The Institute of
Electrical and
Electronics Engineers

IEEE

Automated Highway Systems

Incremental Deployment as a Solution for The Future of Transportation

Luke D. Postema
Washington Internships for
Students of Engineering
August 1998

WISE 1998

About the Author

Luke Postema is a senior electrical engineering major at Cedarville College in Cedarville, Ohio. This paper is the product of work done through the Washington Internships for Students of Engineering (WISE) program in the summer of 1998. His internship was sponsored by the Institute of Electrical and Electronics Engineers (IEEE).

WISE Program

The Washington Internships for Students of Engineering is a ten-week summer program for outstanding engineering students who have completed their junior year of undergraduate study and display evidence of leadership skills and interest in public policy. The students spend the summer in Washington, DC learning how engineers are specially equipped to influence public policy as it relates to scientific or technical fields. Frequent meetings with government and private offices expose the interns to a variety of public policy issues. Each student researches an issue through literature surveys and interviews with experts and completes a policy paper for their sponsoring society. For more information about the WISE program, contact WISE, Attn.: Anne Hickox, 400 Commonwealth Dr., Warrendale, PA 15096-0001 or on the Internet: http://www.ieee.org/wise.

Acknowledgments

The author would like to express his thanks to the IEEE-USA office for their sponsorship and Chris Brantley especially for his help with this paper. Thanks also to Dr. Wolf Yeigh for his planning and leadership this summer. Thanks to the many people who have taken time this summer to host the WISE interns and have shown willingness and excitement in teaching. Special thanks to Mr. Chuck Allport who encouraged me to apply for WISE.

Abstract

Automation can reduce accidents and congestion on highways by using computers to drive vehicles. Some issues need to be resolved before Automated Highway Systems (AHS) can be used. Ideally, AHS would only be used on dedicated lanes, but mixed automated/manual traffic is seen as a possible stepping stone. Engineers must also decide on the roles of onboard and infrastructure intelligence. AHS must also overcome the social barrier of legal liability. Incremental deployment can be used to solve these problems by introducing vehicle intelligence in small steps. The US government should establish a review board to oversee the time schedule of each incremental step.

Executive Summary

Automated Highways Systems (AHS) use sensors, actuators, and computer technology to drive vehicles without human control. Vehicles under automated control will be involved in fewer accidents and reduce congestion in high traffic density urban areas. AHS could reduce vehicle collisions by 31 to 85 percent. Automation could also reduce the estimated $50 billion in productivity that Americans waste each year stopped in traffic. Efficiency benefits would create environmental benefits since smoother traffic flow would result in lower fuel consumption and exhaust emissions.

Recognizing the potential benefits of AHS, Congress legislated in the Intermodal Surface Transportation Efficiency Act of 1991 that research should be done and a prototype AHS should be demonstrated by 1997. In 1994, the National Automated Highway System Consortium (NAHSC) was created to take over the work of building the first working AHS. They chose the HOV lanes on a piece of I-15 north of San Diego, California for the demonstration, which took place in August of 1997. The NAHSC outfitted eight vehicles with magnetometers, radar sensors, computers, and communications equipment for the demonstration. The demonstration was a success and it proved that AHS could solve some of the nation's traffic problems. Congress replaced the NAHSC with the Intelligent Vehicle Initiative (IVI) in 1997 in an attempt to make AHS more "human-centered". The IVI program has changed the primary goal of AHS from efficiency to safety.

Engineers first thought that automated vehicles would have to run on dedicated lanes only, apart from manual traffic. However, since the cost of new lanes could be near $30 million per mile, a mixed traffic scenario has been adopted. Mixed traffic is seen as an intermediate step to dedicated lanes, which provide greater safety and efficiency benefits.

Another question that engineers need to answer is how intelligence and information should be distributed between vehicles and the roadway. Some AHS scenarios incorporate a predominantly vehicle-centered AHS, while others depend strongly on a smart infrastructure system to guide vehicles. The best solution is most likely a system with both complex in-vehicle systems and an intelligent infrastructure, but that does not rely completely on either. The vehicle intelligence and infrastructure intelligence should overlap and be combined for higher safety and redundancy. However, this raises the question of where ultimate control of the vehicle resides when onboard systems do not agree with infrastructure commands.

The means by which automated vehicles will follow their lanes is another issue that engineers have not agreed on. Several types of systems have been developed, but magnetic markers will be the most widely used method of lane keeping in the future.

Government and industry have concerns about their legal liability in the event of an accident. There are no legal safeguards are in place. It is questionable whether consumers will accept full legal responsibility. Tort reform might help this problem somewhat, but it is clear that a better solution is necessary.

Incremental or evolutionary deployment is the best method to solve these problems and begin the use of AHS technology to solve safety and efficiency problems. Engineers hope that by adding AHS features step by step, they can overcome the barriers of cost and liability. Dedicated lanes and an intelligent infrastructure would also be incrementally introduced allowing a coordinated progression of road and vehicle.

Level 0 intelligence is available in some cars today as an option called Intelligent Cruise Control. A level 0 vehicle has the ability to adjust its speed to follow the preceding vehicle at a safe distance. Level 0 vehicles are not equipped to communicate to other intelligent vehicles or infrastructure. The addition of communications gear would give an intelligent vehicle the classification of Level 1. Level 2 would bring both the throttle and brake under computer control. Level 3 would incorporate automatic lane keeping abilities. Level 4 vehicles would have sensors to detect other vehicles so that the onboard computer could make lane changes and merging maneuvers. Level 5 adds the intelligence to sense threatening situations and automatically choose a safe escape from potential accidents.

The US government should control the incremental deployment schedule so that all states and industries can plan for the future. There are several options available for the AHS deployment schedule. First, incremental deployment could not be used and AHS could be deployed in one step. This option is risky because liability is unclear, the public might not accept the technology, and the initial costs are very high. The second option would be to take an accelerated deployment schedule or two years or less between intelligence levels. While not quite as risky, there is still some question about popular acceptance and the impacts this could have on new and used car markets. The third option is the adaptive incremental approach which gives the government flexibility in deciding when the next level of intelligence will become available. Since some of the incremental steps may take less time to develop, the deployment schedule should not be rigid. The last option is a decelerated deployment which allows a minimum of four years between incremental steps. Four years would give engineers sufficient time to create a problem-free system both technologically and socially. However, the public might view a mandatory waiting period as unnecessary red tape that holds back promising technology.

The US government should set up a review board to decide when each level of intelligence should be introduced. The board would study potential social and technological problems that could occur when the next intelligence level becomes available. After those problems are solved, the review board would authorize the next level of AHS.

