AUTOMATED HIGHWAYS

Automated highway systems (*AHS*) refer to electronically instrumented vehicles (cars, buses, and trucks) operating on special lanes, where drivers totally relinquish vehicle control to on-board and infrastructure computers. Once the computer takes over, drivers can take both hands off the steering wheel, both feet off the pedals, and both eyes off the road. Automated highway systems are envisioned not only for surface freeways, but also for underground road networks. The main benefits of AHS include increased highway capacity, reduced traffic congestion, reduced pollution and fuel consumption, and enhanced safety.

The concept of automated highway vehicles in the United States was introduced as early as 1940 at the New York World's Fair, as shown in Table 1 (1, 2). Until the early 1980s, sporadic efforts were made to test automated lateral and longitudinal control of vehicles. The initial significant event was a conference in 1986 sponsored by the California Department of Transportation that discussed the role of advanced vehicle-highway technology in increasing highway capacity and efficiency. This event set the stage for the formation of Intelligent Vehicle Highway Society (IVHS) in 1990, now the Intelligent Transportation Society of America (ITS America), and the development of the California statewide Program for Advanced Technology for the Highway (*PATH*), renamed Program for Advance Transit and Highway in 1992. Subsequently, the National Automated Highway Systems Consortium (*NAHSC*) was formed in 1994, but was dissolved in 1998. In 2000, the Cooperative Vehicle-Highway Automation Systems (*CVHAS*) was formed. The CVHAS consists of systems that provide driving control assistance or fully automated driving, based on information about the vehicle's driving environment that can be received by communication from other vehicles or from the infrastructure, as well as from the vehicle on-board sensors. The long-term vision of the CVHAS includes AHS development. In Europe and Japan, work on developing automated highways started with a smaller scale than in the United States, where the focus was on such features as safety warning and collision avoidance, that may eventually lead to automated driving. Research is currently focusing on developing low-speed automation that would operate only during congested periods.

A milestone in the AHS program was the demonstration on a stretch of a California freeway in 1997 that proved the technical feasibility of automated highways (Figs. 1–3). The automation was accomplished using on-board computer-controlled systems and vehicle/roadway sensors. Nearly 1800 people enjoyed rides in automated vehicles. This event demonstrated several scenarios, including free agent, platoon, evolution, and transition. The free-agent scenario consisted of several passenger cars and two buses; the buses did automatic lane change and passed the passenger cars, and vice versa. The platoon scenario involved eight passenger cars that traveled exactly 6.5 m apart at 105 km/h. The evolution scenario involved passenger cars that demonstrated the developing stages of automated highway systems, starting with adaptive cruise control and evolving to collision warning, collision avoidance, and full automated vehicle control. The transition scenario showed how vehicles might move from a rural setting, where steering is controlled by the vehicle computer vision, to an urban setting, where steering is controlled by the road magnetic markers.

The AHS initiative is an area of the broader intelligent vehicle highway system (*IVHS*), now called the intelligent transportation system (*ITS*). The ITS program aims to improve the efficiency of current transportation systems using advanced technology and includes the following main areas:

- Advanced Traffic Management Systems (*ATMS*)
  Cover freeway management, traffic network monitoring, demand management, electronic toll collection, incident management, and so forth.
- Advanced Traveller Information Systems (*ATIS*)
  Provide travelers with information about traffic routing, vehicle location and arrival, and roadside services, using on-board navigation systems.
- Advanced Vehicle Control Systems (*AVCS*)
  Cover short-term features that aid the driver's control of the vehicle, including collision warning, collision avoidance, blind spot detection, and lane detection. The long-term goal of AVCS is to develop an automated highway system that includes fully automated vehicles operating on specially equipped highways.
- Commercial Vehicle Operations (*CVO*)
  Provide safe movement of trucks, buses, taxis, and emergency vehicles by applying ITS technologies such as automatic vehicle identification, on-board navigation devices, automated brake inspection technologies, and on-board safety monitoring technologies.
- Advanced Public Transportation Systems (*APTS*)
  Cover planning and scheduling systems, dynamic ride sharing, automatic payment, and so forth, to improve the operation of high-occupancy vehicles using ATMS, ATIS, and AVCS.
- Rural Applications of ITS
  Cover incident notification (Mayday), hazard warning, collision avoidance, ATIS, and interactive systems for rail-highway crossing safety.

Among the preceding areas, AHS is expected to produce the most significant efficiency improvement in transportation systems. The long-term goal of AHS is to integrate ATMS, ATIS, and AVCS technologies to produce fully automated vehicles that are guided from origin to destination, where traffic flow is optimized for the entire highway network. In the United States, the initial focus was on developing AHS, but later the effort has shifted to focusing first on developing advanced vehicle control and safety systems that will eventually lead to AHS. A ten-year plan for a national intelligent transportation system program, developed by ITS America in 2002, had the following four themes (3): (a) an integrated network of transportation information, (b) advanced crash avoidance technologies, (c) automatic crash and incidence detection, notification, and response, and (d) advanced transportation management. These themes will be used to achieve the following goals:

