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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, USA (mire@eclair.eecs.berkeley.edu)

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Abstract: The current vehicle-highway system has reached a plateau in its ability to meet the demand for moving goods and people. This paper sketches 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. One design is described that could triple capacity and reduce travel time, guarantee collision-free operation in the absence of malfunctions, limit performance degradation in the case of faults, and reduce emissions by half. Evidence suggesting that the design can be implemented is summarized. It is indicated how the design can be adapted to different urban and rural scenarios and how a standard land-use model can show the impact of AHS on urban density. A summary of the progress of the National Automated Highway Systems Consortium is provided. The paper concludes with a critique of AHS.

Keywords: Automotive control, hierarchical control, traffic 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 automobiles. Public transit is negligible in these aggregate figures, although in particular localities and for some segments of the population, public transit is critically important. This paper focuses on the vehicle-highway system, taking as its 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 reductions in speeds have led to a steady decline 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 owning and 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. Congestion also leads to stop-and-go traffic conditions, increasing pollution and 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 only by 0.04 percent per year.

In summary: private automobile travel is the main mode of travel in the U.S., demand for it is grow-

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ing 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 performance bottleneck of the highway-vehicle system, initially called the Intelligent Vehicle Highway System (IVHS) and now the Intelligent Transportation System (ITS). System performance can be characterized 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 Management Information Systems); DAT (Driver Assistance Technologies) and AHS (Automated Highway Systems). Figure 1 displays the "performance possibility" frontiers of these three technologies (the current system performance is nearest the origin).

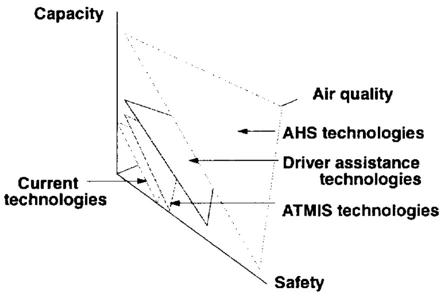

Fig. 1. The performance frontier of ITS technologies.

ATMIS envisages an information (surveillance, data processing, communication) network overlaid on top of the transportation system. As more accurate estimates and predictions of the state of the transportation system are provided to agents (drivers and transportation management center (TMC) operators) they will make better decisions (route selection, trip times, signal control) and improve overall system performance. ATMIS may improve performance by about 15 percent. Many ATMIS technologies are available today; the barriers to deployment are institutional and financial.

DAT will reduce driver 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 aid human vision, especially in adverse weather. DAT systems include obstacle warning, advanced cruise control (ACC), and radar, magnetic marker or vision-based systems for lane keeping. Because 90 percent of accidents are due to driver errors, DAT systems could enhance safety significantly. However, enhancing safety in this way may reduce capacity. DAT technologies will be deployed over the next ten years.

Both ATMIS and DAT are "add-on" systems that improve the performance of existing vehicles and highways. In 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 could triple capacity, dramatically reduce the likelihood of collisions, and halve emissions. However, AHS deployment is 15 years away, although niche systems could be operational sooner. The AHS is the highest-risk, highest-payoff ITS technology.

2. AN AHS ARCHITECTURE

The architecture is described first. There follows a highly automated design that realizes it, with an argument that the design can be implemented, drawing 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 (Varaiya, 1993).

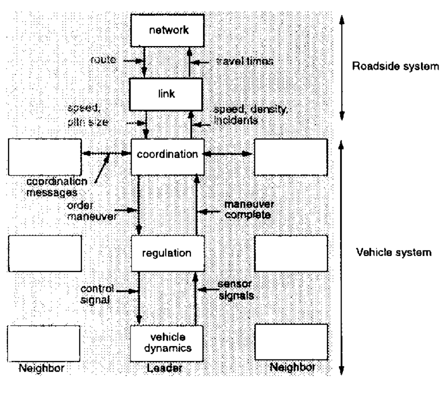

Fig. 2. The five-layer AHS functional architecture.