Table of Contents

I. Introduction and Background

What is AHS?

An Automated Highway System is a vehicle and road based system that can drive a vehicle automatically. This is done using sensors that serve as the vehicle's eyes, determining lane position and the speed and location of other vehicles. Actuators on the throttle, brake, and steering wheel give the vehicle the commands that a driver normally would. AHS vehicles often also have equipment to communicate with other AHS vehicles. The concept of an Automated Highway has been around for a long time. General Motors displayed a working model of an automated highway at the 1939 World's Fair in New York City [8]. Automated trains have been in use since the 1960's. But it has not been until recently that the technology has become available to build Automated highways and vehicles.

Why Automated Highways?

Safety

Ninety percent of all vehicle accidents result from driver-related factors – inattentiveness, inability to respond quickly enough, or bad driving decisions [1]. Over 40,000 people die annually in motor vehicle accidents and property damage is estimated at over $150 billion [2]. Electronic systems that never take over some or all of the driver's responsibilities are the most promising method of reducing these accidents. Analyses of causes show that highway accidents could be reduced between 31 and 85 percent with the use of electronic collision avoidance technologies [3, 4] and fatal crashes could be reduced by at least 50 percent [5].

Efficiency

The National highway system carries eighty-nine percent of passenger ground-miles traveled and thirty-two percent of the ton-miles of commercial freight travel [6]. The number of vehicles on the roads has doubled in the last ten years while highway capacity has for the most part, remained the same. Consequently, the average speed on urban highways and crowded corridors during rush hour is 36 miles per hour. This loss of time and productivity costs the US $50 billion annually [7]. One solution that engineers are exploring now is an Automated Highway System (AHS). By reducing or eliminating driver error and placing cars more closely together safely on the highways, highway throughput could be doubled or tripled [6].

Air Quality

AHS has the potential to reduce traffic delays and traffic jams. As a result, fewer vehicles will be stopped in traffic where they continue to pollute while they aren't going anywhere. Smoothing out the flow of traffic would also reduce fuel consumption. AHS could eliminate the "slinky effect" of stop and go highway driving which accounts for most vehicular emissions and fuel use [6].

History of AHS

AHS from 1992-94

In 1991, Congress passed the Intermodal Surface Transportation Efficiency Act (ISTEA) which introduced funding for many Intelligent Transportation Systems (ITS). Part B, Section 6054 (b) of that Act reads:

> The Secretary shall develop an automated highway and vehicle prototype from which future fully automated intelligent vehicle-highway systems can be developed. Such development shall include research in human factors to ensure the success of the man-machine relationship. The goal of this program is to have the first fully automated roadway or an automated test track in operation by 1997. This system shall accommodate installation of equipment in new and existing motor vehicles. [9]

AHS was at that time called Intelligent Vehicle-Highway Systems (IVHS). Falling under the general category of ITS, the stated goals of the system were:

1. Enhancement of surface transportation efficiency
2. Achievement of national transportation safety goals
3. Protection and enhancement of the natural environment and communities affected by surface transportation
4. Accommodation of the needs of all users of surface transportation systems
5. Improvement of the Nation's ability to respond to emergencies and natural disasters

Because these goals were so broad, the US Department of Transportation (USDOT) formed the Joint Program Office (JPO) which brought together the Federal Highway Administration, Federal Transit Administration, and National Highway Traffic Safety Administration and several other DOT administrations. From 1992-1994, only research and analysis on IVHS was done. Engineers mainly worked on human factors research and traffic safety analysis.

AHS from 1994-97

In 1994, the work in IVHS was contracted out to the National Automated Highway Systems Consortium (NAHSC), a partnership of government, industry, and universities. 80 percent of funding came from the USDOT and the remaining 20 percent from the NAHSC partners. It was their job to design and demonstrate a working Automated Highway System by the end of 1997. They began by establishing design and performance objectives and defined several Representative System Configurations (RSCs). They then chose the best RSC and built prototype vehicles and a test roadway.

In August of 1997, the NAHSC performed its "Proof-of-Technical-Feasibility Demonstration". Its purpose was to show Congress and the world that automated highways are possible and that they do provide the expected safety and efficiency benefits. Eight Buick LeSabres were equipped with throttle, brake, and steering actuators, magnetometers in the front and rear bumpers, a forward-looking radar, communications equipment, and two Pentium computers. Ceramic magnets 1.2 meters apart were imbedded into the roadway so that the vehicles could keep their lanes. A 7.6-mile stretch of Interstate 15 north of downtown San Diego, California for the test track. The high-occupancy vehicle lanes were used because they were separated from manual traffic. The eight vehicles drove a total of about 8,000 miles without any safety incidents [7]. The NAHSC was decommissioned after it had achieved its goals of designing and building the first AHS.

AHS from 1997-98

In 1997, the USDOT established the Intelligent Vehicle Initiative (IVI) to facilitate further research and development. The IVI combines three closely related areas of intelligent vehicle research. They are:

1. Driver-Vehicle Interface. This includes vision enhancement systems and navigational/route guidance systems. Research in this area also focuses on human factors issues related to efficient driver controls and displays;

2. Collision-avoidance systems. This includes systems that warn drivers of potential threats and systems that take control of a vehicle temporarily to avoid an accident; and,

3. Automated Highway Systems. This includes all systems that give full or partial control of the vehicle to computer control.

Not only does the IVI program combine research from three different areas, the USDOT has also chosen to change the goals of intelligent vehicle research. Under the

ISTEA legislation, efficiency was the primary goal and concerns for safety, equity, and liability were often made secondary. The IVI plans to foster "Human-Centered design" in all vehicle technologies. This is done by changing the program goals. The Primary Goal of the IVI is to "Reduce highway crashes and resulting injuries and fatalities." The secondary goals are:

- Mobility - Improve public access to activities, goods and services;
- Efficiency - Improve the utilization of the existing highway system and reduce travel time;
- Productivity - Improve the economic efficiency of the Nation's highway transportation system and reduce operating costs; and
- Environmental Quality - Reduce motor vehicle fuel consumption and emissions [2].

By changing the goals of the program, the IVI focuses on developing technology that will help drivers make better decisions and drive more comfortably and safely. Donald Reed of the Society of Automotive Engineers (SAE) published *Automotive Engineering* magazine notes that:

> To fulfill program requirements, the IVI must identify and conduct the necessary research to ensure that driver warning, driver assistance, driver intervention, and travel information systems work effectively and reliably in both independent and integrated modes. The research must also ensure that these elements operate in a consistent and efficient manner and are easily understood by drivers, and that drivers accept and use the systems. [10]

Despite its brief history, AHS has undergone major shifts in design and purpose. Many questions remain unanswered, but the IVI program has pointed AHS in a new direction, better suited to take advantage of available technology.

