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AHS Demo '97 Issue

PATH – Partners for Advanced Transit and Highways – is a joint venture of Caltrans, the University of California, other public and private academic institutions, and private industry, with the mission of applying advanced technology to increase highway capacity and safety and to reduce traffic congestion, air pollution, and energy consumption.

CALIFORNIA PATH

Demo '97, the highly successful National Automated Highway Systems Consortium (NAHSC) Proof of Technical Feasibility Demonstration held from August 7-10 in San Diego, attracted a level of national and international attention unprecedented in the history of the ITS program, nearly all of it highly enthusiastic. US Secretary of Transportation Rodney Slater, visiting the Demo, said "This kind of technology is going to go a long way toward increasing the safety and effectiveness of the highway system."

As NAHSC Project Manager Jim Rillings put it, "Demo '97 was a complete success – it was bigger, better and smoother than almost anyone expected." The Demo showed that an Automated Highway System, with its goals of improving the capacity and safety of existing roads, should be possible with current technology.

PATH's work received wide exposure, and universal acclaim for the smoothness of the demonstration rides. PATH researchers led the development of two of seven major demonstrations of automated vehicle operations on the Interstate 15 express lanes, and two of four "mini-demo" rides on a half-mile track at San Diego's Miramar College. PATH also developed computer animations, videos, and displays for the NAHSC exhibit, explaining the background and benefits of AHS.

The major demonstration scenarios that benefited from PATH's leadership role were the NAHSC core participants' eight-vehicle Platoon Scenario and the Honda Control Transition Scenario. Backup vehicles from these scenarios were also used for the mini-demos, which were popular attractions for Demo '97 visitors who could not get rides on the express lanes.

The eight-vehicle Platoon Scenario successfully demonstrated the technical feasibility of operating standard automobiles–Buick LeSabres–under precise automatic control, at close spacings, and at highway speeds. Riders experienced real travel in a fully automated AHS vehicle, and were shown that comfortable, high-capacity, automated travel should be technically feasible in the near future. (See article on page 2.)

The Control Transition Scenario demonstrated how an AHS vehicle could transition from a rural environment with no AHS infrastructure support to an urban environment with infrastructure. (See article on page 4.)

The GM–PATH Platoon Scenario

Steven Shladover, PATH

PATH researchers designed the Platoon Scenario to demonstrate how vehicle automation technology can greatly reduce traffic congestion. The eight Buicks operating in tight coordination showed how an automated highway system can provide a significant increase in highway throughput (vehicles per lane per hour moving along the highway).

...the vehicles can respond to changes in the motions of the vehicles ahead of them much more quickly than human drivers.

Since platooning enables vehicles to operate much closer together than is possible under manual driving conditions, each lane can carry at least twice as much traffic as it can today. Also, at close spacing aerodynamic drag is significantly reduced, which can lead to major reductions in fuel consumption and exhaust emissions. The high-performance vehicle control system also increases the safety of highway travel, reduces driving stress and tedium, and provides a very smooth ride.

At Demo '97, the eight vehicles of the PATH platoon traveled at a fixed separation distance of 6.5 meters (21 feet) at all speeds up to full highway speed. At this spacing, eight-vehicle platoons separated by a safe interplatoon gap of 60 m (about 200 feet) and traveling at 65 mph would represent a "pipeline" capacity of about 5700 vehicles per hour. Reducing this by 25% to allow for the maneuvering needed at entry and exit points corresponds to an effective throughput of about 4300 vehicles per lane per hour. Throughput under normal manual driving conditions at this speed would be approximately 2000 vehicles per lane per hour.

Short spacing between vehicles can produce a significant reduction in aerodynamic drag for all of the vehicles (leader as well as followers). These drag reductions are moderate at the 6.5-meter spacing of the Demo, but become more dramatic at spacings of half that length. Wind-tunnel tests at the University of Southern California have shown that the drag force can be cut in half when vehicles operate at a separation of about half a vehicle length. Analyses at UC Riverside have shown how that drag reduction translates into improvements of 20% to 25% in fuel economy and emissions reductions.

Tightly coordinated maneuvering is achieved by combining range information from a forward-looking radar with information from a radio communication system that provides vehicle speed and acceleration updates 50 times per second. This means that the vehicles can respond to changes in the motions of the vehicles ahead of them much more quickly than human drivers. As a result, the space between the vehicles is so close to constant that variations are imperceptible to the driver and passengers. This tight gap even produces the illusion of a mechanical coupling between the vehicles.

