Title

Answering the Challenges of Regulating AutomatedVehicle Testing and Development in California

Journal

Intellimotion, 19(1)

Authors

Christopher, Nowakowski
Shladover, Steven E.

Publication Date

2014

Intellimotion

Keeping up with California PATH Research in Intelligent Transportation Systems

Volume 19, No. 1 2014

California PATH—Partners for Advanced Transportation Technology—is a collaboration between the California Department of Transportation (Caltrans), the University of California, other public and private academic institutions, and private industry.

PATH's mission is to develop solutions that address the challenges of California's surface transportation systems through advanced ideas and technologies and with a focus on greater deployment of those solutions throughout California.

CALIFORNIA PATH

Answering the Challenges of Regulating Automated Vehicle Testing and Development in California

Christopher Nowakowski and Steven E. Shladover
California PATH

Research, development and testing of vehicles that can operate under automatic control has been in progress for decades by university researchers, automobile manufactures, and automotive suppliers. Most of the testing has been undertaken on test tracks or roads closed to the public. As the technology has matured, there has been a growing need for testing on public roads. It is now anticipated that the first public deployment of intermediate levels of automated driving technology will likely be within a decade, therefore a regulatory framework needs to be developed to support testing on the open road. While some have postulated that automated vehicles are probably already legal in the U.S[1]., Google began advocating that states need to clarify existing laws and start creating regulations for automated vehicles.

In June 2011, Nevada became the first state to pass legislation that facilitated testing of automated vehicles on state roadways. In September 2012 California followed suit and passed SB 1298, with Florida, Michigan, and the District of Columbia acting by the end of 2013[2]. California SB 1298 created California Vehicle Code 38750, establishing definitions for "autonomous vehicles", "operators", and "manufacturers", and authorizing and requiring the California Department of Motor Vehicles (DMV) to adopt regulations for the testing and deployment of what it called "autonomous" vehicles on public roads by January 1, 2015. However, since SB 1298 wasn't passed until September 2012, only a little over two years was allocated to research, propose, and approve the automated vehicle regulations.

The development of these regulations is challenging for several reasons, beyond the limited time frame:

1. It requires the DMV, which has no history of working on technology-intensive issues, to regulate some of the most technologically complicated systems in the world;
2. It forces the DMV to define state regulations in a domain that has long been a federal responsibility rather than a state responsibility;
3. It requires regulations to be defined in the absence of technical standards that can be referenced as baselines for acceptable performance and safety;
4. It requires the DMV to find a balance between encouraging technological innovation by California industry and protecting the traveling public from being exposed to safety hazards from immature implementations of the technology.

These challenges have provided an exciting opportunity for PATH to support the DMV with its expertise in road vehicle automation, so that the DMV can develop its regulations based on solid technical footings.

> ***"The new California vehicle code defines an "autonomous vehicle" as a vehicle equipped with technology that has the capability of driving the vehicle without the active physical control or monitoring of the driver."***

Defining Levels of Vehicle Automation

In the frenzy of news media on the topic of automated vehicles, Google announced their "self-driving" car project and GM announced a future product called Super Cruise. Tesla, Nissan, Volvo, and others quickly followed suit with future product announcements that were variously referred to as autonomous vehicles, self-driving cars, and even driverless cars. Some claimed that they would be able to handle any road or situation, while others suggested that freeway capable automation would be first to arrive, and the implementation timelines varied from 5 years to more than 20 years. It quickly became apparent

continued on next page

Lexus RX450h retrofitted by Google for automated driving - photo by Steve Jurvetson

that part of the confusion arose because the different developers and manufacturers were talking about radically different vehicle automation system concepts when using the same imprecise terminology.

In separate but parallel development efforts, the Society of Automotive Engineers (SAE International) and the National Highway Traffic Safety Administration (NHTSA) published taxonomies to describe the levels of vehicle automation to provide a basis for communicating about different concepts. SAE J3016[3] defined six levels of automation: (0) non-automated, (1) assisted, (2) partial automation, (3) conditional automation, (4) high automation, and (5) full automation. The NHTSA proposed hierarchy[4] contained only five levels, preferring to merge the SAE conditional and high automation into a single category.

