Future of Intelligent Vehicle-Highway Systems: A Delphi Forecast of Markets and Sociotechnological Determinants

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The development of intelligent vehicle-highway systems (IVHS) in the United States is characterized by a high level of uncertainty regarding system development and social response. Although there appears to be much interest and support for pursuing this new approach for increasing the capacity, efficiency, and safety of road transportation, it is difficult to say at this point what set of functions, technologies, standards, and institutional arrangements will eventually evolve into an accepted architecture for IVHS in the United States. There is uncertainty about the financing of system development, the outcome of competing systems and desired functions, consumer acceptance of the concepts and products, and about almost every aspect of the development of IVHS. This paper presents the results from a recent survey that summarizes the opinions of experts in a range of fields related to IVHS. The Delphi forecasting methodology was used to generate a consensus on predicted market penetration for various IVHS including motorist information, vehicle navigation, vehicle location and identification, route guidance, automatic tolls and road pricing, collision avoidance and warning, speed and headway keeping, automated highways, and automated guideway systems. In this paper the system is explained, the market forecasts are presented, related institutional and technical barriers are identified, and the results of the survey are compared with similar surveys conducted in Europe and the United States.

The development of technology is always uncertain. The course of technology development is determined in part by undefined societal needs, uncertain institutional support, and unexpected technical breakthroughs. However, technology development is also determined in part by processes that are known or can be influenced. For example, the future of a particular technology can be estimated by current market trends, recent developments in related technologies, current levels of institutional support, and an assessment of the nation's level of commitment to research and development in the area. Given that some things are known, and that others are uncertain, effective planning for technology development requires an assessment of current knowledge and intentions as they impinge on the future of the technology in question. It requires reducing the uncertainty wherever possible, understanding the sources of uncertainty where it cannot be influenced, and formulating a common vision for those who are required to act. This is the task of assessing the future of "intelligent" transportation systems.

Considering the recent and expected technical advances in electronic communication and processing, it is easy to imagine a future transportation system where "smart" vehicles will communicate with "smart" roadways to increase traffic throughput and safety while providing a more hospitable environment for the motorist. Advanced information systems may someday provide the driver with real-time information on traffic incidents, road and weather conditions, traffic congestion, and preferred routes from origin to destination. Advanced traffic control systems may use real-time information on traffic conditions, models of optimal traffic flow, and centrally coordinated signals to direct traffic through the network in a more efficient manner. Advanced vehicle control systems may help the driver avoid collisions, and regulate vehicle speeds in response to traffic. The most futuristic systems may even take complete control of the vehicle, providing fully automated steering, acceleration, and braking for the driver.

In fact, some early incarnations of intelligent vehicle-highway systems (IVHS) are already being tested in Europe, Japan, and here in the United States. Ongoing advances in a range of technologies are likely to spur further research, development, and demonstration activities in IVHS over the next 10 years. In order to set research and development priorities and to coordinate related activities in this area, it is necessary to think carefully about likely implementation scenarios and their possible impacts on society.

Results of an opinion survey conducted at the University of Michigan (UM) to assess the future of IVHS are described. These advanced road transportation systems integrate the intelligence of microprocessors, sensors, scanners, transmitters, displays, and other related electronic systems with the infrastructure of the highway and automobiles, to improve the communication and control functions of road transportation. The Delphi method was used to assess the opinions of a panel of experts in areas of research related to IVHS. Their opinions were elicited and refined through an iterative interrogation process, where a "spiraling dialogue" among the experts converged on a set of forecasts for a range of system categories. These forecasts were used as an input to a research planning process for UM's program in IVHS. In the sections that follow, the issues that the panel addressed, the method that it used to address these issues, and the forecasts and lists of determining factors that emerged from its controlled discussions are described. The opinions indicate that a new era of smarter road transportation in the United States is about to begin.

It is helpful to place the current flurry of activities in historical perspective. The marriage of vehicle and highway

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through advanced technologies is not a new idea. Researchers, inventors, entrepreneurs, and other visionaries have long recognized the benefits and opportunities provided by this marriage, including increased mobility, safer streets, a cleaner environment, more effective use of resources, and improved comfort and convenience, to name a few. Not the least of these opportunities has been the possibility of tapping a large and receptive market for these benefits. In an attempt to investigate or capitalize on these opportunities, the most enterprising of individuals have delivered a host of mechanical and electronic devices designed to inform the driver, control the vehicle, and manage traffic, some of which are commonplace today, others that are left in relative obscurity. In order to provide a commonplace example, the standard AM–FM radio has been the traditional electronic supplement to static road signs for informing the driver of traffic and road conditions. Traffic advisories are not only provided periodically by standard FM carriers, but schemes have been used to override the carriers to provide important traffic bulletins in limited local areas. The citizen band radio provides another ordinary example of a driver information system. During the late 1960s and early 1970s, the two-way citizen band radio experienced a short-lived surge of popularity bringing all sorts of useful and less-than-useful information to the driver. Cellular mobile telephone is the most recent entry in the vehicle-highway communications arena. New and adaptive uses of these commonplace technologies promise to increase the driver's knowledge of traffic conditions and thereby increase the driver's responsiveness to these conditions.

Other more intriguing developments in intelligent vehicle-highway systems have emerged in the areas of navigation, route guidance, vehicle control, and traffic control. French (*1*) provides a colorful historical overview of early developments in vehicle navigation and route guidance, including the description of a device designed in 1910 that had routes encoded on punched disks which activated real-time guidance instructions at points measured by the rotation of the vehicle's wheels. The Chadwick Road Guide sold for about U.S.$1,000 in current dollars and never became a "hot-selling" item. French details a number of similar mechanical and electronic guidance systems that have come and gone over the years, none of which really captured the motorists interest or dollars. It seems that maps have ruled the day.

In a more ambitious attempt to merge driver information with navigation and traffic management systems, the FHWA supported early research on cooperative route guidance, which was intended to tie in vehicle navigation and location technologies with centralized traffic control (*2*). The Electronic Route Guidance Systems (ERGS), which emerged from this effort in the late 1960s, used short-range transmitters mounted on proximity beacons to collect information from induction loops buried beneath the roadways. As cars passed by, they transmitted vehicle location and trip destination information to the roadside beacons. This information was relayed to a traffic management center for processing. Travel times and routes were computed at the center transmitted to the network of beacons. Vehicles near the beacons would receive local route instructions that were displayed on the vehicle's dashboard. The traffic management center would use various types of static traffic information along with the real-time vehicle location and destination data to determine the appropriate timing of signals and routing instructions. This project was terminated by Congress in 1970 following limited testing, but the basic concept is currently being tested in demonstrations of cooperative route guidance systems in Europe and Japan.

Going as far back as 1939, the New York Exhibition presented a scale model demonstration of automatic vehicles traveling smoothly in platoons. Bender, et al. (*3*) reviewed the history of this exotic line of vehicle research. In the early 1960s, General Motors Corporation conducted extensive research on the subsystem aspects of automated vehicle control and electronic highways. During the 1960s and 1970s, operational tests of these systems were conducted at General Motors Corporation, Ford Motor Company, Ohio State University, among other research organizations around the world. During the 1970s, there was also a surge of interest in multimodal transportation systems. For example, the TRW systems group proposed an elevated guideway that would carry automobiles on pallets between cities. Many other similar systems have been proposed, none of which have advanced beyond a limited demonstration stage. For these and other early incarnations of advanced transportation, the effectiveness and cost of the technology were the primary barriers.

Although the concept of IVHS is not new, recent technological advances promise to make these systems more effective and affordable, meriting a second look at the concept. Breakthroughs in integrated circuits, microprocessors, sensors, scanners, displays, and systems engineering promise to make the old concepts new again, and incite new innovations in advanced transportation systems. This is hardly a technology push, because the ideas of vehicle-roadside communication and advanced traffic control have been around for some time. Rather, it is a technology release, in which recent technological advances are providing new opportunity to accomplish an existing vision.