Vehicle-to-vehicle communication capability is used to coordinate maneuvering. These maneuvers include lane changing, in which a vehicle safely coordinates its lane change with adjacent vehicles, so that they do not try to occupy the same place at the same time, and platoon join and split maneuvers — decreasing the space between vehicles to form a platoon and increasing the space to separate from a platoon.

Tight coordination among vehicles also facilitates responses to malfunctions, enabling all vehicles in a platoon to learn about a malfunction within a fraction of a second, so that they can respond accordingly. The vehicles are equipped with malfunction management software, to automatically implement such corrective actions as increasing the separation between vehicles while warning the drivers.

The control system has also been designed with careful attention to passenger ride quality. Both the lateral (steering) and longitudinal (speed and spacing) control systems have been designed, tested, and proven to have higher performance than even highly skilled human drivers. The lateral control system keeps the vehicle to within a few inches of the lane center under virtually all conditions, which is much more accurate than human drivers' steering. The longitudinal control system maintains speed and spacing accuracies that exceed those of all but virtuoso race-car drivers.

The accuracy and fast response of the longitudinal control system provides a reassuring, smooth ride. Although some people are initially startled by the "tailgating" aspect of vehicle following at close separations, most of them quickly adapt and develop a sense of comfort and security because of the constantly maintained separation.

The human/machine interface on the platoon cars has been carefully designed by Delco Electronics to enhance user acceptability. The steering-wheel control buttons can be used to activate and deactivate automation functions, and the flat-panel display in the center of the instrument panel provides timely status information. The latter is important so that the driver can be given assurance during fully automated driving that the system really "knows" what it's doing. Maneuvers that might be surprising are indicated in advance on the display so that there are no surprises and so that vehicle movements will seem natural and logical.

Although the platoon scenario at Demo '97 in San Diego did not include the full range of functions that would be needed for an operational automated highway system, it did include capabilities that would not be needed in normal AHS operations. For example, the entire platoon started from a stop at the start of the demo, and decelerated to a stop at the end, because of the physical constraints of the Demo site. In an operational system, individual vehicles would accelerate on the onramps to merge into the traffic stream, and would decelerate on the exit ramps after lane changing out of a platoon, while the mainline traffic would be flowing continuously. Since the I-15 HOV facility does not have intermediate on- and off- ramps, the entire platoon started and stopped together.

PATH researchers designed the operational concept and control systems for the platoon scenario, and specified the hardware performance requirements. They developed the magnetic reference sensor system for lateral control, the electronic throttle actuation system, the communication protocols for vehicle-to-vehicle communication, and the malfunction management software. PATH researchers also integrated all the in-vehicle software, and debugged and tested the complete vehicle control system. ■

The PATH Platoon Scenario Development Team

Wei-Bin Zhang: Program Manager

Lateral Control System Development:
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Longitudinal Control System Development:
Rajesh Rajamani–lead, Sei-Bum Choi, Farokh Eskafi–communication protocol development

Software Development and Implementation:
Paul Kretz–lead, Benedicte Bougler–system administrator, Boon Law–communication protocol development, Andrew Segal–radar evaluation and configuration management

Vehicle System and Experimental Support:
Jay Kniffen–lead, Sonia Mahal–electronic interface debugging, David Nelson–hardware support, Robert Prohaska–vehicle hardware design and integration

The Honda-PATH Control Transition Scenario

Dan Empey, PATH

Early in 1996 Honda R & D North America, Inc. and California PATH (Partners for Advanced Transit and Highways), a University of California/Caltrans research partnership, launched a joint venture with the goal of demonstrating several aspects of Automated Highway System (AHS) technology. Honda provided vehicles (Accords) equipped with throttle, brake, and steering actuators, as well as a forward looking laser radar, while PATH provided a machine vision system for lane tracking and longitudinal (speed) control, a magnetic marker sensing system for steering control, the control computer, and steering and speed control software. The vehicles demonstrated on the I-15 freeway in San Diego at Demo '97 are the culmination of this joint venture between PATH and Honda. Two of the cars were run on the reversible commuter lanes of I-15 and one car was run as a "mini-demo" at the Demo '97 Exposition site (this ride only took about one minute). The two cars used on I-15 demonstrated the Control Transition scenario described below, while the mini-demo demonstrated vision-based lateral control by driving around a small "peanut" shaped course consisting of a single white line that was tracked by the vehicle's vision system. Both demonstrations were very successful. Over 100 people rode in the two control-transition cars, and approximately 1200 rode in the mini-demo vehicle.