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

Table 1. Historical Automated Highway System Activities in the United States

Date	Activity
1940s	The concept of automated highway vehicles was first introduced in the General Motors Futurama, displayed at the 1939–1940 New York World's Fair.
1950s	Concept-automated cars were developed. Automatic control of steering and speed was demonstrated on test tracks by General Motors in cooperation with Radio Corporation of America.
1960s	Several projects related to the systems analysis of automated highways were initiated by the Bureau of Public Roads (PBR), now the Federal Highway Administration (FHWA). General Motors Futurama II was displayed at the 1964 New York World's Fair.
1970s	Automated lateral and longitudinal control was demonstrated on a test track by the Ohio State University under sponsorship by the PBR, but the industrial effort was less visible. The Urban Mass Transportation Administration (UMTA), now the Federal Transit Administration (FTA), invested substantial R&D efforts on Automated Guideway Transit and Personal Rapid Transit, whose technologies are similar to those needed for automated highway systems.
1980s	In the later 1980s, significant activities took place, including automated highway workshops sponsored by the California Department of Transportation and FHWA during 1986–88, forming Program for Advanced Technology for the Highway (PATH) in California in 1986, now called the Program for Advanced Transit and Highway, and the formation of Mobility 2000 in 1988.
1990s	The Intelligent Vehicle Highway Society (IVHS) was formed in 1990, now the Intelligent Transportation Society (ITS). The Intermodal Surface Transportation Efficiency Act (ISTEA), which called for the development of an AHS prototype, was passed in 1991. The National Automated Highway System Consortium (NAHSC) was formed in 1994, and highway automation was successfully demonstrated in the field in California in 1997.
2000s	In the United States, the Cooperative Vehicle-Highway Automation Systems (CVHAS) which includes AHS was formed. A ten-year plan was developed by ITS America.in 2002. In Europe and Asia, especially Japan, research on automated highway systems continued to progress. In addition, new ideas such as low-speed automation during congestion periods and underground automated highways have emerged.

safety, security, economy, access, and energy. In other countries such as Germany and Japan, research on AHS also continued to progress. More details on international initiatives toward AHS can be found in VanderWerf et al. (4).

The development of AHS involves technical, societal, and institutional challenges. This article is primarily concerned with the technical aspects of automated highway systems. It presents details on roadway configuration, functional planning, control structure, traffic operations, and highway capacity. Before presenting these aspects, it is useful first to describe the general features of AHS (5).

GENERAL FEATURES

Future automated highways will be integrated into existing freeways in two ways. First, an existing freeway lane may be converted for automated vehicles and separated from manual vehicles by a transition lane. Automated vehicles enter the transition lane under manual control, and then enter the automated lane under computer control. Second, new dedicated lanes for automated vehicles served by exclusive on and off ramps may be built within the existing freeway right-of-way.

Before entering the automated lane, the system would electronically interrogate the vehicle to find out its destination, ensure that it is properly equipped for automated

Figure 1. A platoon of eight automated cars moving on the I-15 high-occupancy vehicle (*HOV*) lanes during the AHS demonstration in San Diego. Photo by Bill Stone, California PATH.

Figure 2. Driver Bill Kennedy rests his hands on his legs as his automated minivan travels on the I-15 HOV lanes. Photo by Robert Bryant, Avalon Integrated Services.

travel, and deduct any tolls from the driver's credit account. If successful, the driver would steer the vehicle into a merging area, and then the system would guide it through its entry to the automated lane. If the vehicle is not properly equipped, it would be guided to the manual lanes. Automated vehicles have lateral (steering) and longitudinal (speed and spacing) control systems that use measurements from vehicle and roadway sensors to command the throttle, brake, and steering actuators. When the automated vehicle approaches its intended exit, the computer first ensures that the driver is not preoccupied, asleep, disabled, or even dead. If so, the computer releases control to the driver to complete the exit; otherwise the computer guides the vehicle to a safe stop at a nearby holding area and notifies the infrastructure of an emergency (6). Local control stations along the roadway may be used to assign traffic speeds on the automated roadway based on instructions from a centralized computer that manages the entire highway network. That way, the system achieves optimum performance for the automated lanes, ramps, and local streets.

Automated vehicles may operate as autonomous vehicles, free-agent vehicles, or platoons. The autonomous vehicle relies on its own sensors to detect the range and closing speed of other vehicles, but they cannot detect their accelerations or manoeuvring intentions nor detect vehicles that are out of sight. The spacing between autonomous vehicles depends on, among other factors, the electronic reaction time of the controlling equipment, which is much faster than the human reaction time. In free-agent vehicles, the information about other vehicles is conveyed directly to the following vehicle via a wireless vehicle-to-vehicle (v–v) communication. This reduces the reaction time even more. The reaction time can be further reduced if the infrastructure has the primary responsibility of detecting the presence of an emergency and issues a command to all vehicles to start braking at the same time. Platoons would operate in groups of automated vehicles with a smaller spacing than that of other modes. The vehicles are linked together with a local communication network that exchanges information on speed and acceleration about 50 times per second, thus allowing the spacing between the vehicles to be so close to fixed that it produces the illusion of an electronically coupled train.

One of the major benefits of automated highway systems is that they will greatly increase highway capacity since vehicle spacing is safely reduced, resulting in traffic flows with higher densities and higher speeds. Automated highways will also reduce the number of crashes that are due to driver error (currently 90%) and will reduce the time wasted in traffic jams and thus improve productivity, especially for commercial vehicle operations. Last but not least,

Figure 3. In-vehicle display in automated car. Photo by Mary Beth Lane, Federal Highway Administration.

these systems will reduce gasoline consumption and exhaust emissions.

ROADWAY CONFIGURATION

There are two basic concepts for integrating automated highways into existing freeway systems: the shared space concept and the dedicated space concept. In both concepts, the automated roadway has separate lanes and lies within the freeway right-of-way. Several implementation issues associated with these concepts, including operational features, design requirements, and environmental concerns, have been evaluated by Yim et al. (7). Safety aspects of different AHS configurations are addressed by Hitchcock (8).

Shared Space Concept

In the shared space concept, both automated and manual vehicles use a common right-of-way and common on and off ramps. The automated and manual lanes would be separated by a transition lane, in which vehicles shift between the two modes of operation, as shown in Fig. 4 (7). Clearly, all vehicles would enter and exit the freeway under manual operation. This concept requires at least two manual lanes in each direction to accommodate weaving movements between manual and transition lanes, merging near on ramps, and diverging near off ramps. After vehicles enter the freeway, automated vehicles first enter the transition lane under manual control. The system checks that the vehicle is properly equipped for automated travel and, if successful, shifts the vehicle to the automated mode. The vehicle then enters the automated lane when a gap is available. The automated, transition, and adjacent manual lanes would be separated by lane barriers.

