THE AUTOMATED HIGHWAY SYSTEM: A TRANSPORTATION TECHNOLOGY FOR THE 21ST CENTURY

M. Broucke and P. Varaiya[1]

Department of Electrical Engineering and Computer Science
University of California, Berkeley CA 94720
mire, varaiya@eclair.eecs.berkeley.edu

Abstract. The current vehicle-highway system has reached a plateau in its ability to meet the demand for moving goods and people. We sketch an architecture for an automated highway system or AHS. The architecture can be realized by several designs that differ in terms of performance and sophistication. We describe one design 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. We summarize evidence suggesting that the design can be implemented. We indicate 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. We conclude with a critique of AHS.

Keywords. Automated vehicles, hierarchical control

1. INTRODUCTION

The transportation sector accounts for one-sixth of the GNP of the United States. Forty percent of this sector is freight, the rest is private automobile. Public transit is negligible in these aggregate figures, although in some localities and for some segments of the population, public transit is critically important. In this paper we focus on the vehicle-highway system, taking as context conditions in the U.S.

About 40,000 people are killed and 1.6 million are injured in vehicle accidents each year. Improvements in vehicle design (air bags, ABS) and reduction in speeds have led to a steady reduction in injuries and fatalities per million vehicle miles traveled (MVMT). Despite these improvements, the cost of accidents (from injuries, damage, loss of work) is high, estimated at 156 billion dollars in 1992.

It costs more to operate a private automobile each year: the annual cost of operating an automobile in the San Francisco Bay Area rose from \$5000 in 1986-87 to \$7000 in 1992-93 (in constant dollars), amounting to 17 percent of household income.

According to the California Department of Transportation (Caltrans) congestion wastes 750 million gallons of gasoline each year, estimated to rise to two billion gallons in 2005 . Of course, congestion leads to stop and go traffic conditions, increasing pollution as well as travel time.

Lastly, the vehicle miles traveled will grow until 2030 by an estimated 2.5 percent per year, whereas California highway miles grew from 1987 to 1992 by 0.04 percent per year; that is, hardly at all.

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In summary: private automobile travel is the main mode of travel in the U.S., demand for it is growing while productivity is declining and constructing more highways is increasingly costly. These developments led the Federal Highway Administration to conclude: "The highway transportation system is at a critical crossroads in its evolution and has started to plateau in its ability to provide significant new operating performance in its present form."

A complex response has developed in the face of this perceived performance bottleneck of the highway-vehicle system. Initially called Intelligent Vehicle-Highway System and now termed Intelligent Transportation System (ITS). We can measure system performance in three dimensions: capacity (measured in vehicles per hour per highway lane), safety (measured by some relative index, e.g., accidents/MVMT), and environmental impact (measured by some index, e.g., CO_2 per MVMT). It is possible to group ITS technologies into three distinct classes: ATMIS (Advanced Traveler and Managment Information Systems); DAS (Driver Assistance Systems) and AHS (Automated Highway Systems). Figure 1 displays the "performance possibility" frontier of these three systems (the current system performance is located at the origin).

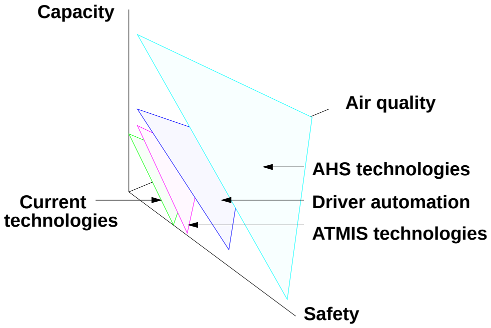

Fig. 1. The performance frontier of ITS technologies.

ATMIS envisages an information (surveillance, data processing, communication) network overlaid on top of the transportation system. More accurate estimate and prediction of the state of the transportation system is provided to agents (drivers and Transportation Management Center or TMC operators) who will then make better decisions (route selection, trip times, signal control) and improve overall system performance. ATMIS is expected to improve performance by about 15 percent. ATMIS technologies are mostly available today, so the barriers to deployment are institutional and financial.

