PATH at 20—History and Major Milestones

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***Abstract*—The California Partners for Advanced Transit and Highways (PATH) Program was founded in 1986, as the first research program in North America focused on the subject now known as intelligent transportation systems (ITS). This paper reviews the history of the founding of PATH and of the national ITS program in the U.S., providing perspective on the changes that have occurred during the past 20 years.**

***Index Terms*—Automated highway systems, intelligent transportation systems, transportation history.**

I. Introduction

IN THE world of institutions, especially, academic institutions, 20 years is not a particularly "big" anniversary. However, for a research program that is focused on a specific field of rapidly changing technology, 20 years is a long time and an anniversary that is worthy of note. For those of us who were involved in starting the Partners for Advanced Transit and Highways (PATH) Program, it is sobering to realize that we have been at it for such a long time and to notice that there has been almost a complete generational change of people who are active in the field. Since most of the people who were active in our field 20 years ago have retired by now and most of the people who are currently active were not involved 20 years ago, it is useful to explain the history behind the creation of PATH and of the entire field of intelligent transportation systems (ITS). This provides an opportunity to revisit the thinking of that time and to contemplate the changes that have occurred in the intervening 20 years.

The story begins with an explanation of the needs and challenges that motivated the start of ITS and the reason that it started in California (at least for North American activities). The "upstart" group that developed the technical and programmatic concepts for ITS had considerable work to do to gain the attention of the transportation establishment, and that process consumed several years before substantive support could be achieved. The key stages of that process are described to provide some history of the development of the national ITS program in the U.S. While the national program was being planned, PATH had already received substantial research funding support from the California Department of Transportation (Caltrans), which made it possible to initiate an ambitious portfolio of research projects on many aspects of ITS, giving PATH researchers several years of lead time ahead of their counterparts elsewhere in North America and making it possible to attract very talented research staff, students, and postdocs.

It is not feasible to cover all the research accomplishments of 20 years and nearly 1000 labor years of work in one paper, but some of the highlights are described here, particularly emphasizing their relationships to activities on the national and international scenes.

II. California Transportation Concerns in the Mid-1980s

The major growth in California's famous network of freeways occurred during the 1950s–1970s, but by the 1980s, the network was essentially static. In the mid-1980s, Caltrans realized that they needed to look ahead a couple of decades to determine how they were going to be able to meet the continually growing transportation needs of a state with a rapidly growing population and economy. Traffic congestion was becoming an increasingly acute public concern, as well as being recognized as an impediment to the future economic health of the state.

A Caltrans planning study for the Los Angeles region considered a variety of alternatives for meeting the projected 20-year travel needs of the region. The only alternative that was considered in the study that could significantly ameliorate the growing congestion problems would have involved double decking most of the major freeways, at a cost of \$28 billion (in 1985 dollars). It was evident to all who were involved that this would be financially, politically, and environmentally infeasible, even before the seismic hazards of double-decked freeways were revealed by the 1989 Loma Prieta earthquake. This led to the important conclusion that "we can't build our way out of congestion." Very importantly, some of the people who were involved in the planning process recognized that there were possibilities for information technology to help with the problem and decided to pursue that seriously.

Caltrans created an Office of New Technology in their Division of Transportation Planning to develop a research agenda to support their longer term needs and initiated a contract with the Institute of Transportation Studies of the University of California (UC), Berkeley (UCB-ITS) for research support. Caltrans convened a small group of experts in Monterey in the spring of 1986 to assist in their planning, which led to the creation of a conference in Sacramento in October 1986.

The Sacramento conference "Technology Options for Highway Transportation Operations" [1], which was organized by Prof. W. Garrison of UCB-ITS, is generally considered to be the landmark event in stimulating interest in what we now know as ITS in North America. Most of the 100 attendees (almost entirely from public agencies and universities, but not private

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industry) were from California, but there were also representatives from eight other states and the District of Columbia, as well as from Canada, Germany, and Sweden. A series of presentations and workshop discussions identified a wide range of ITS opportunities, including automated highways, as well as others that are related to clean propulsion technologies. Much of the Caltrans leadership participated in the meeting, and the conference proceedings contain several impressively visionary statements from people in senior Caltrans management positions. It is vital to recognize that major new initiatives require visionary champions in high places, and in this case, there was a rare combination of such people in positions where they could make a difference.

