Roadway Automation Technology—Research Needs

STEVEN E. SHLADOVER

Although the concept of roadway automation has been in the public eye for nearly 50 years, and although it has now been 30 years since the first test track demonstrations of some of the requisite technologies, virtually no progress has been made toward implementation. This paper reviews the history of roadway automation development efforts and explains why it is worth re-examining roadway automation now in light of current transportation needs and technological progress. The main body of the paper outlines the technical questions that need to be answered in order to make roadway automation a reality, based on the nine functions of an automated roadway system: (a) intelligent traffic signalling; (b) traffic information systems; (c) driver warning and assistance systems; (d) automatic steering control; (e) automatic spacing control; (f) obstacle avoidance; (g) automatic trip routing and scheduling; (h) control of merging of strings of traffic; and (i) transitioning to and from automatic control.

The idea of roadway automation has been with us for a long time, although it has been manifested in many different guises. While the early futurists' visions of modern life (such as the General Motors "Futurama" of the 1939-40 World's Fair) may seem quaint to us now, much of what was contained in those visions has yet to be realized. It took nearly 20 years for the "driverless car" vision of the Futurama to appear on a test track for the first time, implemented with real hardware. In the 30 years since those first experiments, we have moved no closer toward the automated roadway in spite of the dramatic advances in many of the underlying technologies needed to make it work. Even if the automated roadway was ahead of its time 50 years ago and again 30 years ago, we owe it to ourselves to give it a serious look now, as we enter the final decade of the twentieth century.

Roadway automation technology can be interpreted to mean a variety of different things. For purposes of the discussion here, it is defined to be the application of communication and control technology to observe, guide, and/or control the movement of vehicles in a traffic system (or to assist in the performance of those functions). This definition is designed to be sufficiently broad to include advanced traffic signalling and monitoring systems used by drivers retaining control of their vehicles, as well as fully automated "driverless" vehicles, but not so broad as to include automation of special purpose exclusive guideway systems (BART, AIRTRANS, etc.). The terminology "roadway automation" is in itself controversial and has unfavorable connotations for some people. Other authors have chosen to refer to this subject as "intelligent vehicle-highway systems" or "road transport informatics." The ideal terminology has not been found.

The potential benefits to be gained from roadway automation have grown rapidly in recent years, as the underlying technologies have been progressing (and therefore becoming more economical). The primary benefits fall into five categories:

1. Providing a cost-effective roadway capacity increase. By enabling vehicles to travel closer together (longitudinally and laterally), automation can increase the capacity of the existing roadway infrastructure at a lower cost (and with minimal disruption to the neighborhood) than the addition of more lane-miles of roadway. The increased capacity translates into reduced travel delays and, when combined with electrification of the vehicles, reduced environmental impacts as well.
2. Improving safety. By eliminating human error and foolhardiness from the control of vehicles on the roadway, the accident rate can be reduced, and with it the associated deaths and injuries, as well as the additional delays that accidents now impose on traffic flow.
3. Improving speed and reliability. Roadway automation should make it possible to travel safely at higher speeds than at present in urban areas. This speed increase can be obtained without sacrificing potential capacity increases, because fully automated vehicles are not governed by the same speed-volume relationships that apply to human drivers in normal traffic flow. By requiring stringent condition checking of all vehicles that enter an automated roadway, breakdowns should also be significantly reduced. Even when breakdowns and accidents do occur, their impacts on traffic flow should be greatly reduced by the elimination of "rubbernecking" by drivers in other lanes.
4. Increased convenience of travel. Roadway automation eliminates the tedium and stress of driving for travelers who are disabled, fatigued, too old, or too inexperienced to drive effectively.
5. Maintaining industrial competitiveness. If the United States does not proceed aggressively in the development of roadway automation technology, the rest of the world will not wait for us. Active, large-scale programs in Western Europe and Japan are developing roadway automation technology to ensure that their automotive industries will survive in the coming decades. U.S. automotive manufacturers can look forward to accelerated erosion in their shares of both the domestic and international markets unless this country remains competitive in the development of this class of technology.

Program on Advanced Technology for the Highway, University of California at Berkeley, 1301 S. 46th St., Bldg. 452, Richmond, Calif. 94804.

In order to reduce a large subject to units of manageable scale, it is useful to subdivide the functions of an automated roadway system into nine categories:

1. Intelligent traffic signalling;
2. Traffic information systems;
3. Driver warning and assistance systems;
4. Automatic steering control;
5. Automatic spacing control;
6. Obstacle avoidance;
7. Automatic trip routing and scheduling;
8. Control of merging of strings of traffic; and
9. Transitioning to and from automatic control.

Each individual category represents a very useful function, and each will require considerable technology development before it can substantially benefit the traveling public. A system that serves any one of these functions could be highly beneficial, but truly dramatic improvements in our urban traffic systems will not be enjoyed until the "automatic vehicle control functions" (4–9 above) are available. However, these vehicle control functions cannot be provided until the "driver information functions" (1–3 above) are available.

