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“AUTOMATED HIGHWAY SYSTEMS-AN INTELLIGENT TRANSPORTATION SYSTEM”

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Abstract: Automated highway system (AHS) is an intelligent transportation system, which removes human drivers from the operation of vehicles during driving. This talk is focused on activities on AHS at the California Partners of Advanced Transit and Highways (PATH). AHS includes control problems from the vehicle level to the highway network level and offers a number of challenging opportunities for intelligent mechatronics. 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. The current vehicle-highway system has reached a plateau in its ability to meet the demand for moving goods and people. This paper sketches architecture for an automated highway system or AHS. The architecture can be realized by several designs that differ in terms of performance and sophistication. One design is described that could triple capacity and reduce travel time, guarantee collision-free operation in the absence of malfunctions, limit performance degradation in the case of faults, and reduce emissions by half. Evidence suggesting that the design can be implemented is summarized. It is indicated how the design can be adapted to different urban and rural scenarios and how a standard land-use model can show the impact of AHS on urban density. A summary of the progress of the National Automated Highway Systems Consortium is provided. The paper concludes with a critique of AHS.

I. INTRODUCTION

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 (Figure 1). 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.

The consensus in the AHS community is that AHS will evolve over a series of smaller steps in technology. The final step of full automation will not be a leap, but a logical consequence of previous development and deployment efforts. Each step in the technology will have its own benefits and be self-sustaining. Vehicle and infrastructure evolutions will be "synchronous" [James94]. We will briefly mention the steps of this evolution here before introducing the AHS program and discussing automatic vehicle control technologies in detail. When the cruise control was first developed, there was much concern over the safety and user acceptance of the new system; however, it has become widely accepted and used. In the near future, obstacle and headway warning and Automatic Vehicle Identification (AVI) will be added to modern cruise control and existing communications infrastructure.

