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Models, Simulation, and Performance of Fully Automated Highways
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Abstract

This research seeks to provide an understanding of the functioning of a fully automated highway system (AHS). In order to do that, several detailed questions of AHS design need to be answered with a level of detail sufficient to permit the development of mathematical and computer models of the AHS. This is the modeling stage.

The next stage of research is the simulation stage. Its objective is to realize those models in a simulation and visualization program, called SmartPath. SmartPath has undergone several revisions. The latest version, SmartPath 2.0i, is interactive. The user can sit in front of a workstation and "drive" a vehicle on the AHS, while the rest of the vehicles are automatically controlled. SmartPath has proved to be an effective tool for: testing strategies for the automatic coordination and control of individual vehicles, testing TMC (Traffic Management Center) strategies for diverting AHS lanes when an incident occurs, evaluating AHS capacity under a variety of operating regimes (including ACC and platoon organization) and, not least, offering people a limited visual appreciation of what an AHS might look like and how one might experience driving on it.

The third stage of research is the performance evaluation of the AHS under a variety of operating regimes and patterns of demand. Two regimes are investigated in depth: the first assumes ACC (adaptive cruise control), which some experts believe to be the form in which AHS will be realized in the near term; the second assumes the coordinated movement of vehicles organized in platoons. The main performance measures considered are: achievable flows under different patterns of origin and destination, and the ability of the TMC to recover smooth traffic flow following a lane-blocking incident.

The research makes three contributions. First, under the idealized assumptions of the simulations, it is established that the platoon organization of vehicles can achieve flows on the order of 6,000 to 8,000 vehicles per lane per hour (compared with a maximum of 2,000 on today's best highways). Buttressed by other research within PATH, this lends credibility to the claim that automated highway systems can provide dramatic increases in capacity. Second, the simulation program SmartPath creates a useful and versatile synthetic environment for developing, validating and comparing the effectiveness of a variety of strategies for the control of AHS. Third, this and companion research within

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PATH has, over time, persuaded some influential people in the national (and international) IVHS community to move from an initial position of outright opposition to AHS to one of willingness to listen to the proponents of AHS. This change in opinion-evident in the United States Department of Transportation, in the IVHS research community and in industry-has already moved forward the national AHS research agenda.

Keywords: Automated Highway Systems, Automated Highway Systems Control, Adaptive Cruise Control Platooning, SmartPath, Microsimulation.

Executive Summary

An Automated Highway System (AHS) is a complex engineered system. A complete study of an AHS must address technical design and evaluation; legal and institutional issues; the costs and benefits to the state, individual travelers and movement of freight; the impact on the environment. Since no such system has been built, it is difficult to carry out such a complete study. The Federal Highway Administration will, at the end of 1994, let out a six-year $ 180 million contract for the (paper) design of an AHS.

The study reported here began in October 1991. Its objective was to develop a framework and a set of tools for use in the study of AHS, and to illustrate that use by formulating and answering some difficult technical questions about an AHS. That objective has been fully met. The study did not intend to address AHS issues that are primarily of a social or institutional nature. The study also did not address questions of costs. It is believed, however, that the framework and tools developed here can be incorporated into a larger setting that is also concerned with those issues.

The framework requires the specification of the AHS as a hierarchical set of mathematical models. Starting with the bottom of the hierarchy these are models of (1) the vehicle dynamics and control; (2) strategies to coordinate the maneuvers of neighboring vehicles; (3) strategies to regulate the traffic flow in a segment of the highway; and (4) strategies to carry out network-wide traffic management.

The tools developed for the specification and analysis of the models form the simulation and visualization package **SmartPath**. **SmartPath** has undergone several revisions. The latest version, **SmartPath 2.0i**, is interactive. The user can sit in front of a workstation and "drive" a vehicle on the AHS, while the rest of the vehicles are automatically controlled.

The final aspect of this study illustrates the effectiveness of **SmartPath** for formulating and answering technical questions about AHS. **SmartPath** has already been successfully used for: testing strategies for the automatic coordination and control of individual vehicles; testing TMC (Traffic Management Center) strategies for diverting AHS lanes when an incident occurs; evaluating AHS capacity under a variety of operating regimes (including Automatic Cruise Control (ACC) and platoon organization) and; offering people a limited visual appreciation of what an AHS might look like and how one might experience driving on it.

1 Introduction and summary

The research findings presented in this report deal with the modeling, simulation and performance evaluation of fully automated highway systems or AHS. This research began in October 1991, at a time when the concept of AHS was ill-defined and many considered it to be ill-advised or too advanced. The funding of this project in the face of this skepticism, is a testament to the foresight of the leadership in PATH and Caltrans. Today, nearly four years later, the AHS concept is no longer summarily dismissed, and the Department of Transportation is about to initiate a $180 million project to clarify, evaluate and test major AHS concepts. The PATH-Caltrans team is likely to play a major role in the **FHwA** AHS project.

Section 1.1 provides a brief reconstruction of the history of the AHS concept, and a particular AHS proposal that has been intensely studied in PATH. Section 1.2 summarizes the principal findings of AHS performance. Section 2 gives an overview of the simulation program **SmartPath.** Section 3 outlines current work on **SmartPath** and plans for the immediate future. That section also proposes an object oriented distributed software environment that would include **SmartPath** and other tools and data.