Since the vision system is looking ahead of the vehicle, it is able to make steering commands in anticipation of changes in curvature of the roadway.

The Control Transition Scenario

For the AHS technical feasibility demonstration, Honda and PATH choose to emphasize "control transition," or transition from a rural environment with no AHS infrastructure support to an urban environment with infrastructure. The demonstration started with two cars acting as independent but fully autonomous vehicles. Steering was controlled via input from the vision system, and longitudinal spacing via input from the laser radar. The vehicles independently saw a stationary obstacle and made an automatic lane change to avoid it, demonstrated adaptive cruise control and platooning, and finally, while in a platoon, switched from steering by machine vision to steering by sensing magnetic markers.

Machine Vision

The lane-tracking and stereo vision systems used by the Honda-PATH AHS vehicles are under development by researchers from PATH and the Electrical Engineering and Computer Science department of the University of California at Berkeley.

The vision-based lane-tracking system uses sophisticated software running on off-the-shelf computer chips to find the lane markers (lines) in the video image and feed back this information to the vehicle controller, which steers the vehicle to the center of the lane via commands to an electromechanical actuator. The system captures images from one of the video cameras mounted in front of the rear view mirror and looks for features that could be lane markers in each picture. It uses the positions of these markers in the image, as well as the measurements it receives from the on-board fiber-optic gyroscope and the speedometer, to form an estimate of the position and orientation of the vehicle within the lane and the curvature of the roadway. By using robust estimation techniques, the system is able to reject markings that are not lane markings. It performs well in a variety of road surfaces and lighting conditions.

The vision-based steering-control system uses the information returned from the lane-tracking system to compute an appropriate steering command. The system tries to match the curvature of the road and to keep the vehicle in the center of the lane. Since the vision system is looking ahead of the vehicle, it is able to make steering commands in anticipation of changes in curvature of the roadway.

This allows the system to do a better job of controlling the vehicle.

Magnetic Marker Sensing System

The magnetic marker sensing technology employed by the Honda-PATH vehicles utilizes a three-point sensor arrangement that provides extreme accuracy and robustness against external noise. From measurements of the marker's magnetic field at the two closest sensor locations, the distance, as well as the magnet's orientation (i.e., north or south pole up), are computed. The distance estimates are important for lane-keeping, and the sequence of field orientations (e. g., north-south-north-south) are used to encode important travel information, such as mileage markings and roadside services.

Lateral Control

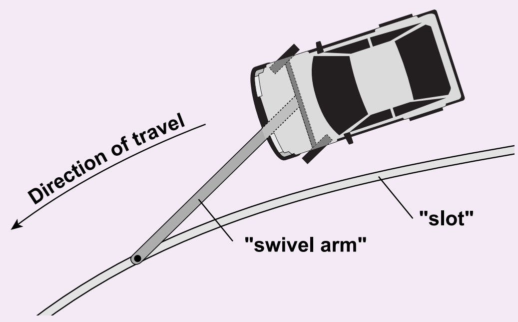
Automatic lateral control can be conceptually represented by the mechanical linkage system shown below. The slot represents the road center, while the swivel arm is analogous to the control law, which in reality is an algorithm or logic set by which the computer determines the commands required to keep the vehicle centered within the lane. The controller draws information from the sensors (velocity, yaw rate, acceleration, lateral displacement, and current steering angle) and outputs the commanded steering angle to the steering actuator. At an update rate of 20 milliseconds, the controller can quickly respond to changing conditions and unexpected contingencies.

Longitudinal Control

Automatic longitudinal control–control of the gap between vehicles–is also a software realization of a mechanically-linked system. Virtual "springs" and "shock absorbers" generate the forces required to position the vehicle relative to its predecessor. The virtual spring displacements are obtained from the laser radar. The virtual shock absorber closing rates are obtained either from successive laser radar measurements (non-cooperative cruise control), or by comparing the velocities of the leading and following vehicles via radio communication between the two vehicles (cooperative cruise control). At highway cruising speeds, errors made by the Honda-PATH cooperative cruise control system are typically much less than those made by the average human driver.