DAS will improve driver performance by reducing stress and enhance safety by providing better information about the neighborhood of the vehicle and by pre-empting driver control when safety is compromised. Better information is obtained through sensors and communication (radar, infrared; roadside signs or radio messages warning the driver of incidents downstream) that can outperform human vision, especially in adverse weather. DAS systems include obstacle warning, advanced cruise control (ACC), and radar- or vision-based systems for lane keeping. Because 90 percent of accidents are attributed to driver errors, DAS systems are expected to enhance safety significantly. DAS technologies will be deployed over the next ten years.

Both ATMIS and DAS are "add-on" systems that enhance performance of existing vehicles and highways. By contrast, the AHS is a system *sui generis*, with coordinated components on vehicles and on the highway. The AHS architecture is open. The designs that implement the architecture may vary significantly in the extent of automation and in how they are tailored to fit local circumstances. Fully automated AHS designs can triple capacity, dramatically reduce the likelhood of collisions, and halve emissions. However, AHS deployment is 15 years away, although niche systems can be operational sooner. The AHS is the highest risk, highest payoff ITS technology.

2. AN AHS ARCHITECTURE

We first describe the architecture. We then present a highly automated design that implements it. We then argue that the design can be implemented. We draw on extensive work conducted in the California PATH program.

2.1 *The five-layer hierarchy*

The functions essential to a vehicle trip are arranged in the five-layer hierarchy of Figure 2.

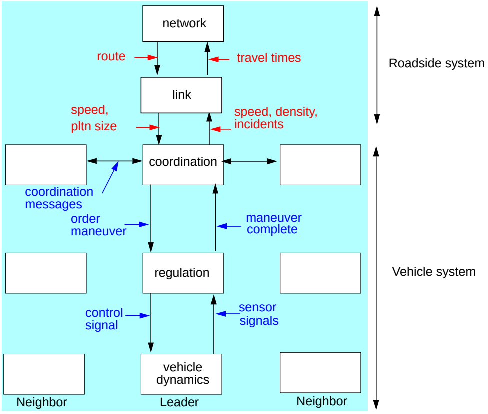

Fig. 2. The five-layer AHS functional architecture.

Consider each layer starting from the top. The *network layer* determines the route of the trip from origin to destination after estimating the highway network state based on roadside- or vehicle-based sensors. The *link layer* manages a "link" of the roadway using the control variables (lane and speed assignment, flow control at entrances and exits) and information (aggregate speed and density, occurrence of incidents) available to it. The *coordination layer* is responsible for executing maneuvers among groups of vehicles in a coordinated fashion. The *regulation layer* executes vehicle maneuvers by control laws for lane keeping, lane change, and vehicle following. Finally, the *physical layer* represents the vehicle dynamics which are controlled by the regulation layer.

Several observations are relevant. First, the hierarchical architecture has the feature that layers are arranged in increasing spatial and temporal scale as one goes up the layers. Regulation layer decisions are made on a time scale of microseconds and the spatial extent is one vehicle. The network layer issues commands every few minutes and its spatial extent is the entire highway network. Second, designs map functions into control elements. A particular design using this architecture as the backbone involves mapping functions needed by the architecture to control elements. Third, the architecture allows for varying degrees of centralization or control. In a fully centralized design, the network and link layer provide all needed control commands to the vehicles. In a decentralized design, the vehicle selects its own speed and safe distance to the vehicle ahead, it coordinates with its neighbors to perform maneuvers, and determines its own route and lane. Finally, the architecture allows for control functions to be performed either by the driver or by computer.