UNIVERSITY OF MICHIGAN PROGRAM IN IVHS

In response to the opportunities looming on the horizon, a number of organizations have recently initiated or renewed the investigation of IVHS. Research arms of the federal government, state and local governments, universities, motor vehicle manufacturers, and electronics companies have recently launched projects or programs in IVHS. A shared goal of the recent activities in the United States is to become competitive with the better organized and funded IVHS programs in Europe and Japan. This goal has led to a cooperative spirit among the leading participants in the United States. It is a commonly held belief that the programs in Europe and Japan have at least a 5-year lead in their administration of IVHS research and implementation of IVHS demonstrations. Levels of funding for these programs are not entirely certain, but estimated in the billions. In the United States, informal cooperation among principal actors in the form of ad hoc workgroups and committees has yielded results in conceptualizing a national agenda for research and development in IVHS. A few cooperative research efforts are already underway, and others are being planned for the near future.

UM is one of the handful of research universities addressing the topic of IVHS. In the spring of 1988, UM initiated a research program to address both technical and institutional issues related to the development of advanced transportation systems in the United States. A program was envisioned that would build on (a) the distinctive research strengths of UM, (b) the interests and support of the Michigan Department of Transportation, (c) the interests and related technical capabilities of the nearby automotive industry, and (d) linkages and complementarities with other research universities. In order to bring these ingredients together, a pragmatic outlook toward the incremental development of IVHS was adopted. The concept merged basic and applied research with an emphasis on the vehicle and driver components of IVHS.

Planning of the research program required insight into the expected development of IVHS so that those areas of research that would have the greatest impact could be targeted. This is where the Delphi forecast came in. The future of a range of intelligent systems and the issues regarding the development and implementation of those systems needed to be assessed to identify propitious topics for research. The Delphi method would enable interrogating the minds of the experts in a wide range of topics affiliated with IVHS toward this end. It would also provide an opportunity to collect market projections that would be of interest to the industrial sponsors.

OBJECTIVE OF THE STUDY

UM's program in IVHS is supported by the voluntary contributions of the nearly 20 participating sponsors of the program. Most of these sponsors are involved because of some recent or long-standing involvement with research and development in IVHS. As such, they represent an invaluable resource with access to experts in IVHS and other related fields of endeavor. The Delphi study provided an opportunity to exploit that expertise in a task of fundamental interest to the university, government, and industry supporters, namely, to obtain technology and market forecasts for a range of system categories.

The principal purpose of this study was to explore the future development and market penetration of selected IVHS categories in light of an optimistic scenario for government support. The research would address the timing of research, systems introduction, and levels of market penetration for 10 systems categories:

- Automatic tolls and road pricing,
- Automatic vehicle location,
- Automatic vehicle navigation,
- Motorist information,
- Cooperative route guidance,
- Collision warning,
- Collision avoidance,
- Speed and headway keeping,
- Automated highway, and
- Automated guideway.

It was important to address each of these categories separately, as each system category is directed at a unique information or control function and typically involves distinctive system components and technologies. For each of these categories, the factors contributing to the emergence and development of these systems, including both social and technical considerations, were to be addressed. These factors would provide leads to topics for potential research and development. Finally, the social and technological impacts of the systems were to be assessed; the benefits associated with each system category were especially to be delineated. This process would provide a basis for estimating the value of each system category. Again, these factors were likely to depend on the type of system being addressed. There is little value in grouping these categories together and addressing them as a single IVHS.

PREVIOUS IVHS DELPHI FORECASTS

The survey was designed and conducted with the advantage of having previous results from earlier Delphi studies on selected aspects of IVHS. The earliest of these surveys was a Delphi study sponsored by the California Department of Transportation (CALTRANS) and undertaken in 1974 by the Center for Futures Research at the University of Southern California (*4*). The study was part of an effort for developing a statewide multimodal transportation plan for California. They polled 46 experts in a wide range of technical and nontechnical fields to reach consensus on forecasts for 146 developments and trends in a broad range of transportation and social areas. One of the forecasts concerned "the introduction of automated highways on a more than experimental scale" in California. The consensus of opinion in 1974 was that the earliest that the introduction of automated highways would occur was in the year 2000, the latest that it would occur was in the year 2020, with a consensus that the most likely year of introduction was, surprisingly, the year 2000.

A more recent Delphi study conducted in Europe addressed the emergence and market penetration of IVHS under the designation of "road transport informatics" (RTI). The research was part of the Automobile Road Information System Evolution (ARISE) Project that was undertaken by the Swedish National Road Administration (SNRA) and later moved to the International Institute for Applied Systems Analysis (IIASA) in the beginning of 1986 (*5,6*). The objective of this study is to create new and better scenarios as a means of investigating how RTI will evolve. In order to accomplish this, Sviden combined the Delphi methodology with the construction of detailed written scenarios. The main results of the research were summarized as descriptive scenario scenes for the years 1990, 1995, 2000, 2010, 2020, and 2040. The scenario has interactive route guidance systems (IRG) being introduced in 1995, speed and distance keeping (SDK) and collision avoidance (CA) systems being introduced in 2000, and an automated highway chauffeuring (AHC) system being introduced in 2010. Also by the year 2010, all of the information and traffic management systems are in use by a majority of all automobiles. By the year 2040, all of the systems, including the vehicle control systems, are being used by a majority of all automobiles. Major improvements are made all along the way in quantified measures of satisfaction, cost, speed and throughput, and safety.

Sviden's Delphi on RTI influenced the design of the UM Delphi on IVHS. It provided the initial idea for system classifications, although the classifications that were eventually settled on did not completely match, and it provided the framework for measuring market penetration. A major advantage of keeping with a similar format is that it allows comparisons of the results across the Delphi studies.

Apparently the FHWA also saw the advantage of keeping with the RTI study format in its 1988 Delphi on advanced vehicle and traffic control technology in the United States (*6*); it followed the system classification-market penetration format for forecasting the emergence of selected IVHS technologies. In this case, the Delphi was one element of an overall evaluation of current and anticipated technological developments that would be expected to improve vehicle and traffic control. The purpose of the Delphi was threefold: (a) to evaluate specific vehicle and traffic control systems for their applicability to U.S. highways, (b) to determine the appropriate role of FHWA, and (c) to estimate when particular milestones might be achieved for the 10 systems. The Delphi administrators surveyed 11 managers and technical specialists from the FHWA on the expected development and impacts of the 10 system categories. They were asked to make their predictions with regard to both optimistic and pessimistic social and economic scenarios. The work forms used by the FHWA panelists include for each system category (a) a questionnaire to assess the anticipated support by various interest groups, (b) a questionnaire to evaluate costs, reliability, and benefits to selected interest groups, and (c) a system description form. The panelists' forecasts of market penetration indicated that the expected system introduction of all systems, with the exception of automated highways, would be achieved by the year 2007. Automated highways were expected to be introduced by 2026. Because of the major public outlays required for an automated highway system, the report concluded that the benefits do not appear to justify the costs, although selective implementation may pay off. Most other systems received more favorable cost-benefit evaluations, noting that most production decisions will be determined by the consumers and the vendors of the products. The panelists did agree that on-board motorist information systems and cooperative adaptive traffic control systems would become widely implemented in the near future and that the FHWA should play a major role in their development.

There is general agreement between the ARISE and FHWA research that most of the advanced systems under consideration will be introduced within the next 10 years. Further discussion of the ARISE and FHWA studies will continue in a later section in which the forecasts are compared with the results of the UM survey.

DELPHI METHOD

In the mid-1950s, the name "Delphi" was adopted by Norman Dalkey and Olaf Helmer at the Rand Corporation for a forecasting method that used the consensus opinion of an expert panel to predict trends and events. The Delphi technique used an iterative procedure for eliciting and refining the opinions of a panel of anonymous experts by means of a series of individual interrogations.