Demo '97 was considered very successful by both Honda and PATH. We are pursuing plans for future joint research utilizing the existing cars and involving such concepts as sensor fusion and fault detection systems.

Mechanical Analogy of Automatic Lateral Control



The Research Team

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Congressman George E. Brown, Jr. (D.-Calif.) and San Diego Deputy Mayor Barbara Warden listen to Congressman Ron Packard (R.-Calif.) at the opening ceremonies

Rodney Slater (center), Secretary of the United States Department of Transportation, with NAHSC Program Manager Jim Rillings (left), and Federal Highway Administration AHS Program Manager Dick Bishop

Senator Barbara Boxer with Caltra

More than 3,500 representatives of government, industry, the media, and the general public attended the National Automated Highway System Consortium Technical Feasibilty Demonstration, better known as Demo '97, from August 7-10 in San Diego, California.

Over 1,350 people rode in vehicles demonstrating seven different automated scenarios, both on the express lanes of Interstate 15 and on a half-mile "mini-demo" track at nearby Miramar College, which was also the site of a mammoth 47-exhibit AHS Exposition Center.

...ans Director James van Loben Sels

Christine Johnson, Director of the USDOT Intelligent Transportation Systems Joint Program Office, and Mortimer Downey, Deputy Secretary of Transportation

Toyota Vice President Akihiro Wada in the PATH booth staffed by researcher Chieh Chen (center)

Stories about the Demo ran on every national TV news program, on hundreds of local news broadcasts, and in over 700 newspapers worldwide. Coverage was more than favorable: USA Today summed up its story on the Demo vehicles, "They worked without a glitch."

delighted with rides in automated cars

Fully automatic: Robert Blum explains to a test rider how a car drives itself. At left, video cameras whirred as people tried out a car at a track at Miramar Community College yesterday. The riders were delighted.

Look, ma, no hands!

Automated cars get 1st big I-15 test

o hands

Senator Boxer: "Fabulous!"

Halfway through a ride in a fully automated PATH Buick LeSabre on the Demo '97 mini-demo half-mile track, Senator Barbara Boxer turned to PATH engineer Satyajit Patwardhan and said "I'm already impressed." Emerging from the car a minute later, Sen. Boxer called the ride "Fabulous! I felt like I was at the Indy 500."

Senator Boxer also rode in an automatically controlled Honda Accord, developed by Honda R&D in conjunction with PATH, which she called "Amazing!"

The purpose of Senator Boxer's rides, and of Demo '97, was to show that an Automated Highway System, with its goal of improving the efficiency of existing roads, is possible with technology available today.

Asked if such a system would be politically feasible, Senator Boxer replied: "Maybe not today, but I think that's definitely what we're looking at in California for the future."

"Without it," she told PATH director Pravin Varaiya, "We're not going to accommodate 40 to 60 million people. We can't keep building roads."

Boxer accepted director Varaiya's invitation to visit PATH headquarters. "I'm really serious," she said, "about helping you guys out."

Scenes from A

HS Demo ‘97

PATH on the AHS Mainline: Our Other Technical Contributions to NAHSC

Jim Misener, Ching-Yao Chan, PATH

PATH's involvement with the NAHSC extends beyond the technology shown at Demo '97. The platooning concept is the most visible contribution of PATH's research heritage, but research from a wide variety of disciplines has contributed substantially to the state of knowledge of Automated Highway Systems (AHS). The considerable body of vehicle control and AHS deployment research at PATH ranges from investigations of both in-vehicle and high-level control architectures and algorithms to safety and deployment through eliciting consumer preferences. It is from this solid technical foundation that NAHSC researchers have investigated the technical feasibility of AHS, its components and subsystems, and it is from this basis that they are now constructing alternate paths to AHS deployment, and developing methods to evaluate intermediate steps along these paths.

Many of these NAHSC researchers are in fact PATH researchers. PATH's work is integral to the concept development portion of the Consortium's work plan, which is critical to developing and evaluating the intermediate and end-state steps in implementing a national AHS. Important feed-ins to concept development are the assessment and development of critical enabling technologies and the identification and development of computer-based tools. PATH's contribution to these ongoing technical tasks is substantial.

James Misener is a Principal Development Engineer at California PATH.