2.2 *Adaptability of AHS*

The hierarchical architecture is sufficiently flexible to operate in a variety of scenarios. The National AHS Consortium has identified the most likely scenarios for AHS: highway networks in highly congested megalopolises, highway corridors in large, congested metropolitan areas, exclusive transit and HOV lanes, heavily traveled intercity highways, exclusive commercial vehicle lanes, and long distance interstate highways. The architecture can be adapted to fit these scenarios by imposing routing and vehicle type constraints in the network and link layers, by metering entry flow types, and by using appropriate vehicle maneuvers in the coordination layer to fit with the physical highway constraints and vehicle types. Regulation layer control laws can also be designed for specific operations and vehicles.

2.3 *A design for full automation*

We will describe one design in which all layers are automated. Vehicles are organized in platoons of up to 20 vehicles, with 1m intra-platoon separation and roughly 60m inter-platoon separation. We consider a network of highways and divide each highway into a collection of links. A link consists of one or more contiguous lanes, with entrances and exits, several kilometers long. Each link is made up of patches, where a patch is a segment of lane roughly 500m long.

Network layer. The network layer is implemented as a shortest travel time or shortest path problem. The problem is formulated by creating a graph for the highway network and assigning nodes at junctions, entrances, and exits. Vehicles entering the automated lane notify the network layer of their entrance and exit nodes. The network layer assigns a path to the vehicle consisting of a sequence of nodes which the vehicle must pass through. The algorithm for obtaining the the short travel time is based on the Bellman-Ford algorithm (see, e.g., [1]). The network layer requires the travel time in each link. This information is provided by the link layer.

Link layer. The link layer controller, developed by Rao and Varaiya [2], sends commands to each patch in a link. The network layer supplies the desired node sequence for each origin-destination (O-D) pair in the network. The link layer performs three functions: (1) command the desired average platoon size in the patch, (2) set the desired speed in the patch, (3) determine the proportion of vehicles that will change lanes in each section in order to balance the density in all the lanes and ensure that vehicles stay on their route.

Coordination layer. The coordination layer comprises a set of vehicle maneuvers initiated by communication protocols. The maneuvers include: platoon merge, platoon split, lane change, platoon leader, platoon follower, entry, and exit. The communication protocols ensure that the maneuvers are coordinating with neighboring vehicles are executed through vehicle control laws. Protocols in the form of finite state machines for the maneuvers platoon merge, platoon split, and lane change, require 13 high level machines on each vehicle [3].

Regulation and Physical Layers. The physical layer includes the vehicle dynamics and engine models. Engine and brake models for longitudinal control have been developed (see [4]). A multiple sliding surface controller is used in simulation and experiments. Lead car controllers and controllers that perform maneuvers such as platoon merge and lane change have been designed [5–7].

The approach for lateral control is based on magnetic markers placed 1-2 meters apart in the center of the automated lane. Hall effect magnetometers on the front of the vehicle sense the magnetic field from the markers. Lateral displacement is determined based on the magnetic field measurements [8]. Both frequency-shaped linear quadratic and fuzzy controllers have been used in simulation and experiments to achieve lateral control. Recent work ties together the longitudinal and lateral models [9].

2.4 *Verification, simulation,and experimentation*

Verification of the coordination layer involves determining that the behavior of the collection of finite state machines that implement the vehicle maneuvers is correct. By correct it is meant that the sequence of states generated by each machine is contained in the set of acceptable sequences. In this case, acceptable behaviors include not initiating a maneuver if there is no trigger from the environment or being able to execute a maneuver infinitely often, as a fairness condition. The protocols for vehicle maneuvers were verified individually and together (the product machine has about 500,000 states) using COSPAN [3].

Experimental validation of the AHS architecture has been focused on the regulation layer. Experiments to validate vehicle following controllers were conducted for a four-car platoon with spacing of 3 meters between the follower vehicles. High speed tests (24 m/s) in which vehicles tracked a constant velocity and performed acceleration maneuvers showed a maximum error in spacing of 20cm.