The essential features of the Delphi are (a) remote and explicit communication, (b) statistical summary of group responses, (c) iteration and controlled feedback, and (d) anonymity among the participants. Participants are generally surveyed by means of a mailed questionnaire; the panel may be described in a general sense, but the participants never meet face-to-face, nor are they informed of the others' precise identity. Anonymity eliminates interpersonal static and influence processes, confining the interaction to exchanges of ideas and formal means of persuasion. After the participants complete their questionnaires, an exercise manager summarizes their responses and returns the summary to the participants so they may use it to revise their earlier answers. In contrast with direct discussion in a typical committee, the Delphi manager controls the communication process in an effort to eliminate redundant or irrelevant material and to focus the effort on the crucial issues. Finally, in the traditional Delphi, the manager uses simpler descriptive statistics, usually the median and interquartile ranges, to summarize the panel response. By using a statistical index, the Delphi process reduces the pressure to conform and ensures that the opinion of every member plays an important role in determining the final response. There is normally some convergence toward the median after several iterations, but the normal outcome usually reflects some range of divergence. Rather than forcing unanimity, the Delphi process allows, and in some cases promotes, divergent responses.

Rationale for IVHS Delphi

Delphi is the method of choice when a consensus of expert opinions is desired and the feasibility of extracting reliable opinions from a standard committee is in question. That was precisely the situation when it was decided to forecast IVHS technologies to assist in project planning effort at UM. IVHS is a complex array of technologies and interdependent systems, some of which have been tested, others of which have not even been thought of. The prospects for trend extrapolation were limited. It would be meaningless at this time to attempt to isolate measurable functional capabilities of IVHS to chart their progression from the past into the future. Rather, talking to knowledgeable people was needed to obtain a quick sense of the prospects for research, development, and implementation of IVHS in both the short and long runs. Because this expertise was distributed among a number of individuals with narrow perspectives on this wide subject, a means of encouraging productive interaction among a set of 20 to 30 individuals, many of whom did not know each other, and who might have difficulty communicating with each other because of their vastly different backgrounds, was needed. The Delphi technique appeared to be the appropriate choice.

The Delphi technique does not require data for trend extrapolation. It merely requires that a representative sample of experts that are seen as credible to both the study sponsors and the study users is identified. Recent efforts to establish a new program in IVHS at UM provided an opportune resource for identifying the needed expertise. The sponsors and newly appointed advisors represented a unique set of organizations with some background and expertise in IVHS-related activities. It was put to them to identify the most appropriate personnel from their sphere of acquaintance. It turned out that the individuals that the advisors nominated for participation had the desired range of expertise to address the wide range of sociotechnical questions posed by the prospects of developments in IVHS. The Delphi technique afforded the panelists the opportunity to interact with one another in a controlled setting in which they could jointly address the opportunities and barriers confronting the development of an IVHS capability in the United States.

Delphi Panel

Sponsors of the UM IVHS project included the big-three U.S. automotive companies, their electronic component suppliers, telecommunications companies, state and federal transportation agencies, and representatives of transportation user groups. All sponsors have representatives that serve as members on the project advisory committee. In June of 1988, members of the committee were asked to identify individuals from their organization that were knowledgeable in IVHS technology or related policy issues and to request that they participate in the Delphi exercise. Most organizations found one person in their organization who could serve as the designated expert in IVHS, others identified up to three individuals, a few could not find an appropriate participant. By the time that the survey was initiated, there were 32 panelists participating in the survey representing 13 sponsor organizations. There was some attrition in each of the three rounds with 22 of the participants responding in the last round.

In keeping with the provisions of the Delphi process, the identities of these panelists remain confidential. The anonymity of the participants ensures that during the process the panelists' ideas are judged on merit and not on the reputation or personality of the panelist. It also enables the panelists to make uncertain forecasts concerning complex social and technical matters without fear of embarrassment or ridicule. The participants can forsake conventional wisdom or their conservative line in favor of an honest assessment of the future.

PROJECTIONS OF IVHS CATEGORIES

Discussion of the IVHS categories is organized by their targeted source of control, with either the roadside, the driver, or the vehicle being the targeted control constituent. Three broad categories of IVHS will be used:

- Advanced traffic management systems (ATMS) for roadside control,
- Advanced driver information systems (ADIS) for driver control, and
- Automated vehicle control systems (AVCS) for vehicle control.

Mobility 2000 addressed heavy vehicle and commercial operations as a fourth and separate category; however, commercial issues have been folded into the first three categories.

These categories were first delineated at the Mobility 2000 workshop that addressed scenarios for a national agenda in IVHS (*8*). For the purposes of this paper, each broad category encompasses a number of specific system categories. An ATMS controls traffic through roadside displays or signals, which may be coordinated, or even optimized, at a central control facility. Although ATMS is a well-developed field of application and research, few of these systems involve significant vehicle-highway interaction; automatic tolls and road pricing (ATRP), as a subcategory under ATMS, was included in this study because of the clear linkage between vehicle and highway components. The ADIS assists strategic and operational driver control functions through effective information distribution, processing, and display. Included in this category are automatic vehicle location, automatic vehicle navigation, motorist service information, cooperative route guidance, and collision warning systems. All of these systems assume driver control of vehicle operations and routing and advise the driver accordingly. Vehicle-highway interaction is mediated by the driver. Finally, automated vehicle control systems transfer control from the driver to the vehicle to simplify the driving task and improve traffic flow. Vehicle electronics that were strictly autonomous were excluded from consideration. Four types of control systems that involved vehicle-highway interaction were addressed: collision avoidance, speed and headway keeping, automated highway, and automated guideway systems. The distinction between automated highways and automated guideways is that automated guideways use modified vehicles and some form of physical guideway, whereas automated highways have intelligent vehicles guided by signals or electronic detectors. Descriptions of the individual system categories follow.

- Automatic Tolls and Road Pricing (ATRP). These are systems that can identify individual vehicles in traffic and assess tolls on the basis of usage and other factors. These capabilities are accomplished without the effort on the part of the driver or a toll collector. The typical system requires several functional elements including: a vehicle-mounted transponder or tag; a roadside sensor; a computer system for processing and storage of data; and a billing system for assessing and collecting user fees. ATRP may be considered a combination of two systems. First, there is an automatic vehicle identification (AVI) system that identifies the individual passing vehicles. Four types of detection are used for vehicle identification: (a) optical and infrared, (b) induction loops, (c) radio and microwave, and (d) surface acoustic waves. Then, there is a computerized charging and billing system that determines the fees on the basis of the time of day, location, and congestion levels.
- Automatic Vehicle Location (AVL). Advanced communication systems would allow fleet managers to monitor vehicles in the field and deploy them more efficiently. This is the primary function of AVL systems that provide vehicle location information to a central authority. The methods for locating the vehicles are, in most cases, identical to those used in automatic vehicle navigation (AVN) systems. Locations are determined through dead reckoning, proximity beacon, GPS satellite, or Loran-C radio frequency navigation. This information is transmitted to a control center where locations are presented as coordinates or on a video mapping system. Location information can be used with fleet management software to dispatch vehicles most efficiently. One example of this type of system is II-Morrow's vehicle tracking system (VTS) that is being used to dispatch emergency vehicles in Detroit. This implementation of AVL has six dispatch stations that monitor some 760 police, fire, and emergency vehicles. The vehicle tracking system, operating on the Loran C navigational network, allows dispatchers at computerized graphic

workstations to route the nearest vehicles to the scene of an emergency.

• Automatic Vehicle Navigation (AVN). Automatic vehicle navigation uses a variety of methods to determine the present position, heading, direction, and distance of the vehicle in relation to a selected destination. The driver is informed of his position relative to a selected address or the existing street geometry, which helps the driver to navigate the vehicle to the desired destination. These systems would generally include devices for positioning, stored digital road maps, a computer, and some form of visual display or voice synthesis.

Navigation techniques currently under development include dead reckoning, proximity beacons, ground-based radio (e.g., Loran-C and cellular), satellite, and map matching. Dead reckoning calculates the vehicle's position by keeping track of the vehicle's travel distances and directions from a known starting point. Proximity beacons communicate location information to the vehicles using short-range radio, microwaves, or infrared signals. Loran-C is an example of a radio navigation system in which the vehicle's position is determined from differences in the arrival time of signals from three or more land-based transmitters. The Navstar Global Positioning System (GPS) will have 24 satellites spaced in orbits to enable vehicles to determine their positions by analyzing the travel times of signals from at least four satellite transmitters. Finally map matching methods, like that used in the Etak Navigator, use artificial intelligence to locate the vehicle by comparing the vehicle's path with the road patterns of a digitized map and using a deductive algorithm. Each approach has a particular set of devices and configuration. All five existing methods may be used separately or in combination, and other methods under development may supersede these in the future.