II. Issues in AHS

Presently, the field of AHS faces some important problems and needs to resolve some important issues. The USDOT, Congress, the auto industry and consumers are asking the same questions. Three of the most important issues that challenge AHS are surveyed in this report. They are:

A. Mixed Automated/Manual Traffic or Dedicated AHS Lanes

B. Low Level or High Level of Intelligent Highway Infrastructure

C. Liability

This section will explain each issue and its history, give the pros and cons of differing opinions, and discuss what is being done now to solve each problem.

The outcome of these conflict points will determine the ultimate success or failure of the AHS program. It is important that policy makers and engineers work together to find solutions that are technologically feasible, socially acceptable, and that accomplish the goals set forth by Congress. Much research has been done and is being done now on these three issues as they relate to human factors, economic impact, land use impact, traffic safety and efficiency, and cost to benefit ratios. An overview of that research will be presented here.

A. Mixed Automated/Manual Traffic or Dedicated AHS Lanes

Dedicated Lanes

There is a question whether automated vehicles should drive on normal roadways with manual drivers or on separate lanes built for automated use only. Cost and equity must be weighed with safety and efficiency to find an elegant solution to this question.

History

For the first few years of AHS under the ISTEA legislation, the predominant thinking among engineers was to plan for dedicated lanes. Many factors influenced that decision. Most importantly, they did not know how to deal with the random factor of human drivers. Engineers knew that if they could control and coordinate every vehicle on a set of dedicated lanes, traffic accidents and slowdowns could be virtually eliminated. The ideal traffic situation would be one where every lane change and merging maneuver, acceleration and braking is controlled by computers. This would eliminate the human error that causes accidents and slows traffic. The early thinking was that these benefits could not be gained in a mixed traffic scenario because human drivers behave randomly, so engineers planned to use AHS only on dedicated lanes. One more reason for dedicated lanes was that proposed systems of that time (1991-95) were very infrastructure dependent. Planners thought that automated lanes would need to be highly specialized, therefore should be reserved for automated vehicles, and not crowded by manual vehicles [11].

Safety features

After it was decided that dedicated lanes would be necessary, there was a question of how those lanes would be separated from the rest of the highway and how automated vehicles would enter and exit the lanes. Most engineers agreed that concrete barriers with chain-link fencing above them would provide the necessary isolation from manual traffic. They chose such drastic separation because of the potential difficulty that automated vehicles could have with road obstacles (stalled cars, animals, or parts thereof). Automated vehicles cannot detect and avoid obstacles with nearly as much efficiency as human drivers can [11]. Engineers also determined that entrance onto the dedicated AHS lanes should require some kind of vehicle system diagnostic check. Before a vehicle could enter the lanes, the highway infrastructure should communicate with the vehicle to verify that its communications equipment, navigation computer and vehicle control actuators are fully functional. It would be unsafe for a malfunctioning vehicle to enter automated traffic. Exiting the automated lanes would require a check that the driver is awake and prepared to take control of the vehicle.

Costs

The largest factor that led engineers to consider a mixed traffic scenario was cost. It was estimated that dedicated lanes could cost up to $30 million per mile for design, right of way acquisition, and construction [12]. Many urban areas that could benefit most from AHS simply have no room to add more lanes to existing highways. From an economic point of view, the cost/benefit ratio of AHS must be compared to conventional highways and mass transportation systems. At $30 million per mile and with benefits that will not be realized until many AHS equipped vehicles are on the roads, dedicated lanes face large financial and political barriers. In contrast, the California PATH (Partners for Advanced Transit and Highways) program on the I-15 corridor has demonstrated a mixed traffic AHS infrastructure for around $10,000 per mile [7].

Equity

Another recently acknowledged problem with dedicated lanes is the potential lack of equity. Prototype AHS equipped vehicles have up to $200,000 of automation equipment. This includes numerous sensors to detect lane position, location of other vehicles and road conditions, actuators for the throttle, brake and steering, extensive communications gear, and multiple Pentium processors [7]. When the systems become commercially available, carmakers hope to offer AHS equipment as a $1000-$2500 option on new vehicles or perhaps more for upgrade of an older vehicle [13]. It is unlikely that the average consumer will want to invest that much money in a system that could only be used in the few places that have dedicated AHS lanes. The wealthy and elite may be the only ones to buy the AHS option. If that becomes the case, dedicated AHS lanes could become a publicly funded highway used only by those wealthy enough to afford AHS equipped vehicles. This is a major political and social barrier to dedicated lanes.

Infrastructure needs

The last and most important problem with the use of dedicated lanes is a question inherent in all infrastructure dependent jumps in technology. Which comes first, the chicken or the egg? Cities do not want to invest $30 million per mile to build automated lanes before automakers have made available and people have purchased vehicles to drive on those lanes. And automakers do not want to build and people do not want to buy AHS vehicles before dedicated lanes are built. For dedicated lanes to become a reality, large infrastructure investments would have to be made on the hope that the vehicles would quickly occupy the AHS lanes. Cities and private investors are unwilling to take that risk this early in the technology development. On the flip side of that coin, consumers will not buy cars with the AHS option in hopes that they may get to use it someday.

Mixed Traffic

All of these factors have led engineers and planners to more closely consider a mixed traffic scenario. Mixed traffic would solve the problems of cost, equity, and a large infrastructure investment. However, some of the safety and efficiency benefits would be lost or reduced. Engineers had hoped with dedicated lanes to completely eliminate traffic accidents. In a mixed traffic scenario, the most they could hope for is that no automated vehicles would be the cause of an accident. Efficiency would also be reduced since high speed, close-spaced platooning could cause a safety hazard in mixed traffic.

Platooning

Platooning is considered the best way to increase highway capacity and decrease delays. Automated vehicles will have the ability to communicate to each other information about speed, headway (distance between vehicles), braking ability and other factors that would enable them to follow each other very closely under automated control. Braking and acceleration actions could be communicated electronically so that even with very short headways (~1m), rear-end collisions could still be avoided. Engineers estimated that platooning could allow up to three times as many vehicles per lane compared to manual traffic. There are also aerodynamic advantages of platoons which would add fuel mileage and emissions advantages [6]. Obviously platooning raises questions about safety in a platoon of mixed vehicle types with largely variable braking ability or platooning on wet or icy road conditions. This paper will not address those issues since that is primarily an engineering problem and not a policy question. There has been much research into ideal spacing distance and estimation of braking ability.