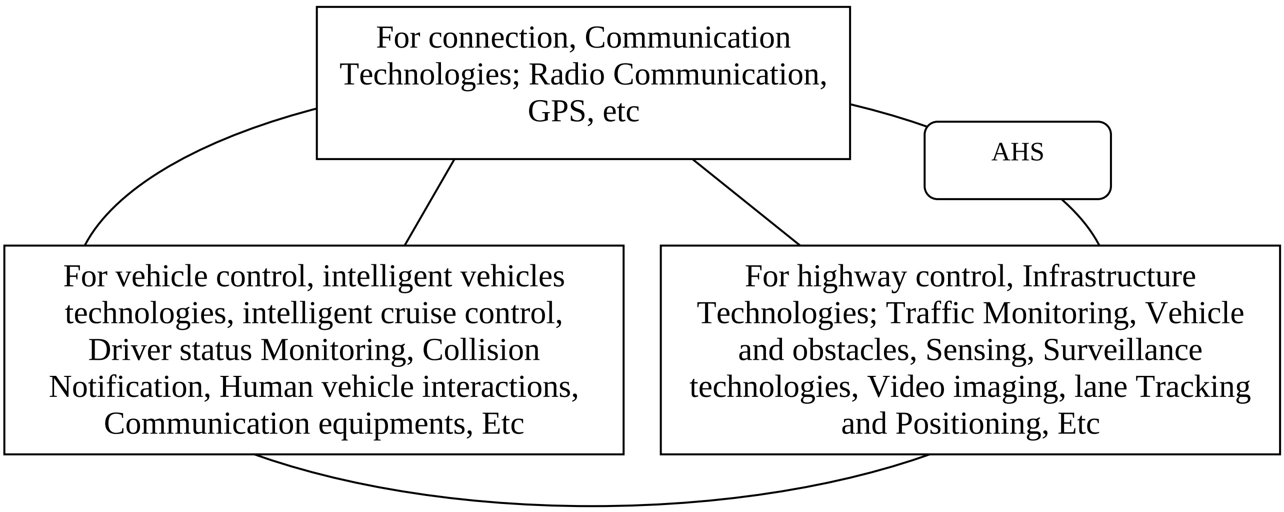

Figure 1: The Concept of AHS Technologies

The success of AHS depends on linking the power of cellular communications and the emerging range of high performance computers to the ongoing vehicle based developments. Ideally, the highway system can be divided into a number of "cells" which contain local radio receivers or beacons that will be linked together through a fiber-optic network. Vehicles will also be equipped with a transceiver unit carrying several user services. The first applications of this technology are the Automatic Vehicle Identification (AVI) and Electronic Toll Collection (ETC). Obstacle and headway warning is the next step in AHS development in vehicles. Vehicle on-board radar (VORAD) systems in many commercial vehicles are already in use for the last two years. An important issue in warning systems is the capabilities of the sensor modules. Differentiating between a large vehicle and a small animal may not be possible using a simple system. A consequent application of the headway warning system is the automatic headway control. Adaptive cruise control systems are currently designed by many automobile manufacturers. The market introduction of the first vehicle with adaptive cruise control is expected in 1997. This will enable the drivers to hold their desired speed as well as the desired headway distance. Although the drivers defined as "creepers" will be cut-of by more aggressive drivers ("hunters"), the ability to set the desired headway may be desirable to many users. Also, the issues such as sensor types, curve handling, merging vehicles, changing lanes, integration of steering and braking all have to be addressed to obtain a complete system design. Applications in advanced traffic management, traveler information and public transportation systems (ATMS, ATIS, APTS) will require more sophisticated vehicle location capabilities. In addition, the number of uses for vehicle-to-roadside communications will eventually increase. MAYDAY services, fleet tracking and automatic vehicle location (AVL) applications will use radio-location beacons as well as more sophisticated transceivers. As a result of AVL and AVI, processing real-time information on vehicle locations will be possible. Although the number of vehicles equipped with AVI/AVL technologies will initially be small, traffic management centers can effectively use a small percentage of vehicles as “probes.” Roadside-to-vehicle and vehicle-to-vehicle communications are also important for the future of AHS. Automatic braking systems may be activated by decelerating vehicles in front, or by the infrastructure sending a deceleration request to the headway control system. The vehicle must be very sure about the imminent danger, and knowledge of following vehicles and their speeds is an important factor to be considered. Inter-vehicle communications and rear sensing both would help in automatic braking.

II. OTHER AHS ISSUES

Besides the automatic vehicle control, there are several important issues that need to be carefully considered for a successful implementation of an automated highway system. During the first few years of the AHS research efforts, the problems related to the issues given here were not investigated as much as vehicle control problems. However, as the AHS related research progressed, it expanded to the areas of sensing and communications, fault tolerance, and human factors. In this section, we will emphasize related research efforts on these areas.

1. Sensors and Communication

The realization of full AHS needs hardware both in infrastructure and the vehicle. Roadside monitors will measure traffic flow and speed, and vehicle paths will be calculated based on this information. Such measurements are currently made with loop detectors, ultrasonic sensors, AVI tags or vision systems. Information may be communicated by infrared beacons, broadcast and cellular radio, or using emergingultra wideband technologies. The vehicles need a longitudinal sensor to measure distance and relativespeed of the preceding vehicle. Such sensors may be based on radar, ultrasound, or vision. Microwave radar sensors perform very well in fog and heavy rain, but they are very expensive. Laser radar systems are low-cost, but cannot handle low visibility conditions. To facilitate lane changes at a range of relative speeds, the vehicle must be equipped with sensors that locate vehicles on the side with a longitudinal range of about 30m. Infrared and laser range finding techniques may prove to be useful in this area. Besides headway and side sensor information, longitudinal and lateral velocity and acceleration, yaw rate, front steering angle, and lateral deviation data is needed to obtain a robust combined lateral and longitudinal control. All of these except the last one can be obtained using on-board accelerometers and encoders. For vehicle position sensing, there are two alternatives: magnetic markers, and vision systems.

Recent research done on vision systems showed significant promise, however these systems are more expensive than magnetic markers which, in turn, require infrastructure deployment as well as on-board sensors. A sequence of single magnetic markers can also form a “word” that transfers information such as curvature, and number of lanes. However, this magnetic marker data contains only the static information (roadway characteristics), not dynamic information (such as information on other vehicles incidents), unlike the vision system. Roadside-vehicle communications is also a critical aspect of AHS.