III. Founding the California PATH Program

Developing and evaluating the effectiveness of new information technologies for transportation required a combination of technological expertise that was not available within the traditional civil engineering and planning capabilities of Caltrans' own staff. Caltrans recognized that the multidisciplinary capabilities of the University of California could be accessed through the Institute of Transportation Studies, which had worked closely with Caltrans since its founding in 1948.

At the same time that Caltrans' interest in using information technology to improve transportation operations was developing, there was parallel work in California in developing a method of inductively transferring electric power to a moving road vehicle, so that its batteries could be recharged "on the fly." This project, which was focused on application to an electric bus for downtown Santa Barbara, was led by Systems Control Technology, Inc., where I was the project manager, and an independent consultant, Howard Ross. This roadway-powered electric vehicle (RPEV) project had federal earmarked funding but needed an institutional "home" after the retirement of the general manager of the Santa Barbara Metropolitan Transit District led to the loss of its local champion. Howard Ross and I recognized the potential synergy between this project and the developing Caltrans interest in highway automation, in which we had both long been interested. We proposed combining the RPEV project with the new highway automation work under the auspices of the Institute of Transportation Studies to the Directors of both Institute branches, Prof. Adib Kanafani at UC Berkeley and Prof. Wilfred Recker at UC Irvine. Prof. Kanafani was intrigued by the opportunity and knew that he wanted to have Robert Parsons lead the project.

Robert Parsons had a long and distinguished career in managing advanced technologies for transportation and had recently been working with UCB-ITS on a railroad systems research program. Earlier in his career, he had served as the Deputy Director of Supersonic Transport Development at the FAA, Associate Administrator for R&D at the Federal Railroad Administration and Manager of the Las Vegas-Southern California Phase II Super Train Feasibility Study. His experience with these diverse projects gave him an excellent understanding of the process of developing advanced technology systems and of trying to implement them via complicated public–private sector interactions.

Fig. 1. Robert E. Parsons (1931–2005): PATH Founding Director during 1986–1990.

Bob Parsons (Fig. 1) accepted the assignment as the first Director of the PATH Program and set it on a solid foundation for future growth and health during its first four years, until his retirement in 1990. He chose the original name for the program (Program on Advanced Technology for the Highway), and when the program scope was broadened to be more inclusively multimodal in 1992, he also chose the replacement name (Partners for Advanced Transit and Highways), preserving the PATH acronym. Parsons was an inspiring leader for PATH, with the rare ability to define a large-scale vision while also understanding the practical steps that need to be taken to advance it to reality. He was a warm and caring colleague and supervisor, giving generously of himself to others. All who worked with him remember him as a man of great integrity who expressed his opinions candidly and without artifice or pretense. Bob Parsons maintained the highest standards of honesty and integrity, inspiring others to follow his example. Unfortunately, he did not live to see PATH reach its 20th anniversary, having died in October 2005, but we have dedicated our 20th anniversary commemorations to his memory.

IV. Outreach to Create a National Program

The initial impetus for using information technology to improve road transportation operations came from California, but the program founders at Caltrans and the University of California knew from the start that this was not something that California could do on its own. They knew that it would be necessary to create a national program in order to ensure nationwide interoperability of vehicles and to provide a large enough market for the new products and services that would be needed. Consequently, as soon as the program was created, they devoted extensive efforts to missionary work in Washington, DC, and in other states and universities that had strong transportation research institutes and analogously strong relationships between their state departments of transportation and research universities.

In Washington, DC, they found receptive ears in the Federal Highway Administration research staff, particularly, with Lyle Saxton, who had supported much previous research on automated highway systems (AHS) at the Ohio State University from 1965–1980 and with Frank Mammano and Burton Stephens, who had worked on the Electronic Route Guidance System during the 1960s. The support at the staff level did not extend to the political level at the Department of Transportation (DOT), where the marching orders throughout most of the 1980s from the Reagan Administration were to cut transportation R&D to the bone and not take any new initiatives that would incur financial commitments. In this atmosphere, it took considerable courage for the staff civil servants to participate in, and before long to lead, national meetings that would formulate the plans for the largest new ground transportation R&D initiative in decades.

The California missionaries (primarily Bob Parsons and Adib Kanafani from PATH and John Vostrez from Caltrans) also found receptive ears in Texas, particularly at the Texas Transportation Institute (TTI) in Michigan (University of Michigan Transportation Research Institute (UMTRI) and Michigan Department of Transportation), in Minnesota, at MIT, and at General Motors. With this relatively small core group of interested organizations, they began a series of workshops to discuss how a national program could be formulated but did not yet have a concise way of describing what the program was about. The first such meeting, involving 25 participants, was held at the FHWA Turner-Fairbank Highway Research Center, McLean, VA, in November 1987, on an agenda called "Advanced Vehicle Control Technology 'Focus' Meeting." It is particularly interesting to note that the focus was on vehicle control from the very start of the activities.