If platoons were to be used in a mixed traffic scenario, some restrictions would be necessary. First, the number of vehicles in a platoon might have to be limited. A platoon of six or more cars could block any mixed vehicles from entering their lane. If that large platoon was driving in the right lane, it could prohibit other vehicles from merging onto the highway or changing lanes to get off the highway. This is because drivers of automated vehicles are less likely to make room for other vehicles since that would require them to override automatic control to make room for manual vehicles. In many cases, this would be an annoyance to other drivers. In some cases, it could cause serious accidents.

Conclusion

Without the advantage of increased efficiency through platooning, the only advantage of using automation in mixed traffic is improved safety. Although safety is an important improvement, it may not be enough to justify investment. The cost/benefit ratio may be too low for government and consumers to make an investment, especially since the value of added safety is difficult to measure. However, mixed traffic intelligent vehicles may be an important first step in the use of AHS that will lead to the building of more and more dedicated lanes. Vehicles should be able to run in either scenario, but perhaps would have some functions limited while driving in mixed traffic. As more AHS equipped vehicles are on the roads, cities and states will begin to build dedicated lanes which will maximize the efficiency of the highway system. If the new dedicated lanes only displaced non-AHS lanes and were not entirely new roadways, there would also be significant cost savings over the construction of new lanes.

B. How should Traffic Intelligence and information be distributed between vehicles and the roadway?

The two necessary ingredients of an automated highway system are information and intelligence. Information about other vehicles and the road and intelligence to make decisions based on that information. The information gathering system and the decision-making system must be distributed between the road and the vehicles. Ideally, there would be some overlap for redundancy. Engineers must balance cost, performance, reliability, and safety when deciding what should be the functions of the infrastructure and the vehicles.

Intelligent infrastructure vs. intelligent vehicles

Infrastructure intelligence

The extreme case of an intelligent infrastructure AHS system would be one where the roadway has complete control over every vehicle. In this type of system, each vehicle would require some communication equipment and actuators on the throttle, brake and steering. Vehicles would become "remote controlled cars". The roadway infrastructure would need communication beacons every few hundred feet, especially to guide vehicles through curves. The infrastructure would also control lane changing, merging, and platooning of each vehicle. Computer systems capable of running such a system would be very expensive and must be 100% reliable. Obviously, this is an extreme scenario, but some things can be learned about the advantages and disadvantages of an intelligent infrastructure from it.

Vehicle Intelligence

The other extreme would be the complete absence of new infrastructure. In this type of system, sensors onboard the vehicles would need to read lane striping, sense other vehicles and obstacles, and communicate with other AHS equipped vehicles for merging and platooning maneuvers. There are, in fact, prototype vehicles under testing that use video imaging to read lane striping, radar or laser ranging systems to determine proximity and relative velocity of other vehicles, and communications systems that enhance safety by coordinating some actions and sharing information about vehicle locations. This type of system would require more complex sensors and onboard computing than an infrastructure dependent system.

Costs

If most of the intelligence is onboard the vehicles, the cost of the system will be passed on to the consumers who buy those cars. On the other hand, a highly intelligent highway infrastructure could cost millions, or even billions of taxpayer dollars. Engineers need to balance vehicle cost, infrastructure cost and total system cost in the design of AHS systems. Since the distribution of costs and money are largely tied up in this issue, all of the stakeholders have strong opinions.

Advantages and disadvantages of Intelligent Infrastructure systems

The advantages of an infrastructure dependent system are safety and efficiency. One single controlling computer can make better decisions than hundreds of onboard computers which are all trying to communicate with each other to make their own decisions. Infrastructure systems also tend to be more reliable since size, external appearance and 12 volts of electrical potential generally limit onboard systems. Onboard systems are also vulnerable to harsh environments including dirt, vibrations and inclement weather (ground based systems can be shielded from these effects). One other consideration is the quality of onboard sensors available. For example, if the range of any available forward-looking sensors is smaller than the stopping distance of the vehicle, those sensors cannot prevent a collision with a fixed object in the roadway.

Totally infrastructure dependent systems have a higher cost than vehicle dependent systems. Since the roadways will be paid for by taxpayer dollars, another question of equity is involved. Poorer citizens should not have to pay for highways that can only be taken advantage of by the wealthy who can afford AHS equipped vehicles.

Finally, the most important question of infrastructure dependent systems is system integrity. Could a hacker break into the system and cause traffic delays, accidents, or even fatalities? To what extent would the flow of traffic be affected if a car were to veer off the road and strike a communications beacon? If all of the traffic intelligence lies in the infrastructure, AHS vehicles cannot drive without it.

Advantages of Intelligent Vehicle systems

The advantages of vehicle based systems are faster deployment and wider use. These advantages are derived from the fact that it could take years to decide which highways and corridors to build an intelligent infrastructure on. It could take less time for intelligent vehicle systems to become available. Non-infrastructure dependent systems could then be used on any roads, not just those that had been upgraded. Consumers could get more use out of an intelligent vehicle system.

Conclusion

The solution to this question lies somewhere between the two extremes. A wise distribution of intelligence promises maximum benefits at a lower cost. Overlapping or redundant vehicle and infrastructure intelligence would provide a higher level of safety, reliability, and system integrity. Infrastructure control is more efficient for lane changing, merging and platoon management. However, vehicle systems have a better ability to sense other vehicles and obstacles, especially in a mixed traffic scenario [14].

Lane keeping

The next question to be addressed is how intelligent vehicles should keep their lanes. The three main types of systems that are being used today are video imaging systems, radar reflective striping, and magnetic markers. Video imaging is an exciting technology because it can read current lane striping so it would require no road improvements. However, the onboard systems are very complex and costly. Radar requires special reflective lane striping that can be seen by onboard sensors. The cost per mile for the new striping is very low and the onboard systems are relatively cheap.

The majority of systems being tested today use onboard magnetometers that read small magnetic "nails" in the roadbed. One advantage of magnetic markers and sensors is that they are not degraded by weather and could potentially keep the car on the road better than a human driver could during harsh weather. Magnetometers are also less effected by dirt and mud than the other systems. The cost per mile to install the magnetic nails is approximately $10,000, but onboard magnetometers are relatively cheap [15].

Engineers have three factors to weigh in this decision: infrastructure cost, vehicle system cost, and reliability. Unfortunately, there is no clear winner of the three. However, since safety is the primary goal of the AHS under the IVI program, magnetic markers are currently the best approach and are the most likely to be used. The cost of building a new highway with magnetic markers installed during construction would be much lower than the $10,000 per mile it would cost to upgrade an existing highway. If it were to be used on a dedicated lane, that lane could be narrower than regular lanes since magnetic systems can hold their position better than humans can. These narrower lanes would save in construction costs and would allow more lanes in urban areas where right of way is limited.