Ching-Yao Chan is a Research Engineer at California PATH.

Concept Development

PATH researchers Mark Miller, Jim Misener, Raja Sengupta, and Jacob Tsao participated with other NAHSC researchers by defining six major attributes of any AHS concept, and devising for each attribute an accompanying range of possible solutions. The attributes are:

- Distribution of Intelligence
- Separation Policy
- Mixing of Automated and Non-Automated Vehicles in the Same Lane
- Mixing of Vehicle Classes (Autos, Trucks, Buses) in Same Lane
- Entry and Exit, and
- Obstacle Handling

The range of attributes and solutions were grouped into six concept families: Vehicle-Centered, Cooperative Plus, Driver Involvement (this concept was dropped at the insistence of the stakeholders), Infrastructure Supported Platoons, Infrastructure Assisted Platoons, and Maximally Layered. Due in part to PATH analyses showing that these concept families involved hard-to-separate mixes of attributes, subsequent work focused on the six principal technical design attributes of an AHS, as described below.

1. Traffic Mix (dedicated AHS lanes or automated vehicles mixing within manual vehicles). PATH researchers Luis Alvarez, Bret Michael, and Mark Miller contributed in this area by showing achievable capacities; Marco Antoniotti, Akash Deshpande, Carl Gibson, Alain Girault, Randy Hall, and Jacob Tsao worked on merge derating of highway capacity.

2. Deployment Sequencing (ordering and timing of steps to advance to automated operations). Steve Shladover and Jacob Tsao contributed in this area by showing various deployment sequences.

3. Distribution of Intelligence (among individual vehicles, groups, and vehicles and the roadway).

4. Vehicle Separation Policy (operations as independent vehicles, coordinated "free agent" vehicles, or closely coupled platoons). PATH researchers Datta Godbole, Bret Michael, and Raja Sengupta showed trade-offs between throughput and the frequency of collisions, and between the frequency and severity of collisions. When these are combined, it becomes apparent that significant throughput increases can be gained with only relatively minor effects on safety.

5. Obstacle Management (obstacle detection and avoidance, or prevention of obstacle intrusion)

6. Driver Roles (driver responsibilities and degree of override capability)

PATH researchers are presently participating in identification of user needs as seen by different categories of stakeholders, development of an AHS system architecture compatible with the national ITS architecture, and evaluation of AHS, including emissions and energy consumption and emerging deployment steps.

Critical Enabling Technologies

Ching-Yao Chan oversees PATH work on this task, which involves the development, evaluation, and procurement of various technologies for AHS. PATH's involvement spans vehicle control to sensing to software safety. Ongoing projects, some of which are sponsored fully by NAHSC and others jointly by NAHSC and Caltrans, include:

1. Integrated Vehicle Control. Headed by Professors Masayoshi Tomizuka and Karl Hedrick of the Mechanical Engineering Department at UC Berkeley. This key project covers the following technical subjects: integration and validation of combined lateral and longitudinal control; robust tractive force control; estimation of road-tire characteristics for adaptive control; transition maneuvers, such as entry, exit, and merging; and alternative sensors for safety and robustness enhancement.

2. Machine Vision for Vehicle Control. Conducted by Professor Jitendra Malik and C. J. Taylor of the Electrical Engineering and Computer Science Department at UC Berkeley. A stereo vision system has been successfully implemented and adapted for real-time control testing.

3. Safety Evaluation Issues in Real-Time Software. Andy Segal of PATH will use commercially available software tools to examine the structure, robustness, and integrity of software being developed at PATH for advanced vehicle control systems.

4. Near-Infrared Detection of Ice on Roadways. Jim Misener of PATH aims to investigate the use of near-infrared measuring devices for ice detection on roadways. This would be a potential on-vehicle or infrastructure-based sensor alternative for improving traffic safety.

Test of lateral control at PATH's Golden Gate Fields facility near the UC Berkeley campus

Other projects being planned include the study of optimizing the design of magnetic markers for vehicle control, and the use of magnetic tape for vehicle guidance and control (with assistance and cooperation from 3M). PATH is also responsible for the administration of subcontracts for studies in control algorithms, which may include subjects in the areas of control strategies, software and hardware implementation, and fault detection and tolerance. These projects are expected to commence after the 1997 AHS demonstration.