Subsequent meetings were held at relatively short intervals, indicating the degree of enthusiasm and commitment among the volunteer participants, who did not generally have project funding to pay for their time or travel expenses:

- March 1988—Berkeley, CA, as "Multi-State Consortium for RD&D on Advanced Technologies for the Highway";
- June 1988—Washington, DC, as "Advanced Technologies for the Highways Ad Hoc Steering Group;"
- October 1988—Ann Arbor and Chelsea, MI, including vehicle demonstrations;
- February 1989—San Antonio, TX, including a workshop with 57 participants, leading to published proceedings [2];
- April 1989—Cambridge, MA;
- July 1989—Berkeley, CA, including vehicle demonstrations;
- August 1989—Washington, DC;
- November 1989—Washington, DC; Ann Arbor, MI; and Berkeley, CA (visit from PROMETHEUS secretary);
- March 1990—Dallas, TX, including a workshop with 200 participants, leading to second-generation published proceedings [3].

The June 1988 meeting was held immediately before a Transportation Research Board national workshop on the "Transportation 2020" program to define the next generation of transportation issues. Transportation 2020 [4] was a product of the leading transportation interest groups in Washington, DC, i.e., the American Association of State Highway and Transportation Officials (AASHTO) and the Highway Users Federation for Safety and Mobility (HUFSAM), representing the traditional approach to transportation issues. It was important for the advanced technology group to present their case for an advanced technology element in the future national transportation plans, and they decided that they needed to have a name for their virtual organization before they could be taken seriously. Out of this necessity was born the name "Mobility 2000," which the group adopted in June 1988 and continued to use until it became the core of a new real organization in early 1991 (the Intelligent Vehicle-Highway Society of America, or IVHS America).

The vehicle demonstrations at the October 1988 and July 1989 events provided good opportunities for outreach to decision makers in both the public and private sectors, as well as representing attractive media events. These became some of the earliest opportunities for television coverage of the possibilities that new technology could bring to transportation and included coverage of new products under development by start-up companies as well as established industry leaders. The Mobility 2000 workshops that were organized by Sadler Bridges and William Harris of TTI in February 1989 and March 1990 produced the first tangible documentation of concepts and program plans for the development of a national program. During this time, it also became evident that the entire technical field needed a name, and Kan Chen and Robert Ervin of UMTRI came up with the name that was eventually accepted—intelligent vehicle-highway systems (IVHS).

The efforts of Mobility 2000 began to bear fruit, attracting the attention and eventual support of the leaders of AASHTO and HUFSAM, Francis Francois and Lester Lamm. They agreed to cosponsor, with General Motors, a National Leadership Conference on IVHS in Orlando, FL, in May 2000, and that meeting led to general agreement on the need to establish a permanent national organization that would be chartered as a utilized federal advisory committee to the U.S. DOT. That permanent organization, IVHS America, was soon founded, with AASHTO and HUFSAM as its founding members and the Mobility 2000 activists becoming the leaders of its technical committees. The U.S. DOT investment in the new field of IVHS was still negligible because there had not been any funding authorized by Congress under its existing legislation. This changed in December 1991, when Congress passed the Intermodal Surface Transportation Efficiency Act (ISTEA), which included a section that is specifically devoted to IVHS, with its own dedicated funding stream (significantly larger than expected by any of its proponents because of technicalities in the way the legislation was drafted).

More detailed information about the formative years of IVHS in the U.S. can be found in [5] and [6].

V. Parallel Activities in Europe and Japan

While the ideas behind ITS were germinating in California, analogous thinking was happening in Europe and Japan, and similar programs were being established. Information exchange was quite limited for a while because the people who were involved did not generally know their counterparts on the other continents and because the programs had some strong elements of industrial competitiveness as well. The communication barriers were gradually broken down, in large part based on a few cases in which individual researchers knew people who were active on the other continents based on their prior work in other fields (magnetic levitation, high-speed rail, personal rapid transit and automated guideway transit, and vehicle dynamics and control).

The activities in Japan were initially difficult to understand because they were divided across four competing government ministries and many automotive industry competitors. Some of the relevant projects had begun in the 1960s and 1970s (Comprehensive Automobile Communication System [7]), analogous to the work in the U.S., leading to projects including the Road-Automobile Communication System and the Advanced Mobile Traffic Information and Communication System [8] at about the time that IVHS was starting in the U.S.