Dedicated Space Concept

The dedicated space concept requires building new dedicated lanes for automated vehicles served by exclusive on and off ramps, at grade, above grade, or below grade. The at-grade concept has at least three lanes in each direction since it does not need a transition lane. Automated and manual lanes are separated by lane barriers. The exclusive on and off ramps for the automated roadway would be connected to either existing or new overpasses and may be located within the median. This configuration would require the lateral expansion of the freeway at the site to accommodate the ramps. A continuous or intermittent emergency lane along the automated roadway may be needed to give emergency crews access and to store disabled automated vehicles temporarily. Such a lane would significantly increase the cost and may be difficult to construct in urban areas.

The above-grade concept would be suitable for downtown areas when the lateral expansion of the freeway is not feasible. The structural supports of the automated roadway are located within the median of the existing freeway. It may be necessary to provide an emergency lane or a shoulder adjacent to the automated roadway to store disabled vehicles temporarily. A single emergency lane may also be used for automated roadways of both travel directions, but this would require openings in the barriers between the automated and emergency lanes. Exclusive on and off ramps would be constructed and connected to existing or new overpasses, but they may be more widely spaced than conventional roadway ramps.

In addition to AHS for surface freeways, new ideas have emerged in 2005 regarding underground automated highways, which are considered the most viable option in high density urban environments (9). Underground parking structures at the origin and destination are built. Besides passenger transportation, the network will also substantially facilitate freight movement between fringe distribution centers, and urban shopping and industrial areas. The development of such networks depends on progress on several enabling technologies, such as: (a) improvement on automated tunnel boring, excavation, and shoring systems, (b) development of super ultra low emission vehicles, and (c) progress in intelligent vehicles and AHS. The idea of underground automated highways was first proposed in Germany in 1997 for freight transportation as a means of promoting sustainable development (10). Concepts and ideas regarding the configuration and infrastructure of underground automated highways will most likely be developed in the near future.

FUNCTIONAL PLANNING

The purpose of functional planning (or functional specification) is to identify the functions of automated highway systems so that a control structure can be developed

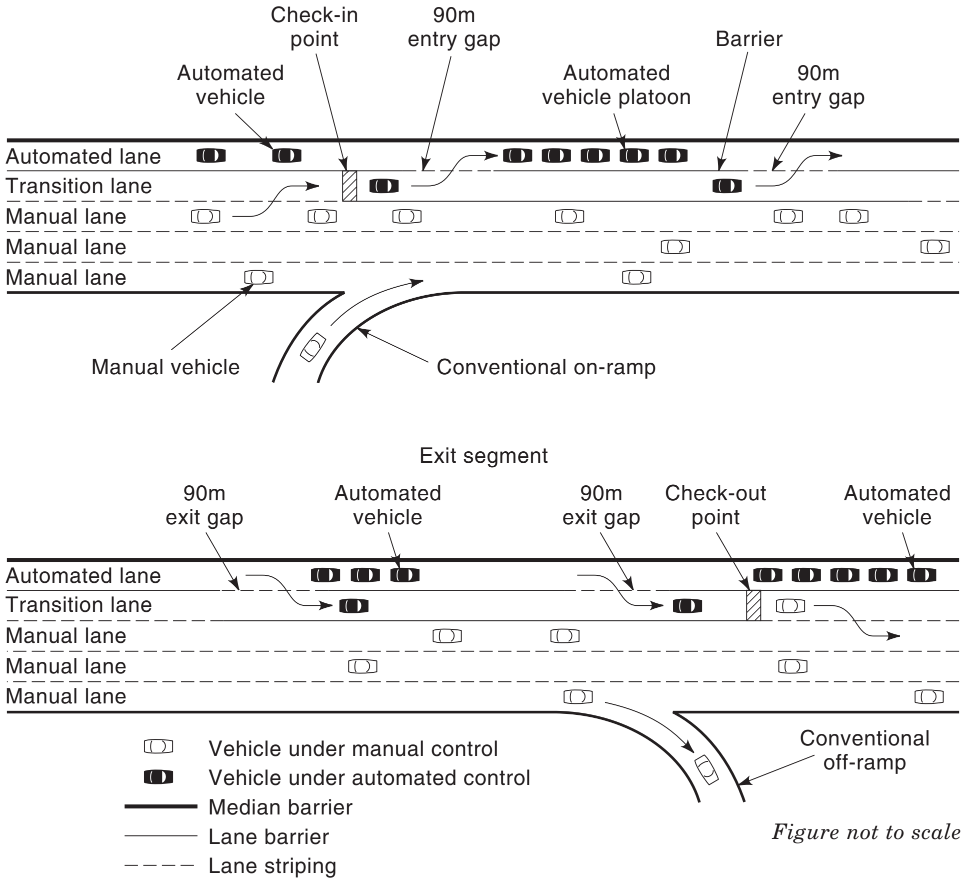

Figure not to scale

Figure 4. Example of a shared space configuration for automated highways (7). Copyright 1997 by Plenum Press, New York. Used by permission.

(11). Functional planning consists of system flow planning functions, vehicle movement planning functions, and implementation functions. System flow planning functions optimize the *macroscopic* traffic flow in the system, while vehicle movement planning functions optimize the *microscopic* movements of individual vehicles. Implementation functions perform the planned route trajectory and maneuvers of each vehicle. This functional planning assumes that the highway is divided into sections, and each is controlled by a roadway computer.

System Flow Planning

This category may require as input the physical configuration of the automated highway and surface streets, vehicle control rules, traffic demand, traffic conditions, vehicle type, and driver preferences (such as fastest route or least-toll route). The output includes entry flows, traffic assignment, and desired speed and density (number of vehicles per kilometer at a given time). System flow planning consists of the monitoring function, entry-flow function, and optimization function. The monitoring function monitors current system flow, which is used as input to the other two functions. The entry-flow function (1) determines if preplatooning at certain locations on the transition lane is needed and, if so, how to organize arriving vehicles into preplatoons; (2) meters the traffic entering the automated lanes from a transition lane during congestion; (3) determines if preplatooning at on ramps of a dedicated space roadway is needed and, if so, how to organize arriving vehicles into preplatoons; and (4) meters automated platoons at roadside metering stations before on ramps. Metering decisions would be made based on traffic conditions and trip length and destination.