Vehicles need to be identified, speed must be communicated to vehicles, and actions need to be coordinated for a fully automated system. In addition, there is a need for vehicle-to-vehicle communications because of the designed longitudinal control methods and coordination issues. Precise control can be obtained using full duplex communication. Networking represents a higher level of communications, in which traffic and hazard information detected by one group of vehicles can be communicated to other vehicles.

2. Safety and Fault Tolerance

Although the solutions to most of the technical problems in vehicle control, traffic management, information systems, and communications have been found, the envisioned AHS will never be deployed unless the safety of the overall system can be verified. One issue which is often overlooked by researchers is the possibility of undesirable interaction of the systems. An example in [Safety92] mentions two devices which try to maintain vehicles at constant lateral spacing using side range sensing. If the devices (and the vehicles) have different dynamics, it is possible that one or both vehicles may become unstable, possibly resulting in a collision. Furakawa [Furakawa92] 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. Furakawa notes that building this instinctive function into automobiles as a form of intelligent control technology is a good approach to improve safety. Current research on safety and fault tolerance includes lane crossing studies [Lin96], sensor validation [Agogino96,Singer95], fault tolerant design for AHS [Lygeros96], emergency maneuvers for automated vehicles [Shiller95], and design constraints on intelligent vehicle controllers [Puri95].

3. Human Factors In an advanced system

Such as AHS, the driver will be confronted with significantly more information, and possibly more controls, than are currently used in vehicles. In a system that uses complete automation during some segments of a trip, the safe transition from automated driving to manual driving is a difficult issue. Also, there exist several advanced vehicle control systems (AVCS) related problems such as the acceptance of a system which takes the control away from drivers, privacy issues related to AVI and AVL systems, and "platooning claustrophobia." For users to accept the AHS, a successful AVC system must address important issues such as dealing with false alarms and system failures to gain acceptance and public confidence, displays and warnings with the right amount and content of information, and driver skills and attentiveness for smooth automated-manual switching [Chira92]. Human factors assessment of the drivers interfaces of existing collision avoidance systems is currently under investigation [Mazzae96]. On the other hand, although AHS deployment has not started yet, simulator tests are conducted to see how drivers behave when they are in the lead vehicle in a string of vehicles and another vehicle enters the automated lane ahead of them [Bloomfield96]. Also, the effect of different AHS automation degrees (manual, semi-automated, fully automated) on driver behaviors while entering the automated lane are tested using a driving simulator [Bloomfield96b]. Levitan presented a comprehensive report on human factors considerations related to the design of AHS. The report is intended as a guideline for effective, efficient, safe and user-acceptable AHS design [Levitan96].

III. AN EXPERIMENTATION AND EVALUATION FRAMEWORK FOR AHS

According to Center for Transportation Research's approach, the progression in AHS development from conceptualization to implementation has four steps, [Kachroo95]. The intelligent controller described in this work is part of the four-block structure visualized at the center. As seen in Figure 2, the first block is computer software simulation thatproceeded by mathematical modeling. The second block consists of conducting small scale experiments in the Flexible Low-cost Automated Scaled Highway (FLASH) Laboratory. Then, hardware tests comprising the third block are performed on a test site with actual vehicles. The "Smart Road" being built near Blacksburg, Virginia will be a suitable test bed for conducting such experiments using actual vehicles and controlled traffic conditions. The fourth block is the deployment of AHS on conventional highways.