In Europe, Daimler-Benz Research stimulated the development of an ambitious industry-led program called PROMETHEUS (PROgraM for European Traffic with Highest Efficiency and Unprecedented Safety), developing a wide range of systems for traveler information, vehicle control, and safety [9], while the public sector traffic management issues were being addressed in a European-Commission-led project called DRIVE (Dedicated Road Infrastructure for Vehicle safety in Europe) [10]. The November 1989 visit to the U.S. of Hans-Peter Glathe, the Secretary of the PROMETHEUS program, was an important milestone in recognizing the parallels between our interests and programs. Each recognized that we could use the competitive threat of the other to stimulate political support for our work, but we also recognized that we had essentially the same goals. Indeed, after I briefed Hans-Peter Glathe on the PATH Program goals during his visit to Berkeley, he asked to borrow one of my slides to use in his presentation of the PROMETHEUS program goals.

VI. Initial PATH Research Topics

The first two years of work at PATH were largely devoted to conceptualization, program planning, and missionary work throughout the U.S. By 1988, additional state resources were available to support the initiation of substantial research work. Since PATH was the only active research program in the field at the time, we were starting with a clean sheet of paper and had a great deal of latitude to identify the most important research issues. We were particularly conscious that we were starting on something new that was meant to lead to large changes in transportation and not something that would be incremental or a continuation of "business as usual." This pointed toward research topics that represented significant departures from the mainstream of transportation research at the time, which was only possible because of the visionary leadership that was provided by John Vostrez at the Caltrans New Technology Program.

The first several years of PATH research were divided into three primary categories:

1) *Navigation*—research on issues that are related to how enhanced information about traffic conditions could lead to more intelligent traffic management and traveler route choice decisions. This evolved into "Advanced Transportation Management and Information Systems (ATMIS)," reflecting the California preference for integrating public sector traffic and transit management with dynamic route guidance for individual drivers or travelers (in contrast to the national program tendency to segregate Traffic Management and Traveler Information as separate functions).
2) *Automation*—research to determine the technical feasibility and transportation system impacts of AHS. From the start, the highest priority in California was to determine how to achieve a highway capacity increase that is large enough to get ahead of the growth in population and economic activity, without requiring such huge civil infrastructure additions that it would be unaffordable and environmentally unacceptable. Since the technologies involved here are closely related to the technologies for safety warning and control assistance systems, this area was given the broader name of Advanced Vehicle Control and Safety Systems (AVCSS).
3) *Roadway electrification*—continuation of the previous RPEV work, to develop and test a viable roadway electrification technology and determine its impacts if it could be deployed on a large-scale basis. This work was important because of the environmental sensibilities in California, political support for the research funding, and the involvement of the private electric utility industry as well as public sector transportation agencies.

The roadway electrification work (Fig. 2) was terminated after a few years because it was not possible to develop an affordable design for the roadway inductor that was needed to supply power to the vehicles, even after several iterations of design and full-scale testing on the test track. This left two main branches in the PATH research program, i.e., ATMIS and AVCSS. The research funding was divided between these areas, in roughly comparable amounts until the advent of the large new activity of the National Automated Highway Systems Consortium (NAHSC).

VII. Work on National IVHS/ITS Architecture

The first large project of the national IVHS program was the development of the National IVHS Architecture, which was stimulated in large part by Bob Parsons' leadership of the System Architecture Committee in IVHS America. Caltrans and PATH were very eager to participate in the project but recognized that they would need to join one of the teams that were being formed to compete for the U.S. DOT contract. These teams were being led by major corporations, primarily from the aerospace industry, several of which were based in California. Caltrans advertised a competition to select the team that we would join, requiring the competitors to submit written proposals and go through oral interviews. Because of the prominence