Level of communication

The third question to be answered in this topic is the level of vehicle to vehicle and vehicle to road communication. Some stakeholders are concerned that driver's privacy could be compromised if a central computer can obtain his origin and destination of travel. It is also undesirable, from the consumer's point of view, for the infrastructure to have the ability to monitor vehicle speed and possibly even issue traffic tickets. Obviously, the infrastructure must be given this information, but safeguards must be set up to guard user privacy.

Should control be given to infrastructure or vehicles?

Finally, the last question of a distributed intelligence is the division of vehicle control. Should the vehicles or the infrastructure have ultimate control of the vehicle? This becomes an especially difficult question when the two systems are giving conflicting instructions. If the infrastructure issued an emergency brake command, but the vehicle's forward-looking sensor did not detect a problem, what should the vehicle do? Either braking or maintaining speed could cause an accident. In another situation, the infrastructure could tell a vehicle to change lanes, but that vehicle's radar might detect another vehicle in that lane.

There is no easy solution to this question. Redundancy is necessary to add safety and reliability, but problems can result when the vehicle and infrastructure issue conflicting instructions. The system then would need to both alert the driver and give him control, or choose the option that will least likely cause an accident.

C. Liability

Liability has been an issue in the AHS program from the beginning. It poses the largest threat to AHS technology because acceptance by automakers, consumers, and the government could be lost if an adequate solution is not found. Because of the danger of platooning and even normal automated control, system malfunctions can cause serious accidents and even fatalities. When those accidents do happen, legal suits could be brought against automakers, drivers, and states if proper safeguards are not installed.

Automakers

Automakers will be unwilling to build AHS vehicles if they could be sued for failure of their systems. Under current law, drivers are responsible for maintaining safe control of their vehicles. If the brakes or steering or any other system were to fail, the driver would be responsible for any accidents that he might cause. This is because drivers are not only responsible to drive safely, but also to maintain their vehicles properly and replace parts that could wear out. Automakers must conform to quality assurance tests which are most commonly Mean Time Between Failure (MTBF) tests. AHS systems would need to have similar quality control procedures [16].

AHS systems must also be "fail soft" and should be robust so that failure of one subsystem does not cause a traffic accident. In many situations, such as platooning or driving on narrow roadways, it would be unsafe for a human driver to be given control of the vehicle. If failure of a subsystem would occur in such a situation, the vehicle should be able to maneuver itself off to the shoulder of the road. A more robust and reliable system would diminish the risk of legal liability.

Government

Another concern is that the parties responsible for construction and maintenance of AHS highways could be held liable for a system failure that results in an accident. Quality controls and maintenance records would be necessary to keep the construction companies and states free from liability.

Drivers

Current AHS systems are said to be “hands off, feet off, brain on”. Although the driver is free from steering, acceleration and braking controls, he is not free to take his mind off the road. Driver input is allowed if he feels that the automated system is not performing as it should. However, drivers should not be required to resolve any unsafe situation [17]. The problem with “brain on” systems is that they are treated as “brain off” systems after they have proven their reliability. After a few hundred hours and several thousand miles of problem free automated driving, the driver’s attention will inevitably shift from the road around him to his morning newspaper or conversations with other passengers. Although AHS systems may warn drivers that they must be in control of their vehicles, a simple warning may not be enough to keep drivers’ attention on the road and their vehicles.

In order to protect drivers from legal liability, there should be required maintenance checkups with a qualified service technician that would insure that the vehicle’s AHS systems are functioning properly and are in good condition. It may also be necessary to certify drivers to drive AHS vehicles.

Tort reform

Overall, attempts should be made to limit tort liability. There needs to be a limit on damages that can be collected from any of the parties involved [18]. Although tort reform has been relatively unsuccessful in many areas, there is good reason to believe that it could work for AHS. The airline industry has established a precedent of liability management [19]. There are many similarities between AHS and the airline industry.

Both systems involve the necessity of quality control in manufacturing control and maintenance checkups. Both also involve a state or federally funded infrastructure. In addition, both involve the transport of passengers who rely on technology and infrastructure to get them to their destination safely. One suggestion that has come from this comparison is that AHS vehicles should be equipped with a data recorder that would help determine the cause of any problems or accidents. AHS can learn a lot from the airline industry regarding liability and consumer acceptance.

Conclusions

The problems and decisions in AHS right now need careful consideration and more research before coming to hasty conclusions. The goals of safety and efficiency must be kept at the forefront of every system without overlooking the important issues of cost, equity and liability. Engineers and policy makers will need to decide together what the best solution is for the future of AHS.

III. Solutions and Policy Options: An Evaluation of the Incremental Approach

One solution that has been suggested and is being pursued by the USDOT is the incremental or evolutionary approach to AHS. This approach adds automated functions one at a time rather than starting with full automated control. This section will discuss the incremental approach, talk about advantages and disadvantages, and provide some policy options that could be used to influence this approach.

Incremental approach

Incremental intelligence levels can be viewed as new car options that make small steps toward full automation. Every few years, automakers would provide a new level of intelligence in vehicles. Intelligence would only be an option on some cars at first, but could soon become a standard feature on some models. Consumers would never be forced to buy the intelligence that is available. Each level needs to be carefully designed to be compatible with past levels and anticipatory of future levels. One primary assumption is that vehicles of all levels will have communications equipment and a main computer for vehicle-to-vehicle and vehicle-to-road communications. The computer could be replaced or loaded with new software to be compatible with new intelligence levels. The second assumption is that each new level will retain all functionality from the previous levels. Some of this Incremental Plan was adapted from [20].

Level 0

Honda currently offers luxury vehicles with an option called Intelligent Cruise Control (ICC). This system uses a forward-looking sensor to measure distance and relative velocity of the preceding vehicle. When the system is engaged, cruising speed can be set as with any standard cruise control. If the sensor detects a slower moving vehicle ahead in its lane, it will let off the throttle and adjust the vehicle speed to match the speed of the car ahead and follow at a safe distance. When the system no longer sees a vehicle in front of it, the cruising speed is resumed. One important thing to note is that this system does not control braking, only throttle position. The current Honda systems do not have communications abilities and therefore will be labeled Level 0 Intelligent Vehicles. The types of collisions this system would prevent are uncommon. Therefore, ICC is primarily sold as a convenience feature and not a safety feature.

Level 1

Level 1 would functionally be equivalent to Level 0, except that Level 1 vehicles would also have communications gear for vehicle to vehicle communication. Vehicles traveling down the same road would share position and speed information. This would add robustness to the system by verifying what the sensors read for position and speed of other vehicles. Large discrepancies would generate an error signal and recommend maintenance of the system. The Level l vehicle could also receive speed commands from the roadway infrastructure. Speed limit beacons could be used to control vehicle speed especially through construction zones or in inclement weather.