• Motorist Information (MI). This is one of the more eclectic system categories representing all systems that communicate travel, traffic, road, and vehicle information to the motorist. Applications might include digitized road maps, local traffic regulations, emergency broadcasts, public service messages (e.g., weather, traffic, incidents, construction, parking availability, etc.), roadside service information (e.g., service stations, food and lodging, rest areas, shopping, etc.), and other forms of information either useful or entertaining to the motorist. Although automatic vehicle location (AVL) and automatic vehicle navigation (AVN) systems are closely related to MI, these two system types are sufficiently distinct to have their own category and therefore are not included here. Limiting MI to at most one-way communication links, from an information transmission center and to the vehicle, distinguishes this category from the two-way cooperative route guidance (CRG) systems.

• Cooperative Route Guidance (CRG). A logical extension of the motorist information and automatic vehicle navigation systems is to establish two-way communication between the vehicle equipment and a traffic control center. The advantage of these closed-loop systems over one-way motorist information systems described above is that (a) the traffic control center can monitor specific vehicles to improve their assessments of areawide traffic conditions, and (b) they can potentially provide better navigation information to the driver by taking account of real-time traffic conditions. CRG systems are of two types: those using long-range radio broadcasts to link the vehicle with a traffic control center, and those also using short-range communications to link the vehicle to roadside infrastructure.

An example of the first type is the Pathfinder experimental demonstration project that is designed to test the feasibility of using a CRG to assist motorists in avoiding adverse traffic conditions. The experiment, which is a collaborative effort between the FHWA, the California Department of Transportation, and General Motors Corporation, is being conducted along the Santa Monica Freeway in California. In this case, the CRG configuration includes an Etak Navigator linked by radio to a packet radio system, which in is in turn linked by radio to a central workstation, providing two-way communication between the workstation and the vehicle. The motorist sends information on the vehicle's location, heading, and speed by radio link to the central workstation, where it is processed along with freeway and arterial data to determine real-time congestion levels, and later relayed back to the equipped vehicles. The motorist receives information on the levels and location of congestion in the form of symbols on the Etak Navigator, text, and voice synthesis. The Advanced Mobile Traffic Information and Communication System (AMTICS) being tested by the Japan's National Police Agency is a similar but more comprehensive system, relying on a teleterminal system for small-zone radio communication, combined with static service information supplied through recording medium.

Examples of systems using short-range communication and beacons are ALI–SCOUT in West Germany, AUTOGUIDE in the United Kingdom, and the Road-Automobile Communication System (RACS) in Japan. The ALI–SCOUT system is a cooperative effort by Bosch-Blaupunkt and Siemens using post-mounted infrared transceivers along the roadside and dead-reckoning navigation in the vehicles providing some computational capability in the vehicle as well as two-way communication between the vehicle and a central computer. Equipped vehicles transmit their travel times to the beacons; they are then relayed to a central computer where they are used to calculate route recommendations. These recommendations are then relayed to the beacons and transmitted back to the vehicle along with part of a city map. The AUTOGUIDE system being tested by the Transport and Road Research Laboratory in London is similar to ALI–SCOUT in that it uses infrared transceivers mounted on beacons to establish two-way communication between the equipped vehicles and a central computer. The Japanese Ministry of Constructions' RACS demonstration also uses a similar approach, but relies on microwave communication between the vehicle and the beacons. In addition, the two-way communications include voice messages and facsimile services between the motorist and a wide range of locations (home, office, etc.) beyond the central computer similar to, but much simpler than, cellular telephones.

• Collision Warning (CW). In-vehicle warning systems caution the driver when on a collision course with another vehicle or object. Not only is the area in front of the car scanned to detect a rapidly closing potential collision, but the driver's blind spots in the rear outermost corners of the vehicle are monitored to facilitate lane changes in traffic. Once an obstacle is detected, a signal or message is delivered to a display on the instrument panel, the windshield (as in a head-up display), or on the rear-view mirror (e.g., for lane changes). The detection component of the system can be based on radar, sonar, infrared, or laser technology. Laser, radar, and infrared are generally preferred for front and rear interval control in existing applications. Ultrasonic waves are likely to be used for monitoring blind spots on the side of the vehicle. CW systems are to be distinguished from incident detection systems that provide motorists with information concerning collisions and other incidents far enough in advance so the motorist can modify his or her route. General Motors has equipped a number of its vehicles with near-obstacle detection systems (NODS) that warn the driver of objects that are in the near-field vehicle's path, but are not necessarily in the driver's view. One vehicle has a detector mounted near the back bumper to warn the driver about objects while backing up. Another GM vehicle warns the driver of objects in the blind spots.

- Collision Avoidance (CA). Automatic braking is the principal component of a collision avoidance system. CA is a logical extension of CW, which detects rapidly approaching objects but does not provide automatic braking for the driver. Like collision warning systems, CA systems use radar, sonar, infrared, or laser detection to sense approaching targets. However, once an approaching object is detected, the signal is sent to a signal processor that calculates and analyzes the distance and relative velocity of the object, as well as the ground speed of the vehicle, to determine the probability of collision. For example, if a collision is deemed probable, electromagnetic actuators may deploy the brakes to an appropriate degree. Radar technology is currently the preferred approach because it is the most resilient in inclement weather. Throttle and steering control are other possible elements of an advanced CA system but they are not considered in this discussion or projection.
- Speed and Headway Keeping (SHK). These systems combine throttle control with possibly some limited radar braking capabilities to ensure safe and efficient distances between vehicles on the roadway. Current implementations of throttle control customarily use pneumatic servos that operate the throttle in response to a vacuum obtained from the engine's intake manifold. Cruise control is one form of throttle control that responds to feedback on vehicle speed. As in the CA system, radar braking would involve target sensing, signal processing, vehicle ground speed measurement, command logic and controls, and electromechanical actuators. However, in the most basic system "intelligent cruise control" would only use throttle control, and perhaps some light braking, adjusting the vehicle's speed in light of information on road and traffic conditions, speed of other vehicles, obstacles, and electronic speed limits. SHK systems promise to allow for shorter headways between vehicles thereby increasing the capacity of the roadway. For example, a number of similarly equipped vehicles would be able to form a platoon, with compressed headways, and travel at relatively stable speeds. Like cruise control, SHK also promises to reduce the overall driving effort. One panelist reported that Volkswagen, Mercedes-Benz, and the German Army Research and Development Center have demonstrated driverless control at 100 km/hr with clear lateral definition. The Martin-Marietta Autonomous Land Vehicle is a similar concept.
- Automated Highway (AH). This form of vehicle control is the most advanced, combining elements of SHK and CA, and adding further control features, to enable vehicles to travel on their own, without any form of continuous control by the motorist. Vehicles would be totally automated in all aspects of control. In an automated highway environment, the vehicle would, in effect, operate itself, taking itself from origin to destination according to programmed instructions. Elements of the total control function have been discussed under SHK and CA. However, AH requires more than automated steering, braking, and throttle control. The AH concept calls for full longitudinal and lateral control of the individual vehicle combined with automated approaches for navigation, entering, egressing, and merging. All issues of control at both the microscopic (individual vehicle) and macroscopic (traffic) levels would have to be resolved. Furthermore, the control systems would have to be fail-safe. Many of these issues have been addressed in the development of automatic guided vehicles systems (AGVS), which have been implemented for materials transport in factories and for traversing hazardous areas. However, the routing and control problem is much more complex in a dynamic highway environment.
- Automated Guideway (AG). This category aims to combine the advantages of automated guideway transit (AGT) and normal street vehicles. AGT is a class of transportation systems in which unmanned vehicles travel along guideways with exclusive right of way. A common form of AGT is the urban shuttle that moves back and forth in a single elevated guideway or around a closed loop; the Detroit People Mover would be an example, but this is not the type of system that the panelists addressed. The dual-mode form of automated guideway in which private vehicles are used in a conventional way in local traffic but are switched to a guideway in dense corridors was addressed by the panel. A system was imagined in which everyday vehicles would travel on the conventional street system in most areas and then switch to a specially equipped guideway at certain access points where pallet cars would carry the vehicles along a guided network. The pallets would conceivably move the vehicles with short headways at a uniform and fast speed. Dual-mode maglev systems also fall into this category. The key distinction between AG and AH is that AG uses standard vehicles and some form of physical guideways whereas AH has intelligent vehicles guided by signals or electronic detectors.

