
Automated Highway Systems and their Impact on Intelligent Transport Systems Research

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1. INTRODUCTION

The idea of automated driving dates back to almost 50 years ago when General Motors (GM) presented a vision of driverless vehicles under automated control at the 1939 World fairs in New York. In the 1950's research by industrial organizations conceptualized automated vehicles controlled by mechanical systems and radio controls. After the first appearance of the computers in the 1960's, researchers began to consider the potential use of computers to provide lateral and longitudinal control and traffic management. The fully automated highway concept was initially examined by GM with sponsorship from the US department of Transportation (DOT) in the late 1970's. During these times, focus was laid on automated vehicles on a highway as computers were not powerful enough to consider a complete fully automated highway system.

Advances in the computing technologies, micro-electronics and sensors in the 1980's provoked commercial interest in the technologies that might enhance driver capability and perception and both private and public researchers examined partially automated products and services. Among others, the University of California Partners in Advanced Transport and Highways (PATH) has carried out significant research and development in the field of highway automation since the 1980's. As various transportation technologies emerged that could assist driving on one hand and also traffic efficiency on the other, interest in fully automated driving or integrated auto-highway technologies grew once again.

With the passage of the 1991 Intermodal Surface Transport Efficiency Act (ISTEA), efforts were on early prototype development and testing of fully automated vehicles and highways. This act prompted the US DOT to develop the National Automated Highway System Research Programme (NAHSRP), whose goal was to develop specifications for a fully automated highway system concept that would support and stimulate the improvement of vehicle and highway technologies.

In 1994, the US Department of Transportation launched the National Highway System Consortium (NAHSC). The consortium consisted of nine major categories of organization including academia, federal, state, regional and local government besides representatives from vehicle, highway, electronics and communications industries. The consortium believed in expanding the program's expertise and resources, and maintained that the collaborative approach among the stakeholders would be critical in building the common interest that would be required in the early development and deployment of fully automated highway systems. Research continues to this day though it is largely sketchy owing to the withdrawal of the financial support for the National Automated Highway Systems Research Programme (NAHSRP) by the US Department of Transportation in the year 1997.

Many studies conducted by the National Automated Highway Systems Consortium (NAHSC) continue in partial way with a couple of federal programmes like the Intelligent Vehicle Initiative (IVI) with more focus on a nearer-term horizon.

2. AUTOMATED HIGHWAY SYSTEMS

2.1 Automated Highway Systems

The Automated Highway System (AHS) concept defines a new relationship between vehicles and the highway infrastructure. AHS refers to a set of designated lanes on a limited access roadway where specially equipped vehicles are operated under completely automatic control. AHS uses vehicle and highway control technologies that shift driving functions from the driver/operator to the vehicle. Throttle, steering, and braking are automatically controlled to provide safer and more convenient travel. AHS also uses communication, sensor and obstacle-detection technologies to recognize and react to external infrastructure conditions. The vehicles and highway cooperate to coordinate vehicle movement, avoid obstacles and improve traffic flow, improving safety and reducing congestion. In sum, the AHS concept combines on-board vehicle intelligence with a range of intelligent technologies installed onto existing highway infrastructure and communication technologies that connect vehicles to highway infrastructure.

2.2 Major AHS Goals

The AHS program is designed to influence how and when vehicle-highway automation will be introduced. AHS deployments will be tailored to meet the needs of public, commercial, transit, and individual travellers in rural and urban communities. The major goals are to:

1. Improve safety by significantly reducing:

- a) Fatalities.
- b) Personal injury.
- c) Pain and suffering.
- d) Anxiety and stress of driving.

2. Save money and optimize investment by:

- a) Maximizing efficiency of the existing infrastructure investment.
- b) Integrating other ITS services and architecture to achieve smooth traffic flow.
- c) Using available and near-term applied technology to avoid costs of conventional highway build-out.
- d) Developing affordable equipment, vehicles, infrastructure, operations, maintenance, and user fees.
- e) Closing the gap on predicted infrastructure needs.
- f) Using public/private partnerships for shared risk; using the National AHS Consortium as a global focal point to influence foreign deployment efforts.
- g) Reducing fuel consumption and costs, maintenance, wear-and-tear, labor costs, insurance costs, and property damage.