Based on entry flows, the optimization function (1) determines the maximum and the target platoon sizes; (2) determines the desired speed, density, and spacing (for vehicles and platoons) and plans the merging and diverging of traffic flow; (3) assigns automated highway traffic based on certain criteria, such as minimizing travel time, using on–off ramp trip demand, vehicle type, and driver preferences; and (4) balances traffic flows on the automated lanes to increase capacity (maximum hourly flow rate at which automated vehicles can reasonably be expected to traverse a point or uniform section of automated lane under prevailing roadway, traffic, and control conditions). Tasks 1 and 2 may vary by section, lane, and time.

Vehicle Movement Planning

This category may require as input the output of system flow planning, trip destination, and other data, and its output includes vehicle trajectory and maneuvers. Vehicle movement planning consists of route planning, path planning, and vehicle/gap planning. The route planning function determines a route for an individual vehicle and may involve (1) selection of an initial route based on the destination input by the driver at the time of entry to the automated highway, and (2) reselection of the route if a change of destination is invoked by the driver during the trip or by the infrastructure because of a change in traffic conditions.

The path planning function determines the vehicle's trajectory from entry to exit, including lane selection and lane change. Lane selection planning assigns the section, lane, and time for the vehicle throughout the trip. Initial lane selection, however, may be changed by the infrastructure to balance the flows on different lanes or after a route change by the driver during the trip. Lane change planning assigns the time/location for a lane change. This task could be completely decentralized, wherein the driver makes a request for lane change and then the vehicle itself negotiates the maneuver, completely centralized where the roadway has the responsibility for the maneuver, or less centralized where both the roadway and the vehicle share the task. The vehicle/gap planning function determines the proper distribution of vehicles (platoons) and gaps to improve overall AHS capacity. This function includes: (1) gap management to monitor and manage the position/length of gaps between individual vehicles, and (2) platoon merge/split management to determine whether and when to split one platoon into two or more and to merge two or more platoons into one.

Implementation

Implementation functions that are likely to be present in any automated highway configuration pertain to check-in and entry, vehicle control on the automated roadway, and check-out and exit. Before entering the automatic lane, the ability of the vehicle to operate on automated highways is checked through on-board diagnostics and roadside check-in stations, which may also communicate the identity and destination of the vehicle to the infrastructure. Once the check-in is successful, the on-board control system and the infrastructure control the vehicle and guide it through its entry to the automated roadway. There, vehicle functions would include lateral control, longitudinal control, and maneuver coordination. When the automated vehicle approaches its intended exit, the computer might signal the approach of the exit and ask the driver for some limited tasks. If the driver acts properly, the computer would release control immediately to the driver to complete the exit. Otherwise, the infrastructure brings the vehicle to a safe stop in a holding area near the exit and declares an emergency.

CONTROL STRUCTURE

Regardless of their precise configurations, automated highways will involve fully automated vehicles equipped with sophisticated sensors and computer-controlled systems, likely to be managed by the infrastructure. A general control structure, based on Varaya (12), which can be used to partition the functions described in the previous section, is shown in Fig. 5 (13). Each layer receives state information from the layer below it and returns commands to it. A microsimulator for automated highway systems (SmartPath) employing this control structure has been developed by PATH researchers (14). Further details on this control structure can be found in Ioannou (13). The five layers of the control structure define vehicle control and infrastructure control.

Vehicle Control

The on-board vehicle control system (*VCS*) consists of three layers: vehicle dynamics, regulation, and coordination. The vehicle dynamics (physical) layer comprises all on-board controllers of such physical components as sensors, engine, transmission, brakes, steering, and transition to and from automatic control. The regulation layer receives data from the lateral and longitudinal sensors and then generates necessary commands to the electronic throttle, brake, and steering actuators to perform maneuvers instructed by the coordination layer. The coordination layer selects the type of maneuver to undertake and coordinates the maneuvers of the vehicle with neighboring vehicles, such as merging, diverging, and lane changing. The type of maneuver can be selected by either the coordination layer itself or the link layer. To perform a specific maneuver, the coordination layer first acquires permission from neighboring vehicles and, if granted, instructs the regulation layer to execute the maneuver. A new algorithm for merging maneuvers involving virtual platooning concept has been recently developed by Lu et al. (15).

The VCS performs several tasks that affect safety and performance, including longitudinal control, lateral control, maneuver control, and emergency control. The longitudinal controller maintains certain speed and spacing and uses a sensor to measure the relative speed and spacing to the vehicle ahead. The controller commands the throttle and brake actuators to follow the same speed and maintain a fixed relative distance. Vehicle lateral control is responsible for steering the vehicle to the center of the lane while maintaining smooth ride (lane keeping) and steering the vehicle from one lane to another safely and comfortably (lane changing). The lateral control system accepts input from the road reference sensing system and vehicle sensors and responds to lane changing commands. Most research work so far has focused on lane keeping because lane changing is inherently complex, requiring a combined lateral/longitudinal control design. A recent study has addressed the effect of uncertainties due to parameter variation and disturbances or perturbations to the vehicle system on the longitudinal and lateral control (16).

Maneuver coordination refers to the coordination of vehicle maneuvers, such as merging, diverging, and lane changing. This may be achieved via v–v communications (and perhaps vehicle-infrastructure communications) and protocols that assign priorities and govern the logic of the maneuvers. It is likely that automated vehicles will also rely on their own sensors to verify the safety of the maneuvers. Details on some preliminary work in this area can be found in Hsu et al. (17).