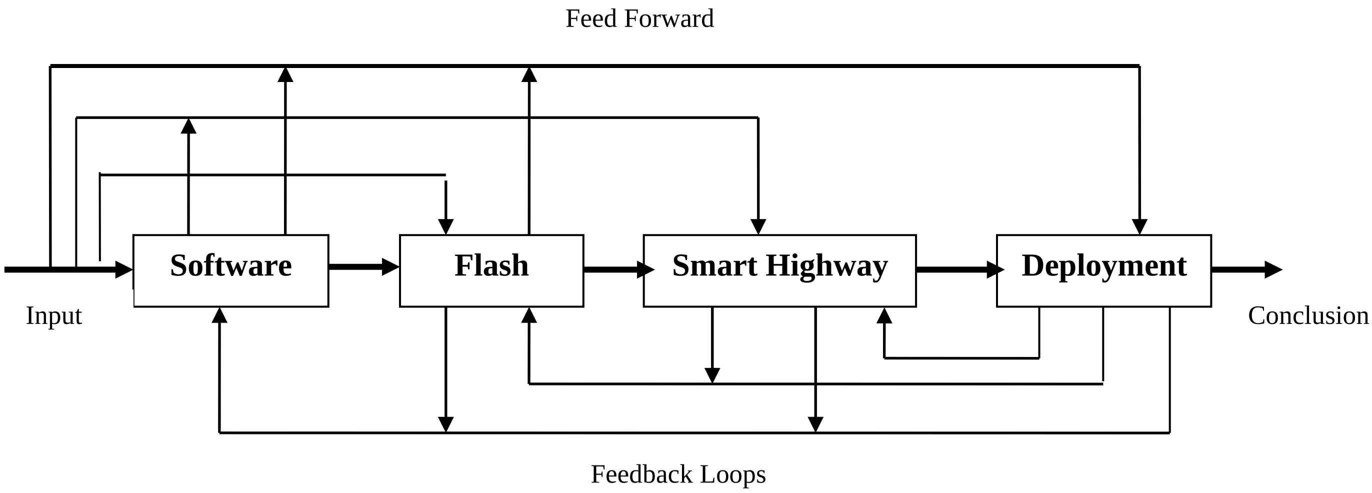

Figure 2. Four block evaluation and experimentation framework for AHS.

These four blocks can be considered as the building blocks of a comprehensive testing and evaluation methodology for AHS. The input can be a hypothesis, a model, or technologies. The evaluation and testing procedure defined by this methodology is not seen as a single feedthrough four-step process, but as having some feedback and feedforward loops depending on the results obtained at each block. These loops represent the changes made to the hypothesis, model or the technological concept. Hardware tests are important since they provide the means to validate computer results or to modify them in the case of discrepancies, due to unmodeled or inadequately modeled dynamics. Without hardware testing, it would be foolhardy to jump into actual implementation. For instance, the FLASH Laboratory could be used to improve the computer simulation via scale model tests before starting the tests with full scale vehicles.

IV. 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.

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. Table 1 shows these alternative concepts and four functions that they can address – vehicle positioning, lane changing, dealing with obstructions in the road, and managing congestion.

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.

V. NATIONAL AUTOMATED HIGHWAY SYSTEM RESEARCH PROGRAM: LIMITATIONS OF PUBLIC-PRIVATE PARTNERSHIP

The National Automated Highway System Research Program (NAHSRP) enhanced the transportation community’s understanding and recognition of the numerous technical and practical issues associated with fully automated vehicles and highways. The 1997 San Diego demonstration was an opportunity to test the capabilities of different automation technologies in a controlled yet complex setting of vehicle and roadways. In addition, the consortium examined several automated highway system concepts, and its system assessments flagged important issues that will warrant early consideration as automation capabilities are developed. Despite these achievements, the Transportation Research Board committee evaluating the program in 1998 argued that the National Automated Highway System Consortium was not effective in achieving its goals. The TRB committee pointed out several major problems of the program. They can be summarized as the lack of consensus in publicprivate partnership and the consortium's conflicting dual responsibilities as both an evaluator and as a promoter of AHS. The following sections discuss these issues. The Difficulty of Consensus Building The consortium included nearly 100 associate members who represented nine categories of stakeholders: the vehicle industry, government agencies, the highway design industry, vehicle electronics, environmental interests, trucking operators, transit operators, transportation users and the insurance industry. This group had widely varying perspectives. The consortium generally sought a fully automated highway concept, but there were conflicting views as to the steps and strategy of deployment. The consortium in general suggested the importance of operating full automation on dedicated lanes to maximize its benefits. However, among the associate members, many state and local officials were skeptical and concerned about the political difficulties of investing in dedicated lanes devoted to fully automated vehicles. Environmentalists and planners were further concerned about overall effects on vehicle emissions, land use, and increase of traffic volumes. Moreover, vehicle manufacturers and insurers were mainly interested in how liability issues could be resolved. Research focused on demonstrating the automated technology, with less attention given to the diverse political and institutional issues raised by stakeholders. Consequently, the consortium did not make much progress on finding ways to resolve these latter issues and reach an agreement. The focus on technical development and deployment largely resulted from the consortium's dual, yet conflicting responsibilities.