Lateral control has been demonstrated experimentally on a track with a minimum radius of curvature of 122 m and a nominal speed of 50km/hr. The controller's performance was three times better than human drivers and maintained a tracking error less than 1.7 cm.

2.5 *Performance of the design*

Capacity. Capacity estimates of an automated lane can be done via static calculations using typical values for intervehicle spacing, vehicle length, and average speed. It can be shown that for a platooning architecture with all vehicles in a 20 car platoon, the capacity is four times that of a manual lane. Static capacity predictions are not reliable as capacity will be affected by entry and exit activities, roadway design, and typical O-D patterns. Two alternatives are available for more accurate capacity predictions. One approach uses SmartPath [10] to run micro-simulations with typical traffic scenarios. In one study, the effect of entry and exit on capacity was investigated [11] where it was shown that high on-ramp flows (1800 vehicles/hr) could be supported without appreciably affecting capacity. However, the exit is a major bottleneck. The disturbance from vehicles exiting using the platoon split maneuver could reduce the capacity 25 percent, or 5500 vehicles/hr.

A second approach to obtain capacity estimates uses an AHS macro-simulator SmartCap [12]. In this approach the flow is differentiated by O-D pair and by the activities vehicles are performing. Activities are vehicle maneuvers such as cruising, platooning, lane change, entry, or exit. The activities must satisfy feasibility conditions; in particular, there should be enough space and time to complete the activity within the patch. The set of constraints and selection of activities forms a linear programming problem whose solution is the maximum achievable flow (or capacity) for stationary O-D patterns.

Safety. An AHS is considered unsafe if there is a possibility of a high relative velocity collision. Safety work has focused on the regulation and coordination layers because vehicles can operate without the network and link layers, which improve performance but are not safety critical. It has been shown by Shladover that platoons are a safe configuration to operate vehicles on the AHS in steady-state conditions. Verification of the maneuver protocols proves that vehicles can accomplish maneuvers safely as long as the regulation layer behaves in a prescribed way. The combined regulation and coordination layer is shown to be safe by formulating an optimal control problem [13,14] in which neighboring vehicle dynamics are abstracted as differential inclusions, and the optimal control problem explores worst-case behavior of the neighboring vehicles to show that a maneuver always reaches a safe state. These safety studies are for nominal operating conditions. An extended AHS architecture in case of failures or degraded modes [15] has also been designed.

Emissions. By combining a power demand emissions model with a AHS micro-simulator, vehicle emissions can be investigated and the findings are summarized as follows [16]. For a maximum manual flow of 2000 vehicles/hr/lane at an average vehicle speed of 48 km/hr the automated lane produces half as much vehicle emissions (of CO, HC, and NO_x). Given the emissions rate for maximum manual traffic volume, roughly twice the traffic volume can occur in the automated lane to produce the same emissions. Finally, the maximum traffic flow for an automated lane (8000 vehicles/hr) with an average speed of 103 km/hr produces roughly twice that of the maximum flow for an automated lane.

3. AHS IMPACT

The impact of an implantation of an AHS in a region works itself out in three phases. The first, or construction phase, refers to the land taken up by the AHS, the additional entries or exits that may be required, the modification of the arterials that interface the AHS and which serve as feeders and recipients of the AHS vehicle flow.

The second, or transportation impact phase, refers to the changes in the routes and travel times induced by the presence of the AHS, assuming *no* change in demand, i.e., the origin, destination and frequency of trips. The calculation here is conceptually straightforward: how do drivers determine which routes to take when faced with the changes in travel time induced by the AHS? In principle one can evaluate this impact using available theories and numerical models of route selection [17]. The transportation impact will work itself out in a short time as soon as travelers become familiar with the new choice available to them. However, if using the AHS requires specially equipped vehicles, the transportation impact will take a longer time to reach "steady state."