1.1 Why AHS?

The overall IVHS program is conceived as a response to the “transportation problem.” We give a synopsis of this problem, discuss how IVHS responds to that problem, and the role of AHS as an element of IVHS.

Traffic congestion is a serious problem. Absent new and effective initiatives, congestion in California will triple by 2005, with average peak hour highway speeds dropping from 35 mph to 11 mph. When speeds drop from 30 mph to 10 mph, fuel consumption doubles. Congestion in California now wastes 750 million gallons of fuel each year. This would increase to 2 billion gallons by 2005. Some 5,000 people die on California’s roads each year; 350,000 are injured. Congestion and safety are related: accident rates triple under congestion; and half of all congestion is caused by accidents and other incidents. The nation’s congestion cost is obtained by multiplying California figures by nine. Congestion used to be checked by building more roads. That approach is now foreclosed in many areas.

Increasing congestion is one aspect of the transportation problem. A related aspect concerns air quality. Pollution increases when vehicles undergo rapid acceleration-which happens in congested, stop-go conditions. A third aspect is the steady increase in vehicle operating costs. The table below shows that the cost of operating a private automobile for 10,000 miles is increasing at four percent per year, after taking inflation into account, and despite a decline in “variable” costs due to fuel efficiency gains and declines in fuel costs. The fourth aspect is the lack of mobility suffered by growing numbers of people. Different aspects of the problem come into view when one studies the transportation needs of commercial vehicles and transit.

Almost 10 percent the total GNP (about $700 billion annually) is spent on the private auto transportation system. (The share of national expenditures on all transportation is about

17%.) When one observes that a large fraction of these expenditures is "dead weight" loss, one sees that the productivity decline in transportation is a significant drag on the economy as a whole.

Year	Variable	Fixed	Total
1985	977	2,328	3,305
1989	833	3,194	4,027
1990	840	3,256	4,096
1991	940	3,245	4,185
1985-91	-0.6%	5.7%	4.0%

Table: Costs per 10,000 miles of travel by private auto (1990 dollars). Sources: ***Transportation in America,*** 1993; MVMA, ***Motor Vehicle Facts and Figures,*** 1992.

For the reasons outlined above, in a statement about the AHS program, the FHwA declared:

> 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 . . .

In its response to the transportation problem Congress passed the ISTEA legislation of 1991:

> to develop a National Intermodal Transportation System that is economically efficient and environmentally sound, provides the foundation for the Nation to compete in the global economy, and will move people and goods in an energy efficient manner.

Congress authorized a $660 million IVHS program over six years. The IVHS program is still being worked out, but as a concept, it can be distilled into the formula

$$\text{IVHS} = \text{Vehicle} + \text{Highway} + \text{Information Technology}.$$

Underlying this simple formula is the belief that information technology-information processing, communication, control and electronics-can be combined to develop systems with better safety, reduced congestion, better mobility, reduced pollution, improved energy efficiency, improved economic productivity.[1]

California's response to the transportation problem led the nation. The 1986437 Legislature established the New Technology Development Program in Caltrans in order

> to tap technology's potential by conducting research and development in partnership with other governmental agencies, academia, non-profit organizations and private industry.

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[1] **These goals for IVHS are formulated by IVHS America** [1].

The New Technology Program in turn helped found the California PATH program in 1986.

Figure 1 is another depiction of the IVHS concept. Vehicles interact in the system of "traffic flow." Improved sensors provide better and more timely data about the state of traffic flow. This data can be processed using communication and computation technology to produce better information. Improved information can be used by control and coordination algorithms to make better predictions about the future state of the traffic flow and to offer better advice to the agents who are continuously making decisions. Those decisions ultimately determine the evolution of the system of traffic flow. The performance of the overall system can be evaluated along many dimensions: capacity, safety, etc.

The most crucial feature about the (highway) transportation system is that decisions are made by a multitude of agents: drivers of individual vehicles and a decentralized collection of traffic operators who set the "rules of the game" to a limited extent. It is obvious that along every dimension of system performance, improvement depends on how well individual decisions are made and how well different decisions are coordinated. The degree of success of IVHS will be determined by the quality of these individual decisions and the quality of their coordination.

Most IVHS research and development activity in the United States is directed towards improving the quality of the decisions of the individual driver by providing better information and advice. Major elements of this activity are devoted to improving traffic flow measurements, obtaining better travel time predictions, providing better route guidance, managing incidents, etc. The assumption is that with better information and advice, individual drivers will better plan their trips, making appropriate changes en ***route.*** The best current estimates are that capacity improvements from an IVHS system that confines itself to providing better information and advice lie between 0% and 15%.[2] The contributions of such a system to safety improvement, pollution reduction and energy efficiency are likely to be equally unimpressive. Of course, this form of IVHS can provide many other user services: navigation aids, databases that give transit and other information valuable to travelers, automatic toll collection, vehicle tracking, etc.

