2. Literature Review

2.1 Introduction

While the concept of an automated highway is nothing new – General Motors showcased a working model at the 1939 World's Fair – most of the "serious" work to test for the feasibility of such a system has come fairly recently. Most of this research has led to and cumulated in the recent AHS proof-of-technical-feasibility demonstration put on by the National Automated Highway System Consortium (NAHSC) in San Diego on August 7-10, 1997.

NAHSC presently defines an automated highway system as "a specially equipped roadway on which vehicles can be operated automatically." They go on to describe the vehicles as being "fully capable of operating under driver control on all roads and … able to use many of the AHS features to improve safety on those roads [3]." Because of the relative vagueness of the "official" definition of an AHS, many different concepts exist both in terms of how such a system will operate and what technologies will be used to make the system operate.

While it is generally felt that whichever system is ultimately accepted, the ultimate results will be the same – a large improvement in highway capacity, safety, efficiency, and travel time. The differences come in when looking at what that improvement will be and its effectiveness when tied in with the rest of our transportation network.

2.2 AHS Demonstration

As required by the ISTEA, the NAHSC ran a demonstration of AHS technology in August 1997 on I-15 outside of San Diego, California. While this demonstration did show what the Automated Highway System might look like in the future, its goal was not to establish which

AHS concept would be used but to allay any doubts that developing an AHS is a realistic and obtainable goal.

In an attempt to demonstrate how a potential AHS would work and what potential benefits could be realized to help solve traffic problems, such as increased congestion and decreased safety, six scenarios were run along the test bed [4] [5]. These scenarios were:

- Free-Agent, Multiplatform Scenario
- Platooning Scenario
- Maintenance Scenario
- Control Transition Scenario
- Alternative Technology Scenario
- Evolutionary Scenario

The Free-Agent, Multiplatform Scenario, demonstrated by Carnegie Mellon University and the Metropolitan Transit Authority of Harris County, Texas (Houston Metro), was used to show the potential of automated vehicles operating in non-automated traffic. It was also used to show vehicle-based AHS technologies applied to different vehicle platforms. Using two 40-foot buses, a minivan, and a passenger car, the scenario showcased full automation, obstacle avoidance, collision warning systems, and vehicle-following. Also demonstrated were an automated lane change maneuver and a potential driver interface. The vehicles acted as free agents but had the ability to communicate with one another. Computer vision technology was used for lateral (lane-keeping) control.

The Platooning Scenario was presented by The University of California Program for Advanced Technology on the Highway (PATH). Eight automated cars were platooned with intervehicle distances under ten meters and traveled in a single-file formation guided by magnets embedded in the roadway. The platoon demonstrated the ability to accelerate, decelerate, and stop as a unit. Also demonstrated was the ability to split the platoon to allow for the entry of vehicles and then to rejoin as one platoon. A Heads-Up-Display (HUD) unit was used to communicate to the driver such information as speed, distance to destination, and what maneuver the vehicle is currently executing.

The Maintenance Scenario provided the opportunity to show how an AHS could be kept in a safe operating condition. Two vehicles, the Infrastructure Diagnostic Vehicle (IDV) and the Debris Removal Vehicle (DRV), were used and both were equipped for automated driving operations. The IDV was also designed to conduct monitoring, physical inspection, and preventive maintenance to the AHS infrastructure. While performing these functions the IDV was traveling at highways speeds under full automation. The DRV demonstrated the ability to automatically remove debris from the AHS lanes.

The Control Transition Scenario was used to demonstrate the ability of an automated vehicle to switch between two approaches to AHS. These approaches were infrastructure-to-vehicle communications and vehicle-to-vehicle communications. Two automobiles transitioned between these two approaches while performing automated maneuvers such as platooning, lane changes, starting and stopping, and obstacle detection and avoidance. Also demonstrated was the use of multiple sensor systems to provide back-up support for better reliability and performance.

The Alternative Technology Scenario, by The Ohio State University, was used to show observers another possible option for lateral control besides the magnets used in other scenarios. Two automated cars and one manually operated car demonstrated the ability of an automated vehicle to pass a manually driven vehicle. For lateral control a single camera-based vision system was used along with radar-reflective tape which was installed on the AHS lanes. Also used were low-powered radar for side vehicle detection and a laser system for longitudinal control.