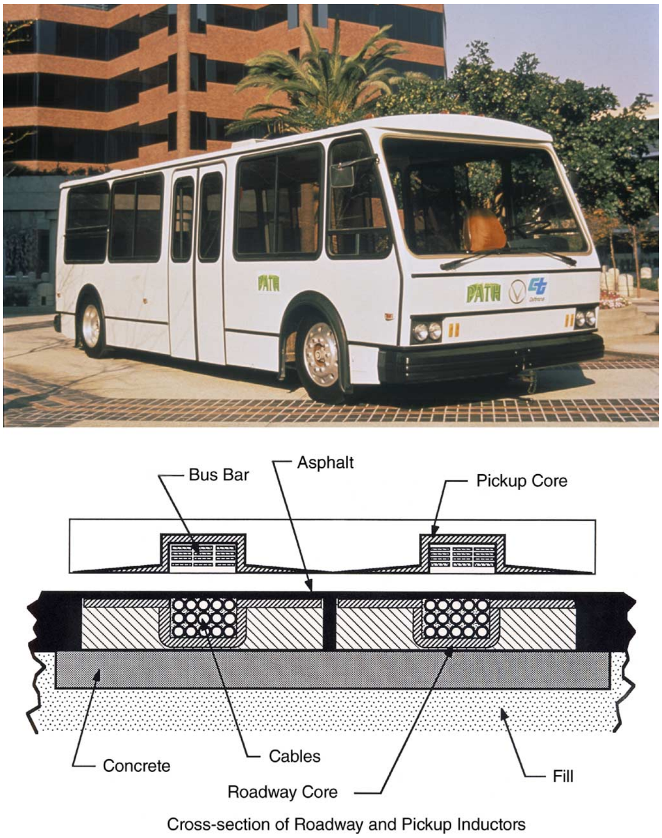

Fig. 2. Roadway-powered electric bus and cross section of roadway and onboard power inductors.

Fig. 3. First PATH lateral control test vehicles (AMC Hornet with magnetic guidance display and Toyota Celica with IMRA steering actuator and line-scan cameras for independent measurement verification).

of Caltrans and PATH in the national IVHS program, most of the leading competitors for the National Architecture program were willing to go through this additional step to gain the Caltrans/PATH partnership on their team. Following an intense competition, Caltrans and PATH chose the Rockwell team as their partner and continued as members of the Rockwell team through both phases of the National Architecture program.

The work on the National Architecture program provided a good introduction to the mixture of technical and institutional issues that characterize most ITS projects. Indeed, the major focus of the Caltrans and PATH participants in the Architecture project involved ensuring that the institutional issues were given appropriate weight alongside the technical issues that are more typical of aerospace system architecture work and evaluating the transportation system impacts of eventual ITS deployments based on the architecture.

California was among the most enthusiastic and persistent advocates of changing the name of IVHS to ITS in 1992–1993 in order to emphasize the broader multimodal applications of the systems. It was important that this be not just seen as a program for "vehicle industry" and "highway" interests but that it address the needs of the transportation system as a whole. PATH changed its own name at about the same time in order to make the same point.

VIII. Research on Automated Highway Systems

PATH is the only ITS research program to make a comprehensive long-term investment in research on AHS. From the very start of the program, the primary goal was to develop the capabilities that are needed to make a significant leap forward in reducing congestion, and AHS has long appeared to be the only alternative that could make such a strong contribution. The original sponsors at Caltrans and the original researchers at the University of California saw these opportunities and seized on them.

PATH began building its vehicle experimental capabilities in the late 1980s, acquiring the hardware and software support staff, test vehicles, shop facilities, and test tracks to enable experiments with vehicle automation technology. The first PATH experiments on the use of permanent magnets that are embedded in the roadway for vehicle guidance were conducted in 1988–1989, proving the ability to detect vehicle position accurately based on magnetic field measurements [11]. PATH built a short test track (about 300 m) at the University of California's Richmond Field Station in 1991–1992 to provide the venue for testing automatic vehicle steering control based on the magnetic guidance concept and implemented its first automatic steering control on a Toyota Celica that was provided with an electronic steering actuator by IMRA America, Inc. (Fig. 3).

In 1989, Ford provided PATH with four vehicles to use as experimental platforms for automatic longitudinal control in a close-formation platoon. PATH equipped these vehicles with throttle and brake actuators, forward ranging radars, and wireless LAN communication systems, as well as control computers and software to implement cooperative vehicle following at close separations [12]. By 1992, the first vehicle-platooning experiments were successfully concluded, and the four-vehicle platoon capability was demonstrated for visitors on the I-15 HOV lanes in San Diego, CA, in 1994 (Fig. 4).

The ISTEA transportation reauthorization legislation included a provision stating that, "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." This language was inserted by the

Fig. 4. Four-car automated platoon in San Diego, CA, in 1994.

Fig. 5. Eight-car NAHSC platoon demonstration in San Diego, CA, in 1997.

Chief Scientist of the House Committee on Science, Space, and Technology after their Technology and Competitiveness Subcommittee received testimony from me and a few others about the potential opportunities that AHS offered. It became the basis for the creation of the federal research program on AHS.