> *"To make the regulatory process more manageable, the DMV divided it into two components or regulatory packages based the two primary topics set forth in the new section of the vehicle code."*

The new California vehicle code defines an "autonomous vehicle" as a vehicle equipped with technology that has the capability of driving the vehicle without the active physical control or monitoring of the driver. However, the definition specifically excludes automation technology used in collision avoidance and driver assistance systems such as blind spot awareness, forward collision warning, forward collision mitigation braking, park assist, adaptive cruise control, lane keeping assist, and even traffic jam assist systems. These exclusions clearly apply to the SAE Level 1, assistance, and Level 2, partial automation systems, whereas the California definition applies to the higher levels of automation (conditional, high, or full automation) since these are the levels where active monitoring by the driver would no longer be required on a continuous basis.

New Frontiers for the California DMV

NHTSA has been responsible for establishing and enforcing automotive safety and performance standards since the National Traffic and Motor Vehicle Safety Act of 1966, but it does not regulate the actions of vehicle owners, the operation of vehicles on public roads, or the maintenance or repair of vehicles. The authority to establish licensing requirements for drivers and registration requirements for vehicles has always been in the hands of the individual states, and there are differences among states. With the introduction of automated vehicles, the regulatory challenges are no longer limited to measuring safety through mechanical or electronic defects and crashworthiness. Regulatory agencies must also be concerned with how to regulate automated system behaviors and potential violations of traffic laws, previously the sole responsibility of human drivers.

> *"One of the most important aspects of crafting the regulations for an automated vehicle testing program was understanding that failures are expected during testing."*

Over the past year, PATH has been supporting DVM by providing expertise and conducting research on a host of automated vehicle regulatory topics. PATH assembled a team of experts to advise the DMV, including Steven Shladover, Christopher Nowakowski, Ching-Yao Chan, Han-Shue Tan, Wei-Bin Zhang, and Roberto Horowitz. The project was kicked off at the 2013 Transportation Research Board (TRB) summer Workshop on Road Vehicle Automation, where PATH held a half-day workshop with almost 200 attendees to discuss selected regulatory topics identified by the researchers at PATH and the regulators at the DMV. In the following months, PATH researchers met with various automated vehicle developers and manufacturers in the Bay Area and assembled a panel of industry experts to provide feedback on best practices and potential regulations.

To make the regulatory process more manageable, the DMV divided it into two components or regulatory packages based on the two primary topics set forth in the new section of the vehicle code. The first regulatory package deals with regulations necessary to conduct automated vehicle testing on public roads, and the sec

continued on next page

ond regulatory package deals with regulations necessary for the deployment of automated vehicles to the driving public at large.

Automated Vehicle Testing Regulations

The new section of the California vehicle code provided a framework for the DMV to create a testing permit application process, but the vehicle code itself mandated several automated testing requirements such as proof of self-insurance or surety bond in the amount of five million dollars, certification that the tested vehicle has a means to allow a driver to take over, a requirement that a qualified test driver be seated in the driver's seat and ready to take over, and data recording and archiving requirements. In creating the application for a testing permit, the DMV needed to know how to ensure public safety while automated vehicles are being tested on public roads. What documentation should be provided by manufacturers? What are the characteristics of a good testing program, of a good test driver candidate, or of a good test driver training program?

One of the most important aspects of crafting the regulations for an automated vehicle testing program was understanding that failures are expected during testing. The safety of any testing program is less dependent on the technology employed, because ultimately, safety is achieved through the combination of the test driver and the vehicle. The selection of responsible test drivers, a good driver training program, and an institutional focus on creating, documenting, and following safety-related procedures and policies were all found to be common elements of manufacturer testing programs. Given the diversity of system concepts being tested and the size and scope of the testing programs underway, it was clear that there is not going to be a one-size-fits-all solution, and the best we can do is recommend the elements of good safety programs so that the DMV can review applications on a case-by-case basis.

After several pre-notice workshops, the DMV released a first draft of the proposed automated vehicle testing regulations in November 2013 for public comment, with a public hearing held on January 14, 2014. The final testing regulations were adopted[5] on May 19th and went into effect on September 16, 2014. The DMV began accepting applications for automated vehicle testing permits on July 1st, 2014.

Automated Vehicle Deployment Regulations

The second regulatory package to be proposed by the DMV covers requirements related to the deployment of automated vehicles to the driving public. This set of regulations is particularly challenging because automat ed vehicles are still in the prototype phase and potential manufacturers are less than willing to disclose potential future products, timelines, or business strategies. Will the first automated vehicles to be deployed resemble the low-speed urban shuttles demonstrated in the CityMobil2 project[6], or will they more resemble traditional cars that are capable of some limited automated driving on freeways or automated parking? How can the safety of automated vehicles be ensured prior to deployment?