The Evolutionary Scenario was used to showcase the evolution of vehicle automation. Two automated and two non-automated passenger cars were used on the existing highway infrastructure. The vehicles demonstrated lane-departure warning, obstacle-detection warning, blind spot warning, the use of Intelligent Cruise Control for longitudinal control, the use of a vision system for lateral control, the use of laser detection for obstacle avoidance, and automated lane-change maneuvers. These demonstrations were consecutively executed as the vehicles traveled along the highway. Many of the above-mentioned technologies are actually on the market and are being offered today on some higher-end luxury vehicles.

Some of the other elements of an AHS that were demonstrated throughout all of the scenarios are Check-in, Entry, and Exit [6]. The test of Check-in requires vehicles wanting to access the AHS to pass through a check-in station without stopping. One vehicle which did not pass was rejected. The Entry element entailed transferring from manual to automatic control in the multipurpose lane. The vehicle, once successfully under automatic control, would accelerate to the speed of the AHS traffic to prepare to merge. Exit, essentially the reverse of Entry, saw the demerging of the vehicle into the multipurpose lane and then transfer to manual control, with the driver’s confirmation, before exiting the highway.

While many of the scenarios showed off some of the available technologies that can be used to realize the ultimate goal of an operational Automated Highway System, it was not so much a test of the technologies as a demonstration that automation can be accomplished. Realistically, this Demonstration was not needed to prove the feasibility of automation, as the Japanese demonstrated the automation of convoys of vehicles from the same manufacturer and of mixed convoys of vehicles from several different manufacturers in 1995 and 1996, respectively [7]. Even as far back as 1970 was prototype equipment operationally tested. One of the requirements needed to help the eventual implementation of an Automated Highway System is keeping the public educated and informed throughout the development process [8]. This was one of the major goals of the Demonstration, and not just to educate the public but government officials as well [5].

2.3 AHS Operational Concepts

Current AHS concepts on the system's operation can be placed in one of the following five "Concept Families" [9]:

- Independent Vehicle Concept
- Cooperative Concept
- Infrastructure-Supported Concept
- Infrastructure-Assisted Concept
- Adaptable Concept

The Independent Vehicle Concept essentially puts all the smart technology into the vehicle and lets it act individually as a free agent, or a one vehicle platoon [10] [11]. No infrastructure support is required, allowing the vehicle to use the technology on any highway. The Cooperative Concept takes the Independent Vehicle Concept of smart vehicles on dumb roadways and adds intervehicle communication to allow for the coordination of the vehicles' driving operations. The Infrastructure-Supported Concept improves upon the Cooperative Concept by providing dedicated lanes on which smart vehicles can operate. Smart Infrastructure tied into these lanes will provide global system information to assist in vehicle decision-making and operation. The Infrastructure-Assisted Concept has the automated roadside system providing intervehicle coordination during entry, exit, and merging maneuvers, and during emergencies. This concept is closest to what most people envision when thinking of an AHS. Finally there is the Adaptive Concept. This concept considers that each locality has different requirements, and thus would create standards which would leave as many of the architecture decisions, solutions, and deployment steps as possible open to the localities.

When one looks at what was presented at the NAHSC Feasibility Demonstration, the different scenarios can be placed in one or more of the Concept Families, essentially covering all five. Yet in an article written by James Rillings, project manager of NAHSC, just after the Demonstration [11], it was stated that there are "two distinct types [of AHS] … on the drawing board." The two types are a dedicated lane system and a mixed traffic system [11].