By contrast, AHS has the potential of offering dramatic improvements in capacity, safety, energy efficiency, and pollution reduction. However, the AHS is also the most advanced and highest risk element of the overall IVHS program. It is the most advanced element, not only because it embodies the most sophisticated form of computer-based "intelligence," but also because it must show dramatic gains in highway capacity and safety (to justify its high initial cost). It involves the highest risk, not only because it requires the introduction of information technology that will significantly replace driver control, but also because its implementation will require a radical change in the ***system*** of highway traffic.

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[2] A simulation study based on the CACS project suggests that travel time in Tokyo could be reduced by 6% [2]; U.K. researchers estimate an average benefit of 10 % from dynamic route guidance [3]; preliminary results from the Berlin route guidance experiment show no savings in average travel time under normal conditions [4]; simulations of the Santa Monica freeway (SMART) corridor suggest insignificant savings under recurrent congestion and savings on the order of 10 minutes for a 40 minute trip under incident induced conditions [5, 6]; theoretical considerations also suggest little or no benefits from route guidance under recurrent congestion [7]; lastly, experiments using the CONTRAM simulation model show that single 'best route' guidance can even lead to *negative* benefits [8].

There have been several proposals for AHS, but underlying them is one "behavioral law" of traffic engineering, one observation and one hypothesis. The "law" is that as long as the human driver is in control of the steering, throttle and braking commands, there is a limit to the achievable traffic flow-about 2,000 vehicles per hour per lane. The empirical observation is that upwards of 90% of accidents are due to driver errors. This leads to the hypothesis that if the driver's decisions are replaced by automatic processes, a much larger and safer flow can be achieved. The proposals differ as to the form of these automatic processes.

At one extreme lie proposals in which a centralized controller determines the position of every vehicle, similar to the way trains are controlled. Such designs were studied in the early 1970s by groups at TRW, GM, Rohr Industries and elsewhere. Those studies and others are carefully reviewed in [9]. At the other extreme lie proposals made since the late 1980s and inspired by robotics and AI-based approaches to the control of an autonomous vehicle navigating in an unstructured environment [10, 11, 12, 13, 14]. Such approaches emphasize recognition, learning, and trajectory planning in the face of diverse "threats" and "obstacles."

The particular AHS proposal investigated in PATH lies in between these two "extremes" of centralized vs autonomous control. Investigation of the that AHS proposal is the subject of this project. Those findings are summarized next.

1.2 Research findings

A 1991 PATH report [15] proposed the four-layer AHS control architecture depicted in Figure 2. We give a very brief description. Starting at the top, the layers are: network, link, coordination, and regulation. It is assumed that traffic on automated lanes is organized in platoons of up to 20 vehicles: intra-platoon spacing is very small, inter-platoon spacing is very large. With this arrangement, spacing between vehicles is either very small or very large. As first shown by Shladover [16], and later confirmed by others, the platoon configuration minimizes the relative speed upon collision, thereby increasing safety.

We outline the functions of the four layers. There is one network layer controller (not shown in the figure) for the whole AHS network. Its task is to assign a route to each vehicle entering the AHS. There is one link layer controller for a section of each highway. (A section may be about 1 km long.) Its tasks are to assign a path to each vehicle in ways that balance traffic across all lanes and to assign a target speed for each section in order to smooth flow, avoid congestion, and adapt to incidents. The network and link layer controllers are largely part of the roadway infrastructure.

There is a coordination layer controller and a regulation layer controller for each vehicle. Their respective tasks are to evolve a plan which is close to the path assigned by the link layer and to execute the vehicle's trajectory which conforms to the plan. A path logically consists of a sequence of maneuvers. Each maneuver is then realized as a trajectory. There are three maneuvers: ***join,*** in which two platoons join to form one platoon, ***split,*** in which a platoon splits into two at a designated position, and ***change*** lane, in which a one-vehicle platoon changes lane. There is a default, fourth maneuver, ***lane keeping,*** in which the platoon keeps to its lane, cruising at the speed assigned by the link layer, while maintaining a safe distance from the platoon in front of it.

Based on its current position on the highway and its assigned path, a vehicle's planning layer determines which maneuver it should undertake. It then exchanges messages-called ***communication*** protocols-with the planning layers of neighboring vehicles to coordinate their movements so that the maneuver can be carried out safely. It then instructs the regulation layer to execute the appropriate (pre-programmed) feedback law that realizes the trajectory corresponding to the maneuver.

The PATH AHS architecture proposal has many attractive features in comparison with the extremes of centralized and autonomous proposals mentioned above. However, a great deal of work needed to be done to specify the layers of the architecture at a level of detail sufficient to carry out a performance evaluation of the proposal. This is the modeling stage.

Model development

Work in this area resulted in detailed models of

- Regulation layer, together with vehicle dynamics.
- Coordination layer.
- Link layer.
- Sensors in vehicles and in roadway.
- Communication services between vehicles and between vehicles and roadway.

Models of longitudinal and lateral vehicle dynamics used in our work are adapted from previous or current work in PATH undertaken by other research teams. These are nonlinear differential equation models. Because we are interested in the movement of large numbers of vehicles, these are "system level" models rather than models of individual subsystems (engine, torque conversion, drivetrain) that are used in the study of individual vehicles. The longitudinal follower control laws are taken from prior work as well. The control law for the lead vehicle in the platoon was initially adapted from AICC laws developed by other PATH researchers. However, it turned out necessary to modify that work in order to provide safety features which were not considered [17].[3]

The coordination layer protocols are modeled as finite state machines. The protocols have been proved correct [18], and implemented as code in the simulation.