> *"Time is short and everyone at the DMV is marching forward to ensure that regulations are circulated for public review and then officially adopted."*

One topic of particular importance to the DMV was investigating the alternative models of safety certification. In the U.S., vehicle manufacturers self-certify that the vehicles they build meet the Federal Motor Vehicle Safety Standards (FMVSS), but currently there are no FMVSS for automated vehicles, nor are there any SAE or ISO voluntary standards for automated vehicles. PATH investigated models of safety certification used in the rail industry, by the EPA, and even the third-party safety process certifications commonly used in the European automotive industry. Although each certification model has advantages and disadvantages, there is no clear best solution.

Google's most recent prototype automated vehicle concept does not include traditional driver's seat or controls - photo courtesy of Google

continued on next page

Furthermore, it is important to distinguish between the capabilities (or competency) and the functional safety of the automated driving system. Competency is how well the automation deals with the external driving environment, whereas functional safety is focused on how well the system deals with internal faults and failures. Both are prerequisites for achieving a safe system, but they are developed and assessed differently. Competency could potentially be evaluated through performance standards and tests, but the development of such standards would require an effort far beyond the scope of the current project and the DMV's regulatory timeline. At this stage, the most that could be accomplished with regulations would be to identify minimum behavioral competencies for automated vehicles and verify that manufacturers have tested their products for those behaviors. These would represent necessary, but by no means sufficient, capabilities for public operation.

A methodology for achieving functional safety already exists in the international standard ISO 26262 for the automotive industry. Unfortunately, one of the key principles of this methodology is that the driver is always available as a backup, and at higher levels of automation, that assumption will not be true. Although there is discussion within ISO about updating the functional safety standard to better accommodate automated vehicles, such an undertaking will not be completed for years. In the absence of standards, there are very few avenues available for defining sensible functional safety regulations.

Moving beyond trying to ensure the safety of the automated driving systems, many additional questions had to be considered in developing the regulations:

- Will drivers need special training to operate an automated vehicle? Who should ensure that the training occurs, the manufacturers or the DMV through a license endorsement program?
- What information should be recorded about automation systems on the vehicle registration, considering the needs of vehicle owners, potential buyers, law enforcement, and DMV or other researchers?
- Will there need to be any special driver-vehicle interface requirements (beyond those specified in the original SB 1298 legislation) to ensure the safe operation of the vehicle?
- Will automated vehicles need to be externally identifiable to law enforcement or to other road users?
- Will the introduction of genuinely driverless vehicles, those capable of operating without a driver in the driver's seat, require additional regulations or changes to any of the proposed regulations?

While PATH has been working diligently to provide technical recommendations on these types of regulatory issues, draft regulations have not yet been released. Time is short and everyone at the DMV is marching forward to ensure that regulations are circulated for public review and then officially adopted. However, these regulations are not the end of the story, but rather still an early chapter in this rapidly evolving field. We should expect additional regulations to be proposed in the coming years as the technology continues to mature and understanding of vehicle automation capabilities, risks, and limitations continues to grow. ⊛

References

[1] Smith, Bryant Walker. (2012). Automated Vehicles are Probably Legal in the United States (White Paper). Stanford, CA: Stanford University, Center for Internet and Society. Available: http://cyberlaw.stanford.edu/publications/automated-vehicles-are-probably-legal-united-states

[2] http://cyberlaw.stanford.edu/wiki/index.php/Automated_Driving:_Legislative _and_Regulatory_Action

[3] SAE J2016. (2013). Taxonomy and Definitions for-Terms Related to On-Road Automated Motor Vehicles. Warrendale, PA: Society of Automotive Engineers.