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 coordinating maneuvers among groups of neighboring vehicles. The *regulation layer* executes those maneuvers by control laws for lane keeping, lane change, vehicle following, entry and exit. The *physical layer* represents the vehicle dynamics under regulation-layer control.

Several observations are relevant. First, the hierarchical architecture has the feature that layers are arranged in an increasing spatial and temporal scale as one goes up the layers. Regulation-layer decisions have a time scale of milliseconds, and their spatial extent is a single vehicle. At the other end of the hierarchy, the network layer issues commands every few minutes, and its spatial extent is the entire highway network. Second, the design task is to realize the functions at each layer of the architecture by means of controllers. Different designs will propose different controllers. The architecture allows for varying degrees of centralization of 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, coordinates its maneuvers with its neighbors, and determines its own route and lane. Lastly, the architecture allows for control functions to be implemented by the driver, by computer, or by driver-computer cooperation.

2.2 *Adaptability of AHS*

The hierarchical architecture offers a structured approach to controller design. It is flexible, and can be adapted to different scenarios. Plausible scenarios for AHS include highway networks in 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, metering entry-flow types, and 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*

One decentralized design in which all layers are automated is described next.[2] Vehicles are organized in platoons of up to 20 vehicles, with 1m intra-platoon spacing and roughly 60m inter-platoon separation. Consider a network of highways, and divide each highway into a collection of links, each link consisting of one or more contiguous lanes, with entrances and exits, a few kilometers long. Each link is made up of lane segments, each roughly 500m long.

Network layer. The network layer solves 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 comprising a sequence of nodes through which the vehicle must pass. The shortest travel time path is based on the Bellman-Ford algorithm (see, e.g., (Eskafi, 1996)). The algorithm requires the travel time in each link. This information is provided by the link layer.

Link layer. The link layer controller (Rao and Varaiya, 1994) sends commands to each segment in a link. The network layer supplies the desired path or 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 segment, (2) set the desired speed in the segment, (3) determine the proportion of vehicles that will change lanes in each segment in order to balance the density in all the lanes and ensure that vehicles stay on their route. A more sophisticated link layer controller that stabilizes the flow around a desired flow field is presented in (Li *et al.*, 1997b).

Coordination layer. The coordination layer comprises a set of communication protocols that coordinate vehicle maneuvers. The maneuvers include: platoon merge, platoon split, lane change, platoon leader, platoon follower, entry, and exit. The communication protocols coordinate the movement of neighboring vehicles, governed through appropriate vehicle-control laws. Protocols in the form of interacting finite state machines for the maneuvers "platoon join," "platoon split," "lane change," "entry" and "exit" have been designed (Hsu *et al.*, 1993; Godbole *et al.*, 1995a).

Regulation and physical layers. The physical layer includes the vehicle dynamics and engine models. Engine and brake models for longitudinal con-

[2] The research briefly reviewed below is being conducted under the California PATH Program. Details can be found at the website http://www.path.berkeley.edu.

trol have been developed (Hedrick *et al.*, 1991; Maciuca *et al.*, 1994; Choi and Hedrick, 1995). 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 (Godbole and Lygeros, 1994; Narendran and Hedrick, 1993; Frankel *et al.*, 1996).

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 (Peng and Tomizuka, 1993). The magnetic markers can be used to encode information to support motion control, multiple vehicle coordination and vehicle navigation (Guldner *et al.*, 1996). Frequency-shaped linear quadratic, fuzzy, and robust controllers have been designed (Chen and Tomizuka, 1997; Hingwe and Tomizuka, 1997). It is possible to combine longitudinal and lateral control (Pham *et al.*, 1994).

2.4 *Degraded modes*

When a vehicle develops a fault, its capability is reduced. A general strategy for fault management is proposed in (Lygeros *et al.*, 1995). Following the detection of a fault, emergency maneuvers are initiated with appropriate protocols (Godbole *et al.*, 1995b), the faulty vehicle is isolated from its neighbors, and if it is possible to do so the vehicle exits. During this time, the performance of the AHS degrades in the neighborhood of the faulty vehicle, but safety is secured. Fault-detection algorithms have been developed (Garg, 1995; Douglas, 1995; Rajamani *et al.*, 1997).