The link layer controller views the traffic flow as a fluid flow. Model development started using a standard model used in traffic studies [19]. However, the standard model had to be modified in two important ways. First, because vehicle control is automated, the usual driver car-following behavior (which forms the basis of the standard model) is inappropriate.

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[3] **This is an example of a continuous process of updating the models that we are using. When better models or control laws are invented, or as deficiencies are discovered, the models incorporated in SmartPath are updated.**

Second, the standard model does not adequately account for lane-changing behavior, which we wish to incorporate explicitly. These considerations led to a new fluid flow model for an AHS. The model itself was calibrated using the microsimulation SmartPath (described in the next section). Based on that model, link layer control laws were proposed. Our current model and the control laws are described in [20].

The regulation layer longitudinal control laws are based on sensors that measure relative speed and distance of the vehicle in front. The control law that governs a lane change is based on a sensor that measures the distance of the vehicles in the adjacent lane. Sensor models are parametrized by a range variable: it is assumed that vehicles within that range (longitudinal or lateral) are sensed perfectly, vehicles beyond that range are not “seen” at all. The link layer controller assumes that measurements of aggregate traffic-speed, density, and proportion of traffic headed for each destination-are available.

The coordination layer assumes that a lead vehicle can communicate with neighboring lead vehicles within a certain range, that is, communication infrastructure is available that provides this service without error and without delay. No communication is possible beyond the specified range. Similarly, it is assumed that the link layer controller can send broadcast messages to the vehicles in its section without error or delay. (Note: it is not assumed that the link layer can communicate with individual vehicles.)

In creating these models there is an interplay between the desire to be as realistic as possible about portraying the capabilities of sensors and communication services on the one hand, and the demand to create a simulation model that is not overly computationally-intensive on the other hand.[4] This interplay works itself out in. a sequence of models of growing versatility and flexibility.

Simulation development

A major part of work under this project was devoted to the development of the simulation program SmartPath, which is described in greater detail in the next section. We will highlight some features of the development process. The first version of SmartPath was written by the end of 1992. It was fairly “monolithic” in the sense that the regulation and planning layers (there was no link layer) were “wired in” making it difficult to test new control strategies. The results of the simulation could be displayed only by the usual time-distance plots of individual vehicles. This first version proved that microsimulation is an important tool for performance evaluation. It also suggested that two features need to be added: it had to be modular-to permit users to enter their own control laws, sensor parameters, etc; and a three-dimensional visualization of the movement of the vehicles in the AHS was essential to provide the user a “feel” for how the AHS might function.

SmartPath has gone through several versions.[5] The latest version is SmartPath 2.0i. Its

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[4] In virtually every case these sensors and communication services do not exist as standard items, so there are no reliable, validated models of these sensors or communications services. Nevertheless, the modeling assumptions are as plausible as we can make them. For example, in the current version of SmartPath intra-platoon communication is modeled by an idealized version of the infra-red communication link developed under another project.

[5] The simulation program is written by Farokh Eskafi, the animation program by Delnaz Khorramabadi.

noteworthy features are:

- It is modular: users have found it possible, although by no means trivial, to change regulation layer laws, to change traffic parameters and highway configurations. [6]
- The output of the simulator can be input to another program which animates it. The user can now navigate through the AHS in a "stealth helicopter" and view the AHS from any position (in 3D space) and any angle.
- In the interactive version of the program the simulation and animation are run together. The user can select any vehicle in the AHS and "drive" it by issuing keyboard commands to change speed, to change lanes, to exit. The other vehicles are under automatic control and respond and react to the maneuvers and movement of the user-driven vehicle. This feature is useful in testing the robustness of the control algorithms.

1.3 AHS performance evaluation

As indicated in Figure 1, AHS performance evaluation has many dimensions. Work in this project is concerned with achievable capacity. It is important to understand that estimating achievable capacity is tantamount to figuring out the quantitative relation between the magnitude of the flows achievable on the AHS as a function of the pattern of origin and destination and lane changing behavior. The reason is simple. Consider a single, long automated lane with no exit or entry. Then the maximum flow ϕ is given by the formula:

$$\phi = v \times \frac{n}{ns + (n-1)d + D} \text{ vehicles/lane/min,} \tag{1}$$

where platoon size is n, intra-platoon spacing is d, inter-platoon spacing is D, vehicle length is s, and the speed is v m/min.

Because of automatic control, the calculation of ϕ does not depend on any assumption about driver car-following behavior. This is in contrast with the situation of a manually driven highway, in which it is not entirely trivial (because of driver behavior) to figure out the maximum flow over a long stretch of highway with no entry or exit.

The formula above no longer holds if vehicles are entering and leaving and changing lanes. These maneuvers reduce the achievable flow. This is clear from highway driving experience. A more technical argument which holds for automated traffic as well is the following. When a vehicle changes lane (or merges into a lane from an entry), it needs space in both the departing and receiving lanes to complete the maneuver. This space is larger than what the vehicle would need if it did not change lane. This extra space needed for the time it takes to

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They are also responsible for SmartPath releases. Others have directly enhanced SmartPath: Bobby Rao developed the link layer; Datta Godbole and John Lygeros contributed to the regulation layer and proposed the interface between it and the coordination layer. The users of SmartPath continuously make suggestions many of which are incorporated into SmartPath. SmartPath has been released to 25 external users in universities and industry. SmartPath is available via ftp.