[4] NHTSA (2013, May 30). Preliminary Statement of Policy Concerning Automated Vehicles. Washington, D.C.: U.S. Department of Transportation, National Highway Traffic Safety Administration. Retrieved May 30, 2013, from http://www.nhtsa.gov/staticfiles/rulemaking/pdf/Automated_Vehicles_Policy.pdf

[5] https://www.dmv.ca.gov/vr/autonomous/testing.htm

[6] http://www.citymobil2.eu/en/

Field Operational Tests of Transit Vehicle Assist and Automation Technologies

Han-Shue Tan, Jill Huang and Wei-Bin Zhang

Since 1988, California PATH has developed, integrated and extensively tested magnetic guidance systems on various vehicle platforms, including passenger cars, Class-8 tractor/trailer rigs and three full-size transit buses. A magnetic guidance system provides completely automated steering control at highway speeds which provides a smooth, comfortable ride with high degree of steering accuracy. The magnetic guidance system has also been field tested for snowplow guidance and snow blower automated steering applications under the most severe operating conditions. Magnetic guidance requires that magnets be placed in the roadway. Testing of the guided snowplows demonstrated that the magnets remained in place through multiple freeze/thaw cycles each year. In 2003, two 40 foot CNG powered New Flyer buses and one 60 foot articulated diesel New Flyer bus were retrofitted with a magnetic guidance system. Lane assist, lane change and automated/manual transitions were demonstrated on the I-15 HOV lane in San Diego

Under the sponsorship of USDOT Federal Transit Administration (FTA) and Research and Innovative Technology Administration (RITA), development and field operational tests of Vehicle Assist and Automation (VAA) is being conducted by a partnership with USDOT, Caltrans, AC Transit in San Francisco Bay Area and Lane Transit District in Oregon. VAA provides the rail-like service quality by improving lateral ride smoothness, particularly at higher speeds, and by making it possible for buses to dock precisely at stations, so that wheelchair-bound riders can roll on or off the buses with a small gap between the bus floor and the loading platform at the station. Accurate automatic steering can also help reduce right-of-way and busway construction costs by making it possible for buses to operate in lanes that are only slightly wider than the buses are themselves. Operating a bus in a confined space makes it possible to expand bus routes into currently congested urban highways or former rail rights of way in high-density urban locations where no other rights of way may be available. Longitudinal control is also very beneficial for BRT buses to be able to stop at bus stop at predetermined location, to travel along the dedicated bus with desired speed profile, and to couple electronically with each other to form a bus platoon (convoy).

The VAA research program was initiated in 2008. An integrated magnetic marker-based guidance system was implemented for lane keeping and precision docking operations for LTD in Eugene, Oregon. The goal of this project work is to demonstrate the technical merit and feasibility of two VAA technology applications in transit revenue service, and to identify and evaluate the costs and benefits. Both quantitative and qualitative measures are to be collected and evaluated throughout the field operational tests.

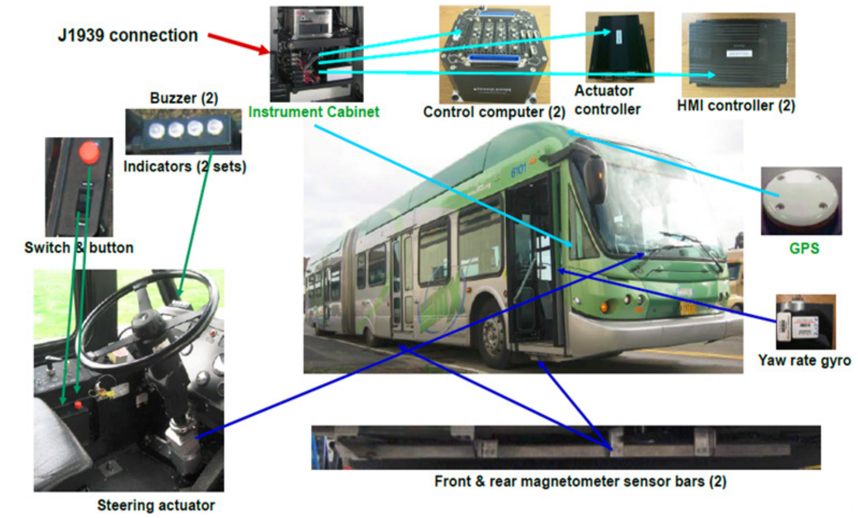

Photo courtesy of PATH Staff

As the guidance system is implemented for revenue service, safety is the highest priority for this project. Safety design concept has been implemented to include redundancy, comprehensive fault detection and diagnosis and fail-soft strategies to enable drivers to safely take over the system when system faults occur. Substantial testing has been conducted to validate the safety designs.