Computer-Based Tools

PATH leads the NAHSC effort to supply modeling and simulation tools for analyzing, evaluating, and designing all aspects of automated highway systems. The primary short term thrust is to provide an objective basis for concept development activities; longer term thrusts are to provide modeling and simulation support toward concept selection, and to the prototype design and development tasks. Overall, there are twenty-one separate tool development efforts, with about 50% of the effort stemming from PATH. Highlights of some of the larger-scale efforts include:

1. SmartAHS Microsimulation [Marco Antoniotti, Peter Cooke, Akash Deshpande, Farokh Eskafi, Alain Girault, Aleks Göllü, Bruce Hongola, Delnaz Khorramabadi, Michael Kourjanski, Tunc Simsek,

continued on page 14

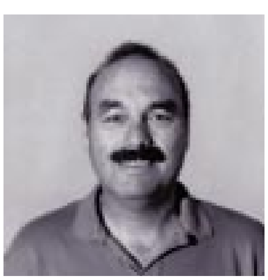
Societal and Institutional Issues of Automated Highway Systems

Mark Miller, PATH

The National Automated Highway Systems Consortium has the mission of specifying, developing, and demonstrating a prototype automated highway system (AHS). The AHS program is a sociotechnical program, since it must address not only the technical issues associated with AHS, but numerous societal and institutional issues as well. Two of these issues, now under investigation at the California PATH Program, are how to integrate the national AHS effort with planning and decision-making processes at the level of State Departments of Transportation (DOT) and regional Metropolitan Planning Organizations (MPO), and how to integrate transit operations with AHS.

Planning and Decison-Making at State, Regional, and Local Levels

Successful implementation of automated highway systems will need to be tailored to local and regional transportation needs and priorities. The planning and development of successful AHS must be national in scope, yet flexible enough to meet transportation goals, objectives, and requirements at the state, regional, and local government levels where such systems will be implemented. In particular, an automated highway system must be adaptable enough to fit the planning and decision-making processes at the MPO and State DOT levels. How these processes work must be understood to determine the appropriate fit. Guidance derived from the Intermodal Surface Transportation Efficiency Act (ISTEA) regarding the use of federal funds recognizes the need for local control to meet local need. Thus AHS will need to be tailored to local and regional transportation needs and priorities. Planning and decision-making mechanisms will likely be different within each organization or group of organizations. General concerns at these different institutional levels are under investigation, and recommendations for addressing these concerns will be developed.



Mark Miller is a specialist at PATH Headquarters.

Many interviews, conversations, and focus groups, involving representatives from many governmental organizations, have been conducted in the current and ongoing effort to better understand the concerns and priorities of governmental organizations at all levels about AHS, and to develop recommendations for addressing them. Issues that have been identified include those of funding, operations, maintenance, regulation and law enforcement associated with system access, tort liability, deployment paths, means of mainstreaming AHS within Intelligent Transportation Systems (ITS), finding the means of integrating AHS within the overall planning process and conforming with the guidelines of ISTEA, the interface between an AHS and surrounding roadways, and risk of embarking on a new venture with no guarantee of counterbalancing benefits. How some of these issues could be addressed depends on how an AHS is described, both from system architecture and functional design points of view. Currently a multitude of potential AHS attributes are undergoing investigation and analysis to help form a foundation from which such issues can be addressed.

While automated highway systems are part of the much larger set of ITS, AHS is usually considered in the context of long-term implementations. Just as ITS should generally be seen as a natural extension of the current transportation environment, as offering a toolbox of solutions to transportation-related problems, it is important that AHS be seen as a natural extension of the more "conventional" aspects of ITS. The mainstreaming of ITS within the conventional, more low-tech transportation environment will be an important determinant of its success. Similarly, the mainstreaming of AHS within the ITS world will be an important determinant of the success of AHS.

Transit Operations

Transit gives AHS the opportunity to meet the needs of people and markets not well served by the automobile. The integration of transit vehicles into the set of automated vehicle types has the potential for significant benefits in such roadway transportation problem areas as congestion, safety, air quality, and fuel consumption, as well as in addressing social equity, land use, and environmental considerations regarding AHS. Transit applications also offer the opportunity to demonstrate advanced technologies with a cadre of trained drivers. The focus of PATH's research is on developing ways to integrate AHS with transit operations. A concept of AHS-based transit operations has been studied to explore ways specific transit systems could benefit from a variety of AHS-based concepts. Several U.S. transit systems where different concepts of vehicle/highway automation for transit are being developed have also been studied, as these systems are considering the possible advantages of automation for current and future operations.