[6] A more radical modularity is discussed in section 3.

complete the maneuver reduces the maximum achievable flow.[7] Once we see this argument it becomes clear that the maximum achievable flow will be a function of four factors:

- the pattern of origin-destination and the length of a trip;
- the headway distribution of vehicles entering the AHS;
- the control strategy that is employed in change lane, entry, exit; and
- how the maneuvers of the other vehicles are affected by a lane change "disturbance."
- the distance between entry and exit in the automated lanes.

This function is likely to be complex. We have estimated this function for three scenarios. Below we summarize our findings in a very general manner. For details the reader is referred to the cited references. The details are important to appreciate that the five factors listed above have to be carefully modeled.

AICC scenario In [22], we imagine that automation is limited to AICC (Autonomous Intelligent Cruise Control).[8] We also permit AICC-equipped and manually driven vehicles to occupy the same lane. The principal conclusion is that

> AICC can offer modest improvements to lane capacity at low market penetration levels and probably has a beneficial, if slight, effect on stream stability. At higher levels of implementation, greater increases in capacity become harder to achieve because of problems of stream stability and limits on the rates at which vehicles can [enter the highway].

The problem of "stream stability" may be important if there is a large penetration of AICC equipment. When a sequence of AICC vehicles is formed, it behaves as an uncoordinated platoon. As a result, disturbances can propagate creating a so-called "slinky" effect.[9] Figure 3 summarizes some of the flow results.

AHS scenario In [24], we imagine that the AHS organizes traffic in short headway platoons as in the PATH architecture described above. We estimate maximum achievable flows under three different strategies for entry and exit. We also estimate the length of time it takes vehicles to enter the automated lane. This time estimate in turn translates into an estimate of the length of the entrance lane.[10] Figure 4 displays the time-distance diagrams of vehicles, showing how an entering vehicle is accommodated.

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[7] For a very elegant model which develops this idea and leads to an analytical estimate of the achievable capacity see [21].

[8] Because an AICC-equipped vehicle operates using only information available from its own sensors, there is no requirement for communication and coordination between vehicles. For this reason, there will be a gradual market penetration of AICC systems. This makes AICC a plausible initial stage leading towards AHS deployment.

[9] Another problem with large sequences of AICC vehicles is the possibility of relatively high speed collisions following a brakes-on failure [23].

[10] In an *ongoing* FHWA-sponsored AHS Precursor Systems Analysis study, we are undertaking a detailed examination of the physical dimensions of such entrance lanes or ramps. That study should be available in September 1994.

It is assumed that vehicles enter into and exit from an automated lane via a transition lane. The three entry and exit strategies can be described briefly as follows.

In the first strategy, a vehicle in a transition lane immediately enters the automated lane if no vehicles are within a "safe" distance. (The safe distance is quite large.) If a vehicle in the transition lane is adjacent to a platoon it will enter in front of it if the vehicle is toward the front third of the platoon, behind it if the vehicle is toward the rear third of the platoon, or the middle of the platoon otherwise. In all cases the whole platoon, split platoon, or vehicle must decelerate to a safe interplatoon distance before the lane change occurs. The platoons may then join in a separate maneuver. Vehicles that wish to leave the automated lane do so from the rear, front or middle of the platoon, but again these maneuvers entail a deceleration to safe separation before lane change. (This deceleration for entry and exit is what causes the reduction in achievable flow.) There are two main conclusions for this strategy. First, high flows (up to 9,000 vehicles per lane per hour) can be sustained, with entrances at rates up to 1,800 per hour. However, each platoon accelerates and decelerates many times to accommodate these entrances, and driver comfort will be reduced. Second, exiting vehicles cause large disturbances, because platoons in two lanes must split to accommodate entry.

In the second strategy, when a vehicles joins a platoon from the rear (following a lane change) it does so with a short initial gap. This virtually eliminates disturbances caused by entry.[11] The disturbances caused by exiting vehicles are, of course, not reduced by this strategy.

The third strategy seeks to reduce disturbances due to exit, by insisting that vehicles leave only from the rear of the platoon. This requires that vehicles in a platoon be sorted by destination: vehicles leaving from closer exits are behind those leaving later. This requires a change in the coordination layer "join" maneuver. This strategy virtually eliminates exit-caused disturbances. However, the platoon sizes are reduced because of the sort-by-exit requirement which, in turn, reduces the maximum achievable throughput as indicated in formula (1).

Link layer AHS model In the two scenarios above, achievable flow was estimated through simulation and the results are summarized in graphical form or in the form of time-distance diagrams as shown in Figures 3,4. This form is unsuitable for the design of link layer controls. For that design one needs an explicit functional form. Development of that functional form is reported in [20]. Again, the reader is referred to the cited reference for details. The most important innovation in the model is a specification of the "lane-changing capacity" of an AHS as a function of the flows in the two lanes. The functional specification itself is estimated from numerous SmartPath Monte Carlo runs. Armed with such a model, the paper goes on to propose and evaluate a link control strategy. The objective of the strategy is to maintain a flow of traffic that is balanced across all lanes and, more importantly, to divert traffic when an incident occurs. It must be noted, however, that the proposed link layer model is ***not*** theoretically well-supported. It is essential to obtain such support.