2.5 *Verification, simulation, and experimentation*

Verification of the coordination layer requires a formal proof that the behavior of the collection of finite state machines that implement the vehicle maneuvers is correct. By "correct" 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 (safety), or being able to execute a maneuver if desired (liveness). The protocols for vehicle maneuvers were verified individually and together using COSPAN (Har'El and Kurshan, 1987). Formal proof is not always possible. A detailed microsimulation with animation of the output is used to increase confidence in the design, and to assist intuition (Eskafi *et al.*, 1995).

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 at freeway speeds, with constant spacing under 2m and with a maximum deviation of less than 20 cm.

Lateral control has been demonstrated experimentally on a track with sections that have a small radius of curvature and at speeds that cause a lateral acceleration of up to 0.8g, and with maximum deviation of 10 cm from the center of the lane (Healey, 1997). A lane-change maneuver has been demonstrated (Chee *et al.*, 1995).

2.6 *Performance of the design*

Capacity. The capacity of an automated lane can be estimated by means of static calculations using typical values for intervehicle spacing, vehicle length, and average speed. Up to 8,000 vehicles per lane per hour can be accommodated if traffic is organized in automated 20-car platoons—almost four times the current freeway capacity. Achievable capacity will be lower, depending on entry and exit activities, roadway design, and typical O-D patterns. Two alternatives are available for more accurate capacity predictions. One approach uses SmartPath (Eskafi *et al.*, 1995) to run micro-simulations with typical traffic scenarios. In one study, the effect of entry and exit on capacity was investigated (Rao *et al.*, 1993) where it was shown that high on-ramp flows (1800 vehicles/hr) could be supported without appreciably affecting capacity. However, in the study the exit was a major bottleneck. The disturbance from vehicles exiting using the platoon-split maneuver could reduce the capacity by 25 percent, or 5500 vehicles/hr.

A second approach to obtaining capacity estimates uses an AHS macro-simulator, SmartCap (Broucke and Varaiya, 1996). In this approach the flow is differentiated by an O-D pair and by the activities that 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 segment. 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 collision at a specified relative velocity (which may be zero). Safety studies have 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 is known 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 (Puri and Varaiya, 1995; Lygeros *et al.*, 1996). 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. Safe feedback laws have also been designed for several maneuvers (Frankel *et al.*, 1996; Li *et al.*, 1997a). The trade-off between safety and capacity for several vehicle-separaration policies has been evaluated (Carbaugh *et al.*, 1997).

Emissions. A study of emissions was conducted by combining a power demand emissions model with an AHS micro-simulator (Barth and Norbeck, 1994). Due to the reduction of aerodynamic drag while platooning, the emissions for the platoon are significantly lower at higher steady-state speeds, up to 50 percent compared with manual driving. However, AHS platoon maneuvers (e.g., splitting, merging, etc.) can have a significant impact on vehicle emissions, since the vehicles involved will incur a number of acceleration and deceleration events. Wind tunnel measurements on scaled models show that the average drag coefficient for a four-vehicle platoon is about 55 percent of the drag coefficient in isolation at spacings in the range 0.1-0.3 vehicle length (Zabat *et al.*, 1995).

3. AHS IMPACT

The impact of the 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, and the modification of the arterials that interface with 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 (Ran and Boyce, 1994). 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 changes 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 a 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 (Mills, 1972; Schweizer *et al.*, 1976). 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., (Hartwick *et al.*, 1976)) 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. NATIONAL AUTOMATED HIGHWAY SYSTEM CONSORTIUM

The NAHSC was formed in 1995 in response to a U.S. Department of Transportation initiative to carry out the design, feasibility, demonstration and prototype of an automated highway system, capable of substantially improving vehicle throughput, safety and air quality along high-demand urban and rural traffic corridors. The NAHSC is a unique public-private partnership with nine core members[3] and many associate