3. Improve accessibility and mobility by:

- a) Improving employee on-time performance, resulting in a more effective work force.
- b) Facilitating "just-in-time" deliveries.
- c) Improving public transportation service, increasing customer access, and expanding service levels, resulting in increased revenue, reduced costs, and reduced accidents.
- d) Achieving a smooth traffic flow, reducing delays, travel times, travel time variability, and driver stress.
- f) Making driving more accessible to less able drivers.

4. Improve environmental efficiencies by:

- a) Reducing emissions per vehicle-mile travelled.

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- b) Providing a solid base for reliable, lower cost transit.
- c) Providing an efficient base for electric-powered vehicles and alternative fuel vehicles.
5. Create jobs by:
- a) Providing a stronger national economy and increasing global competitiveness.
- b) Increasing jobs in research and development and in early ITS deployment.
- c) Facilitating technology transfer (e.g., from military to civilian use).
- d) Creating new U.S. automotive products and new technology-based industry to compete in the international marketplace.



Figure 2.1 – A concept drawing of an Automated Highway System with dedicated lanes in the centre of the highway.

2.3 Methodology

As shown in figure 2.1, a driver electing to use such an automated highway might first pass through a validation lane, similar to today's high-occupancy-vehicle (HOV) or carpooling lanes. The system would then determine if the car will function correctly in an automated mode, establish its destination, and deduct any tolls from the driver's credit account. Improperly operating vehicles would be diverted to manual lanes. The driver would then steer into a merging area, and the car would be guided through a gate onto an automated lane. An automatic control system would coordinate the movement of newly entering and existing traffic. Once travelling in automated mode, the driver could relax until the turnoff. The reverse process would take the vehicle off the highway. At this point, the system would need to check whether the driver could retake control, then take appropriate action if the driver were asleep, sick, or even dead.

The alternative to this kind of dedicated lane system is a mixed traffic system, in which automated and non-automated vehicles would share the roadway. This approach requires more-extensive modifications to the highway infrastructure, but would provide the biggest payoff in terms of capacity increase.

In fact, a spectrum of approaches can be envisioned for highway automation systems in which the degree of each vehicle's autonomy varies. On one end of the range would be fully independent or "free-agent" vehicles

with their own proximity sensors that would enable vehicles to stop safely even if the vehicle ahead were to apply the brakes suddenly. In the middle would be vehicles that could adapt to various levels of cooperation with other vehicles (platooning). At the other end would be systems that rely to a lesser or greater degree on the highway infrastructure for automated support. In general, however, most of the technology would be installed in the car.

3. THE SYSTEM CONCEPT AND TECHNOLOGIES

Concepts of Automated Highway System (AHS) can be classified into two groups, partially automated systems and fully automated systems, depending on the extent of the automation. Partially automated systems include notification and warning systems, temporary emergency controls and continuous partial controls, which take limited control of the vehicle in emergency situations. They automate certain routine parts of driving but rely on manual control for most driving functions. Fully automated driving would let drivers be totally disengaged from all driving tasks.

3.1 The Five Concept Families

1. Independent Vehicle Concept: This concept puts a smart vehicle in the existing infrastructure. In-vehicle technology lets the vehicle operate automatically with on-board sensors and computers. The vehicle can use data from roadside systems but does not depend on infrastructure support.

2. Cooperative Concept: This concept lets smart vehicles communicate with each other, although not with the infrastructure. With on-board radar, vision, and other sensors, these AHS-equipped vehicles will be able to communicate with each other and coordinate their driving operations, thereby achieving best throughput and safety.

3. Infrastructure-Supported Concept: A smart infrastructure can greatly improve the quality of AHS services and better integrate AHS with local transportation networks. This concept envisions automated vehicles in dedicated lanes using global information and two-way communication with the smart infrastructure to support vehicle decision-making and operation.

4. Infrastructure-Assisted Concept: In this concept, the automated roadside system provides inter-vehicle coordination during entry, exit, merging, and emergencies. This concept may provide the greatest throughput benefit; it also may require the greatest civil infrastructure investment.

5. Adaptable Concept: This concept acknowledges the fact that AHS implementation will vary by locality. It envisions the development of a wide range of compatible standards that leave as many of the specific architecture decisions, solutions, and deployment progressions as possible to area stakeholders.

The National Automated Highway System Consortium (NAHSC) defined several alternative AHS concepts, from cooperative to fully automated, depending on the degree to which vehicles and infrastructure work together as listed above.