In the spring of 1992, shortly after ISTEA was passed, DOT invited Caltrans and PATH to join with several of the major automotive companies and suppliers to form a consortium to develop the AHS. After a few months of intensive planning work by all of the invited organizations, DOT concluded that they would not be able to negotiate a contract with this consortium on a sole-source basis and had to revise their program concept. This led to the creation of a quick procurement for the cluster of one-year projects known as the AHS Precursor System Analyses in 1993, while DOT worked on their plans for procuring the larger AHS program. The new AHS procurement was issued in early 1994, and two teams formed to compete for it, one led by General Motors and the other was led by Ford and TRW. Because PATH had such a strong track record in AHS research, it was the only organization that was invited to participate in both proposal teams. This created an interesting challenge because PATH had to form two separate proposal-writing teams to work on the competing proposals, with no contact permitted between the members of those teams.

In the fall of 1994, the team that was led by General Motors won the competition and established itself as the NAHSC. PATH and Caltrans were very active participants in NAHSC, and indeed PATH devoted more labor years of work to the Consortium than any of the eight other members (approximately 85 labor years, representing 25% of the entire consortium). This was an opportunity to significantly expand the scope of PATH's research on highway automation in several dimensions, including operational concept definition and evaluation, modeling and simulation tool development, and experimental implementation of fully automated driving on a platoon of eight automobiles. The PATH research staff expanded to about 60 people, of whom about half were working on NAHSC research. PATH had the lead role in 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.

The most visible product of NAHSC was Demo '97, which was the highly publicized demonstration of AHS concepts and technologies in San Diego, CA, in August 1997. Although many people outside the NAHSC thought that this was the sole focus of the NAHSC's work, in fact, it represented less than half of the NAHSC effort. Demo '97 received a level of attention from the general-interest media that was unprecedented for an ITS activity, with prominent coverage from leading national print and electronic media outlets. PATH's platoon demonstration (Fig. 5) was probably the most visible element of Demo '97, providing vivid imagery of the eight automated vehicles following each other in close formation, with one changing lanes and shifting its position in the platoon formation while the "drivers" waved their hands to show that they were not steering.

The NAHSC program was originally planned and proposed for a seven-year period, leading to the development and testing of a prototype AHS and the creation of technical specifications. However, the U.S. DOT lost its vision of AHS early in 1997 and decided that it would terminate the program, following the legislatively mandated 1997 demonstration. The result was that much of the research was interrupted in midstream, before it was complete enough to be published. The interim findings from this work were documented in the extensive NAHSC reports to the U.S. DOT, but those reports were never made available to the public, so much of the work that was accomplished and the knowledge that was gained from that work were only known to the direct participants in the program [13].

The termination of the NAHSC program was a major disappointment at PATH and forced a significant shrinkage in the size of our research program and staff (fortunately almost entirely by attrition). Caltrans continued to support work on advancing knowledge about AHS concepts and technologies through a variety of research projects and initiatives, such as The Phoenix Project and a multistate pooled fund project on Cooperative Vehicle-Highway Automation Systems.

The NAHSC work provided such high visibility to PATH's highway automation work that we were invited to demonstrate our automated vehicles to help stimulate local interest in a variety of locations, beginning with a precision docking demonstration in Houston for their Metropolitan Transit Authority and an automated moderate-speed minidemo on a closed course in Tempe, AZ, for the leadership of Arizona DOT, both in the fall of 1997. The highest profile demonstrations were two international events, i.e., Demo '98 in Rijnwoude, The Netherlands, and Demo 2000 in Tsukuba, Japan. PATH was the only non-European organization participating in Demo '98, and our three-car automated platoon and one-car low-speed precision minidemo on a closed course received the most intensive media coverage, including an inaugural ride by the Dutch Transport Minister. At Demo 2000, where we demonstrated vehicle lateral guidance and control using a Japanese version of magnetic sensing and reference magnets in a test track, PATH was the only North American participant, and one of only three non-Japanese organizations participating.

The continuing Caltrans-funded research projects included a major activity to experimentally implement fully automated driving of three transit buses and two tractor–trailer trucks in 2003. The bus automation work included full-speed highway driving and precision docking at two types of bus stations, as well as demonstration of a realistic driver–vehicle interface. The truck automation work was highlighted by carefully controlled testing of the fuel consumption and emissions effects of closely coupled longitudinal control of tractor–trailer rigs at separations as short as 3 m.