The above listing, which serves as the framework for the main body of this paper, can also serve to indicate the sequence in which the automation functions are likely to become available. It is not a statement of research priorities, however, because the (later) automatic vehicle control functions are also the most difficult and will require the greatest investments of time and labor and the longest development lead times. Of course, they also offer the greatest potential capacity, safety, and travel time benefits and therefore deserve high current priority. The automatic vehicle control functions are essential if the capacity of the existing roadway infrastructure is to be doubled or tripled, if speeds are to be substantially increased or if accidents are to be reduced dramatically.

Consider, for example, the capacity increase that could be obtained by applying automatic steering and spacing control to a freeway or bridge having five 12-ft lanes. If steering control makes it possible to reduce lane width from 12 ft to 8.5 ft, the same pavement and structure could accommodate seven lanes instead of five. If automatic spacing control allows vehicles to operate at half-second average headways, each lane could accommodate 7,200 vehicles per hour (vph), rather than the approximately 2,000 vph achievable under driver control. The combined effect is an increase in capacity from 10,000 vph to more than 50,000 vph for the same structure and right of way.

With careful design of the control systems for safety and reliability, the incidence of accidents could be reduced significantly, particularly those caused by driver inattention and lapses of judgment. Furthermore, automatic control systems will completely eliminate the "rubbernecking" phenomenon, so that a breakdown or accident in one lane will not cause the vehicles in all the other lanes (in both directions) to slow down. The reduction of accidents and elimination of rubbernecking will substantially reduce the disruptions to traffic flow arising from incidents, enabling effective lane capacity to approach the theoretical limit the large majority of the time. Smooth flow, at constant speed, with the elimination of "stop and go" instabilities, also offers the potential for major improvements in energy efficiency and pollutant emissions.

The implementation concepts for roadway automation cover the range from completely centralized control of every vehicle in a network to fully autonomous vehicles with no centralized control (sometimes referred to as "automatic chauffeuring" in Europe). Each of these extremes has important limitations, so any realistic system is likely to represent a compromise between them. Such a compromise solution means that an automated roadway system will include significant elements that are both privately and publicly owned and controlled.

HISTORICAL BACKGROUND OF AUTOMATIC VEHICLE CONTROL SYSTEMS

Although we are no closer to driving on automated roadways now than we were 30 years ago, there has been much engineering activity devoted to roadway automation during this period. During the late 1950s, General Motors and RCA developed and demonstrated (on test tracks) automatic control of steering and longitudinal spacing of automobiles for what they called the "Electronic Highway" (*1,2*). By 1962, the first university research on automatic steering control of automobiles was reported from Ohio State University (OSU), under the sponsorship of the Ohio Department of Highways and the Bureau of Public Roads (*3*). This led to a later, long-term research program at OSU on both steering and longitudinal (spacing) control, under the sponsorship of the Ohio Department of Transportation and the Federal Highway Administration (FHWA), from 1965 to 1980 (*4,5*). The first broad-scale investigation of the application of automation technologies to urban transportation problems appears to have been in the MIT Project METRAN, in the spring of 1966(*6*).

Major federal government involvement in the pursuit of roadway automation began with the New Transportation Systems Research Act of 1966, which instructed the U.S. Departments of Housing and Urban Development and Commerce to study new systems for urban transportation [since the Department of Transportation (DOT) did not yet exist]. This "New Systems Study" led to the creation of series of reports from the Stanford Research Institute and General Research Corporation, culminating in the summary report, *Tomorrow's Transportation: New Systems for the Urban Future,* in 1968 (*7*). Six new urban transportation systems were recommended for development in that report, one of which, called "Dual Mode," was essentially the automated roadway using vehicles that could operate in either a manual or an automated mode (hence the name).

Although several research programs grew out of the recommendations in *Tomorrow's Transportation*, the progress in the dual-mode area was particularly slow. The DOT Transportation Systems Center (TSC) conducted a major economic evaluation of dual mode in 1971-73, leading to the recommendation that dual-mode systems be developed for both transit and private (automotive) vehicles (*7*). UMTA initiated studies of three different dual-mode transit (bus and pallet) systems in 1973, but the program never advanced beyond the initial concept development phase, and "dual mode" soon became a dirty word within the transportation establishment.

The work on dual mode and automated highway technologies was reported in a Transportation Research Board conference in 1974, although the proceedings unfortunately did not contain full texts of many of the papers (*9*).

In addition to the ongoing work at OSU, FHWA sponsored a study of the feasibility of an automated highway system, leading to a report in 1977 that recommended several areas needing further research (*10*). A second FHWA study of automated highways by General Motors in 1980-82 examined the technical potential of the automated highway in the context of realistic implementation problems (*11*). The most recent thinking of the FHWA in this area is represented in Working Paper No. 7 of the FHWA's "Future National Highway Program—1991 and Beyond" (*12*).

Privately funded work on the development of roadway automation technologies is not generally reported because of proprietary restrictions on release of information. This makes it difficult to tell how much activity there actually has been in this area. Certainly General Motors has been active in work on roadway automation technology since the time of their original work, although only limited glimpses of this have been available to the research community in general (*13*).