3.2 Current Technologies

While current vehicles use new technologies mostly for safety or driver convenience, e.g., air bags, antilock brakes, adaptive cruise control, power steering, the vehicles on an AHS system would require much more new technology that communicates with the roadway. In the simplest forms of AHS these would focus on the detection of other vehicles and obstacles. Technologies that already do this to some extent are beginning to be added to luxury vehicles or are sometimes an option that can be selected by the consumer; e.g., collision warning systems. Other technologies that would be precursors to the communications technologies in an AHS system are also being introduced; these include navigation assistance systems, traveler information systems, and vehicle locator systems. Their acceptance in the market is taken as an indicator of eventual consumer acceptance of the broader AHS concept.

4. CONTROL DESIGN OF AN AUTOMATED HIGHWAY SYSTEM

The Control design of an Automated Highway system can be looked upon the basis of a 5 layer theory which together comprise the two systems viz. the On-board Vehicle System and the Roadside System. The control design is explained with the aid of the figure 4.1:

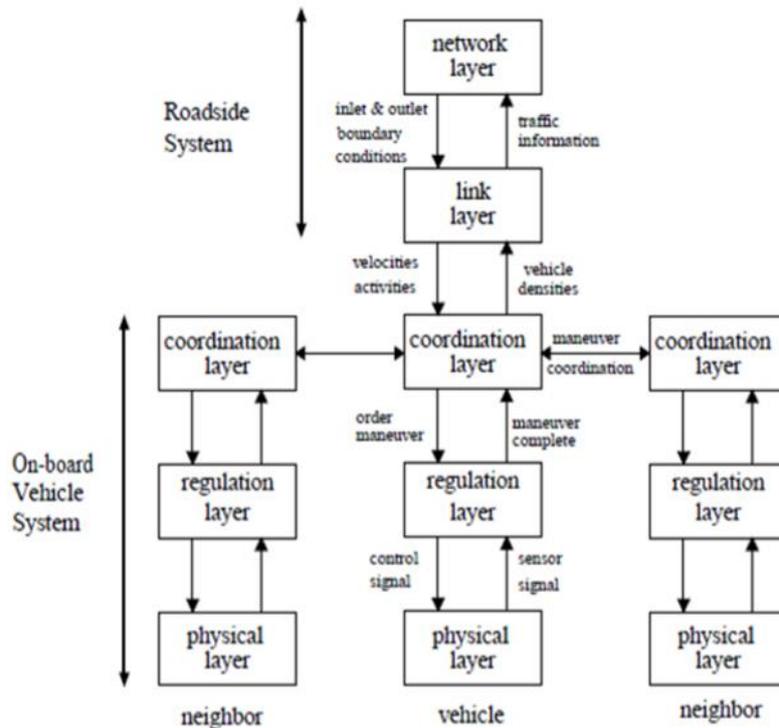


Figure 4.1 – The Control Design of an Automated Highway System

4.1 The Five Layer Theory

The *physical layer* comprises all the on-board vehicle controllers of the physical components of a vehicle. These include the engine and transmission, brake and steering control systems, as well as the different lateral and longitudinal vehicle guidance and range sensors. The main function of the physical layer is to decouple the longitudinal and lateral vehicle guidance control and to approximately linearize the physical layer dynamics.

The *regulation layer* is responsible for the longitudinal and lateral guidance of the vehicle, and the execution of the manoeuvres ordered by the coordination layer. The regulation layer must carry out two longitudinal control tasks. The first task is that of a vehicle follower in a platoon and consists in maintaining a prescribed constant spacing from the preceding vehicle. The second task is that of a platoon leader or free agent and consists in safely and efficiently executing a manoeuvre commanded by the coordination layer.

The *coordination layer* is responsible for selecting the activity that the vehicle should attempt or continue to execute, in order to realize its currently assigned *activity plan*. It communicates and coordinates its actions with its peers—the coordination layers of neighbouring vehicles—and supervises and commands the regulation layer to execute or abort manoeuvres. It also communicates with the link layer roadside control system, from which it periodically receives an updated activity plan.

There is one *link layer* controller for each 0.5 to 5 km-long segment of the highway, called a link. Its task is to control the traffic flow within the link so as to attain its full capacity and minimize vehicle travel time and undesirable transient phenomena, such as congestion. A link is itself subdivided in sections, one per lane. A link receives and discharges traffic flow from and to neighbouring links, as well as AHS entrances and exits. The controller measures aggregated vehicle densities in each of the link's sections. These densities are specific to vehicle type, including origin and destination, and whether the vehicle is a platoon leader, follower or is changing lanes. It broadcasts commands in the form of a specific activity plan for each vehicle type and section, to the vehicle coordination layer controllers.