Emergency control would continuously monitor the state of the vehicle and the surrounding environment; identify the threatening situations, such as a potentially dangerous object on the road; and take the proper actions to

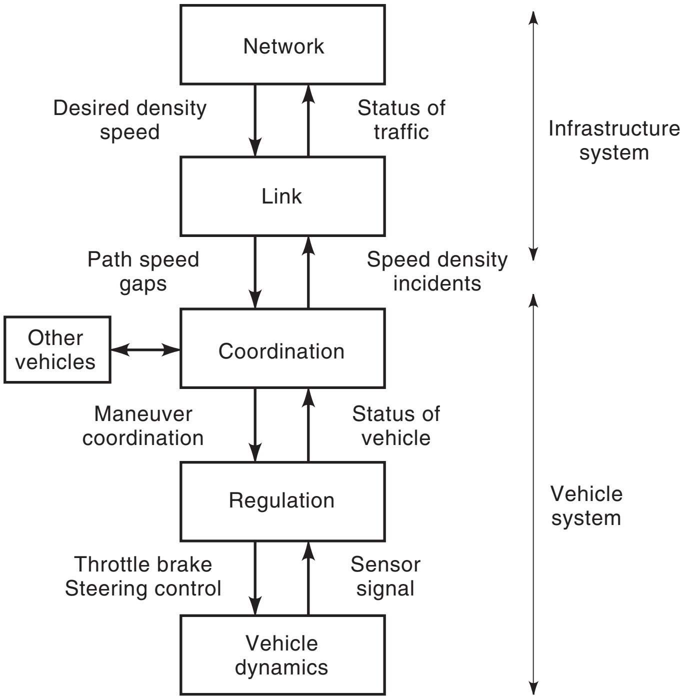

Figure 5. Control structure for automated highway systems (13). Copyright 1997 by Plenum Press, New York. Used by permission.

prevent collisions. Since in emergencies the primary objective is safety and not ride quality, higher bandwidth inputs for the vehicle throttle, brake, and steering than those for normal operations may be required. The emergency controller should also be able to detect vehicle subsystem failure and, in turn, declare an emergency.

Infrastructure Control

Infrastructure control consists of the link and network layers (Fig. 5). Although automation eliminates the disturbance at the vehicle level, other disturbances associated with lane changing, accidents, and congestion on local streets may adversely affect the operation of the automated highway. For this reason, macroscopic control at the link and network levels would be needed. The link layer provides appropriate commands regarding speed, headway, and path planning to the vehicles on each section to ensure smooth flow. These commands are based on traffic measurements for the section and desired traffic density and speed distributions provided by the network layer. A link-layer controller for multi-destination traffic that is based on density and flow has been presented by Alvares et al. (18).

The network layer manages the entire highway network, including automated lanes, on and off ramps, manual lanes, and local urban street systems. Overall network traffic management is essential because if the throughput capacity is substantially increased and the local urban street system is not monitored and controlled, overall optimization of the urban area will not occur. The network controller issues instructions to the link layers to optimize overall traffic performance. The network layer may be an overall centralized controller or a collection of decentralized controllers interacting with the local link layers. Network control is a challenging problem, but rapid computer advances will aid the development of controllers that can manage large networks. The link and network layers generally perform, respectively, vehicle movement planning functions and system flow planning functions described previously, but some interactions exist.

Sensor Requirements

Sensors are perhaps the most important technology that makes automated highways feasible. A wide variety of sensors are required for longitudinal control, lane keeping, lane changing, and other functions (19, 20). For longitudinal control, radar sensors on board are used to measure the relative speed and spacing between the subject vehicle and the preceding vehicle. Despite their success, current ranging sensors use a narrow beam that may miss the preceding vehicles on curves. Using a wide-beam sensor, on the other hand, may capture wrong targets, such as vehicles in the nearby lane. A combination of narrow-beam radar and vision sensors offers a promising alternative.

For lane-keeping control, several sensing systems have been proposed, including magnetic marker systems, vision-based systems, and radar-based systems. Evaluation of these systems by researchers indicated that the magnetic marker system is the most feasible. In this system, magnetic markers are embedded in the pavement at the lane centerline at about 1.2 m intervals (Fig. 6). The vertical and horizontal components of the magnetic field generated by each marker are measured by two magnetic sensors placed under the vehicle and used to orient the vehicle constantly within the lane boundaries. The magnetic system can also be used to encode information on upcoming road curvature, mileage markings, and roadside services.

Figure 6. Automatic steering control system uses magnetic markers buried along the center of the lane 1.2 m apart. Photo by Gerald Stone, California PATH.

Figure 7. The steering control system uses a small camera mounted on the windshield. Photo by Robert Bryant, Avalon Integrated Services.

The vision-based sensing system uses sophisticated software to find the lane markers (lines) in video images captured from a video camera mounted on the rear-view mirror or windshield (Fig. 7). The information from the camera is fed back to the vehicle controller. The marker positions and the measurements received from an on-board fiber-optic gyroscope and the speedometer are used to estimate the upcoming road curvature and the vehicle position. The controller then issues commands to an electromechanical actuator to steer the vehicle to the lane center. Recently, a binocular stereopsis, which generates a 3-D obstacle map, was investigated by Malik et al. (21). The vision-based system, however, requires high computational power and may not be accurate during snow, fog, rain, or at night. The radar-based system uses reflectors mounted along the lane to track the vehicle's position, but its applicability is limited because it requires a wall near the lane and provides little preview information.

Lane-changing sensor requirements are enormous because the vehicle needs to detect the speed, position, and acceleration of the vehicles not only in its own lane, but also on the adjacent lane and the next-to-adjacent lane. This is important to avoid collision with another vehicle that is changing into the same lane at the same time. These requirements can be relaxed with v–v communications that may synchronize lane changing, but such communications would require a high bandwidth to guarantee robustness. Recently, on-board inertia measurement sensors (yaw rate sensor and accelerometer) and a magnetic reference system were used to investigate lane changing (20). Lane changing is a complex maneuver that requires further research and experiments.