The combined efforts of PATH research staff, faculty, and students developed answers to most of the key questions about AHS that confronted us at the start of the program. The key things that we learned are presented here.

- The AHS system could be decomposed in a hierarchical architecture to reduce the complexity of design and analysis to a readily manageable scale.
- Automated vehicle maneuver protocols can be designed and verified to be comprehensive, efficient, and safe.
- Operation of AHS vehicles in automated platoons could increase the capacity per lane of passenger cars by factors of 2–3 above the conventional lane capacity, when conventional vehicles are excluded from the automated lane.
- The entry and exit of vehicles to and from a high-capacity AHS facility can be accomplished without adverse impacts on adjacent freeway or arterial lanes by use of dedicated entry and exit ramps, and the transitions between manual and automatic vehicle control can be managed through electronic "check-in" and "check-out" processing at these ramps.
- Vehicle positions within lanes can be measured sufficiently accurately for smooth and precise steering control under all weather conditions when vehicles can be driven.
- Automatic steering control can be accurate enough to permit significant reductions in lane widths for passenger cars while providing smooth ride quality.
- Through use of fault detection and identification, and fault management, an automated passenger car can be successfully steered to remain within its lane even after experiencing a sudden blowout of a front tire.
- The speed and longitudinal positioning of a conventionally propelled vehicle can be controlled with sufficient precision to enable automated driving within close-formation platoons (so that drivers cannot perceive any variations in separations, even while accelerating or decelerating, or driving up or down a grade).
- The precise longitudinal control that is needed for safe driving within an automated platoon can be provided with smooth, comfortable ride quality.
- Vehicles can be driven at highway speeds and at very short gaps without exposing passengers to excessive exhaust gases or denying sufficient cooling air to vehicle radiators.
- Close-formation automated driving within platoons can significantly reduce aerodynamic drag and fuel consumption for vehicles driving at highway speeds, particularly for large trucks, but has a small effect on reducing pollutant emissions.
- Once vehicle passengers have experienced 1 or 2 min of automated highway driving within a close-formation platoon, they become very comfortable with the experience.
- Conversion of a limited number of conventional freeway lanes to automated operations could produce significant reductions in traffic congestion in regions that suffer from serious traffic congestion, even if the conversion involves only one lane in each direction in most cases.
- AHS operations require minimal electronic infrastructure on the roadway, with most of the additional equipment being required on the vehicles. Recent and continuing improvements in vehicle design are already implementing many of the capabilities that will be needed for AHS (sensors and actuators).
- Deployment sequences can be defined to overcome the "chicken and egg" conundrum of vehicle and infrastructure implementation by initially focusing on applications of automation to transit buses, then heavy trucks, vanpools, and carpools.

A comprehensive review of the state of knowledge of AHS issues for light-duty vehicles, largely based on the PATH research, is available in [14].

The knowledge and experience gained through the cumulative 600 labor years of research that PATH has devoted to AHS provided the foundations for a variety of subsequent research activities in other aspects of ITS, including development and evaluation of several types of collision warning systems, precision docking of transit buses, snowplow guidance and control, the traffic performance measurement system, and the development of the cooperative communication capabilities behind the current interest in vehicle–infrastructure cooperation.

IX. PATH ATMIS RESEARCH

In contrast to the PATH research on highway automation, the PATH research on ATMIS was not aimed at designing a new transportation system but was rather seeking the most highly leveraged opportunities to improve the performance of existing legacy systems, with their significant inertia. At the outset, the fundamental limitations of the existing systems were identified, to serve as the basis for defining the most important research problems to solve, which are given as follows:

- traffic surveillance—poor performance and high costs of existing methods;
- traffic signal control—need for systematic methods to optimize performance for both arterial control and freeway ramp metering applications;

— traveler information—need for much better accuracy and timeliness of information in order to be useful enough to influence traveler decisions;
— data and models—need for much higher fidelity in order to be useful for predicting system performance, identifying problems, and evaluating potential solutions.

Much of the ATMIS research was done by small teams of faculty members and graduate students working on independent projects. Some of the larger projects were associated with the federally funded field operational tests (FOTs) of ITS that began in the mid-1990s, and PATH played the lead role in performing independent evaluations of most of the FOTs that were done in California, such as

— Santa Monica Freeway Smart Corridor (simulations of this pioneering test);
— TravInfo Bay Area traveler information system (precursor of its pace setting 511 system);
— Anaheim FOT of the SCOOT signal control and video detection system;
— Irvine FOT of the integration of ramp metering with arterial traffic management;
— San Diego FOT of smart call boxes;
— Los Angeles FOT of wireless networking of a traffic control system;
— Orange County FOT of a mobile surveillance system;
— TransCal FOT of traveler information between the Bay Area and Reno, NV.