A large portion of the technology development work relevant to roadway automation has actually been performed in pursuit of automated guideway transit (AGT) systems, formerly referred to as personal rapid transit systems. This activity was primarily sponsored by the Urban Mass Transit Adminsitration (UMTA) during most of the 1970s and produced a large body of research results, which must be absorbed and understood by anyone hoping to advance the technologies for roadway automation. AGT researchers had to address most of the issues that must be solved for roadway automation, except for the problems associated with transitions to and from automatic control and with developing vehicles that can operate under both manual and automatic control. The results of the AGT research are scattered across an extensive range of reports, journal papers, and conferences. The central references, from which a more comprehensive literature search can be started, are the four conference proceedings (*14–17*).

The development of the roadway automation technologies never achieved a high enough priority on the national agenda to proceed very rapidly. In the late 1970s its priority declined, leading to a virtual disappearance in the 1980s. Virtually no new domestic work on vehicle automation has propagated into the literature since 1980.

Overseas, however, roadway automation work has recently seen a dramatic revival (*18*). There are hopes for a domestic revival with the advent of the PATH program in California and Mobility 2000 on the national level. Indeed, the climate should be more favorable for roadway automation now than it has ever been in the past, because of many of the changes that have occurred within the past decade:

- Significant growth in urban and suburban congestion;
- Further increases in the real costs of contruction of new roads;
- Public opposition to construction of new roads;
- Environmental problems created by the use of fossil fuels for transportation (pollution, greenhouse effect, petroleum dependency);
- Dramatic technological advances in sensing technologies, computer hardware and software, communication technologies, and control theory;
- Increased foreign competition for the automotive industry; and
- The threat of losing U.S. technological leadership in the world.

All of these factors provide encouragement for a concentration of effort on the development of roadway automation technologies. Such development efforts must not go about reinventing the wheel, but must build on the generations of work that have gone before, and must be carefully planned in order to avoid wasting time and effort. The development work must be based on clear statements of goals and a clear understanding of how to go about achieving those goals. The remainder of this paper outlines an agenda for such development efforts, indicating the technical problems that need to be solved before we can enjoy the benefits of automated roadways. More detailed statements of the research needs outlined in the next section of this paper may be found elsewhere (*19*).

CRITICAL TECHNICAL ISSUES

The operations embedded within a roadway automation system primarily consist of gathering data, processing the data, and then communicating the results elsewhere for action. These operations can be understood best by illustrating them schematically, showing the flow of data from one component of the system to another (see Figure 1). The components to be considered are:

- The vehicle being controlled (or more specifically its sensors and its onboard computer);
- The driver of the vehicle;
- The roadway;
- External objects;
- Other vehicles and their drivers;
- Wayside computer(s); and
- Wayside traffic signals.

Each of the nine functions of roadway automation can be described in terms of the data flows among these components. Once those data flows are specified, it becomes easier to focus on the technical issues that must be resolved in order to implement each automation function.

Intelligent Traffic Signalling

Modern traffic signals already incorporate some elements of "intelligence," whether it be programming that varies with the time of day or some responsiveness to measured traffic conditions (generally vehicle presence detection). This function assumes that the vehicles of today continue to operate entirely under driver manual control, making it the least advanced and nearest-term of the nine automation functions. All the technology changes would be on the wayside, in the

collection of real time traffic data, processing of the data, and displaying it to drivers. Considerable advances have been made toward implementing this function in demonstration systems in recent years, such as the Los Angeles "Smart Corridor," the Australian SCATS, and the British SCOOT and CITRAC systems (*12*).

The data flows needed to implement intelligent traffic signalling [also referred to as advanced traffic management system—(ATMS)] are illustrated in Figure 1. Most of these data flows already exist in current traffic systems and involve no automation functions. The new development work will need to be focused on collecting data about the vehicles as they travel, processing that data, and displaying it to the drivers so they can take appropriate actions. The technical issues that must be addressed here include:

- Selection of performance measures by which to judge success;
- Selection of the information to be collected;
- Selection of monitoring and communication methods;
- Development of control algorithms;
- Application to an urban corridor; and
- Application to a complete urban region.

Traffic Information Systems

Traffic signal systems are, of course, traffic information systems of one limited type. However, this function also includes advanced driver information systems (ADIS): two-way communication of information between the wayside computer system and the vehicle's onboard computer, which serves as the interface to the driver. This requires that the vehicle owner invest in additional equipment on the vehicle, but it continues to leave the driver in complete control of the vehicle. As with the previous function, much of this functionality is starting to enter some urban demonstration projects. These include the "Pathfinder" demonstration planned for the Los Angeles "Smart Corridor," the AMTICS (Advanced Mobile Traffic Information and Communication Systems) demonstration in Tokyo (*20*), and the ALI-SCOUT demonstration in Berlin (*21*).

The data flows needed to implement a comprehensive traffic information system are illustrated in Figure 2. As before, many of these flows already exist as a natural part of driving. The new developments involve the communications between the wayside computer and the computers on the individual vehicles (as well as the processing of the data at both ends). The technical issues to be addressed here include:

- Selection of performance measures;
- Selection of the information to be collected;
- Selection of monitoring and communication methods;
- Selection of information to display to the driver;
- Selection of how to convey information to driver;
- Development of the technologies to convey the information to the driver;
- Development of control algorithms; and
- Selection of centralized functions (AVM, etc.).