Other vehicle and roadway sensors will be needed for specific operational functions. For example, vehicle sensors are needed to provide information on the highway and the lane traveled by the vehicle, such as section number, lane type (automated, transition, or manual), lane number, and so forth. Such information would be used by the coordination layer to access the link layer. Also, at on and off ramps, the regulation layer needs to know the distance from the vehicle to the stop light, and this information can be encoded in the roadway and then decoded by the vehicle sensors. Within-vehicle sensors would measure vehicle speed, acceleration, manifold pressure and temperature, and brake pressure. Two types of roadway sensors are needed to provide information on traffic flow conditions to the link layer and on traffic occupancy to assist the entry and exit maneuvers.

Communication Technologies

Automated highway systems require technologies to provide real-time, reliable data communications between vehicles, between vehicles and the roadway, and between the roadway and the network central control. Several existing and emerging technologies for AHS applications have been described by Polydoros and Panagiotou (22). The candidate technologies include highway advisory radio, frequency modulation subsidiaries, radio data systems, high-speed FM subcarrier data system, vertical blanking interval and secondary audio programming, roadside beacons, infrared technologies, digital cellular systems, personal communication services systems, mobile satellite systems, and meteor burst. The authors evaluated the suitability of these technologies to various AHS applications and found that no single technology can accommodate the communication needs of all applications. A promising future technology for AHS communications is packet radio, which has been successfully implemented in a variety of other systems. However, designing and building a communication network for automated highway systems is a challenging endeavor that involves defining service requirements, system specifications, alternative physical layer technologies, and network layer protocols (2). An object-oriented approach for AHS that promotes communication, flexibility, and stability has been proposed by Al-Qaysi et al. (23).

TRAFFIC OPERATIONS

Automated highways will improve traffic operations through automation and intelligence. One of the key parameters is the safety distance between vehicles, which needs to be maintained in case the vehicle ahead slows down or stops by applying the brakes. In conventional highway operation, when a vehicle applies its brakes, the following vehicle starts braking after the human perception and reaction time (a couple of seconds). In automated operations, the electronic delay in detecting and reacting to the leading vehicle deceleration is very small. Two basic concepts have been suggested for the operation of automated traffic: the vehicle-following concept and the infrastructure-slotting concept (24). While most AHS have primarily focused on automobile traffic, automating the operation of trucks and commuter buses on interstate rural highways has also been explored (4, 25).

Vehicle-Following Concept

Under this concept, automated vehicles may operate in three basic modes: autonomous vehicles, free-agent vehicles, and platoons. Autonomous vehicles drive so that a vehicle would be able to stop without colliding with the vehicle ahead even if the vehicle ahead applies maximum braking. The spacing required between vehicles depends on the braking capabilities of both vehicles, road surface conditions, and the electronic reaction time of the controlling equipment. Autonomous vehicles operate independently and have no v–v communication. Each vehicle relies on its own sensors to determine the intentions of the vehicle ahead based on relative speed and spacing measurements. Therefore, in calculating the intervehicle spacing, a worst-case stopping (emergency) scenario is used, as shown in Fig. 8 (24). If the leading vehicle decelerates at $t = 0$, the following vehicle will start to decelerate after a detection and brake actuation delay t_{fa} to maintain the desired spacing. The jerk of this initial deceleration, J_{fc}, will maintain passenger comfort since the follower does not know this is an emergency. Eventually, the follower detects and initiates emergency braking with maximum jerk and deceleration at t_{fc}. Typical values of t_{fa} and t_{fc} are 0.2 s and 0.3 s, respectively.

Free-agent vehicles have communications between vehicles and between vehicles and the infrastructure, where the infrastructure may *support* or *manage* the vehicles. In free-agent vehicles infrastructure supported, the infrastructure would just issue warnings and instructions about desired speed and headway but would not directly command the vehicles. In emergencies, v–v communication informs the following vehicles when the leader starts to perform an emergency braking. Therefore, the following vehicle receives the information about emergency braking at the same time it detects that the leader starts to brake. Thus, the limited jerk/deceleration stage for driver comfort in Fig. 8 is eliminated. The delay before applying emergency braking is considerably reduced because the vehicle knows in advance it will have to apply the brakes. In free-agent vehicles infrastructure managed, the infrastructure has the primary responsibility of detecting the presence of emergencies and issues a command to all vehicles to start emergency braking at once. Therefore, the leader and the following vehicles will apply maximum braking at $t = 0$, which implies that there is no delay before braking.

Platoons (10 to 20 automated vehicles) would operate in closely coordinated groups to maximize highway capacity. The vehicles are linked together with a local communication network that enables the vehicles to operate like an electronically coupled train. The communication network continuously exchanges information about speed, acceleration, braking, obstacles, and so forth. This electronically coupled train is dynamic, allowing forming, splitting, and rejoining to meet traffic needs. The spacing between vehicles would be small (perhaps 1 to 2 m), but the gap between adjacent platoons would be sufficiently large to avoid collisions if the lead platoon suddenly stops.

Platoons may be in the autonomous, free-agent mode supported by the infrastructure, or in the free-agent mode managed by the infrastructure. The distinction between these modes is similar to that between individual vehicle modes. Platoons would allow no mixing of vehicle classes and may operate with or without coordinated braking. In platoons without coordinated braking, in emergencies each vehicle provides the vehicle behind with its braking capabilities and the magnitude/time of the braking force used. There is obviously a delay while the message propagates from each vehicle to the vehicle behind. In platoons with coordinated braking, the leading vehicle in the platoon has the primary responsibility of detecting emergencies and provides each vehicle in the platoon with the magnitude/time of braking applied through v–v communication, thus reducing the communication delay.