The dedicated lane system refers to a system in which certain lanes are dedicated for automated traffic only – much in the way that HOV lanes are dedicated for high occupancy traffic only. The dedicated lane(s) could be separated by a barrier from conventional traffic like reversible lanes are. Such a system might operate in the following manner. At the beginning of a trip the driver would designate the destination in the on-board computer. Upon arrival to the AHS, two methods of joining the traffic flow are possible. The first is the utilization of a "transition lane." The driver would enter the highway under manual control and then move into the transition lane. While in this lane control is handed over to the automation system which would then proceed to merge the vehicle onto the AHS lane(s). A disadvantage to this option is the need of a "transition lane," which cannot be used by traffic, therefore not contributing to the capacity of the highway. Essentially this lane is lost when a conventional highway is converted into an automated highway [12]. The second option for entry is through special on-ramps. A vehicle would check-in, providing its final destination while the system checks to make sure all necessary AHS equipment is present and operational. If the vehicle passes, the transition to automatic control would happen on the ramp, with the vehicle eventually merging into traffic on the AHS under full automation. Mainline operations would include the forming of platoons under automatic control, much like what was demonstrated in San Diego. Exiting from the system would be pretty much the reverse of the entry procedures, but with an addition. Before returning control to the driver, some sort of confirmation would have to be given to the computer from the driver. This is due to the possibility that the driver may not be able to take back control, due to being asleep, preoccupied, sick, or even dead. In the event that a driver would not be able to resume control, a notification would be sent to authorities while the system brings the vehicle to a safe stop at a holding area.

The mix traffic system refers to a system in which fully automated vehicles would share the road with partially automated or manually controlled vehicles. In this case an automated vehicle would enter the highway under manual control. If the infrastructure is available, or if the vehicle is equipped for operation as an independent entity, the vehicle would convert to automatic control. All passing, weaving, and collision-avoidance would be handled by the AHS and/or the vehicle's automation equipment. To exit the system, control would be returned to the driver, again only after confirmation, and then the vehicle would be maneuvered onto the exit ramp manually.

While both of these operational concepts involve automated control, thus increasing efficiency and safety to some degree, full automation under the dedicated lane system will result in greater returns than under the mixed traffic system [11] [10]. Probably the biggest difference would be in capacity.

2.4 Potential AHS Benefits

As stated previously, the biggest benefit expected out of the AHS program is increased capacity. But when considering the time and funding being put into the program, more tangible benefits should be presented. This includes estimating what the potential increase in capacity would be and estimating what the potential costs and benefits to both the government and the user could be.

When discussing capacity, one must be careful in how the capacities of the two alternatives being compared are found. For AHS the capacity of a lane is usually estimated by [12]

$$C = \frac{3600VN}{NL_v + (N-1)L_b + L_p} \qquad \textbf{(2.1)}$$

where

V = velocity in ft/sec

N = average platoon size

L_v = average vehicle length

L_b = intraplatoon distance

L_p = interplatoon distance

The problem comes when using that capacity and comparing it to the capacity of today's highways. The calculated AHS capacity is for mainline operations without interference of entrance or exit ramps, while the capacity of the current highways is found empirically, therefore including the effects of the ramps.

The negative effects of both entrance and exit ramps on capacity can be clearly seen by anyone who has experienced highway driving under near-capacity conditions. As the traffic stream approaches a ramp speeds slow. Near exit ramps weaving becomes more predominate as vehicles attempting to leave the highway must get into position. At entrance ramps the vehicles attempting to merge cause weaving and require increased headways between vehicles already on the roadway. The combination of slower speeds, weaving, and increased headways leads to a decrease in capacity at that section. And the capacity of the highway is dictated by the capacity of the section with the worst capacity.

Castillo et. al. [12] attempt to reconcile this difference by altering Equation (2.1) to include factors to account for the affects of exiting and entering vehicles on the traffic stream. The AHS system they were considering consisted of automated lanes separated from manual lanes by a transition lane, which itself is separated from the automated lanes by a barrier. Vehicles can pass from the automated lanes into the transition lane through gates in the barrier.