In the sections that follow, each of the 10 system categories are described in terms of their function and components, and illustrate by real-life examples when they exist. The market projections will address five steps of development. In order of likely occurrence, these are defined as

1. Successful Laboratory Tests. Satisfactory completion of the research, development, and demonstration phase, with agreement on standardized interface specifications.
2. System Introduction. Vehicles and corresponding roadside components are marketed and sold for either public or private use, however limited the initial deployment may be.
3. Majority Use by Commercial Vehicles. The majority of commercial trucks and cars in commercial use is outfitted with the required components. Majority means greater than 50

percent of the vehicles in those areas where the system is deployed. Some of the systems, for example the automated toll systems, are of a nature that restricts their use to specific regions or areas, and this limitation was considered by the panelists in providing their estimates.

4. Majority Use by All Automobiles. The majority of all automobiles including passenger cars. Again, this is greater than 50 percent within the area of implementation.

5. Mandatory Use by All Road Vehicles. All new vehicles are required by statute to be equipped with the IVHS feature in question.

COMPARISON OF PROJECTIONS

In this section, the trends among the specific system groupings are compared. This process will involve three levels of analysis. First, the extents of market penetration of the advanced traffic management systems (ATMS), advanced driver information systems (ADIS), and the advanced vehicle control systems (AVCS) are described and compared. Again the distinction between these categories is the source of control, with ATMS emphasizing the roadside, ADIS the driver, and AVCS the vehicle. Second, the developments of the 10 individual system categories (ATRP, AVL, MI, etc.) are compared to illuminate significant similarities, differences, and groupings that might affect research and policy agendas. Finally, several significant groupings of IVHS that are distinguished on the basis of some unique technical feature are compared. The most interesting subgroupings are ADIS1, which combines automatic vehicle location and automatic vehicle navigation, AVCS1, which combines the two early forms of control systems—collision avoidance and speed and headway keeping—and AVCS2, which combines the fully automated highway and guideway systems. In presentations of the preliminary results of the IVHS Delphi, the term "backup system" was used for the AVCS1 category because collision avoidance and speed and headway keeping assist or "back up" the driver; they do not take complete control of the vehicle (*9–11*).

Figures 1–3 show both aggregate and disaggregate projections of the assorted IVHS categories. For each of these figures, the vertical axis presents the succession of levels of product development and market penetration, starting with "successful laboratory tests" on the bottom and moving all the way up to "mandatory use by all road vehicles" on the top. The horizontal axis presents a timeline of the future in 5-year increments up to the year 2080. Following the year 2080 are the "later" and "never" responses.

The forecasts for the aggregate groupings (e.g., ADIS, ATMS, AVCS) were determined by taking the median panel projections for the IVHS categories in that group.

Perhaps the most informative comparison is among the projections of the broadest IVHS categories, ATMS, ADIS, and AVCS, shown in Figure 1. A quick glance at the graph should reveal a distinct sequence in the development of the three technology categories. The ATMS category, which consists of only automatic tolls and road pricing in this case, is the first to attain majority use; the ADIS category is the second, and AVCS category is the third.

In terms of majority use by all automobiles ATMS precedes ADIS by 10 years, which in turn precedes AVCS by 20 years. The panelists predicted that it will be 2035 before the control systems are used by a majority of automobiles. This precedent relationship is nearly uniform, from successful laboratory tests through mandatory use, with the exception that the panelists did not expect ADIS to be mandatory.

The second striking characteristic is that according to the panel both ATMS and ADIS systems have been successfully tested in the laboratory. Again, the panelists ignored the requirement of standardized interfaces in making the determination of success in the laboratory. Although evaluation, human factors, institutional, and other applied social and be-

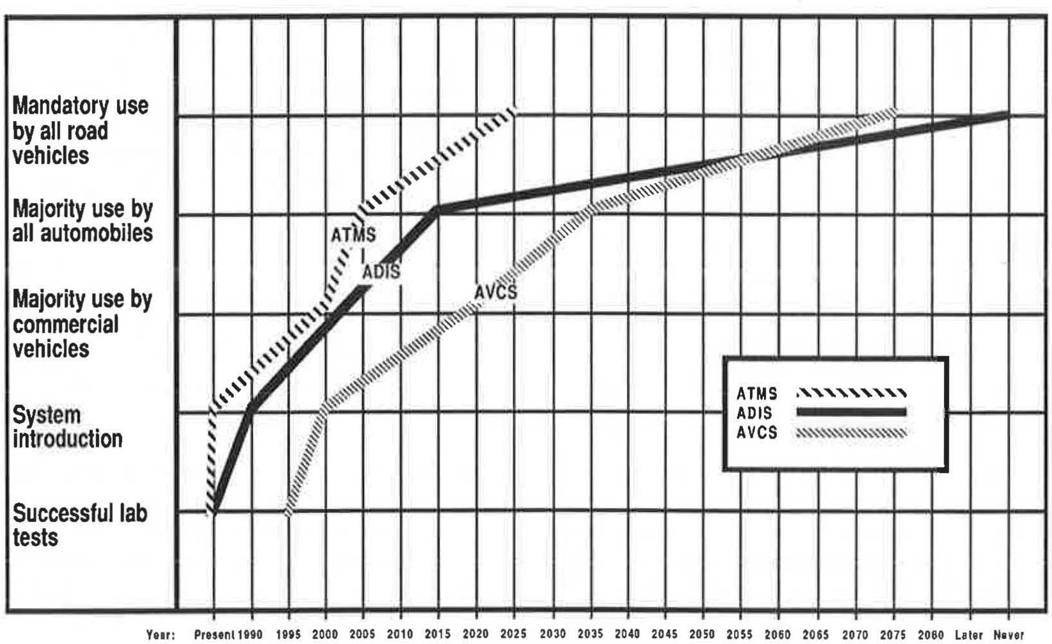

FIGURE 1 Median projections of IVHS market penetration by primary group.

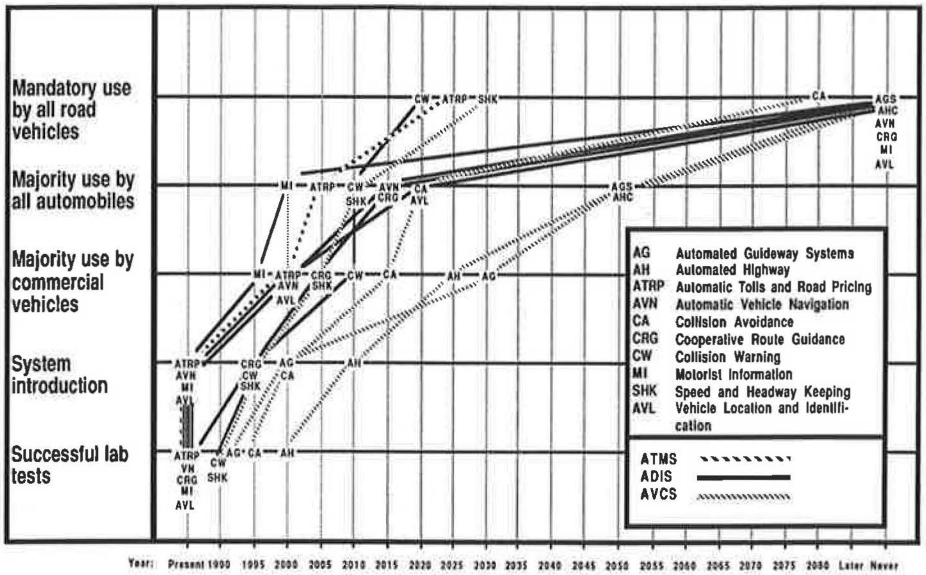

FIGURE 2 Median projections of IVHS market penetration by functional categories.