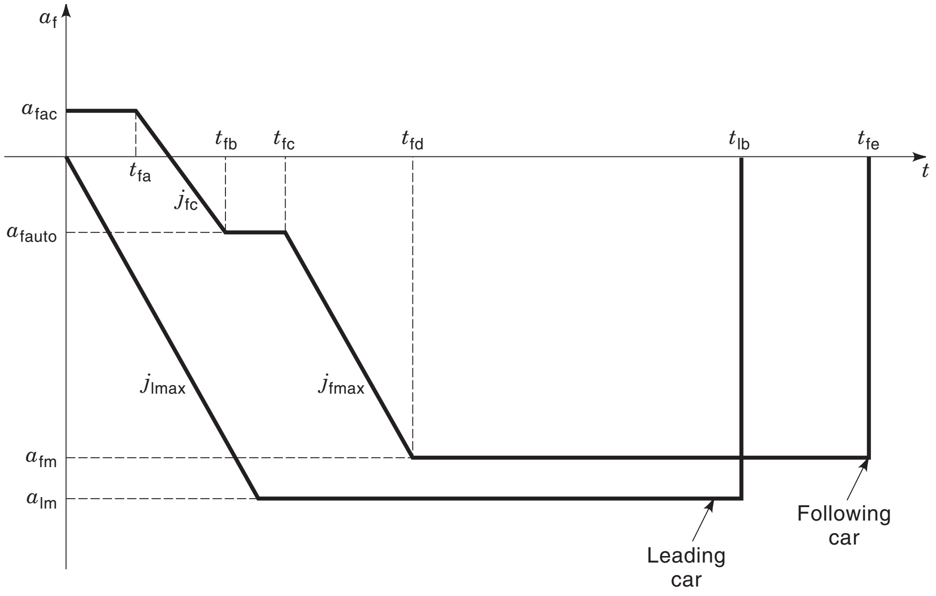

Figure 8. Deceleration profiles of the leading and following vehicles in autonomous operations (24).

Infrastructure-Slotting Concept

In the vehicle-following concept, each vehicle optimizes the spacing between itself and the vehicle ahead based on the braking capabilities of the two vehicles involved (*asynchronous* structure). Under the infrastructure-slotting concept, vehicle slots of fixed lengths are created and maintained in space and time to identify and manage vehicles. Each vehicle is assigned to follow the virtual leading edge of the slot and not another vehicle, and the vehicle can never violate the edges of its assigned slot. The size of each slot must be sufficient to accommodate the vehicle, with the worst braking performance that the system is trying to accommodate within a single slot (*synchronous* structure). Other vehicles with better braking performance cannot utilize this capability to shorten the spacing to the vehicle ahead. A vehicle with a braking performance less than that used to design a single slot may be assigned two slots, resulting in a wasted space. The synchronous structure is obviously inefficient, unlike the asynchronous structure, which maximizes performance at the expense of increased complexity.

Automated Bus Rapid Transit Systems

Automated bus transit systems include, among other features, automated bus operation on segregated busways. The automation may include precision docking, lane-keeping, automated speed and spacing control, and maintenance yard operations. Complementary elements include collision warning, vehicle diagnostic warning, electronic fare payment and pre-pay systems, and transit management center operation (e.g. traffic signal priority and passenger counting systems). VanderWerf et al. (4) stated that automation could be achieved in sequence by building on existing and emerging technologies and then combining additional technologies in building-block fashion. Existing technologies include forward collision warning, lane departure warning, adaptive cruise control, and vehicle-roadside communication. The overall benefits of the automated systems include improved mobility and quality of service.

The initial scenario of bus transit automated may be a pure line-haul run with few intermediate stops. First, the bus would be driven manually to the origin location, with precision docking, where passengers are collected. At the entry to the protected busway, the driver would switch the bus to automated operation, where the bus continues to operate automatically until the destination. If there are intermediate stops, the bus would operate exactly like current automated guideway transit systems. At the destination, the driver resumes manual control of the bus and drive passengers to local stops. An algorithm for automatic steering of buses based on roadway markers along with a mini demonstration using a test track can be found in Tan et al. (26). In the long-term, subsequent developments would include coupling of buses together to form platoons, automation of entry maneuvers, and development of automated network of bus lanes. However, there are concerns over the complexity and reliability of such new technologies that must be first addressed (4).

Automated Truck Operations

Truck traffic follows well-established routes, and therefore automation would allow truck platoons to travel between major cities. Truck automation includes lane keeping, automatic speed and spacing control, and automatic backing to a loading dock. The complementary functions include collision warning and/or avoidance, driver drousiness detection, vehicle condition warning, and truck management center for processing of information from communication and advanced vehicle location systems. Individual trucks will be driven manually from within the city to designated arrival/departure stations to join platoons departing to the destination city. At the same time, drivers who are not in the departing platoons will drive vehicles of the platoons arriving at the stations to their individual destinations within the city. Kanellakopoulos and Tomizuka (27) stated three major reasons for truck automation. First, full automation will be particularly significant for truck platoons because it allows the elimination of the drivers from the following vehicles, where the driver would take only supervisory or managerial role (truck fleet drivers account for almost half the total cost of operation). Second, the ratio of automated equipment cost to the vehicle cost for a passenger car is much greater than that for a truck. Third, operational safety benefits resulting from automation of commercial vehicles will be much more significant than those of passenger cars because their operational and physical characteristics are different.

The lateral and longitudinal control of commercial vehicles, however, is much more complex than that of passenger cars because of the different actuation-to-weight ratios, physical dynamics, actuator delays and nonlinearities, and disturbance effects. Research work on automation of trucks focusing on their specific characteristics has been completed by Yanakiev and Kanellakopoulos (28). They developed a model that is being used for the design of integrated lateral/longitudinal vehicle control. The automated highway would conceivably support the transition of automated trucks from rural (interstate) settings to urban settings, where steering may be controlled by computer vision and magnetic markers, respectively.