Field testing has been conducted along the BRT route in Eugene Oregon. The data collected from the field operational tests demonstrated that the standard deviation of the tracking errors within 10 cm except including the sharp S-curve transition when getting in and out of the stations at speeds up to 32km/hr. The accuracy of the bus docking is within a 1.5 cm centimeters. The guidance system achieves very tight tracking performance as well as superior ride comfort. Further field testing will be carried out in the next a few months to collect additional data. This project facilitated substantial experience with and knowledge of both the technical and deployment aspects of advanced vehicle control technologies.

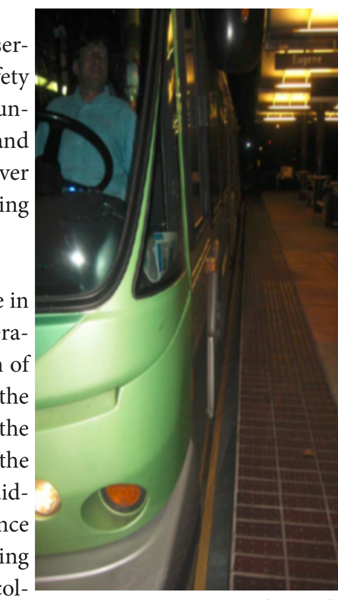
Photo courtesy of PATH Staff

The VAA project represents a bold effort, on the part of a University based research institution, toward the deployment of automated bus operation (based on magnetic guidance system). The transit partners desire for early deployment of VAA technologies. ⊛

Vehicle Automation Research at California PATH

California PATH has been a pioneer of vehicle and roadway automation research since the late 1980s. In addition to those projects highlighted in articles of this newsletter, brief introductions of selected projects conducted by the PATH researchers and associated faculty members are provided here.

Hyundai Center of Excellence

Under the direction of Prof. Karl Hedrick and Prof. Francesco Borrelli, at the Department of Mechanical Engineering of UC Berkeley, a team of engineers, scholars, and students have been engaged in developments of advanced driver assistance functions and autonomous driving systems. In addition to collaborative work on campus, testing of experimental research vehicles is also carried out at the Hyundai proving ground in Southern California.

A sampling of research projects at the Hyundai Center includes the following:

- Advanced techniques for estimating various states of the ego vehicle
- Implementation of Interacting Multiple Model (IMM) filters for tracking the states of a target vehicle
- Dynamic model based approaches for predicting target vehicle trajectories on highways
- Hidden Markov Model (HMM) approaches for predicting target vehicle behavior on highways and at intersections
- Reference generation for Model Predictive Control (MPC) for intelligent highway driving
- MPC formulations for autonomous driving in low speed and autonomous parking
- MPC for improving the vehicle safety and drift control in emergency situations
- Stochastic MPC for autonomous driving, based on a systematic handling of uncertainty in the environment

Cooperative Adaptive Cruise Control (CACC)

PATH has recently initiated two new research projects that focus on applications of CACC. These new projects are a direct result of CACC projects separately sponsored by FHWA and Nissan Motor Co. Ltd. In the first of the new projects, under the FHWA Exploratory Advanced Research Program, PATH researchers are working together with partners at the Delft University of Technology on "Using CACC to Form High-Performance Vehicle Streams". This project is defining operating strategies for grouping vehicles together so that they can use CACC and for separating them when they split to go to separate destinations, with the goal of having the most favorable impact on overall traffic flow. The work is being executed using traffic microsimulations based on the most recent and accurate models of ACC and CACC car-following behavior, calibrated from experimental data collected in PATH's Nissan vehicle experiments.

In the second project, for the FHWA Saxton Transportation Operations Laboratory, PATH researchers are implementing CACC control on a new fleet of five experimental vehicles that will be housed at the FHWA Turner-Fairbank Highway Research Center. The testing of these vehicles will provide a basis for comparison with the test results previously generated on the Nissan vehicles. That will help in understanding the extent to which CACC can harmonize the performance of vehicles that have very different underlying performance characteristics.