The link layer controller receives commands from the network layer in the form of demands on the inlet traffic flows at the AHS entrances, and outlet flow constraints at the AHS exits, as well as desired inlet-to-outlet traffic flow split ratios, in case a vehicle can take more than one route to each the same destination, while travelling in that highway link,

The task of the *network layer* is to control entering traffic and route traffic flow within the network of highway links that constitute the AHS, in order to optimize the capacity and average vehicle travel time of the AHS and minimize transient congestion in any of its highway links.

4.2 On-board vehicle control system

The overall on-board vehicle control system comprises the control systems for the coordination, regulation, and physical layers. Its primary objective is to safely control the vehicle while efficiently executing its activity plan. By *safely* it is meant that the vehicle should not collide under normal circumstances, in the absence of major hardware malfunction. By *efficiently* it is meant that the vehicle should complete the manoeuvres in its activity plan in a manner that tends to optimize the capacity and traffic flow of the AHS. This involves completing manoeuvres, such as join, split or change lane in the minimum possible time, and performing platoon follower and leader laws while maintaining as high a speed and as small a distance from the preceding vehicle as practicable.

However, since the on-board vehicle control system does not have the overall AHS capacity and traffic flow information, overall AHS optimality is not monitored or guaranteed at this layer

4.3 Roadside Control System

The roadside control system's primary objective is to optimize the capacity and traffic flow of the overall AHS. The models used in the link layer involve aggregated vehicle densities and traffic flows but not individual vehicles. Thus, vehicle safety, as defined in Section 3, cannot be monitored, much less enforced. The roadside control system can control the network and link layers in ways that *tend* to increase vehicle safety, such as maintaining sufficiently low aggregated vehicle densities and decreasing the inlet traffic flow into links.

5. POTENTIAL BENEFITS

Researchers have attempted to estimate benefits that might accrue from the implementation of automated highway systems. Table 2 summarizes potential benefits. Many of the benefits shown in the table are fairly speculative; the systems they would depend upon are not yet in existence and there is no clear evidence that the system can produce the following benefits in reality.

It is anticipated that automated highway and related advanced vehicle control and safety technologies would significantly reduce traffic congestion and enhance safety in highway driving. This in turn would potentially cut travel time, and therefore, driving would be more predictable and reliable. The Mobility 2000 report, sponsored by the Texas Transportation Institute, projected that collision prevention systems could reduce accidents by 70 percent or 90 percent on fully automated highways.

Research focused on collision prevention systems has estimated possible savings in a relatively short period of time. For example, collision avoidance systems have been estimated to have the potential to reduce annual

loss of life on U.S. roads by 50 percent by 2020. In addition, preliminary National Highway Traffic Safety Administration estimates show that rear-ends, lane-change, and roadway-departure crash-avoidance systems have the potential to reduce crashes by one-sixth, or about 1.2 million crashes a year.

6. SOCIAL AND INSTITUTIONAL CHALLENGES FOR AUTOMATED HIGHWAY SYSTEMS

The introduction of new technologies often creates social tensions. For instance, although talking on the phone while walking, or driving is commonplace nowadays, there are concerns about its safety, and debates continue over whether it is rude to use a cell phone in public places such as restaurants or on a bus. Similarly, mature technologies experienced social challenges when they were introduced. The first automobiles were seen as rich people's toys, and former President Woodrow Wilson, then head of Princeton College, warned students about showing off their vehicles before the townsfolk, who he presumed would never have cars.

The programs to achieve the transportation improvement through new technologies likewise face social and institutional challenges. For automated highway systems the challenges include concerns about land use and environmental impacts, effects on people's mobility if they are unable to afford or use the new technologies, effects on local government-owned transportation systems, and impacts on financing systems. These impacts will be discussed here.

6.1 Unclear Social and Environmental Impacts

One of the critical problems for the automated highway system development is that the impact of AHS on society and environment is unclear yet. Studies necessarily must be speculative since the system has not yet been implemented apart from the San Diego demonstration project. The following topics are ones that have generated considerable disagreement.

6.1.1 Congestion at Entry and Exit

There is concern that if AHS are implemented the greater numbers of vehicles on an automated highway could create bottlenecks at its entry and exit points as more traffic reenters non-automated streets. This might offset most of the benefits of the traffic flow improvement on the automated highways. The U.S. DOT acknowledged that it was a serious concern to design an interchange that can integrate with surrounding non-AHS roads to ease the problem.