Automated Houston Metro transit buses carried passengers on Interstate 15 express lanes at Demo '97 in San Diego.

Transit-related aspects of ITS are tied to more immediate transit improvements. City buses are becoming mobile platforms for ITS in urban areas, because the USDOT initiative to encourage intelligent transportation infrastructure investment in the transit industry is focused on "Smart" buses. Transit property managers and riders will soon know where "their bus" is as automatic vehicle location technology is rapidly put into practice to assist bus fleet operations. Efforts to deploy an intelligent transportation infrastructure will lead to much more flexible and customer-responsive transit services. As these developments become successful, the increased volume of business will require a much improved supporting trunk line service. This is one area where it will be important for transit to take advantage of AHS technologies as they become proven.

Mechanically guided and coupled rail systems now operate automatically with high precision, but are expensive and difficult to retrofit into the land-use patterns of many of our urban areas. AHS offers great potential for transit, particularly the electronic guidance that would operate the automated highways. Some effort has been given to electronic guidance for buses in Europe, and possibilities also exist U.S. application. The development of low-floor buses, hybrid electric power systems, and the new information infrastructure together are examples. AHS provides an opportunity to plan new transit service with the positive features of rail, but with greater flexibility and lower cost. Buses would operate, individually or in platoons, at close intervals but without bunching, and at level loading platform stops. They would operate on or off the automated highway lanes to efficiently link to our developing land use patterns in urban areas.

One vision of automated transit includes buses operated automatically on special lanes of the highway system, and operating under manual control off the automated sections. Automated operations would consist of automatic electronic guidance for the buses. This innovation would free transit from mechanically guided systems, with their very high inherent cost and rigid architecture. With transit guided electronically, designers could plan less costly and more flexible line haul and feeder systems. Such systems would be logical extensions of the direction transit is already headed within ITS. The eventual result may be an automated vehicle system that resembles light rail, but with neither rails nor trains.

Such a "bus rapid transit system" could offer the performance features of rail transit at substantially lower cost. Capital costs would be reduced where the line haul is on shared automated lanes, and the vehicle system would be smaller and lighter, therefore lowering structural costs. The design approach would be flexible: transit improvements could be made to fit the community served, rather than force-fitting the developing community to the architecture of the transit system. Such an automated bus

continued on page 14

continued from page 13

rapid transit system would be ideal for a typical city with a beltway around the urban area, and interstate highways along radial routes from the downtown core.

Even though such vehicles would operate manually while off the automated highway, their exact location would be monitored by an automated vehicle location system. Bus entry and circulation throughout the automated system would be well coordinated and communicated to customers. For better overall system performance, adjustments for demand shifts and incidents would also be made. Drivers would be freed to operate additional services, focus on customer service, or monitor safety concerns, depending on service priorities.

I would like to acknowledge my colleagues and co-authors in this research effort, namely Ronald J. Fisher of CTA International, Inc., Matt Hanson of the California Department of Transportation (Caltrans) New Technology and Research Program, and Alan Lubliner of Parsons Brinckerhoff Quade & Douglas, Inc.

PATH on the AHS Mainline: Our Other Technical Contributions to NAHSC

continued from page 11

SHIFT is a programming language developed at PATH for describing dynamic networks of hybrid automata, such as AHS.

Pravin Varaiya, Daniel Wiesmann, Sergio Yovine, Marco Zandonadi]. SmartAHS/Hybrid Systems Tools Interface Format (SHIFT) is the general hybrid systems simulator for user-defined AHS architectures, with SHIFT as a high-level language invented to specify AHS-specific models for highway layout, vehicle dynamics, actuators and sensors. SHIFT is a programming language developed at PATH for describing dynamic networks of hybrid automata, such as AHS. SmartAHS/SHIFT is available at http://www.path.berkeley.edu/shift.