HIGHWAY CAPACITY

The capacity of an automated lane depends on the vehicle mode of operation. For autonomous and free-agent modes, the capacity in vehicles per hour (*veh*/*h*) per lane, C, is given by

$$C = \frac{3600V}{S_1} \tag{1}$$

where V is the speed of flow (m/s) and S_1 is the average distance between the fronts of two consecutive vehicles (m). For mixed traffic (passenger cars, trucks, and buses), and assuming that a bus or a truck is always between two passenger cars, S_1 is given by

$$\begin{aligned} S_1 = {} & (1 - 2W_{\mathrm{T}} - 2W_{\mathrm{B}})(L_{\mathrm{P}} + d_{\mathrm{PP}}) + W_{\mathrm{T}}(L_{\mathrm{P}} + d_{\mathrm{PT}} + L_{\mathrm{T}} + d_{\mathrm{TP}}) \\ & + W_{\mathrm{B}}(L_{\mathrm{P}} + d_{\mathrm{PB}} + L_{\mathrm{B}} + d_{\mathrm{BP}}) \end{aligned} \tag{2}$$

where W_{T} and W_{B} are the proportions of trucks and buses in the mix, respectively; L_{P}, L_{T}, and L_{B} are the lengths of passenger car, truck, and bus, respectively (m); d_{PP} is the minimum distance headway between passenger cars; d_{PT} is the minimum distance headway between a passenger car and a truck that follows it; and d_{TP}, d_{PB}, and d_{BP} are defined similarly. Equation (2) can be easily modified if the traffic mix includes recreational vehicles.

For the autonomous mode, Eq. (2) assumes that the passenger car recognizes whether its leader is a truck or a bus. This can be accomplished by using radar sensors that distinguish between different vehicle classes. Without this assumption, each vehicle has to assume the worst possible condition: The leading vehicle has the highest braking capability (a passenger car). In this case, d_{TP} and d_{BP} in Eq. (2) are replaced by d_{PP}.

For platoons, there is no mixing of vehicle classes and the capacity of the automated lane is given by (29)

$$C = \frac{3600VN}{S_2} \tag{3}$$

where N is the number of vehicles per platoon and S_2 is the minimum spacing between the fronts of the lead vehicles in consecutive platoons (m). For platoons with passenger cars, S is given by

$$S_2 = NL_{\mathrm{P}} + (N - 1)d_{\mathrm{PP}} + D_{\mathrm{PP}} \tag{4}$$

where D_{PP} is the spacing between consecutive platoons (m). The safe intervehicle spacing depends on the deceleration profiles of the lead and following vehicles and can be calculated using numerical analysis. Table 2 shows the capacity of an automated lane for platoon operations (24). As shown, the capacity ranges from 6090 veh/h to 7790 veh/h, which is about three to four times the ideal capacity of a conventional freeway lane (2200 vph).

Note that the capacity of Eq. (1) or (3) represents the theoretical (not actual) capacity because it does not consider the effects of such factors as merging, diverging, and lane changing. Further research to model the actual capacity based on these factors is needed. A study of merging capacity by Hall et al. (30) showed that infrastructure-supported platooned entry is the most promising concept. Their evaluation indicates that entrance/exit spacing on the order of one per 2 km would be required to support highways with total capacity of 20,000 vehicles per hour.

LOOKING AHEAD

This article has presented key technical aspects of automated highways related to roadway configuration, functional planning, control structure, traffic operation, and roadway capacity. Field demonstration in 1997 in the United States and recent demonstrations in other countries showed that automated highway systems are possible with current technology. Most agencies around the world have now focused on safety, not congestion. Initiatives related to intelligent vehicle control and safety systems are being developed, and will eventually lead to AHS. It is expected that the first pilot AHS will be implemented in a few pioneering cities by 2025. In the United States, current effort focuses on the automation of heavy vehicles (buses and trucks) that operate on their own special right-of-way. In addition, research on low-speed automation is currently being developed in Europe and Asia. In such systems, during congestion periods the vehicles would operate in full-automation mode so that drivers can relax, and once the congestion clears drivers would take control of their vehicles. A review of the challenges that are still facing highway-vehicle automation can be found in Shladover (32).

Although much progress has been made, further developments are needed before their expected deployment. In this regard, it is critical to identify relevant lessons for AHS that can be learned from past systems that share important features with AHS. The following 10 lessons have been identified (31): (1) Help the public perceive overall

Table 2. Capacity of Automated Highway Lane for Platoon Operations on Dry Pavement Surface (Vehicles per Hour)[a]

Mode of Operation	Coordinated Braking	10-Car Platoon	20-Car Platoon
Autonomous platoon	No	6,090	6,260
Free-agent infrastructure-supported platoon	No	6,310	6,370
Free-agent infrastructure-managed platoon	No	6,430	6,430
Autonomous platoon	Yes	7,220	7,530
Free-agent infrastructure-supported platoon	Yes	7,530	7,700
Free-agent infrastructure-managed platoon	Yes	7,700	7,790

[a] See Kanaris et al. (16) regarding the assumptions used in the analysis.

benefits, (2) clearly demonstrate safety and reliability, (3) secure long-term and continuous financial support for deployment, (4) seek high-level support to enhance success of the project, (56) implement an evolutionary deployment, (6) design AHS for integration within the overall transportation system, (7) accurately determine cost and time estimates, (8) form consortiums of private and public agencies to ensure long-term success, (9) keep the general public educated and informed throughout planning, design, and development, and (10) do not overlook potential markets for AHS.

Automated highways represent an exciting option for satisfying our seemingly insatiable appetites for more highway capacity in large cities to reduce traffic congestion. It should be stressed, however, that there are other viable options for reducing congestion that focus on reducing traffic demand, such as innovative land use planning and improved public transit. These options should help planners and politicians to make important decisions that will likely shape the future of our transportation systems.

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Useful Organizations and Websites

Information about frequent developments on automated highway systems are regularly published by the following organizations:

- Intelligent Transportation Society of America (ITS America): A membership-based, non-profit organization that coordinates the development and deployment of ITS in the United States, Internet: www.itsa.org
- IEEE Intelligent Transportation Systems Society: This Society advances the theoretical, experimental, and operational aspects of electrical engineering and information technologies as applied to ITS, Internet: www.ewh.ieee.org/tc/its/
- Partners for Advanced Transit and Highways (PATH): A division of the Institute of Transportation Studies at University of California, Berkeley, in partnership with California Department of Transportation (Caltrans), Internet: www.path.berkeley.edu/

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