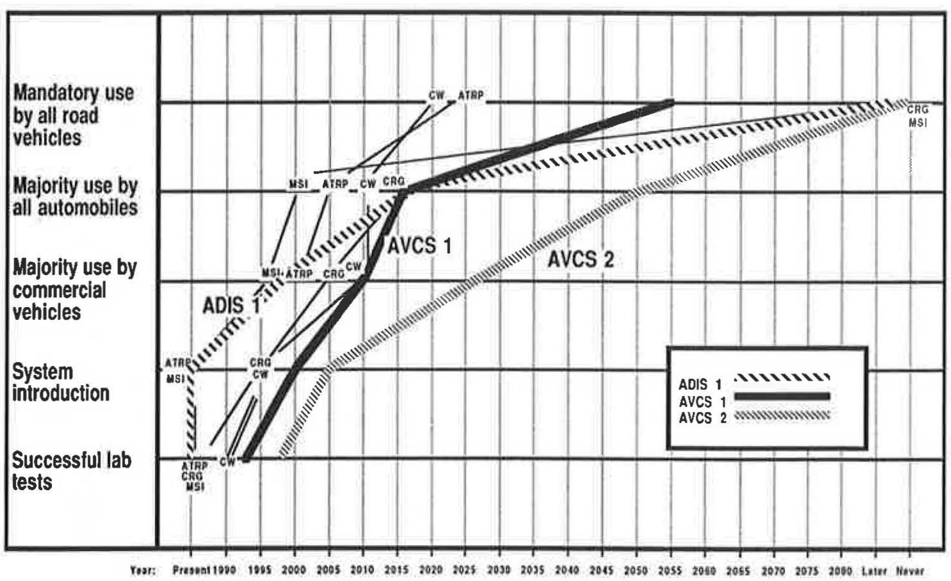

FIGURE 3 Median projections of IVHS market penetration by subgroup.

havioral research questions remain, most of the basic technical research has been successfully completed in these categories. Exceptions are technical research in the areas of traffic science and system integration. However, there are few unique technical research issues at the device or component level. In fact, automatic tolls and road pricing have already been introduced in a few applications, as is the case with most ATMS. Many of the ADIS categories have also been introduced with complete introduction of this grouping being just a few years away. Projected testing and introduction of AVCS lags about 10 years behind ADIS, with all three system categories being successfully introduced by the year 2000. These system technologies are not futuristic imaginings, but real-life, mostly proven approaches that will be implemented by the year 2000. According to the panel, only the more complex ADIS and AVCS categories require any form of basic technical research in the years to come.

The third characteristic worth noting is that in all three cases majority use by commercial interests will precede majority use by the general public. Apparently, trucking and emergency fleets will recognize and benefit from the economies of these systems before the private automobile consumer.

The last pattern of interest in this broadest level of analysis is that most of these systems, most notably the ADIS and AVCS systems, with a couple of exceptions that will be discussed later, are not likely to be required for all road vehicles. The vast majority of these systems will be optional and will depend on the motorists' purchase of the required in-vehicle components.

Figure 2 allows a more detailed comparison of both the broadest and finest system categories. The key in Figure 2 shows the line patterns for each of the broadest system categories as discussed in the preceding paragraphs (i.e., ATMS, ADIS, and AVCS). With this finest level of detail, the patterns discussed earlier reflect the most general tendencies for market penetration, and in reality some overlap occurs in the market penetration of the broad system types. For example, Figure 2 shows that motorist information systems, under the ADIS category, is on the leading edge of market acceptance. The panelists predict that MI systems will be accepted and deployed before the lone ATMS (i.e., automatic tolls and road pricing) is deployed. Similarly, the commercial use of collision warning, under the ADIS category, will follow the commercial use of speed and headway keeping, under the ATMS category. In fact, according to the panel, speed and headway keeping will attain widespread use before most of the ADIS technologies. The point is that there is indeed some overlap in the market penetration of the broad categories when viewed from the most detailed perspective. Nevertheless, as can be easily seen from the shading of the trend lines the general sequence of development is ATMS, ADIS, and then AVCS.

Figure 2 shows that the panelists predicted that MI systems will be used by a majority of automobiles by the year 2000. This system is the first of all the systems to reach this stage. It implies a rapid deployment of autonomous in-vehicle and roadside-to-vehicle information systems over the next decade. The most likely first step into widespread use of MI is continuous or periodic FM traffic and weather broadcasts from a traffic monitoring center. With this modest system, the government authority would be expected to provide the monitoring and information broadcasting services while automotive and radio manufacturers would be expected to provide modified radio units, if required. In any case, if a majority of vehicles will be using this type of system by the year 2000, and if it is assumed that the system requires a modified radio that would come with a new car purchase, then it can be concluded that discussions of system and technology standards will be initiated and concluded in short order. Both government and industry will have to move rapidly if this level of market penetration is to be achieved for even the simplest of systems by the year 2000.

The two-way communication capabilities of cooperative route guidance (CRG) will lag behind the developments of MI systems by 5 to 15 years. Figure 1 shows that while both MI and CRG systems have been successfully tested in the laboratory, only the one-way MI systems have reached the introduction stage; the two-way CRG systems are not expected to be introduced until 1995. Again, system introduction denotes the stage in which manufacturers market components for public or private use. With a later start, CRG will also take longer to penetrate the market. Although MI will take 5 years to reach majority commercial use after introduction, and 10 years to reach majority general use, CRG will take 10 and 20 years after introduction to reach these respective stages. In other words, the expected market penetration for MI will proceed at approximately twice the rate of the expected CRG market penetration. Although MI will reach majority use of all automobiles by the year 2000, CRG will not reach majority use until the year 2015.

Motorist information and cooperative route guidance systems are not entirely independent concepts and MI may well be a building block for CRG if the MI systems are designed for upward compatibility. Alternatively, CRG is a target system that may be composed of the other ADIS elements including motorist information, navigation, and location components, along with the new element of two-way information flow and the use of vehicle location and destination information to monitor, predict, and route traffic. CRG also incorporates elements of advanced traffic management. As a result, CRG is likely to become the focus of an effort to develop an integrated approach to vehicle-highway information and control.

CRG and CW are the slow runners in the ADIS field. Figure 2 shows that system introduction for both these systems is expected by 1995. This date diverges slightly from the aggregate ADIS projection in Figure 1, in which the systems are introduced by 1990. This divergence is important because it indicates that some fundamental research will be required for selected ADIS topics. The panel expects that it will take some time to develop and implement the vehicle-to-center information retrieval and analysis component of CRG and reliable detection in CW. Fundamental technical research is needed in both of these areas.

According to the panel, nearly all of the systems, with the exception of AH, are expected to be introduced by the year 2000. The concentration of systems at "system introduction" in Figure 2 implies intensive research and development within the next 10 years. Most of the systems, with the notable exceptions of the two most advanced control systems, AH and AG, will have reached majority use by the year 2020. This includes CA and SHK, the two early forms of vehicle control. The clustering of systems reaching "majority use" before 2020 in Figure 2 implies a major effort in system implementation and vehicle component sales over the next 30 years.

Figure 2 also shows the sequence and timing of mandatory system use. According to the panel, most of the systems will never become mandatory. Several exceptions, however, are worth noting. These are CW, ATRP, SHK, and CA. Three of these systems could have a significant impact on traffic safety: CW, CA, and SHK. If they prove reliable and affordable, it seems reasonable that they would be required on certain vehicles. ATRP is the other mandatory system; it would be required on those roads for which the system is implemented to eliminate congestion at toll booths and possibly to implement variable user fees.