“Safety considerations also favor the small gap. However, this maneuver will require new coordination and regulation layer control laws, and sensors with a greater capability. The new control laws are being designed and tested as part of the study referenced in footnote 10.

2 SmartPath structure

In this section we outline the important features of SmartPath [25]. As already mentioned, most of the work under MOU 63 has gone into the specification, design and implementation of several versions of the simulation package SmartPath for an AHS. The AHS assumes the availability of certain elements: vehicles with appropriate lateral and longitudinal sensors and actuators, highways with appropriate sensors, and the ability to communicate among vehicles and between a vehicle and the highway.

SmartPath may be used to understand how the AHS would perform under various control policies in terms of highway capacity, traffic flow, and other performance measures of interest to transportation system planners and engineers. SmartPath also can be used to test, simulate and analyze the designs of different modules and equipment like engine models, sensors and communications.

The package consists of two separate modules: simulation and animation. In order to use the animation, one needs a Silicon Graphics workstation. The simulation runs on a Sun Sparc or a SGI workstation. The animation program produces a three-dimensional, color animation of the traffic in the AHS.

SmartPath is a microsimulation: the system elements and the control policies are each individually modeled. The control policies and the traffic demand are for the most part parametrically specified, so users can study the variation in performance by changing these parameters. SmartPath is written in C, and consists of 25,000 lines of code, excluding CSIM.

SmartPath is built upon CSIM, a process-oriented simulation environment, designed to simulate a discrete event system. The CSIM structures, routines and facilities used in SmartPath are: mailboxes, wake up call "events," "send" and "receive" for message passing, "set" an event, "wait" for event, and "hold" for delays to simulate the passage of real time. These features permit message passing and other means to synchronize processes.

Two basic entities are modeled in SmartPath: a vehicle and a highway. These entities must possess the sensing, control and communications capabilities underlying the control architecture of Figure 2.

Vehicle

A vehicle is composed of five independent, communicating modules. Figure 5 shows these modules, and the direction of information flow among them. The modules are: sensors, communications, regulation, maneuvers and supervisor. Sensors and communications modules provide information about a vehicle's surrounding environment, upon which the coordination and regulation layer decisions are based. The regulation layer module represents the regulation layer and the supervisor and maneuver modules together represent the coordination layer. In the current version of SmartPath the physical layer is part of the regulation module. The link layer is currently "wired" in. However, the next version, currently under test, will have a separate link layer.

The sensors module provides the other three modules with the position, speed and acceleration of the vehicles within the sensor range. Those ranges are user-settable parameters. Typical sensor ranges that have been used in simulations are 60 m for longitudinal sensors and 30 m for lateral sensors. ("Lateral" range means longitudinal range in the adjacent lane.) Sensors also tell each vehicle its position on the highway.

The communications module provides the coordination layer with facilities to exchange information from neighboring vehicles and with the link layer controller on the roadside.

The regulation, coordination and supervisor modules provide a faithful model of the corresponding controllers.

Highway

In SmartPath a highway is specified by its length, maximum number of lanes, number of automated lanes (the others are manual), number and locations of entries and exits. The physical topology of the highway (width of lane, curvature, etc.) are not needed by the simulation, but they are needed for the animation.

A highway is divided into smaller structures called section. Each section has a definite length and can contain at most one entry or exit. In the current version of SmartPath, a transition lane separates automated lanes from manual lanes (if any) and entrance or exit ramps. (See Figure 6.)

Lastly, SmartPath permits a network of highways. Two or more highways can be connected together in a special section called a junction which specifies the interconnection of the various lanes.

To run SmartPath, one specifies an input file which gives the configuration of the highway and various parameters in the vehicle modules. One must also specify statistics of the vehicle arrivals at each entry, together with the distribution of exits. The output of SmartPath can be analyzed in various ways. One may produce time-distance plots of individual vehicles as shown in Figure 4, or one may animate the output. Various error files are also produced, indicating abnormal behavior (e.g., collisions, or missed exits).

3 Conclusions

Research conducted under MOU 63 was aimed at the performance evaluation of an AHS control structure that has been propsed within PATH. In order to conduct the study detailed models of the vehicle and highway and of the control strategies were developed. Those models were then implemented in SmartPath. The simulation package was used in order to evaluate many variations of the control structure.

The first substantive conclusion is that the PATH architecture and control design can indeed support very high flows. The most significant limit on those flows is placed by the pattern of entry and exit. Current research seeks to improve entry and exit maneuvers.

The second conclusion is that SmartPath is fairly modular. Several researchers, not part of the SmartPath development team, have successfully used it to test their own regulation layer strategies. The animation program has proved to be a very effective means of presenting to non-expert audiences the concepts of AHS and how it may operate. For that reason, Caltrans and PATH have exhibited SmartPath at several IVHS America meetings.