The third, or land use impact phase, refers to the change in the location of economic activity (or land use) in the region as a result of changes in travel times. The basic model used by urban planners and economists is quite simple. Each economic agent (firm or worker) computes the cost of locating at a point in the region as a sum of two components: cost of travel (shipments in the case of the firm, commuting and other trips in case of a worker) plus the cost of rents (for production or residence) at that location. Call this the locational cost. Each agent seeks to locate at at point that minimizes this locational cost. The resulting decisions create a demand for land at each point in the region. Finally, land rents adjust in such a way that demand for land at each point equals the supply of land at that point. (See [18,19].) The land use impact takes a much longer time to work itself out, because there is much inertia in changing location.

It is useful to obtain a qualitative appreciation of the likely land use impact. This can be done with the help of simple analytical general equilibrium models, in which one varies the transportation cost structure and determines the directions of change in the land use equilibrium. For example, a simple version of the standard model (see, e.g., [20]) implies that the rent difference between two locations is proportional to the difference in the transport cost from those two locations. The implantation of an AHS will alter the transport costs from those locations from which trips will make use of the AHS. This provides the link with rent differentials. In turn those rent differentials will cause changes in the least cost locations of economic activity. The objective of the analysis is to determine the direction of those land use changes.

4. CRITIQUE

Our discussion about the usefulness of the AHS and its practicability is optimistic. It is necessary to balance this optimism with some cautionary remarks, grouping them under technical, economic, and social categories. Because of limitations of space, we merely list what seem to us to be the most important concerns.

The main technical question deals with safety: conceding that under normal conditions the AHS is safe and eliminates accidents caused by driver error, can the AHS introduce new accidents due to its own hardware and software failures? Will it cause drivers to become less alert, thereby increasing the chance that they will make errors after they leave the AHS? The answer is: we simply don't know, we are at too early a stage to be able seriously to formulate and answer these questions. One must anticipate, however, that the technology of fault-tolerant hardware, software and system design and testing will progress over time, so that these questions can be addressed by the time AHS might be deployed.

The main economic questions are: what will be the cost of the AHS, who will pay for it, and will there be sufficient demand for AHS travel? Again, we don't know because the questions call for projections ten to twenty years in the future. However, some obvious points can be made. First, each year vehicles contain 15 percent more electronics. Soon, throttle, braking and steering will become electronic, there will be many more sensors and associated on-line diagnostics, so that the cost of equipping a new vehicle for AHS use will be marginal. The division of AHS cost between the public and private sectors depends largely on whether the AHS design is more roadway infrastrucure- or vehicle-intensive. Thus this division is a decision of public policy. Whether there will be sufficient demand for AHS travel depends on several factors. Will changes in the locational pattern of economic activity exacerbate congestion, or will they relieve congestion? Will demographic changes (especially, aging of the population) increase the need for automation? And, lastly, will non-private automobile "niche markets" (trucking, transit) be sufficient to spur transportation system operators and vehicle manufacturers to invest in AHS?

The social questions emerge from negative evaluations of changes in lifestyle and settlement patterns that AHS might induce. The most serious concerns are that AHS will increase the dependency on the private automobile, further eroding support for transit, damaging the environment, increasing urban sprawl. These predictions depend on many factors. As noted in section 2, AHS can be used to improve transit. For any given demand, travel over AHS will reduce vehicle emissions, so that the overall impact on the environment will be determined by the increase in AHS-induced demand. That demand, in turn, can be managed by other public policy "control variables," notably pricing for AHS access. Finally, urban "sprawl" is an outcome of forces—family structure, the demand for residential space, the locational decisions of firms, land use regulation and taxes—that are significantly more powerful that the impact of AHS must be negligible.

There is little doubt that the highway transportation system has reached a performance plateau. In the U.S., personal and freight transportation is synonymous with highway travel, and that will not change over the forseeable future. Within ITS technologies, the AHS is the only one that offers a dramatic improvement in performance. Moreover, as we have attempted to show, AHS can be tailored to specific needs. In the final analysis, AHS is an element in a portfolio of ITS responses available to public policy.

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