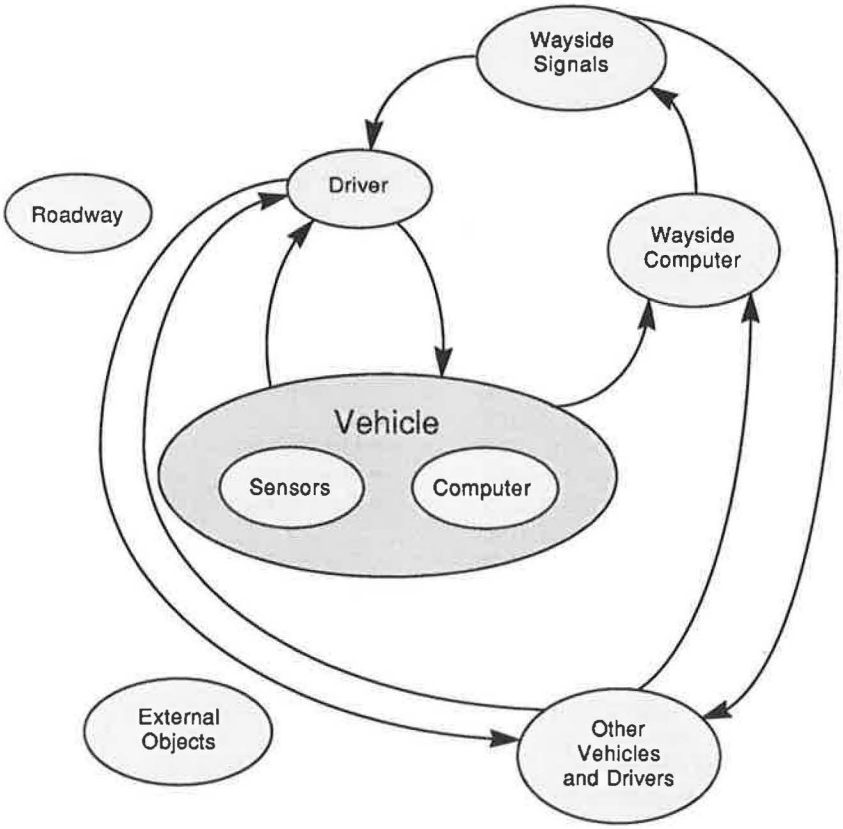

FIGURE 1 Information flows in intelligent traffic signalling system.

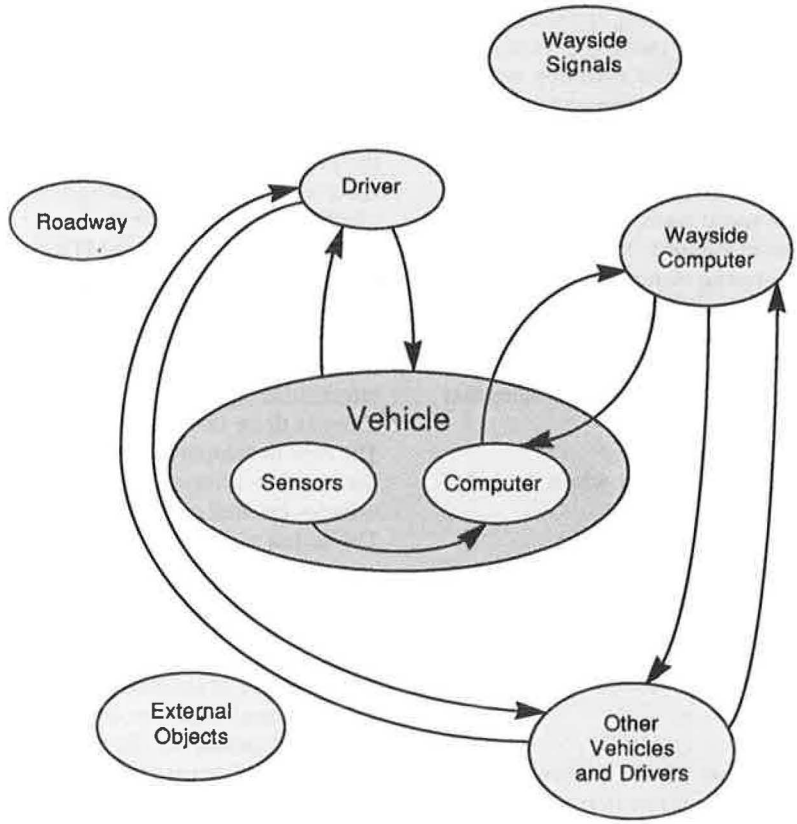

FIGURE 2 Information flows in traffic information system.

Driver Warning and Assistance Systems

Modern electronics can make automobiles safer and easier to drive in a variety of ways (antilock braking systems and cruise control, for example). However, there are realistic near-term opportunities available for significantly more dramatic electronic driver aids, performing higher-level functions than those now available on automobiles. These can be implemented entirely onboard the vehicle, without requiring the involvement of any public agency or wayside facility.