Truck Platooning

Under the sponsorship of the FHWA Exploratory Advanced Research Program, PATH is starting a new project on "Partial Automation for Truck Platooning", implementing cooperative adaptive cruise control (CACC) for trucks. The project partners include Caltrans, Volvo Group, Cambridge Systematics, the Los Angeles Metropolitan Transportation Agency and the Gateway Cities Council of Governments. Based on the strong local interest in improving goods movement along the I-710 corridor from the Los Angeles/Long Beach port complex towards downtown Los Angeles, that corridor is the site for case studies and demonstrations. PATH and Volvo Group engineers are developing the CACC systems for three tractor-trailer trucks, based on their combined prior experience in earlier truck platoon projects, and building on the commercially available Volvo ACC system, with the addition of V2V cooperation using DSRC. The vehicle-following gaps are to be chosen based on the preferences expressed by truck drivers in a human factors experiment, and the energy savings will then be measured in a series of carefully controlled tests at those preferred gaps. The results of those tests will be applied in simulation models to estimate the broader energy saving potential of this near-term application of truck platooning that could be applied in mixed traffic on current highways.

Ground Automated Transportation - Foundation for Innovation

An industrial partnership has been formed between automotive suppliers Valeo, Safran and automotive manufacturer PSA (Pugeot Citroën) to share their forces to make progress toward fully automated ground vehicles. The partnership targets two vehicle platforms: road vehicles (passenger cars) and first responder vehicles in unstructured environment. The industrial partners will collaborate with first-class academic research centers around the world, including MINES ParisTech, the Ecole Polytechnique Fédérale de Lausanne (EPFL), the Shanghai Jiao Tong University (SJTU), and California PATH at the University of California at Berkeley (UC Berkeley). These organizations are internationally recognized for their work in the scientific and technical fields necessary for driving automation. In addition to these 4 academic partners, two French laboratories agree to join this initiative: INRIA and IFSTTAR, both equally recognized their expertise in advanced vehicle technologies as the four above mentioned academic partners.

A foundation for innovation is established to facilitate the collaboration of the academia partners. The scientific program of the foundation will provide the knowledge necessary to go beyond the state of the art in key technologies that are necessary in order to deploy automated ground vehicles in real environment. The activities under this program, expected to begin in the second half of 2014, are structured for a 4-year period, and will include engineering implementation as well as real-world demonstrations. UC Berkeley will contribute to the program in areas of its expertise: safety, control, and cooperative systems. ⊕

PATH History of Research on Road Vehicle Automation

Despite the fact that automated driving has recently become a popular topic, based in large part on the publicity attracted by Google's work in this field, it has not always been such a popular topic in the ITS community. For much of the history of ITS research, development and deployment, PATH and Caltrans were the main proponents of road vehicle automation, while most of the ITS world believed it to be too futuristic. When PATH was founded in 1986, automation was one of its three main focus areas of attention, together with roadway electrification and "navigation" (the term that was used at that time to describe the combination of advanced traffic management and traveler information systems). This emphasis on automation derived directly from the primary original goal of Caltrans and the UCB Institute of Transportation Studies in starting PATH, which was to develop information technology approaches for producing dramatic increases in the throughput of highway infrastructure to accommodate the growing need for capacity (at least doubling the throughput).

"During this initial period from about 1988 to 1993, PATH was the only research group in the U.S. that was focusing so much attention on automation."

The first few years of PATH research featured pioneering studies on automation concept evaluation and explorations of several of the key enabling technologies to determine basic technical feasibility. A large-scale evaluation of the impact of highway automation on the Los Angeles region was performed using the regional transportation planning models of the Southern California Association of Governments (SCAG). The traditional 4-step SCAG regional model was modified to represent the capacity increases that could be achieved by automating one to three lanes in each direction on the major freeways in the region, showing the potential for significant reductions in congestion throughout the network. The key enabling technology studies included:

No hands vehicle test - photo courtesy of PATH Staff

- Development of a magnetic guidance system to serve as the location reference for automatic steering of road vehicles under all conditions (demonstrating that it could provide very accurate position measurements regardless of lighting conditions or

Photo courtesy of PATH Staff

the presence of snow or ice on the road surface).
- Development and testing of an automatic steering control system to steer a test car accurately and smoothly along a test track with multiple curves.
- Development of vehicle-to-vehicle communication capabilities to support close coordination of the driving behavior of vehicles.
- Development and testing of a platoon of four cars driving at highway speed at very short separation gaps (4 m), demonstrating for the first time the feasibility of providing smooth and accurate gap control in a car with a conventional internal combustion engine and automatic transmission.
- Definition of a hierarchical architecture for an automated highway system, making it possible to decompose this potentially very complicated system into distinct layers so that the system could be designed and developed at a manageable level of complexity.