SmartAHS contains the following features:

- Highway Models: Supports user-defined description, compatible with UC Berkeley/Caltrans SmartPATH; can specify lane, segment, section, block, barrier, weather, source, sink.
- Vehicle Models: Provides simple, 2-D, three levels of intermediate vehicle models (between 2- and 3-D), 3-D and articulated simple vehicle dynamics.
- Controllers: Provides physical layer (steering, throttle, brake and tire burst) controllers; also supports open loop trajectory following controller and cooperating independent vehicle controller.
- Communication Models: Provides spherical, perfect receiver, transmitter and message communications.
- Sensor Models: Provides a spherical, perfect closest vehicle sensor.
- Animation: Allows simple, 2D (top view) animation and high fidelity texture-mapped 3D animation (with reused code from SmartPATH). Allows full vehicle/environment/roadway processing and interaction.

These features are coded in SHIFT, as is the user-created model of the notional AHS system, then translated to C via a compiler. Hybrid systems consist of components that can be created, interconnected, and destroyed as the system evolves. Components exhibit hybrid behavior, consisting of continuous-time phases separated by discrete-event transitions. Components may evolve independently, or they may interact through their inputs, outputs, and exported events, and the interaction network itself may evolve.

SmartAHS was successfully applied to the Houston Katy Freeway corridor case study, and within the zero-crash safety constraint, a merge protocol for independent (or autonomous) vehicles was designed and demonstrated using the simulation.

As an important SmartAHS developmental note, the CORSIM API was acquired to interface TRAF-NETSIM with SmartAHS, and work was begun to develop the capability of assessing entry and exit ramp effects.

Finally, a modal emissions and energy consumption supplement to SmartAHS, based in large part on the NCHRPT work by UC Riverside is currently being incorporated [Matt Barth, Carl Gibson].

2. SmartCap Meso-Scale Simulation [Luis Alvarez, Mireille Broucke, Pravin Varaiya]. SmartCap is a meso-scale simulator for studying AHS capacity. It allows the user to specify the highway configuration by connecting sections of the highway consisting of contiguous lanes. The simulator evolves vehicle flows according to conservation and velocity dynamics laws, keeping track of different flow types, where flow types are distinguished by vehicle class (e.g., light-duty passenger vehicle) and by the exit to be taken by the vehicle. The model is intended to capture the basic capacity impact of vehicle control laws, abstracted through activities, and to capture secondary effects such as queuing, bottlenecks in a system due to exit or entrance, effects of lane change, and imbalance of density among lanes.

The SmartCap simulator has recently been applied to the NAHSC Houston Katy Freeway Case Study, with travel time used as the primary basis for distinguishing various AHS concepts. These concepts were evaluated by PATH to determine which met the expected travel demand.

To further address capacity analysis needs, a high level or aggregate merge simulator was developed to represent entry onto AHS [Jacob Tsao, Randy Hall], with different policies of mainline vs. entry ramp slowdown.

3. Safety Analysis Tools [Datta Godbole, Veit Hagenmeyer, Natalia Kourjanskaia, Bret Michael, Raja Sengupta] A suite of Safety Evaluation Tools (Spacing Design, Intervehicle Spacing, String Analysis, Collision Probability, AIS Injury and Multiple Collision Analysis Tools) were developed to address deterministic and probabilistic (e.g., varying braking rates) consequences of collision resulting from safe spacing policies. These have been recently supplemented by obstacle avoidance and lane-change maneuver tools.

Several of these tools were used to address deterministic and probabilistic (e.g., varying braking rates) consequences resulting from spacing policies. Levels of cooperation and decision making, ranging from independent or autonomous vehicles through fully cooperative operations, were abstracted as information structures, and appropriate lags and responses were modeled. These tools produced intervehicle separation, and for the platooning case, intra- and interplatoon separations, for all, as functions of speed. In determining separations, AHS concept type vs. frequency of collision vs. severity of collision, given a hard braking disturbance tradeoff curves, were applied. From these curves, concept team analysts could chose the operating point, or separation policy, and from various separation policies, “pipeline” or maximum throughput rates were also determined.

4. Non-AHS Regional Impact/Planning Tools [Mark Miller]. Plans were developed to include investigation of travel forecasting tools in use by Metropolitan Planning Organizations (MPO’s) in the U.S., particularly those who have good potential of being NAHSC case study participants, then to identify and implement AHS-specific improvements to those tools.

The SmartCap simulator has recently been applied to the NAHSC Houston Katy Freeway Case Study, with travel time used as the primary basis for distinguishing various AHS concepts.

PATH Presentations and PATH on Paper will return next issue.

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