The data flows needed to implement driver warning and assistance functions are shown in Figure 3. The driver interacts with the automobile as he would under any normal circumstances. However, his vehicle would also be equipped with sensors to detect the vehicle's status relative to the roadway, as well as other vehicles and indeterminate external objects. The sensors would supply information to an onboard computer, which would in turn signal the appropriate information to the driver or the vehicle's other systems. Examples of this include collision-warning radar, near-obstacle detection, lane-center detection for driving assistance, and automatic steering compensation for external force disturbances.

The collision-warning radar and near-obstacle detection systems would issue a warning to the driver of impending danger, in effect supplementing his own eyes and ears. These systems could begin the evolution to the obstacle avoidance function, described below, in which the vehicle would take the corrective action without the driver's intervention. The lane-center detection system could help the driver steer in conditions of bad visibility (rain, snow, fog) or when he is fatigued, by supplying a dashboard or heads-up display of the vehicle's position relative to lane center. The steering compensation system could estimate the effect on the vehicle's steering of sudden external force disturbances (wind gusts or wakes of passing vehicles) in real time and compensate for them by adjusting the steering system, without requiring the driver to make abrupt and stressful corrective maneuvers.

The technical issues that must be addressed to lead to the development of such systems tend to be quite system-specific, but they can, in general, be related to the sensing, computation, and display functions:

- Development or selection of sensors;
- Development of computational capability; and
- Development of display capability.

Automatic Steering Control

With this function, we clearly cross the threshold from driver control of the vehicle to automatic control of one of the key driving operations. This will require extensive modifications to the vehicles, as well as some equipment very carefully installed within the roadway. This function therefore requires cooperation between the vehicle and roadway (and hence between the public and private sectors) in order to work. Fully automatic steering control is not likely to be implemented on a large scale independent of the other automatic vehicle con-

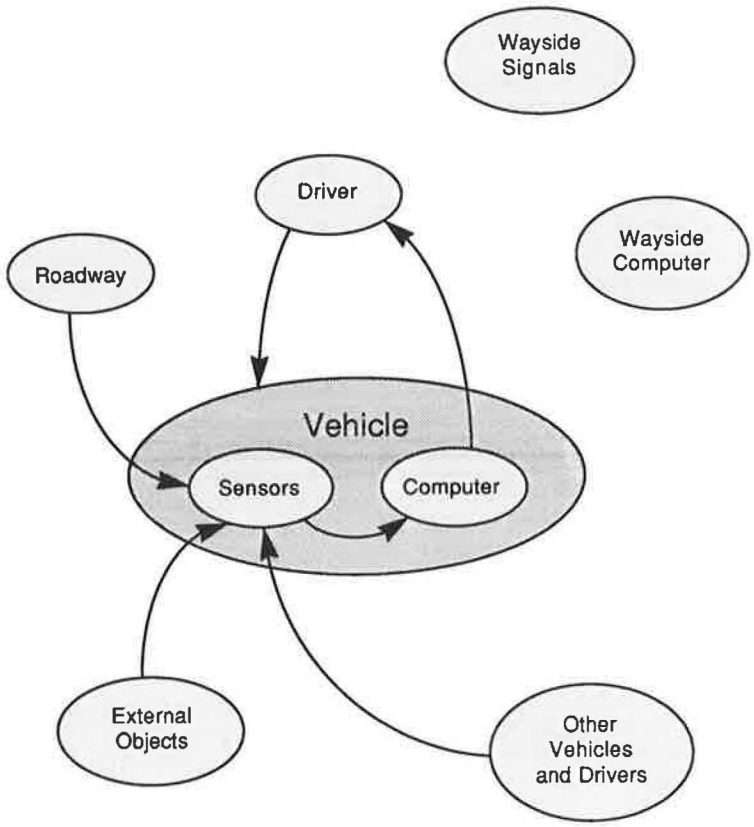

FIGURE 3 Information flows in driver warning and assistance systems.

trol functions (automatic spacing control, obstacle avoidance, etc.) because of the safety implications, particularly in terms of driver alertness. There does not appear to be a safe way to implement partial automation, because a vehicle must be under the control of either the driver or the automatic system, but not a mixture of the two.

The data flow needed to implement automatic steering control is simply from the roadway to the on-vehicle sensors to the computer. The complexity in automatic steering control is found at a lower level in the hierarchy of data flows. More than any of the other nine functions, the automatic steering function can be decoupled from the operations of the other vehicles in the traffic system and from the wayside computer system(s). The technical issues to be addressed here are:

- Selection of steering reference and sensors;
- Adaptation to varying conditions;
- Tradeoff between accuracy and comfort;
- Design of feedback control law;
- Development of actuation system;
- Provision of redundancy, backups, and fault accommodation; and
- Tradeoff between vehicle and roadway costs.

Automatic Spacing Control

This function represents another example of a driver ceding the control of his vehicle to an automatic system, with all of the reliability and safety implications that entails. The data flows are more complicated than they were for the automatic steering because of the strong interactions with the other vehicles on the road and with the wayside computer. The vehicle being controlled must detect its proximity to adjacent vehicles, using special sensing equipment, and the wayside computer needs to keep track of all of the nearby vehicles so that it can provide the appropriate instructions to the controlled vehicle's onboard computer. Although it is in theory possible to implement some spacing control without involving the wayside computer, that would require each vehicle to obtain information about vehicles other than those immediately adjacent to it, which would introduce other problems of comparable complexity. The technical issues to be addressed here are:

- Selection of safety criteria;
- Defining performance requirements;
- Defining permissible demands on vehicle performance;
- Tradeoffs between vehicle and wayside intelligence;
- Tradeoffs between vehicle following and point following;
- Selection of references and sensors;
- Definition of communication requirements;
- Definition of feedback control laws for asymptotic stability;
- Defining reliability requirements;
- Provision of redundancy, backups, and fault accommodation; and
- Deciding whether vehicles should be operated individually or in platoons.