During this initial period from about 1988 to 1993, PATH was the only research group in the U.S. that was focusing so much attention on automation. This placed PATH into a unique position when FHWA started to create a national program of research on automated highway systems in response to the Congressional mandate in the 1992 Intermodal Surface Transportation Efficiency Act (ISTEA), which stated:

"…the Secretary [of Transportation] shall develop an automated highway and vehicle prototype from which future fully automated intelligent vehicle-highway systems can be developed….The goal of this program is to have the first fully automated roadway or an automated test track in operation by 1997."

continued on next page

NAHSC 1997 Demo in San Diego - photo courtesy of PATH Staff

This Congressional mandate, which unfortunately was not accompanied by a dedicated funding stream, led to a large upsurge of national activity on highway automation. PATH was an active participant with several of the teams that won projects under the FHWA Automated Highway System Precursor Systems Analysis program in 1993-4, and was also a partner with Honeywell, developing operational concepts for the initial study of the human factors issues associated with automated driving. When FHWA solicited proposals for a national consortium to develop and test a prototype automated highway system, PATH and Caltrans had such unique qualifications in this field that they were the only organizations chosen to be on both of the teams that competed for that national consortium, one led by General Motors and the other led by TRW and Ford. The General Motors-led team won that competition and became the National Automated Highway Systems Consortium (NAHSC). PATH was one of the nine core participants in the NAHSC and had the largest single share of the NAHSC work of any of the participants (about 25% of the labor, representing about 30 full-time people).

"The NAHSC Demo'97 was such a success that PATH was invited to demonstrate its automated vehicles in international demonstrations in the Netherlands in 1998 (where we were the only non-European demonstrator) and Japan in 2000"

PATH had the lead role in the NAHSC for the development of modeling and simulation tools, for the second stage of operational concept development and evaluation, and for the demonstration of an automated platoon of eight cars. PATH researchers performed in-depth studies of many of the fundamental issues associated with road vehicle automation, including the low-level control and maneuvering of individual vehicles; intermediate level issues such as vehicle-vehicle interaction coordination, management of automated traffic at the level of highway links or junctions, and modeling of the highway capacity and safety improvements that could be gained.

PATH's automated platoon demonstration was the most visible product of the NAHSC's Demo '97 demonstration in San Diego in August 1997, which attracted huge media attention and thousands of visitors. About a thousand visitors had the opportunity to take 7.5-mile demonstration rides in the fully-automated vehicles along the I-15 HOV lanes in San Diego, experiencing automated driving at highway speed at a one-car-length gap, and including lane changing and platoon joining and splitting maneuvers. The surveys of the riders showed overwhelmingly favorable reactions to the experience. PATH also developed a two-car demonstration for Honda, combining magnetic and computer vision based lateral guidance approaches, as well as a "mini-demo" of one car doing high-precision maneuvers on a short test track.

The NAHSC Demo'97 was such a success that PATH was invited to demonstrate its automated vehicles in international demonstrations in the Netherlands in 1998 (where we were the only non-European demonstrator) and Japan in 2000 (where we were the only American demonstrator, and one of only three non-Japanese demonstrators). We also demonstrated the ability of the test cars to do precision low-speed maneuvering in Houston, Sacramento and Tempe AZ and at TRC Ohio.

Following the Congressionally mandated Demo '97, DOT terminated the remaining 2/3 of the planned work of the NAHSC because they thought it would take too long to become deployable. For at least the subsequent decade, automation was an unpopular topic within DOT because of the aftermath of the decision to terminate the NAHSC. However, Caltrans continued to support additional vehicle automation research at PATH, developing capabilities that were identified as important needs during the NAHSC research but that could not be accomplished before the NAHSC was terminated. This research included:

- Automated merging of passenger cars on a test track, with wireless coordination of the maneuvers of the cars to form a "virtual platoon" upstream of the merge
- Automated steering control of a tractor-trailer truck
- Automated close-coupled platooning of two tractor trailer trucks at gaps between 3 m and 10 m, with careful measurements of pollutant emission and energy consumption effects as a function of gap
- Precision docking of transit buses, showing consistent stopping within a 1 cm gap between the edge of the bus floor and the passenger loading platform at the station
- Automated close-coupled platooning of three transit buses, combining one diesel-powered 60-ft articulated bus with two CNG-powered 40-ft standard transit buses
- Case studies of early deployment opportunities for automated bus rapid transit and automated truck platoons on dedicated infrastructure in the Chicago region, under the auspices of the Cooperative Vehicle-Highway Automation Systems pooled-fund study
- Development of a first-generation cooperative adaptive cruise control (CACC) system, enhancing the capabilities of commercially available ACC by adding vehicle to vehicle communication.