VI. THE CONSORTIUM'S STRUCTURAL AND OPERATIONAL LIMITATIONS

The inflexibility of the partnership

Given the consortium's role as a promoter, its inclusive, consensus building structure limited program flexibility and complicated management. The fixed membership, preallocated budgets, and consensus decision-making process slowed its responsiveness, and it made it difficult for the partnership to respond to changing government funding levels and priorities. By the same token, given the consortium's responsibility for evaluation having members with an interest in favorable outcomes supporting deployment of new technologies and concepts affected the objectivity of the work, and hindered the effectiveness of open discussion on many issues during the collaborative process.

The overly optimistic mission

The consortium initially envisioned that it could demonstrate fully-automated highway technologies and scenarios in three years and to select a preferred system within seven years. However, selection of the system is closely related to active outreach to transportation users and providers to reach a meaningful agreement. Given that the consortium failed to resolve the social and institutional issues entangled with automated highway system, and that its dual, yet conflicting role undermined the effectiveness of the partnership, this mission was excessively optimistic and difficult to achieve.

Failure to address the non-technological issues

The consortium focused on the technical aspects of automated driving (e.g. obstacle detection, platooning, and lane-keeping). Given the overly optimisitic mission, this focus was perhaps unavoidable. While some stakeholders emphasized the need to address the many non-technical concerns (e.g. liability, socioeconomic impacts), these concerns were not given enough attention, leaving them as major barriers to further action.

Public Acceptance

For AHS to obtain public acceptance, it must be designed and implemented with many complex human factors45 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.46 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.

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 late1970'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.

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.
   e) Making driving more accessible to less able drivers.
4. **Improve environmental efficiencies by:**
   (a) Reducing emissions per vehicle-mile travelled.
   (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:**
   (d) Providing a stronger national economy and increasing global competitiveness.
   (e) Increasing jobs in research and development and in early ITS deployment.
   (f) Facilitating technology transfer (e.g., from military to civilian use).

(g) Creating new U.S. automotive products and new technology-based industry to compete in the international marketplace.

VII. METHODOLOGY

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.

BENEFITS OF AHS

Recent research has proven that the benefits of AHS on the performance of the existing U.S. transportation system will, over time, be enormous and far-reaching. Over the long term, traffic overcrowding will be reduced; safety will be improved to produce a virtually collision-free environment; driving will be predictable and consistent. More specifically, the advantages of AHS implementation include the following.

- More vehicles can be accommodated on the highway, and the number of vehicles per hour per lane can be considerably increased as traffic speeds are standardized and increased and headway distances are decreased.
- Driving safety will be significantly greater than present; while the human error factor will be removed.
- High-performance driving can be conducted without regard to weather and environmental conditions. Fog, haze, low sun angle, rain, blowing dirt, snow, darkness, and other conditions affecting driver visibility and thus, safety and traffic flow will no longer obstruct progress.
- All drivers using AHS can be safe, efficient drivers. AHS offers enhanced mobility for people with disabilities, the elderly, and less experienced drivers.
- Fuel consumption and emissions can be reduced. In other way these reductions will be accomplished because start-and-stop driving will be minimized and because on-board sensors will be monitored to ensure that the vehicle is operating at top performance. In the long term, the AHS can support future vehicle force/fuel designs.
- Land can be used more efficiently and roads will not need to take up as much room, since AHS facilities should allow for more effective use of the right of way.
- More competent commercial operations; and commercial trucking can realize better trip reliability to support "just-in-time" delivery.
- More proficient transit operations. Transit operations can be automated, extending the flexibility and convenience of the transit option to increase ridership and service.

VIII. CONCLUSION

It is important to demonstrate that AHS brings major transportation benefits in terms of safety, efficiency, affordability and usability, and environment in order to achieve its development goals. Yet, as we can see in the case of NAHSRP, program acceptance is not just based solely on technological capabilities but also on people’s social, economic, and environmental concerns.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.

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