These evaluations not only involved the researchers in technological issues but also immersed them in the real-world operational and institutional issues that constrain the opportunities to improve transportation system performance. The higher level of deployment of traffic management infrastructure in southern California and the research interests in traffic at UC Irvine led to the main concentration of the PATH researchers there being on traffic management. In contrast, the UC Berkeley and Davis PATH researchers generally focused more on traveler information issues in the early years of the program, before broadening out to address the full breadth of ATMIS.

The major thrusts of the PATH ATMIS research accomplishments have been well aligned with the fundamental problems that were defined at the outset of the program—development of new traffic surveillance technologies, development of improved traffic control methods, collection of comprehensive data sets for in-depth analysis, and development of improved modeling tools.

PATH has developed and evaluated a wide range of traffic surveillance technologies, based on Caltrans' urgent need for improvements beyond the current state of the art. This has included advanced loop-detector methods based on recognizing the inductive signatures of individual vehicles and clusters of adjacent vehicles as they proceed through the highway system. PATH has also developed remote surveillance methods based on video image processing and laser scanners, making it possible to avoid the problems that are associated with traditional inductive loops. PATH also did some of the initial research in the U.S. on tracking cell phones to provide traffic probe data, a subject that has received much wider attention in recent years by others.

The PATH research on traffic control improvements has focused primarily on freeway applications because of their importance to its main research sponsor, Caltrans. The primary attention here has been on the development of ramp metering strategies that can help freeways achieve volumes closer to their theoretical maximum traffic volumes while avoiding unacceptable wait times or queue lengths at the ramp meters. [15] This research has been able to make use of the unique freeway-arterial instrumented test bed environment that was established by UC Irvine, in Orange County, CA.

One of the major advantages that PATH has long enjoyed is access to experts in information technology, outside the traditional pool of transportation researchers. These experts have been accustomed to working with higher quality data than are normally available to transportation researchers, so they initiated serious new data collection efforts in support of their PATH research. The evaluation of the effectiveness of the Freeway Service Patrols along a 10-mi section of I-880 provided the motivation for development of a comprehensive database combining complete archiving of all the freeway loop detector data with detailed probe vehicle records, using vehicles equipped with Global Positioning System receivers and data acquisition systems. That database has been a valued resource for transportation researchers around the world. Once the value of that database was recognized, it led to the development of other significant transportation databases.

— The freeway Performance Measurement System now provides Web-based access to the loop detector data from freeways throughout California, including several years of archived data and a comprehensive set of tools for analyzing and displaying the data [16]. It serves as a management diagnostic tool for Caltrans, provides data to support traveler information systems used by the general public, and is a vital resource for transportation researchers everywhere, who can access it at http://pems.eecs.berkeley.edu/.
— The Berkeley Highway Laboratory combines imagery collected from an array of video cameras on the roof of a tall building overlooking I-80 in Emeryville, CA, with data from the loop detectors installed in that freeway section to produce a uniquely detailed characterization of traffic characteristics. PATH-developed video image processing has provided detailed trajectories of each vehicle traveling through this complicated weaving section, which are valuable truth references for models of traffic behavior. These are now being used as a basis for developing new traffic models in the federally sponsored Next-Generation Simulation Model (NGSIM) project (accessible through http://www.tfhrc.gov/about/06137.htm) and are helping to meet the needs of many other transportation researchers.

X. More Recent Development of PATH

In recent years, the relationship between PATH and Caltrans has been redefined, and the research program has been reorganized. The Caltrans research program has shifted to a "customer-driven" perspective, with priorities set by the mainstream Caltrans operations and maintenance people rather than those who specialize in research. This means that there is more interest in near-term incremental research than in longer term transformational research. The selection of research topics for the request for proposals and of proposals for funding is more strongly determined by Caltrans than in the past.

PATH has been reorganized into four programmatic areas to align with Caltrans interests: traffic operations, transit operations, transportation safety, and policy and behavior [15], [17]–[19]. The core research at PATH continues to be the projects that are sponsored by Caltrans, but PATH researchers are continually seeking opportunities to combine state and federal resources to participate in the national ITS research program. This has led to major research projects under the Intelligent Vehicle Initiative, Next Generation Traffic Simulation program (NGSIM), and the newer US DOT Tier One ITS initiatives.

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