Obstacle Avoidance

The automatic steering and spacing control functions described previously are intended to address vehicle operations in the presence of other automated vehicles, but not in the presence of other (unanticipated) obstacles. The appearance of a foreign object in the path of an automated vehicle has serious safety implications. If the object should be a person or a domestic animal, one would want to have the vehicle stop or swerve to avoid running over and harming it. If the object should be large or heavy, the vehicle should avoid running into it to save both passengers and vehicle from harm. On the other hand, if the object is inconsequential (leaves, newspaper, squirrel) the vehicle should continue on its way rather than changing its course and producing delays.

The most important flows of information are from the external objects to the onboard sensors and then from the sensors to the computer. The other data flows are needed to warn adjacent vehicles of the evasive measure about to be taken by the vehicle that detects the foreign object. This kind of direct advance warning is needed to ensure high performance and safety in a short-headway, high capacity system.

The obstacle detection and avoidance function described here differs from the driver warning and assistance function, in that it extends beyond providing a warning to the driver and includes directing the vehicle to take corrective actions as well. The technical issues that must be addressed here include:

- Development of sensing technology;
- Development of data processing capability; and
- Development of coupling to vehicle steering, speed, and spacing control systems.

Automatic Trip Routing and Scheduling

This function enters a new realm of scope and complexity, considering the number of vehicles it involves and the volume of the information that must be handled. Automatic trip routing and scheduling can assume a wide range of forms, with different degrees of centralization. On the one extreme, it can consist of complete prescheduling of every vehicle trip from origin to destination at the time the vehicle enters the automated system. On the opposite extreme, it can consist of en route rerouting of vehicles to obtain smoother flows and better utilization of line-haul capacity throughout the system, plus coordination of merge junctions and vehicle entries and exits. Many intermediate concepts are possible as well, offering a variety of tradeoffs between complexity and performance.

The data flows required for automatic trip routing and scheduling involve two-way communication between each vehicle and the wayside computer(s). The quantity of information to be passed to and from each vehicle is likely to be relatively limited (origin, destination and present locations, plus the command to turn or not turn at each demerge junction), but because of the number of vehicles that could be operating at once in a large-scale system, the total communication burden could be very large. The heaviest burden is in the computations that must be performed by the wayside computer(s) in real time. The technical issues that must be addressed here include:

- Selection of performance measures,
- Design of network for desired capacity,
- Tradeoff between prescheduling and en route rescheduling,
- Selection of degree of centralization of control,
- Development of routing and scheduling algorithms, and
- Detection of capacity limit in real time.

Control of Merging of Strings of Traffic

An essential feature of an automated roadway that consists of more than a single network link is automatic control of merges, which include lane changes, entries, and exits. Consecutive vehicles in a string of traffic may need to branch off to different destinations, or two strings of traffic may need to merge to form a single string (which poses more difficult problems). The wayside computer serves a central role in exchanging information to and from all the vehicles involved. In addition, the vehicles may communicate directly with each other, sensing the positions of their neighbors and possibly even commanding their neighbors to make minor course corrections. The technical issues to be addressed here include:

- Definition of safety requirements;
- Definition of priorities at merges;
- Definition of sensing requirements;
- Definition of communication requirements;
- Definition of reliability requirements;
- Provision of redundancy, backups, and fault accommodation; and
- Definition of merging for platoons.

Transitioning to and from Automatic Control

The final function of roadway automation is unique to the roadway automation technology, because it is not an issue for manually driven vehicles or for fully automated captive guideway vehicles. This is the function of transitioning between the manual and automatic modes of operation, where the driver cedes control of the vehicle to the automatic system upon entry to the automated roadway and then recovers control upon leaving the automated roadway.

The driver communicates with his vehicle and the vehicle's computer communicates with the wayside computer to effect the handoffs between the two modes of control. Safety and reliability issues are of prime importance here, in order to ensure that a vehicle is in good working order before it is admitted to the automated roadway and to ensure that the driver is awake, alert, and ready to take command when it returns to the normal street system. The technical issues to be addressed here include:

- Integration of entrances and exits with local street system;
- Entrance of a vehicle to the automated system; and
- Exit of a vehicle from the automated system.

The Fully Automated Roadway System

The fully automated roadway would incorporate all of the functions from category 4 to 9 described above, employing the information flows shown in Figure 4. It would obviously be quite a complicated system, and one that would take years to develop and implement. There is no single "best" way to implement the research and development plan for such a system. Each of the research groups working in this field will be devoting considerable effort to developing its own plan. The definition of needed elements or capabilities, as outlined above, is a necessary first step. However, development of a research plan is well beyond the scope of this paper.