Level 2

Level 2 incorporates braking controls into the vehicle's intelligence. This could also be called "Autobrake." The system has the ability to engage emergency braking when it detects an object in the roadway ahead that poses a threat of collision. Level 2 forward-looking sensors may need to be upgraded over Level 1 or 0 sensors. Obstacles would need to be detected at distances well greater than the stopping distance of the vehicle. When an obstacle is seen, the system would determine its relative velocity and calculate the risk of a collision. Prior to the critical point where emergency braking is necessary to avoid a collision, the system should alert the driver of the potential danger. If the driver does not respond within the time necessary to stop and avoid the obstacle, the Autobrake would engage to stop the vehicle. The system acts primarily as a warning system and secondarily to prevent an accident if the driver cannot respond quickly enough.

Levels 1 and 2 together can be called "Autogap" as they can be used to safely control the distance between two vehicles. Autogap allows platooning among Level 2 vehicles which could greatly increase highway capacities (see Section II, *platooning*). Close platoons are possible because each vehicle can communicate with the vehicles behind it to tell them that it is stopping so that they can stop also. However, platooning should have some restrictions in mixed traffic. Studies have also shown that this level of automated control would reduce the slinky effect in heavy traffic [15, 5]. Therefore, Level 2 Intelligence is primarily a safety feature, secondarily a convenience feature, and also has efficiency benefits. Up to this point, there are no necessary infrastructure improvements.

With the Autogap feature installed, drivers may begin to rely on the systems to perform the task of braking for them. At that point, some kind of system self-diagnostic should be in place to verify that the system if working properly. It may also be necessary to require maintenance checkups on intelligent vehicles at 10,000 or 20,000-mile increments [21].

Level 3

Level 3 intelligence gives the vehicle the ability to hold its own lane. There may be some roadway infrastructure necessary such as magnetic nails or reflective striping (See Section II, *Lane keeping*). This level, also called "Autolane", could come in two steps. The first step would be a driver warning system that alerts the driver that he is not keeping his lane. Step two would be full-time automatic steering of the vehicle. This step would require the vehicle to sense the lane and to steer the vehicle to stay within that lane. Engagement of the turn signal would temporarily suspend the action of Autolane. After the new lane has been acquired and the intelligence is able to resume control, the system would signal the driver that he could take his hands off the steering wheel. The Level 3 vehicle may or may not have lane change warning sensors that tell the driver when it is safe to change lanes or merge.

Since Level 3 vehicles have steering actuators, and throttle and brake actuators, they are ready for full AHS control. An Intelligent Infrastructure could be used to coordinate merging and lane changing. However, since the vehicles would not be equipped with 360º sensors those maneuvers would not be safe. Without any type of backup system, the infrastructure could cause an accident.

With Level 3 vehicles on the roads, some areas may wish to add dedicated lanes to maximize efficiency. The lanes could be built at a narrower width than standard lanes since automated vehicles can follow lanes much better than humans can [7]. Dedicated Lanes are not necessary for Autolane, but they would greatly enhance highway efficiency.

Level 3 intelligence has the potential to greatly reduce highway accidents. Some estimates say that 90% of highway accidents are caused by human error [1]. A Level 3 vehicle would never be the cause of an accident, as long as its systems are operating properly. To prevent system failure, it would be necessary for Level 3 vehicles to go through mandatory periodic maintenance inspections.

Level 4

Level 4 would give vehicles the ability to automatically change lanes and merge into traffic. These vehicles must have sensors with 360º coverage that can determine the position and relative velocity of other cars on the highway. Level 4 vehicles would be potentially safer than manual lane changes or merges since the sensors could be designed to eliminate “blind spots”.

Level 4 intelligence would greatly benefit from vehicle to vehicle communication. Level 4 vehicles could broadcast information about the location and speed of every other vehicle that their sensors have located. This information would be beneficial to vehicles of all other intelligence levels. This could also be used to continuously check each vehicle’s sensors. For example, if one Level 4 vehicle tells another Level 4 vehicle what it sees and they do not agree on some things, one or both of the vehicles might have a problem with its sensors. However, false alarms on this type of checkup system might be common. Another benefit of vehicle to vehicle communication would be coordinated merging. If a Level 4 vehicle wanted to get into another lane that was occupied by intelligent vehicles of any level, it could request that those vehicles make room for it.

Level 5

Level 5 would incorporate collision avoidance into the vehicle’s intelligence. No new sensors or actuators would be needed, but a very intelligent computer would be necessary. The reason that this is treated as a new level is that it may take several years to test and verify that automatic collision avoidance can perform as well or better than humans in dangerous driving situations. The Level 5 computer would have the ability to detect threats or hazards to the vehicle. If a threat were perceived, the computer would choose a safe course of action to avoid that threat. The computer may choose to accelerate to avoid a rear-end collision, steer around an obstacle in the road, engage the brakes, or some combination of these actions. If there is no clear path to escape the threat, the system may choose the crash scenario that would least likely result in a fatality. Perhaps Level 5 intelligence could even drive well enough to never be in that situation. As Level 3 gives each vehicle the potential to not be the cause of an accident, Level 5 gives each vehicle the potential to not be involved in any accidents.

From there, the picture of the future gets too fuzzy to discern new levels. Perhaps

Level 7 could incorporate GPS and navigation technology to automatically change highways and choose exits that would be most expedient to travel. Another possibility is to give vehicles the ability to choose alternate routes during congested travel.

Pros and Cons of Incremental Approach

The primary advantage of the incremental approach is that it allows engineers and planners more time to research and plan each level of intelligence. The most advanced systems near the end of the plan would be tackled sometime in the future when more research has been done and technology has advanced. The slow approach also gives the systems time to prove themselves. Liability would not be such a big issue since the risks would be understood better. The step from 4 to 5 is easier to accept than the step from zero intelligence to Level 5. Research indicates that consumers would be open to steady increases in intelligence, but would be opposed to placing blind faith in an full AHS system [18].

Costs are also much less of an issue since infrastructure is not required until the later stages. Dedicated lanes should be added after Level 3 vehicles have saturated the market. An even cost/benefit ratio would occur at approximately 9% penetration of AHS vehicles during peak hours. That is, the savings from increased efficiency and safety would offset the costs if 9% of the VMT in rush hour on a highway were AHS vehicles in AHS lanes. In off-peak hours, a 33% penetration would be necessary for improved highway efficiency [4].