The third set of projections, shown in Figure 3, accentuates three system subgroups that present combinations of similar IVHS categories. The first subcategory worthy of attention is labeled ADIS1 and could be called automated navigation and location systems. It combines AVN and AVL systems because they share a similar technological foundation and follow a similar course of development and implementation. These systems have already reached the "system introduction" level of development and should be employed in the majority of commercial vehicles by the year 2000. Transfer to majority private use is expected to take much longer, between 15 and 20 additional years, primarily because of the relatively high cost for the private consumer. It is expected to be 2015 before AVN is adopted by a majority of all automobiles and 2020 before AVL is adopted at that level. Private use coincides with a similar penetration of CRG and there may actually be a linkage between integrative system configuration and consumer demand. In other words, if CRG configurations adopt an in-vehicle map display and user interface, then it is quite likely that the demand for vehicle navigation and location systems will be determined by the deployment and demand of CRG systems, and vice versa. In any case, these systems are never expected to become mandatory.

The second subgroup shown in Figure 3 is the combination of CA and SHK, which has been labeled AVCS1. These systems have also been called "backup" systems because they supplement the driver control task without relieving the driver of all control functions. In actuality, CA is an authentic backup system that takes over the braking function when the driver fails to respond promptly. SHK is intended more to assist the driver by providing full and continuous relief from selected control functions, namely, regulation of vehicle speed through throttle and braking control. The similarity between these IVHS categories is that they represent partial vehicle control and they are both in the fundamental technical research stage. Braking is a common element of these systems, although with unequal emphasis. SHK is expected to advance faster than CA because SHK targets the throttle control function in continuously moving traffic, similar to cruise control, except it involves sensing of distances between vehicles. Braking may also be involved in SHK, but is not the pivotal element. In contrast, braking is the central element, and often the only element, of most CA systems. CA is not just relied on to regulate speed in a fairly clear and continuous path. Rather, CA is intended to detect and avoid obstacles that are either unnoticed by the driver or are moving too quickly for the driver to respond to them. This technical problem appears to be much more difficult. Nevertheless, the pattern of market penetration of these systems is similar and distinct from the more advanced control systems represented by AVCS2. A major feature of this subgroup is that the systems are expected to become mandatory sometime in the future.

The final subgroup is the complete control classification AVCS2. The systems included are the AH and AG systems. In these systems, the driver is relieved of all vehicle control functions for long stretches along the highway or guideway. As described in the individual system description, AH is more than a simple combination or extrapolation of the autonomous CA and SHK technologies. It requires full longitudinal and lateral control of the vehicle in dynamic traffic, including the ability to enter, exit, and merge with traffic. Vehicle guidance may be another element. As shown in Figure 3, these advanced control function are not expected until far into the future. The panel does not expect AVCS2 to be mandatory.

CROSS-CATEGORY ANALYSIS

The panel forecasts are presumably the product of the accumulated knowledge and assumptions of the panelists. In order to fully interpret the projections presented earlier, it is useful to know what factors the panelists considered in making their estimates. The panelists were instructed that they were to be optimistic about the allocation of government funds for IVHS research, development, demonstration, and implementation activities. However, beyond this general guideline the panelists were free to envision whatever sociotechnological dynamics they regarded as likely and important. As part of the Delphi exercise, the panelists were asked to identify and explain those factors that they considered in estimating the market penetration of the 10 categories of IVHS. Specifically, the panelists were asked to delineate what they viewed as (a) the driving forces for implementation, (b) the barriers to market penetration, (c) constructive government policy initiatives, and (d) the expected sociotechnical impacts from adoption of the systems. They listed factors for each of the 10 IVHS categories.

- Barriers to Implementation. The principal barriers to implementation of IVHS were social, economic, and institutional. Only system reliability and human factors could be considered technical. The cross-cutting barriers to implementation are listed in order of importance as ranked by the panelists:

1. Cost to the consumer;
2. Reliability;
3. Lack of demand;
4. Government and manufacturer liability;
5. System effectiveness;
6. Setting appropriate standards;
7. Planning for transition to new, more advanced, technologies;
8. Cost to government;
9. Human factors in system design;
10. Slower traffic, and
11. Limited applicability.

- Driving Forces. What will lead society to adopt these new systems? The panelists addressed this question by identifying and ranking a number of driving forces for adoption of IVHS. In this section only those forces are addressed that cut across a number of system categories. The driving forces for implementation of IVHS listed in order of the ranking by the panelists are

1. Increasing traffic congestion,
2. Desire for improved safety,
3. Motorists' desire for comfort and convenience,
4. Public's demand for travel information,
5. Declining technology and operating costs,
6. Incremental process toward advanced systems,
7. Commuter's preference for highway over rail,
8. Novelty of the technology, and
9. Promise of travel on designed lanes.

- Government Policy. How will the federal, state, and local governments be able to assist in the development and implementation of IVHS? The following lists presents the cross-cutting items ranked highest by the panel:

1. Limit the liability borne by manufacturers and government,
2. Establish effective standards,
3. Federal funding or incentives for research and development,
4. Department of Transportation leadership and commitment,

5. Provide the necessary public infrastructure,
6. Federal funding for construction and operation,
7. State and local enabling legislation, and
8. Dedicate lands and roadways.

- Social Impacts.
- The list of social impacts is similar to the list of driving forces, except that it also includes several negative outcomes. The cross-cutting items in order of rank are

1. Reduced congestion,
2. Improved safety,
3. Increased comfort and convenience for motorist,
4. Driver acceptance of automated control,
5. Increased automobile commuting, and
6. Smoother flow of traffic.

- Consistency Among the Delphi Studies. The forecasts by UM, ARISE, and FHWA were relatively consistent in terms of the pattern and sequence of system development. There was some discrepancy about the timing in system introduction in the United States, with the FHWA placing introduction of most systems about 10 years behind the other surveys. This could be explained by the FHWA's exclusive focus on public highways. However, this explanation is not certain.

Perhaps the most significant finding from the survey is that, given the right conditions, there is likely to be a great deal of progress made in the development of an intelligent vehicle-highway system in North America over the next 10 years. As an indication of things to come, the survey indicates that all of the systems, with the exception of AH, will be introduced by the year 2000. This implies significant technical and institutional advances between now and the turn of the century. It also assumes significant levels of government support and cooperation between the public and private sectors.

COMPARISON WITH OTHER DELPHI RESULTS

In an earlier section, the results of several previous Delphi surveys on IVHS were reviewed. At this point, it seems appropriate to compare the results of the UM survey with those of the ARISE and FHWA projects. For this purpose, two simple, but useful, comparisons of the trends that emerged from the three studies will be made, not for the purpose of selecting the "correct" forecast, but to get a sense of the robustness of the results when all three surveys are combined. The comparisons will examine the forecasted dates for system introduction and for majority use. This type of comparison was made possible by the close similarity in the formats of the questionnaires.

Before a discussion of the results is presented, the differences between the three surveys need to be clarified. These differences may explain some variation in the results. First, there is a difference in the geographic regions that the panelists were to consider in making their forecasts. The panelists in the ARISE survey were mostly from Western Europe and North America; however, there were a few members from Japan and several other countries. Although the panelists were not instructed to consider any specific geographic region, it can be assumed that the diversity in their origins would result in a global perspective on "road transport informatics." There might be some emphasis on Europe because that was the source of the project and the home of nearly half of the panelists. By way of contrast, the UM and the FHWA panelists were all from North America and they were instructed to only forecast technology applications within North America. The FHWA panel was the most restrained by instructions to address only those applications on public highways in the United States.

Second, there were distinct differences in the composition of the panels with regard to professions and sector of employment. The FHWA panel only included experts that were employed by the FHWA. The largest group of ARISE panelists were also employed by government agencies. However, approximately 20 percent of the panelists were employed by industry. A substantial number were also employed by research and academic institutions. The reverse was true of the UM Delphi panel. Nearly 70 percent of the panelists were employed by industry, the remainder were employed by government. None of the UM panelists were employed by research at academic institutions.

A third difference, that one will see immediately when looking at the tabulations of forecasts, is that the panelists in the three surveys did not address identical sets of systems categories. The FHWA survey addressed more traffic control systems, the UM survey addressed more vehicle control systems, and the ARISE survey fell somewhere in between. Furthermore, the system descriptions were not identical, but they were similar enough for useful comparisons.