The most important issues in the development of a research plan are ensuring that the plan has a coherent focus and that it follows good system engineering principles. This means that it should proceed from the statement of needs to mathematical modeling and analysis, design, and implementation of limited-scale experiments, and then multiple cycles of design refinement and testing, before proceeding to public demonstrations of any substantial scale. Politically inspired near-term demonstrations are very risky, as proven by the damage done to the entire AGT activity by the Morgantown demonstration of the early 1970s.

Many of the technologies needed for the automated roadway have been developed and demonstrated in experimental form during the past 30 years, but very little of that has been in evidence during the past decade. The first priority should therefore be in rebuilding the knowledge base of that prior work and then applying the new technological developments of today to that foundation in carefully conceived experiments. We should expect a major application of effort to providing the needed reliability and safety for each of the functions and to reducing the costs of the needed equipment. The most difficult topic is likely to be the development of generally applicable automatic routing and scheduling methods for complicated networks. The routing and scheduling issues have only been addressed for small, topologically simple systems to date, and even these have proven to be very difficult.

POLICY ISSUES AFFECTING ROADWAY AUTOMATION

In spite of the very large potential benefits that could be gained from large-scale implementation of the more advanced roadway automation functions (i.e., those involving automatic vehicle control), there has been virtually no movement in that direction by any public agencies. It is apparent that a similarly large set of potential problems stands in the way of progress toward complete roadway automation. The solutions to these problems will be challenges of a very different type from the solutions to the technical problems described above.

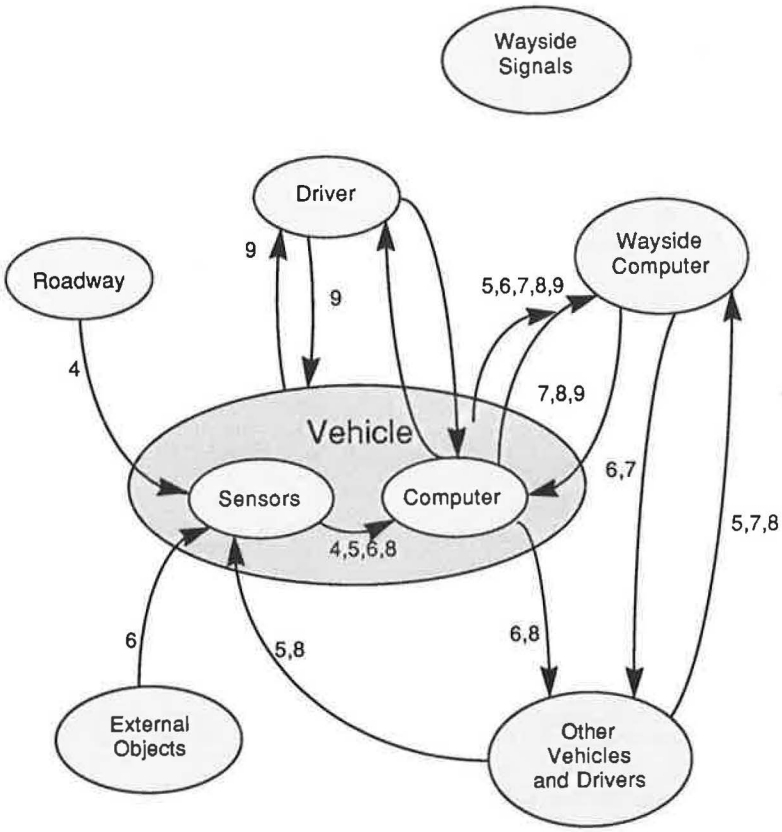

FIGURE 4 Information flows in fully automated system.

Political Need for Near-Term Results

Politicians need near-term results, which can be demonstrated to their constituents before the next election, in order to develop enthusiasm for new programs. Roadway automation is not well suited to this need because of the lengthy, laborious research needed to bring its most attractive features to the point that they can be demonstrated. Some incremental progress can be made towards short-term goals, but only at the expense of sacrificing the much greater long-term benefits of solving the harder problems.

Scale Effects

The benefits of roadway automation have very strong scale effects. A small-scale automation project or a project in a small city will show relatively small benefits, and quite possibly it will not show benefits that exceed its costs. The dramatic benefits of this technology can really be gained only with large-scale implementation in the largest and most congested metropolitan areas, where it can most significantly reduce delays and increase capacity. It is obviously not practical to make such a large and risky investment until the technology has been proven to work on a smaller scale. By the same token, it is difficult to justify the small-scale demonstration on its own merits if its benefits will not exceed its costs. Some strong political leadership, imbued with a long-term perspective, will be needed to overcome this problem.

The Chicken and the Egg

Apart from the scale effect problem cited above, there is an additional "chicken and egg" problem to confront. It is difficult to gain public support for the infrastructure investment needed to install a roadway automation system if very few people have vehicles equipped to use the system. At the same time, people will not be willing to invest in the additional equipment needed to automate their private vehicle if there is no roadway available on which to use it. The cycle must be initiated by somebody willing to make an investment for the long term, without hope of a near-term payback.