[3] These are Bechtel Corporation, Caltrans, Carnegie-Mellon University, Delco Electronics, General Motors, Hughes, Lockheed Martin, Parsons Brinckerhoff, California PATH, and the Federal Highway Administration.

members representing different industries, local and state agencies and universities interested in AHS. NAHSC's mission is to specify, develop and demonstrate a prototype AHS by the year 2002. A significant milestone was a live demonstration in August 1997 on an eight-mile track of I-15 in San Diego. The demonstration showed various enabling technologies needed for an AHS, including automated check-in, check-out, entry and exit, platooning and obstacle detection. A concurrent exposition at Miramar College displayed commercial and prototype ITS technologies.

5. CRITIQUE

This 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, only an enumeration of some important concerns can be accommodated.

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: one simply doesn't know, it is too early 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, one doesn'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, and 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, and 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 than the impact of AHS.

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 the discussion attempts 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.

6. REFERENCES

Barth, M. and J. Norbeck (1994). "Transportation modeling for the environment," PATH Research Report UCB-ITS-PRR-94-27, Institute of Transportation Studies, University of California, Berkeley, CA 94720.

Broucke, M. and P. Varaiya (1996). "A theory of traffic flow in automated highway systems," *Transpn Res.-C*, vol. 4, pp. 181–210.

Carbaugh, J., D. Godbole and R. Sengupta (1997). "Tools for safety analysis of vehicle automation systems," in *Proc. American Control Conference*. To be presented.

Chee, W., M. Tomizuka, S. Patwardhan, and W. Zhang (1995). "Experimental study of lane change maneuver for AHS applications," in *Proceedings of the American Control Conference*, (Seattle, WA.), pp. 139–143.

Chen, C. and M. Tomizuka (1997). "Vehicle lateral control on automated highways: a backstepping approach." Submitted to IMECE.

Choi, S. and J. Hedrick (1995). "Vehicle longitudinal control using an adaptive observer for Automated Highway Systems," in *Proceedings of the 1995 American Control Conference*, (Seattle, WA.), pp. 3106–3110.

Douglas, R.K. (1995). "Fault detection and identification with applications to advanced vehicle control systems," PATH Research Report UCB-ITS-PRR-95-26, Institute of Transporation Studies, University of California, Berkeley, CA 94720.

Eskafi, F., D. Khorramabadi and P. Varaiya (1995). "An automated highway system simulator," *Transportation Research-C*, vol. 3, no. 1, pp. 1–17.

Eskafi, F. (1996) *Modeling and Simulation of the Automated Highway System*. PhD thesis, University of California, Berkeley.

Frankel, J., L. Alvarez, R. Horowitz and P. Li (1996). "Safety-oriented maneuvers for IVHS," *J. Vehicle Systems Dynamics*, vol. 26, no. 4, pp. 271–299.

Garg, V. (1995). *Fault detection in nonlinear systems: Applications to IVHS*. PhD thesis, University of California, 1995.

Godbole, D.N. and J. Lygeros (1994). "Longitudinal control of the lead car of a platoon," *IEEE Transactions on Vehicular Technology*, vol. 43, no. 4, pp. 1125–1135.

Godbole, D.N., F. Eskafi, E. Singh and P. Varaiya (1995a). "Design of entry and exit maneuvers of IVHS," in *Proceedings of the American Control Conference*, (Seattle, WA.), pp. 3566–3570.

Godbole, D.N., John Lygeros, E. Singh, A. Deshpande, E. Lindsey and S. Sastry (1995b). "Design and Verification of Communication Protocols for Degraded Modes of Operation of AHS," in *Proceedings of the IEEE Conference on Decision and Control*, pp. 427–432.

Guldner, J., S. Patwardhan, H-S. Tan, and W-B. Zhang (1996). "Coding of road information for automated highways." Available at http://www.path.berkeley.edu.

Har'El, Z. and R. P. Kurshan (1987). *COSPAN User's Guide*. AT&T Bell Laboratories, Murray Hill, NJ.