6.1.2 Unclear Impact on Land Use and Environment

There are concerns that commuters might live farther from the work place, because an automated highway system promises to increase the accessibility of more distant locations through higher freeway speeds. Therefore, it possibly encourages urban sprawl and greater dependence on the automobile. The concern about land use pattern and urban development raises also the serious question on the AHS's positive role regarding air quality, noise, etc. If more vehicles were accommodated at faster speeds on a fully automated highway, vehicle emissions might increase and degrade air quality, as AHS might encourage more Vehicle Mile Traveled (VMT). This conflicting result may provoke the fundamental question of whether or not automated highway system is much more efficient, comparing to traditional highway or other transportation modes such as light rail and high-speed rail.

6.1.3 Safety

Some argue that it is uncertain how Automated Highway Systems impact on overall highway safety, because the failure of a vehicle's braking or steering system could severely disrupt the highway traffic flow and cause a chain reaction accident. In addition, there are remaining questions: What level of safety is attainable and sustainable within a realistic cost? How much safety equipment can be required and still achieve public acceptance? How efficient can the system be if safety requirements are set at extremely high levels? The trade-offs between the technology level, cost, and the safety level have not been addressed yet.

6.1.4 Equity

Since tremendous amounts of public funds could be spent to deploy an automated highway system, social equity issues must be addressed. A key question is whether it would be fair and politically feasible to dedicate

travel lanes to automated vehicles, and spend public funds, if many low-income motorists cannot afford automated vehicles.

Studies have not addressed specific issues of whether and how state and federal government might provide incentives to commercialize automated vehicles, how the system should be financed (e.g. toll system/ other sources), and how equity concerns could be reduced. There also may be different equity issues involved with different vehicle users.

6.2 The Dilemma of Transition From Conventional Highway to Automated Highway

There has been a debate between those who favor an evolutionary deployment of automated high systems and those who promote full-scale conversion of regional highways to the system.

Some researchers involved in the National Automated Highway System Research Program believed that a regional conversion strategy would be a more effective way to implement a fully automated system. The argument is that the evolutionary approach would be neither easy nor efficient since many drivers will not invest in such basic technologies as adaptive cruise control and lane-keeping technologies. It was recommended that at least one lane of a regional highway should be converted to an AHS-equipped corridor so that initial users can fully benefit from the system. In addition, to demonstrate the benefits, government vehicles and transit vehicles would be converted first to automated vehicles.

Others argued for gradual implementation, believing that there would be inadequate justification to convert or build highway lanes with full automation with public funds if only a few vehicles, mostly owned by the affluent, would be able to use the system in its initial years. This side also argued that even the vehicle owners who can pay for automation technologies may not be willing to equip their cars with this technology, if only one or a few corridors have highway lanes equipped for AHS use. Thus, the suggestion was that, as an evolutionary approach, focus should be placed on market penetration of near-term advanced vehicle control and safety technologies.

After the U.S. DOT's decision was made to withdraw from the National Automated Highway System Research Program, AHS research has mostly followed the evolutionary model. Today, many efforts are being made to develop and commercialize the basic AHS-related technologies such as adaptive cruise control and collision-warning features.

6.3 Public Acceptance

For AHS to obtain public acceptance, it must be designed and implemented with many complex human factors and operational reliability considerations. The decision on which vehicle controls are automated and how these systems interface with the driver will affect seriously system safety and the level of public acceptance. In addition, the extent to which motorists would accept reduced manual control of their vehicles of be willing to travel in automated vehicles at close following distances, on narrower lanes, and at higher speeds is not clear yet. Full automation of the nation's road cannot be attained in a day, until a careful review as to human response and system safety, and market analysis on potential users can be successfully addressed. User fears, inertia, and distrust on new technology are typically too strong to be eliminated without gradual and systematic implementation strategies.

6.4 Institutional Issues

The vision of deployment of local and regional automated highways requires the public sector to consider the issue of institutionalization of automated highway systems. Successful institutionalization would reduce potential political and economic conflicts and would specify the roles and responsibilities of each public and private actor. Key institutional issues include finance, regulation, and organization.

