the issues of deployment and maintenance. In particular, it appears that no one has addressed the possibilities of applying robotics and automation techniques in the construction and maintenance of an AHS. These issues, as well as the impact of automated construction and maintenance on the overall AHS operation, are the focus of ongoing research at the AHMCT Research Center.

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