Hartwick, J., U. Schweizer and P. Varaiya (1976). "Comparative statics of a residential economy with several classes," *Journal of Economic Theory*, vol. 13, pp. 396–413.

Healey, J. (1997). "One thing builders can't do is to get people to trust the car." USA Today, Cover Story, April 9.

Hedrick, J., D. McMahon, V. Narendran and D. Swaroop (1991). "Longitudinal vehicle controller design for IVHS system," in *Proceedings of the American Control Conference*, (Boston, MA), pp. 3107–3112.

Hingwe, P. and M. Tomizuka (1997). "Robust and gain-scheduled h_∞ controllers for lateral control of passenger vehicles in AHS." Submitted to IMECE.

Hsu, A., F. Eskafi, S. Sachs and P. Varaiya (1993). "Protocol design for an automated highway system," *Discrete Event Dynamic Systems*, vol. 2, pp. 183–206. 1993.

Li, P., L. Alvarez and R. Horowitz (1997a). "AVHS safe control laws for platoon leaders," *IEEE Transactions on Control System Technology*, 1997. In press.

Li, P., R. Horowitz, L. Alvarez, J. Frankel and A. Robertson (1997b). "An AHS link layer controller for traffic flow stabilization," *Transportation Research-C*. In press.

Lygeros, J., D. N. Godbole and M. E. Broucke (1995). "Design of an extended architecture for degraded modes of operation of IVHS," in *Proceedings of the American Control Conference*.

Lygeros,J., D. N. Godbole and S. Sastry (1996). "A game theoretic approach to hybrid system design," in *Hybrid Systems III*, Springer Verlag, LNCS.

Maciuca, D., J. Gerdes and J. Hedrick (1994). "Automatic braking control for IVHS," in *Proc. International Symposium on Advanced Vehicle Control (AVEC'94)*, (Tsukuba, Japan).

Mills, E. (1972). *Urban Economics*. Scott, Foresman.

Narendran, V. and J. Hedrick (1993). "Transition manoeuvres in intelligent vehicle highway systems," in *Proceedings of the 32nd IEEE Conference on Decision and Control*, (San Antonio, TX), pp. 1880–4.

Peng, H. and M. Tomizuka (1993). "Preview control for vehicle lateral guidance in highway automation," *Transactions of the ASME Journal of Dynamic Systems, Measurement and Control*, vol. 115, pp. 679–86.

Pham, H., J. Hedrick, and M. Tomizuka (1994). "Combined lateral and longitudinal control of vehicles for IVHS," in *Proceedings of the American Control Conference*, (Baltimore, MD), pp. 1205–6.

Puri, A. and P. Varaiya (1995). "Driving safely in smart cars," in *Proceedings of the American Control Conference*.

Rajamani, R., J. Hedrick and A. Howell (1997). "A complete fault diagnostic system for longitudinal control of automated vehicles." Symposium on Advanced Automated Technologies, ASME International Congress, 1997. To be presented.

Ran, B. and D. Boyce (1994). *Dynamic urban transportation network models: theory and* *implications for intelligent vehicle-highway systems.* Springer-Verlag, Berlin, New York.

Rao, B.S.Y. and P. Varaiya (1994). "Roadside intelligence for flow control in an IVHS," *Transportation Research-C,* vol. 2, no. 1, pp. 49–72.

Rao, B.S.Y., P. Varaiya and F. Eskafi (1993). "Investigations into achievable capacity and stream stability with coordinated intelligent vehicles," *Transportation Research Record,* vol. 1408, pp. 27–35.

Schweizer, U., P. Varaiya and J. Hartwick (1976). "General equilibrium and location theory," *Journal of Urban Economics*, vol. 3, pp. 285–303.

Varaiya, P. (1993). "Smart cars on smart roads: Problems of control," *IEEE Transactions on Automatic Control*, vol. 38, pp. 195–207.

Zabat, M., N. Stabile, S. Frascaroli and F. Browand (1995). "The aerodynamic performance of platoons: Final report," PATH Research Report UCB-ITS-PRR-95-35, Institute of Transporation Studies, University of California, Berkeley, CA 94720.