A fourth difference is that the panelists were asked to make different assumptions regarding social and economic trends. The ARISE questionnaire listed a series of social and economic trends that appeared relatively conventional and were void of surprises. The FHWA questionnaire provided the panelists with both optimistic and pessimistic background scenarios. Only the results from the optimistic scenario are reported here. The UM questionnaire instructed the panelists to assume a healthy economy and that the federal government would be strongly committed to research in this area.

Given that these differences are known, it is worthwhile to review the differences and similarities in the outcomes of the forecasts. Table 1 presents the comparison of expected dates for system introduction from each of the three surveys. Note the overall similarity in the UM and ARISE forecasts. The FHWA forecasts system introduction to be approximately 10 years further into the future for each and every system category, despite taking estimates on the basis of their optimistic scenario. Although no explanation is offered, this expectation may be related to the restriction of addressing implementation only on public highways. Despite the higher values for the FHWA, the pattern of projections is fairly uniform among all three surveys.

CONCLUSIONS

This Delphi study combined both exploratory and normative approaches to forecasting in order to assist the UM IVHS research planning project in anticipating near-term events and in developing a research and administrative strategy designed

TABLE 1 COMPARISON OF EXPECTED DATES FOR SYSTEM INTRODUCTIONS

System category	UM	ARISE	FHWA [1]
Automatic tolls and road pricing	Achieved	1993	2007 [2]
Coordinated adaptive traffic control (FHWA)	--	--	1997
Interactive, adaptive traffic control (FHWA)	--	--	2007
Automatic vehicle location	Achieved	Achieved	1996
Automatic vehicle navigation	Achieved	Achieved	1996
Motorist information	Achieved	Achieved	1999
Motorist information 1 (FHWA)	--	--	1991
Cooperative route guidance	1994	1995	2001
Collision warning	1995	--	--
Collision avoidance	2000	2000	--
Speed and headway keeping	1995	2000	2014
Automated highway	2010	2010	2026
Automated guideway	2000	--	--

[1] This is the FHWA prediction for introduction of new vehicle and traffic control systems onto U.S. public highways. These forecasts were based on an optimistic economic scenario.

[2] This projection is specifically for congestion pricing on U.S. highways.

to meet realistic goals. The individual system forecasts were exploratory in the sense that they predicted market penetration on the basis of selected assumptions. The forecasts describe the near-term limits to IVHS developments given sufficient institutional support for these efforts. The listing of factors that may influence the development of these systems is more normative in nature; these lists may serve to illuminate potential opportunities and roadblocks along the path to developing an IVHS capability in North America. Knowledge of these factors also helps to circumscribe reasonable goals and strategies for research and development in the area. This section describes the limitations of the exploratory forecast and how the normative assessment, along with the plan for periodic updates of the Delphi study, provides a sound basis for formulating a research strategy in IVHS.

The survey indicates that progress in the development and the implementation of IVHS will depend on significant technical and institutional advances over the next ten years. The technical problems appear to be fairly well-defined; the design of driver information systems being the most immediate technical concern and the reliability of the advanced vehicle control systems being the crucial long-run issue. The institutional considerations are much less certain. The survey indicates that the turbulent institutional environment has the potential to slow, or even halt, the progress toward a comprehensive IVHS capability in the United States. In fact, the most likely and consequential near-term barriers to development and implementation of IVHS are the possible lack of consumer demand for and acceptance of these new transportation alternatives and the failure of our institutions to support the cooperative development of IVHS. Thus, the successful implementation of IVHS in North America will require a concerted effort on the part of the participating manufacturers, government agencies, and other interest groups to cooperate in resolving the issues of liability, standards, and support for research, development, and demonstrations. Cooperation among the key participants will need to continue through implementation and operation of many of the systems presented because both the vehicle and the highway elements will be fused into a unified whole. Existing institutional arrangements are unlikely to provide adequate support for these efforts and institutional innovation must be sought. The unconventional nature of the institutional problems posed by IVHS limits the ability to predict relevant social, political, and economic events with any degree of certainty.

In his respected critique of forecasting methods in public policy making, William Ascher (*12*) contends that the predictive value of a forecast is determined primarily by the core assumptions on which it was based. If the core assumptions are uncertain or wrong, then the conclusions of the forecast are likely to correspond. If the assumptions are accurate, then the forecast is likely to have greater predictive value. Ascher's insights have significant bearing on the strategy for and use of forecasting in deliberations on the future of IVHS. Because the institutional arrangements are so critical to the progress in IVHS, any forecast of technical advances in this area will be extremely sensitive to anomalies in the institutional arena.

The primary difficulty in providing accurate predictions of developments in IVHS is precisely that the environment for social decision making in North America is complex and rapidly changing, limiting the ability to anticipate events in a turbulent institutional environment. The core institutional assumptions for the survey were highly optimistic and uncertain; should the assumed institutional mechanisms fail to produce the anticipated levels of support, then the predictive value of the forecasts will diminish. For example, should the federal government fail to support the development of IVHS, or should the central institutional actors fail in their efforts to collaborate in this area, then little progress should be expected in the area of cooperative route guidance, which requires substantial levels of government support and institutional cooperation. Therefore, the expert forecasts that resulted from this survey should be viewed with an understanding of the optimistic assumptions on which it was based, and used more as a tool for setting goals and making near-term decisions rather than for predicting the long-run future. The optimistic explanatory forecasts are most useful in assessing the technological feasibility of meeting societal goals regarding the development of particular systems. They should be interpreted as the lower threshold for advancements in these technologies.

With the limitations of the forecasting methodology in mind, a strategy was developed for anticipating institutional events and technological breakthroughs for the purpose of developing and revising the research strategy. First, great emphasis was placed in the Delphi study on identifying and ordering a number of impinging factors, including possible barriers to implementation, driving forces for implementation, government policy initiatives, and the social impacts of IVHS. Knowledge of and sensitivity to these factors will assist in anticipating possible difficulties that lay ahead and in channeling research and administrative efforts more effectively. A relatively open-ended approach was taken in this portion of the survey to encourage originality on the part of the participants and to avoid the possibility of overlooking important factors. Second, the plan is to repeat the Delphi on a periodic basis to update the assessments as events unfold. This will help avoid what Ascher (*12*) terms "assumption drag," where the forecast relies on outdated core assumptions, which accounts for the gross inaccuracies of many policy-related forecasts. This initial Delphi study was designed with the intention to provide a foundation for a series of similar studies in the years to come. For example, the structure of the next Delphi should emerge from the results of the initial study.

Institutional issues notwithstanding, the prospects for rapid development of intelligent vehicle-highway systems in North America suggest that organizations with stakes in the future of road transportation get organized to guide progress in this area and respond swiftly to opportunities as they arise. Motorists demand the freedom of mobility delivered by the automobile. To the extent that IVHS can increase the throughput of existing roadways, reduce vehicle travel times, increase the motorists' comfort, convenience, and safety, and generally provide the motorist with information that either makes the driving time less aversive, more productive, and possibly more entertaining, the motorist freedoms will be extended and a market for these products will be assured. If IVHS can deliver these advantages as expected, the primary question becomes one of cost—to vehicle manufacturer, automobile insurance companies, and ultimately the vehicle owner; to the government operating organization and the local taxpayer; to the U.S. Department of Transportation and the taxpayers. As the cost of these systems tumble, the markets for the products and services will surface.

Elements of IVHS have already been introduced, but the full market potential of IVHS will not be realized until the key actors in the public and private sectors commit to a common vision of "smart" road transportation. The results of the Delphi survey indicate that, under the right institutional conditions, the commercial and noncommercial market will arise in relatively short order. Majority commercial use of most advanced driver information systems is expected by the year 2000. Adoption by the general public is not far behind. This result implies a lot of work between now and the imminent turn of the century. Research on system integration and the human consequences of IVHS must be supported and conducted at an internationally competitive level, systems must be designed and demonstrated to be effective and reliable, new technical standards need to be set, potential shifts in liability risks must be reconciled, operating organizations must be established, and a host of other milestones must be accomplished before a fully integrated and supported IVHS capability is established in North America. The survey of experts was directed at determining feasible progress in IVHS in the years to come and at issues that will require action if this is to be achieved. Perhaps the results can serve to inform the individual stakeholders about what is possible and to help shape a shared vision of IVHS in North America.

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