continued on next page

The transit bus precision docking was demonstrated at the FHWA Turner-Fairbank Highway Research Center and both the docking and bus platooning were demonstrated for visitors at the I-15 HOV facility in San Diego in 2003. The transit bus precision docking work expanded into the Vehicle Assist and Automation project, with support of Caltrans and FTA, which is described more fully in a separate article in this IntelliMotion.

The return of the U.S. DOT to sponsorship of automation research began with the initial Broad Agency Announcement for the FHWA Exploratory Advanced Research Program (EARP) in 2007, under which PATH won two automation-related projects. One of these was a continuation of the Caltrans-supported CACC work into a formal human factors experiment with 16 drivers from the general public, and the second was an expansion of the earlier truck platooning experiments to three trucks. The CACC experiment showed excellent driver acceptance of CACC at significantly shorter gaps than the drivers were comfortable selecting with the production ACC system, demonstrating the potential for CACC to nearly double the capacity of a highway lane. A second-generation PATH CACC project sponsored by Nissan showed the dramatic contrast in string stability between the production ACC system and the CACC system. The EARP truck platooning experiments included truck platoon maneuvers (joining and splitting), as well as operations on positive and negative grades and cruising at gaps between 4 m and 10 m, with estimates of energy savings based on measurements of fuel consumption.

Automated Bus Demonstration 2003 - photo courtesy of PATH Staff

"As of ten years ago, PATH had already invested more than 600 person-years of labor on development and evaluation of automated driving systems."

Current PATH projects on road vehicle automation include:

- The Vehicle Assist and Automation project for transit buses, described more fully in a separate IntelliMotion article.
- Assisting the California DMV with the technical issues involved in their development of regulations to govern the testing and public sale and operation of automated vehicles, described more fully in a separate IntelliMotion article.
- An FHWA STOL laboratory project developing a CACC system for implementation on a new general-purpose vehicle experimental platform.
- An FHWA EARP project on using CACC to form high-performance vehicle streams, determining the higher-level traffic management strategies for capitalizing on the traffic advantages that CACC can provide.
- A new FHWA EARP project on partial automation for truck platooning, developing a CACC system in cooperation with Volvo Trucks and then testing it to determine driver preferences for CACC gap settings and the energy savings that can be gained at the preferred CACC gaps.

As of ten years ago, PATH had already invested more than 600 person-years of labor on development and evaluation of automated driving systems. Within the past decade, more research has been done and our scope has widened from full automation to various levels of partial automation that have the potential for somewhat earlier deployment. This combination of experience in full and partial automation systems, combined with extensive experience with connected vehicle technology, puts PATH in a leadership position for the upcoming initiatives on connected automation. Most of the PATH research staff who have been responsible for the major accomplishments cited here remain actively engaged and eager to make further progress on development of road vehicle automation systems – Steven Shladover, Wei-Bin Zhang, Ching-Yao Chan, Han-Shue Tan, Xiao-Yun Lu, Jihua Huang and Christopher Nowakowski. Similarly, the faculty members who have led many of the major automation research projects are also ready to make further progress on new projects – Professors Roberto Horowitz, Pravin Varaiya, Masayoshi Tomizuka and Karl Hedrick.

University of California Berkeley
California PATH
3 McLaughlin Hall, MC 1720
Berkeley, CA 94720

Address Service Requested

Intellimotion
Keeping up with California PATH Research in Intelligent Transportation Systems

California PATH Directors
Roberto Horowitz PhD and Thomas West

For more information or to offer comments about this newsletter, please write, call, fax or e-mail:

3 McLaughlin Hall
University of California, Berkeley
Berkeley, CA 94720
Tel: 510-642-4522
e-mail: path@path.berkeley.edu
http://www.path.berkeley.edu

Layout Isaura Linares

ITS Berkeley
Institute of Transportation Studies

CALIFORNIA PATH
Partners for Advanced Transportation Technology

Primary funding provided by:

Caltrans

Department of Transportation United States of America

ITS America Member ITS CA
Intelligent Transportation Society of California

ISSN-1061-4311