Competing Interests of Public and Private Sectors

The public and private sectors must cooperate with each other to achieve an automated roadway system. The public sector must furnish the roadway and wayside facilities, while the private sector must equip its vehicles with the necessary onboard equipment. The equipment and facilities must be standardized for compatibility with each other, and these standards must at least apply on a nationwide basis (if not internationally) so that vehicles can use the same onboard equipment everywhere. There are many tradeoffs in the system design which affect the distribution of costs and risks between the vehicles and the roadway, but there is no impartial, unbiased entity to decide how to balance those competing interests. This raises the possibility of battles between self-interested entities over the very nature of a roadway automation system.

Liability

In our litigious modern society, every accident has the potential to become a major tort liability case. An injury-producing accident on an automated roadway could be a trial lawyer's dream (and the nightmare of everybody else) unless policies are implemented in advance to preclude that. Indeed, roadway automation will not be able to advance beyond the test track until the liability issues are resolved so that all of the interested parties (designers and builders of systems and components, public agencies, testing laboratories, consultants, insurance companies, etc.) can be assured that they will not be liable for unlimited damages when failures occur. Creative legislation is likely to be needed to reduce the liability threat to manageable proportions.

Hope

In spite of the technological and institutional problems that need to be solved in order to make roadway automation a reality, the benefits to be derived from solving those problems appear to be so great that it is still worth doing. If we in the United States persist in applying short-term decision criteria to discourage attempts to solve our large-scale transportation problems, the solutions will eventually be imported from Europe or Japan. If the implications of that for the health of our automobile and electronics industries, as well as for our national balance of payments, can be raised in the public consciousness, perhaps we will be able to generate the interest needed to enable us to get to work solving the problems.

REFERENCES

1. K. Gardels. *Automatic Car Controls for Electronic Highways*. Report GMR-276. General Motors Research Laboratories, Warren, Mich., 1960.
2. V. K. Zworykin and L. E. Flory. Electronic Control of Motor Vehicles on the Highways. *HRB Proceedings*, Vol. 37, 1958.
3. D. Barrick. Automatic Steering Techniques. *IRE International Convention Record*, Vol. 10, Part 2, 1962, pp. 166–178.
4. An Investigation of Highway Automation. Reports EES 276A-6 and EES 276A-15. Ohio State University, Columbus, Ohio, 1969 and 1974.
5. *Fundamental Studies in the Longitudinal Control of Automated Ground Vehicles*. Report FHWA-RD-77-28, Ohio State University, Columbus, Ohio, 1976.
6. M. E. Hanson, ed., *Project Metran: An Integrated, Evolutionary Transportation System for Urban Areas*. MIT Press, Cambridge, Mass., 1966.
7. *Tomorrow's Transportation: New Systems for the Urban Future*. U.S. Department of Housing and Urban Development, Washington, D.C., 1968.
8. P. Benjamin, et al. Analysis of Dual Mode Systems in an Urban Area. Report DOT-TSC-OST-73-16A. Transportation Systems Center, U.S. Department of Transportation, Cambridge, Mass., 1973.
9. *Special Report 170: Dual Mode Transportation*. TRB, National Research Council, Washington, D.C., 1976.
10. Calspan Corp. *Practicability of Automated Highway Systems*. Report DOT-FH-11-8903. FHWA, U.S. Department of Transportation, Washington, D.C., November 1977.
11. J. G. Bender, et al. *System Studies of Automated Highway Systems*. Report FHWA/RD-82/003. FHWA, U.S. Department of Transportation, Washington, D.C., 1982.

12. *Advances in Vehicle and Traffic Control Technology*. The Future National Highway Program 1991 and Beyond, Working Paper No. 7. FHWA, U.S. Department of Transportation, Washington, D.C., 1988.
13. R. R. Smisek and G. A. Harder. Automated Control of Guideway Transit Vehicles. *Proc., 29th IEEE Vehicular Technology Conference*, Arlington Heights, Ill., March 1979.
14. J. E. Anderson, et al. eds., *Personal Rapid Transit*. Institute of Technology, University of Minnesota, Minneapolis, Minn., 1972.
15. J. E. Anderson, ed., *Personal Rapid Transit II*. Institute of Technology, University of Minnesota, Minneapolis, Minn., 1974.
16. D. A. Gary, ed., *Personal Rapid Transit III*. Institute of Technology, University of Minnesota, Minneapolis, Minn., 1976.
17. *Proc., International Conference on Advanced Transportation and Urban Revitalization*, Advanced Transit Association, Indianapolis, Ind., May 1978.
18. T. Karlsson. PROMETHEUS: The European Research Program. Presented at 67th Annual Meeting of the Transportation Research Board, Washington, D.C., 1988.
19. S. E. Shladover. Research Needs in Roadway Automation Technology. Presented at SAE Conference on Future Transportation Technology, Vancouver, Canada, August 1989.
20. H. Okamoto. Advanced Mobile Information and Communication Systems (AMTICS). Presented at Future Transportation Technology Conference and Exposition, San Francisco, Calif., August 1988.
21. R. Von Tomkewitsch. The Traffic Guidance System ALI-SCOUT. *Proc., Conference on Technology Options for Highway Transportation Operations*, Sacramento, Calif., October 1986, pp. 130–142.

Publication of this paper sponsored by Task Force on Advanced Vehicle and Highway Technologies.