6.4.1 Finance: Who Will Pay for AHS?

U.S. DOT's 1996 report identified several issues concerning the finance of automated highways, but these issues have not been discussed actively since the U.S. DOT withdrew its financial support for the long-term research on AHS. Yet, it is worth summarizing the significant issues in the following:

1. The main ways to cover automated highway system costs and the cost structuring.

2. The priority to be given to investment in normal highways v/s. automated highways.
3. The rights and privileges that the operating entity can have.

A principal dilemma is that, given limited financial resources and a backlog of needed investments in conventional traditional transportation projects, AHS deployment is likely to be limited for the next decade or more, unless alternative funding sources are found.

In many urban areas, maintenance alone absorbs the majority of available funds, and transportation agencies are left with little funding to use on new projects of any sort.

This suggests that either new funding source would need to be found or else the benefits of AHS would have to be so convincing that transportation officials would put AHS projects ahead of other desired transportation investments.

6.4.2 Organizational Issues

Many operational issues can arise in considering the role of state and local government in building and operating highways. The AHS will include technically complex components such as advanced electronic sensors, on-line computers and software, and communication systems. Installation and maintenance of these systems may present a significant challenge to the operators. Since AHS will introduce an increased level of complexity for highway operations, the following issues should be addressed:

1. The ability of state and local transportation agencies to build, operate and maintain the sophisticated networks of automated highway; changes that might be needed in personnel hiring practices, pay scales, etc.
2. The capability of state and local jurisdictions to work together effectively in planning and operating AHS
3. The regional institutional integration to support the efficient operation of AHS
4. The training of technical staff to deal with the system
5. The structure of ownership of facility (public or private)
6. Responsibility for standard-setting for new equipment and operations.

6.4.3 Liability issues

Presently, the primary burden of the cost of vehicle accidents rests with the drivers and the owners of the vehicles, because most of highway collisions are due to driver error. However, the increased automation resulting from the adoption of certain automated highway technologies could shift liability to the developers and operators of automated systems. Thus a major issue concerns the resolution of who is to be responsible for accidents on automated highway systems: the non-driving driver, the auto-highway authority, or the auto manufacturer.

7. VEHICLE PLATOONING

The eight-vehicle platoon demonstration at the National Automated Highway Systems Consortium Technical Feasibility Demonstration, held in San Diego from August 7-10, 1997, shown in figure 7.1, successfully demonstrated the technical feasibility of operating standard automobiles – Buick LeSabres– under precise automatic control at close spacings, at highway speeds. Riders experienced real travel in a fully automated AHS vehicle, and were shown that comfortable, high-capacity, automated travel is technically feasible in the near future.

The platoon demonstration was designed by researchers at the California PATH program to show how vehicle automation technology can be used to make a major contribution to relieving traffic congestion. The eight Buicks operating in tight coordination showed how an automated highway system can provide a significant increase in highway throughput (vehicles per lane per hour moving along the highway).

Since platooning enables vehicles to operate much closer together than is possible under manual driving conditions, each lane can carry at least twice as much traffic as it can today. This should make it possible to

greatly reduce highway congestion. Also, at close spacing aerodynamic drag is significantly reduced which can lead to major reductions in fuel consumption and exhaust emissions. The high-performance vehicle control system also increases the safety of highway travel, reduces driving stress and tedium, and provides a very smooth ride.



Figure 7.1 – A typical Vehicle Platoon experiment done in San Diego, CA.

8. CONCLUSION

Automated Highway Systems brings major transportation benefits in terms of safety, efficiency, affordability and usability, and environment in order to achieve its development goals.

A key feature of the control design architecture is the separation of the various control functions into distinct layers with well-defined interfaces. Each layer is then designed with its own model that is suited to the functions for which it is responsible. The models at the various layers are different not only in terms of their formal structure (ranging from differential equations to state machines to static graphs), but also in the entities that have a role in them.

The AHS is a complex large-scale control system, whose design required advances in sensor, actuator, and communication technologies (not discussed here) and in techniques of control system synthesis and analysis. It is a measure of the advanced state of the art that these techniques have reached a stage that they could be successfully used in the AHS project.

Though it has been said so, the reasons why many federal programs like the National Automated Highway System Research Program (NAHSRP) failed was that the program was trapped in technology-optimism. Several U.S. DOT reports on AHS show that there are no technical and non-technical showstoppers. However, legal, institutional, and societal challenges just as critical as technical issues. Moreover, these institutional and

societal issues cannot be settled in one day, because they are much to do with people's perception, behavior, consensus and social changes based on those.

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