SmartPath has also served as a vehicle for research in simulation, visualization and control that is supported by the National Science Foundation and the Army Research Office. That work in turn has benefitted PATH-supported research.

In the immediate future, SmartPath will be extended to accommodate separate link and network layers, new maneuvers for entry and exit, and new (highway) structures of entrances and exits. We also anticipate early development of a version of SmartPath that will run on the massively parallel connection machine, the CM5, which belongs to the Department of Electrical Engineering and Computer Sciences at Berkeley. This will permit a region-wide real time microsimulation. (At present, about 300 vehicles can be simulated in real time.)

For the longer term, we have plans for an object oriented database environment, called SmartDB. SmartDB will support SmartPath configurations, simulation and storage of simulation histories. It will support an object library of vehicle engines, sensors, controllers, and communication models, as well as a library of highway structures. A user can use this library in a “mix and match” mode and synthesize a huge variety of highway networks. A graphical user interface will facilitate this synthesis. SmartDB will also support storage of real data (like that collected in the I-880 project) and interfacing with other simulation packages.

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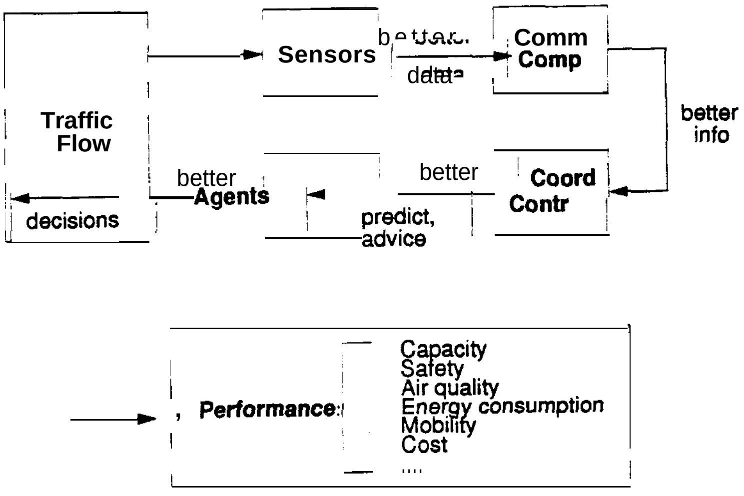