When considering the exit maneuver, Varaiya [13] showed that for safe execution only one vehicle from a platoon can exit through an available gate. Thus an approaching platoon which contains more exiting vehicles than gates is required to split into multiple platoons until the condition is satisfied. The binomial distribution was used to estimate the number of exiting vehicles in any particular platoon which, depending on the available number of gates, leads us to the required number of splits the platoon must perform. This likewise gives us the extra distance required to perform these splits. Ultimately, the new capacity equation becomes [12]

$$\frac{1}{C} = \frac{1}{C_0} + \frac{\beta_G L_p}{3600VN} \qquad \textbf{(2.2)}$$

where

C_0 = nominal capacity given by Equation (2.1)

and

$$\beta_G = \max\left\{0, \frac{N\mu}{G} - 1\right\} \tag{2.3}$$

where

μ = fraction of the upstream freeway flow desiring to use the exit

G = number of exit gates

The effect of entering vehicles must also be considered. Assume that vehicles entering on a ramp have been grouped into a pre-platoon before attempting to merge onto the AHS. Also assume that each pre-platoon contains the same number of vehicles as just exited from the target platoon. This can be accomplished through scheduling. The goal is to find the distance between platoons so that there is always a distance of at least L_p between the pre-platoon and the following platoon. Consider a vehicle merging at a speed $v_e<v$, with a margin of safety of Δ feet. This vehicle will fall behind the tail end of the lead platoon by a maximum distance of [12]

$$L_m = \frac{(v - v_e)^2}{2a} + \Delta \tag{2.4}$$

if the vehicle accelerates at a uniform a ft/sec^2. Thus to maintain the proper interplatoon distance between the merging vehicles and the trailing platoon the interplatoon distance upstream should be at least L_p+L_m.

Consider an example of an AHS system as presented at the AHS Demonstration [5] – speeds of 65 mph and intraplatoon spacing of under 30 feet. Applying those conditions to the above concepts appears to support NAHSC's estimate of an increase of 100-200% when comparing an AHS to a conventional roadway. Obviously, increasing the travel speed would increase capacity one-to-one (i.e. a ten percent increase in velocity leads to a ten percent increase in capacity).

Another consideration when examining the benefits of an Automated Highway System is the cost of implementation and the savings to the user. With the present state of our transportation network it is estimated that congestion alone costs our nation over $100 billion annually [3]. Accidents cost us more than 40,000 lives and in excess of $150 billion every year [5]. Meanwhile, over 90% of all vehicle accidents involve some degree of driver error.

The traditional solution has been to build more lanes of highway. but it costs on average one million dollars a mile to add one lane. Comparatively it cost ten thousand dollars a mile to retrofit the HOV lanes in San Diego with the infrastructure to support AHS operations [14]. And with a potential increase of 100-200% in capacity, retrofitting one lane of a highway would amount to the construction of two to three normal lanes.

The real test comes in providing vehicles with the technology needed to utilize the AHS, as without automated vehicles the automated lanes are useless. It is generally felt that the buying consumer is willing to spend up to $800-1,000 on a feature to be added to a vehicle [5] [11]. The strategy is to gradually add components, like adaptive cruise control and collision warning, over time until they become “standard” on the vehicles. This way auto manufacturers can get the cost of “added” features down under the cost ceiling.

Drew et. al. [15] considered this issue while examining a completely different type of AHS – one based on Maglev technology. It was found that by placing a Maglev guideway in the right-of-way of the existing Interstate Highway System, speeds could be obtained in the neighborhood of 200-300 mph. Costs were found as follows:

$$FC = 500 \times 10^9 \left[1 + \frac{V - 100}{300 - 100} \right] \qquad \textbf{(2.5)}$$

where

FC = fixed facilities costs in dollars

V = design speed

and

$$LC = 5650 \times ULC \times \sqrt{V - 150} \qquad \textbf{(2.6)}$$

where

LC = land costs in dollars

ULC = unit land cost (130,000 dollars/acre)

To examine the feasibility of such a system, a benefit/cost ratio was used in the economic study. Alternative One was the do-nothing option, while Alternative Two was the construction of 20,000 miles of 2-lane guideways for the AHS. The following are the results.

Design Speed (mph)	B/C Ratio
100	2.1
200	3.3
300	3.8

These ratios, being greater than 1.0, signify that the implementation of Alternative Two is economically beneficial.

With the above considered, it appears that the implementation of some kind of AHS is beneficial. For the user there is the savings of lost time from congestion and the cost of accidents in exchange for an up-front cost of roughly one thousand dollars. For the government there is the potential to use the AHS to replace the seemingly endless task of the construction of new roads.