Incremental deployment also provides an elegant solution to the problem of intelligence distribution. In all levels, the vehicle must be controlled by onboard systems, but infrastructure intelligence may be added when it is necessary or when it provides additional safety benefits. The method for lane keeping does not need to be decided until Level 3 deployment, which leaves engineers and planners more time to evaluate each option or develop new ones.

However, as time is the biggest advantage of the incremental approach, it is also the biggest disadvantage. If the US decides on incrementalism, some other country may get to full automation first. Many European countries such as France, Germany, and the Netherlands have plans for some form of AHS. Japan is also investing in research and development of AHS to solve their traffic problems. Being the global leader is important for two reasons. First, the American economy would be boosted by growth of new AHS industries. These industries would have an advantage over foreign industries because they would be given a head start on developing manufacturing processes. When other countries begin to also use AHS systems, American industry could supply the world with AHS vehicle and infrastructure systems. Secondly, American leadership is necessary for the development of standards that will eventually become world standards. As AHS begins to spread to many countries, America has the opportunity to establish system standards that can be shared throughout the world. Disunity and diversity between countries could lead to confusion and slow progress.

Another disadvantage is system upgradeability. Consumers may not want to buy a new intelligent vehicle that will be obsolete in a few years. Nor will consumers want to buy a used vehicle of lower intelligence than what is available in a new car. Fear of obsolescence could cause consumers to not want intelligent vehicles at all.

Policy Options

The Federal Government has several options within its power to change the future of AHS. It controls the system definitions of each Intelligence Level, and the timeline for research, development, and deployment. With these factors, the US government controls how AHS will be used to solve the nation's traffic problems. The USDOT should control the system definitions of each level so that states and automakers will all be in agreement on what the intelligence levels mean. The timeline must also be standardized so that automakers do not need to sell different intelligence levels to different parts of the country. The federal government's role in the deployment of AHS should only be to introduce each intelligence levels for the states to adopt. Some states may choose to build an extensive intelligent infrastructure, while some states that won't benefit as much from AHS may choose not to build new infrastructure. Citizens in those states could still buy intelligent vehicles, but they would not have the infrastructure to support higher levels of AHS in their home states.

The deployment timeline could be set at a very slow or very quick pace. Also, the amount of money appropriated for infrastructure improvements will make or break AHS. This section gives four policy options and evaluates each of them on four criteria: safety, which can be measured in accidents per vehicle mile traveled (VMT); travel efficiency, measured in average rush hour speed or average trip time; short term costs and benefits; and long term costs and benefits.

The Federal Government could not use the incremental approach and go ahead with one step implementation.

The technology is already here to put AHS systems in place. The Government has already spent seven years and many millions of dollars on research, prototyping, and testing. The NAHSC has demonstrated an effective AHS. The next step should be deployment of this technology in a few selected cities or corridors. Consumer acceptance and system performance in terms of safety and efficiency should be measured at these model deployment sites. After two years of successful operation, full AHS would be ready for use all across the nation.

Safety and efficiency benefits of the full AHS system have already been measured on operational tests done by the NAHSC. Redundant and robust systems have achieved safety levels at least five times greater than manual driving. At least half of all fatal auto accidents occur on highways. AHS is the most promising technology available to reduce traffic deaths and expensive accidents. The National Highway Traffic Safety Administration estimates that if all vehicles were equipped with even basic collision avoidance technologies, there would be a 17 percent reduction in vehicle accidents. This would amount to a savings of $26 billion annually [22]. Full AHS could reduce accidents as much as 70 percent [4]. Efficiency would also be increased as automated lanes can carry as much as three times as much traffic as manual lanes. Overall efficiency would be improved, not just in AHS lanes, because the diversion of some traffic into AHS lanes would leave more room on manual lanes and increase the total throughput of the highway.

Near term costs are the largest problem with this option. In the first five years of deployment, the government would spend billions of dollars in infrastructure. The cost of converting 7,500 lane-kilometers to dedicated AHS lanes in and around the nation's cities is an estimated $11 billion. However, near term benefits are slim since it could take several years for consumers to buy AHS equipped vehicles in enough quantity to make AHS lanes financially solvent.

In the long term, the benefits of this option offers greatest opportunities to provide increased safety and efficiency from not only AHS, but other ITS as well. A near term deployment would increase long term benefits since the amount that AHS is used in the future is directly related to how soon AHS deployment begins. Other new ITS programs such as intersection collision avoidance and rail crossing safety systems would benefit from benefit from the use of AHS.

One possible drawback of near term full AHS deployment is the effect of system failures early in deployment. The public could view the technology as dangerous and unproved if accidents occur, especially fatal accidents. It may not be possible to overcome the problem of public perception.

The Federal Government should adopt an accelerated incremental AHS approach.

The US needs to be the world leader in AHS technology. Essentially, all of the components or Levels of intelligence exist in current AHS test vehicles. There should be a span of no more than two years between each intelligence level.

The safety and efficiency benefits coming from this approach will ease the increasing amount of VMT on highways. Vehicle intelligence is seen as the most promising method of managing the increased travel demands in urban areas. The accelerated approach will give planners the ability to increase efficiency to offset increased travel demands. Another benefit would be continued American leadership in AHS technologies. No other nations have adopted a plan as aggressive as this.

One problem with this approach is that some of the intelligence levels may take more than two years to be ready for deployment. It is difficult to predict how long development will take and mandate that it must be ready in two years. Another problem may result from consumers wanting to wait to purchase new vehicles until the next level of intelligence is in use. A new level every two years could affect new car sales in an unpredictable way. The used car market could suffer since consumers might not want to buy a vehicle of lower intelligence level than is currently available. This could severely lower used car values. Intelligent vehicles would then become a financial burden because of their low resale value. More research needs to be done in this area.

The Federal Government should use an adaptive incremental AHS approach.

Some of the steps between Levels of intelligence are easier than others. For example, the step from 4 to 5 is essentially only a software upgrade. The larger steps are ones that incorporate new sensor and actuator systems (Level 2 to 3 and Level 3 to 4). Some steps may take only a year to develop, test, and prove. Some other steps need to be taken slowly and could take up to 5 years to complete. This approach allows the government to assess the traffic needs of the country to decide when each step shows enough potential benefit to be worth the cost. It also could be flexible enough so that the US remains the world leader in AHS.

The best quality of this approach is *flexibility* of the deployment schedule. This flexibility will lead to better quality products and higher consumer acceptance. The short-term costs would be small since the first two levels do not require any new infrastructure. The vehicle systems for the first two levels are also very nearly ready for deployment in new cars. The flexibility would also ensure that the cost to benefit ratio could be kept high in the long term. Each level of intelligence should be deployed only when it would be financially solvent to do so. This keeps government, industry and consumers from buying into a losing technology.