Figure 1: IVHS concept

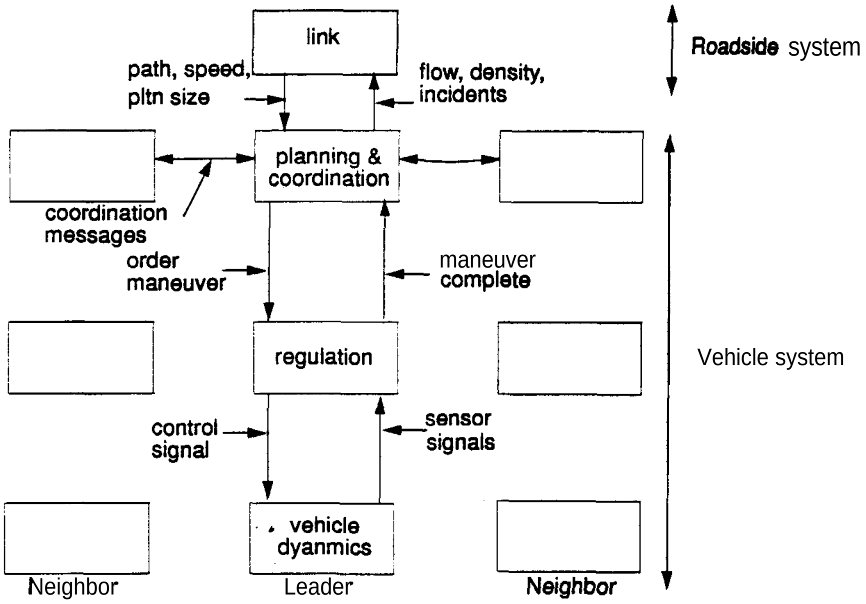

Figure 2: PATH AHS control architecture

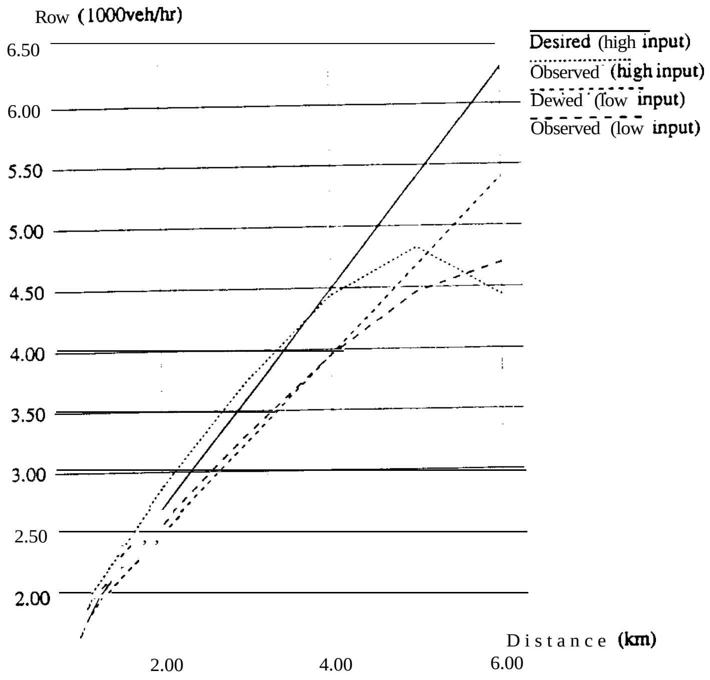

Figure 3: AICC achievable flow for different penetration

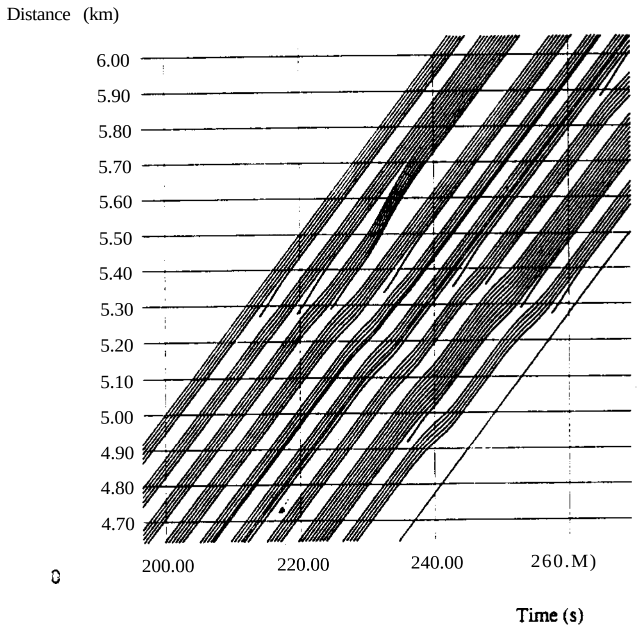

Figure 4: Time-density profiles showing effect of entry

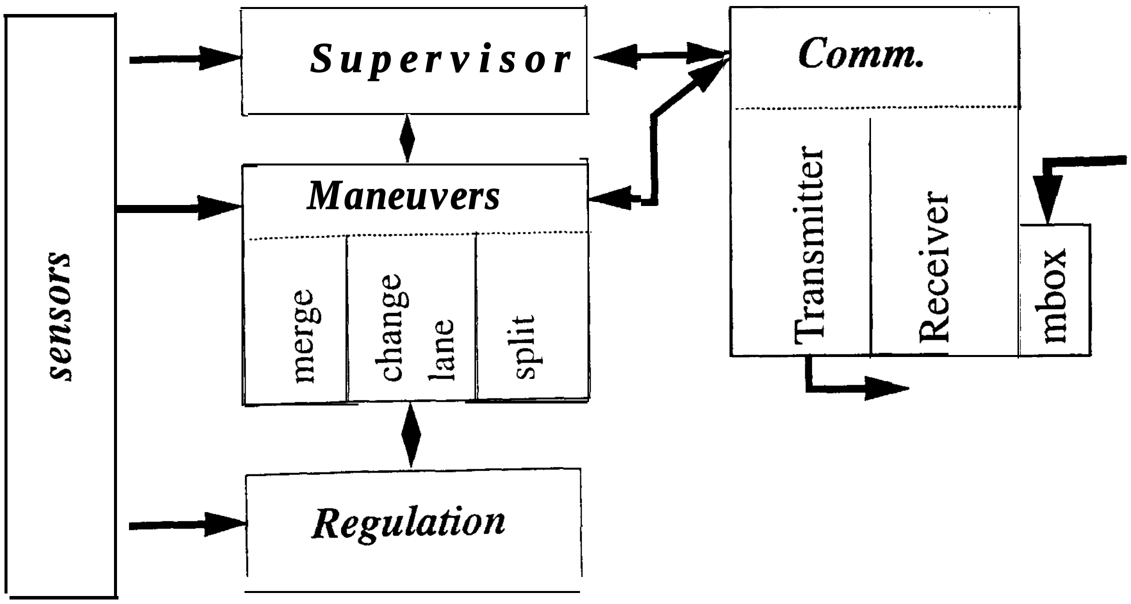

Figure 5: Vehicle model in SmartPath

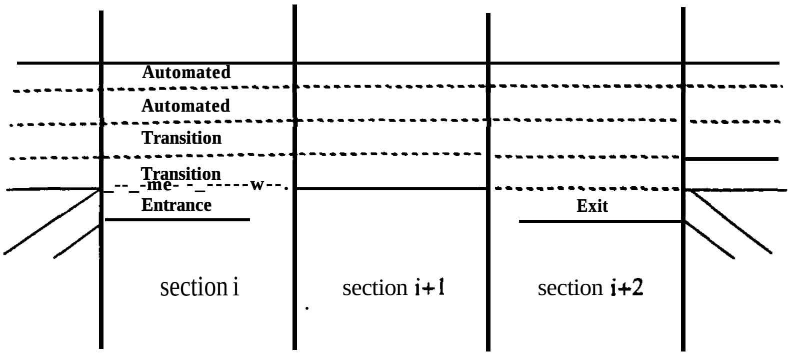

Figure 6: Highway model in SmartPath