The Federal Government should adopt a decelerated incremental AHS approach.

This would give consumers more time to accept the technology and would ease the burden of liability. AHS is not something that should be rushed into. There should be a minimum of four years between each Level of intelligence so that the systems can be the best they possibly can be. This mandatory waiting would also solve some of the potential problems with intelligent vehicle resale. Resale values would stay high since the life of each model would be at least four years.

In the near term, it would take a while for intelligent vehicles to show significant safety or efficiency benefits. However, the slower approach holds the most potential for consumer readiness and acceptance. For example, in 12-15 years when Level 4 is introduced, intelligent vehicles will make up a large percentage of vehicles on the roads. By that time, there should be many miles of dedicated lanes in place and Level 4 intelligence would immediately show major safety benefits.

The long-term benefits of this approach are probably the best of all four options. Engineers would never be rushed to produce a system which is the best it can be. Four years would be enough time to make several prototypes and test them to find which one is best. There would also be enough time for human factors research and an evaluation of how the public will accept the new technology.

IV. Recommendations

The tradeoffs between these policy options are complex. The first two involve a very large initial investment to deploy the systems. The second two involve essentially the same infrastructure as the first, but the cost is deferred several years. The infrastructure and vehicle intelligence should go down in price over time so the last two options could cost less in the long run.

The immediate and accelerated deployment options could be plagued by low consumer acceptance. It is difficult to assess how consumers will respond to the introduction of these systems. Until safety and reliability have been proven over several years, consumers will not want to invest in these systems. The problem with resale value also needs to be addressed.

The decelerated approach (option 4) is too slow. It would be several years before Level 2, the first safety and efficiency feature, is deployed. Consumers could become too anxious for the next level and feel like that a 4-year span between levels to be unnecessary red tape that only delays the new safety features that they want.

The adaptive incremental approach (option 3) is the best option since it can be flexible over time. Engineers and policy makers can work together to decide when the best time for the next level of intelligence. Together, they can avoid consumer acceptance problems and resale problems and also provide quality systems in a timely manner.

Congress should create a review board that will decide when to introduce each level of intelligence. The review board should be made up of government, industry and consumer groups to provide an unbiased view. To insure the success of intelligent vehicles, the board must examine the following areas prior to deployment of each level:

- Technological feasibility
- Marketability
- Real and perceived risk of accidents and liability
- Cost/benefit ratio of vehicle systems and intelligent infrastructure
- Impact on new and used car markets

The review board should study these areas and provide recommendations to government or industry if the board finds any potential problems. After the board is satisfied that all problems with the next level of AHS have been solved, it is in their power to recommend deployment of that level. The goal of the review board should be to speed along deployment by working with government and industry to solve those problems.

V. Conclusion

In conclusion, Automated Highways are one of the most promising technologies to reduce traffic accidents and urban traffic congestion. At the doorstep of new technology, engineers and policy makers have some important decisions to make that will effect the future of transportation. The problems such as liability, equity and consumer acceptance will require special attention, but there are not any problems that cannot be solved. The technical issues of mixed traffic or dedicated lanes and intelligence distribution can be solved using incremental deployment.

The potential to save lives is what makes this technology so exciting. Over 40,000 people die each year in auto accidents and millions are injured. The use of AHS could eliminate all highway accidents, where most fatal and near-fatal accidents occur. Automated highways can also reduce delays and congestion in urban areas and high-density corridors. Spending less time in traffic could save American workers billions of dollars each year.

Bibliography

1. Recht, Phillip. Deputy Administrator of NHTSA. Presentation given at ITS America Annual Meeting, April 1996.
2. US Department of Transportation, Intelligent Vehicle Initiative, *Business Plan* Washington, DC: 1997.
3. Calspan Corporation, "Precursor Systems Analyses of Automated Highway Systems." Report number FHWA-RD-95-123. November 1994.
4. Delco Electronics Corporation, "Precursor Systems Analyses of Automated Highway Systems." Report number FHWA-RD-95-152. November 1994.
5. National AHS Consortium, Technical Feasibility Demonstration, Event Program, August 1997.
6. About AHS. United States Department Of Transportation. n.d. <http://ahs.volpe.dot.gov/aboutahs/aboutahs.html> (6/8/98).
7. Ashley, Steven. "Smart Cars and automated highways". *Mechanical Engineering*, vol. 120, no. 5, May 1998, pp. 58-62
8. Rillings, James H. "Automated Highways", *Scientific American*. Oct 1997.
9. Intermodal Surface Transportation Efficiency Act of 1991
10. Reed, Donald. "The intelligent vehicle initiative" *Automotive Engineering International*, March 1998, pp. 121-2.
11. Hitchcock, Anthony. "Layout, Design and Operation of a Safe Automated Highway System". California PATH Research Report number UCB-ITS-PRR-95-11. April, 1995.
12. California Partners for Advanced Transit and Highways, "Precursor Systems Analyses of Automated Highway Systems." Report number FHWA-RD-95-155. November 1994.
13. The U.S. Automated Highway System at a Crossroads: A discussion with Project manager Dr. James Rillings. ITS Online <http://www.itsonline.com/nahsc1.html> (June 16, 1998).
14. National Automated Highway System Consortium, *Automated Highway System (AHS) WBS C1 Draft Final Report*, February 16, 1996.
15. Ioannou, Petros. "Evaluation of Mixed Automated/Manual Traffic". California PATH Research Report number UCB-ITS-PRR-98-13, March 1998.
16. Delco Electronics Corporation, "Precursor Systems Analyses of Automated

Highway Systems." Report number FHWA-RD-95-151, November 1994.

17. Battelle Transportation Systems, "Precursor Systems Analyses of Automated Highway Systems." Report Number FHWA-RD-96-044, n.d.
18. Calspan Corporation, "Precursor Systems Analyses of Automated Highway Systems." Report number FHWA-RD-95-135, November 1994.
19. Science Applications International Corporation, "Precursor Systems Analyses of Automated Highway Systems." Report number: FHWA-RD-95-154, February 1995.
20. Rockwell Autonetics Electronics Systems Division, "Precursor Systems Analyses of Automated Highway Systems." Report Number FHWA-RD-96-051, n.d.
21. Rockwell Autonetics Electronics Systems Division, "Precursor Systems Analyses of Automated Highway Systems." Report number: FHWA-RD-96-050, November 1994.
22. U.S. Department of Transportation. *The National Intelligent Transportation Systems Program: Where We've Been & Where We're Going.* Washington, DC: March 1997.