INTELLIGENT TRANSPORTATION SYSTEMS

Intelligent transportation systems (ITS) are transportation systems that apply information and control technologies to help their operations. Given this broad definition, ITS is an umbrella that covers a wide range of transportation systems,

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

some of which have been implemented for many years while others are just getting deployed or are still under research and development for future applications (1).

For example, time-proven adaptive traffic signal controls, using information about traffic flows at or near the traffic signal lights to provide coordinated signal controls, are an early form of ITS. Intelligent cruise control, which automatically adjusts vehicle speed to maintain safe headway from the car in front, is another example of ITS that is on the verge of deployment. Dynamic route guidance which advises drivers the optimum route to take for a given destination, taking into account the current and predicted road and traffic conditions, is yet another example of ITS that has been tested but may take more years to develop for wide deployment due to its complexity in information collection and communications.

Thus, a popular definition of ITS is the application of computer, control, and communication technologies to help drivers and operators make smart decisions while driving smart vehicles or controlling traffic on smart road networks. Although not very rigorous, this definition brings forth the notion that ITS keeps the human driver and operator at the center. Therefore, ITS is by no means synonymous to automation even though automated driving is an option for the distant future under the ITS umbrella.

The technical and institutional descriptions of ITS will appear after the overview.

FUNCTIONS

The overarching ITS function is to improve transportation system operations, which in turn support the transportation objectives of increasing efficiency, safety, productivity, energy savings, environmental quality, and trip quality. These objectives are common to all regions around the world even though their relative priority may vary from one region to another.

Relatively high on the priority lists of practically all countries is the increase of efficiency through ITS-assisted operations to the extent that the capacity of existing road systems can be increased substantially. In many countries, the current traffic congestion would only get worse since construction of new roads has little hope of catching up with increasing traffic demand due to financial and environmental constraints. In other words, they can no longer build their way out of congestion; and ITS offers a new approach to help reduce or postpone construction needs. This is particularly true in industrially mature countries such as the United States, Japan, and most of Western Europe. Even in countries where major road construction programs are still ahead of them, such as in many developing countries and economies in transition, ITS offers the possibility of increasing capacity per lane thus reducing the need for scarce capital. The same can be said on the vehicle side. For example, ITS-assisted transit or commercial vehicle operations would reduce the number of needed vehicles to handle the same passenger or cargo load, thereby saving capital and operational costs of these vehicles.

TECHNICAL CONCEPTS

The technical core of ITS is the application of information and control technologies to transportation system operations. These technologies include surveillance, communications, automatic control, and computer hardware and software. The adaptation of these technologies to transportation requires the knowledge from many engineering fields—civil, electrical, mechanical, industrial—and their related disciplines: for example, traffic engineering, vehicle dynamics, computer science, operations research, and human factors. The amalgamation of these technologies to perform ITS functions is based on the principles of systems engineering.

From a system perspective, the major components of transportation systems are the transportation infrastructure, the vehicle, and the people in the system, including the system operator (for example, in the traffic or transportation management center) as well as the traveler who may ride, drive, or just walk. All of these people make decisions based on available information and their decisions often affect one another. Many of the transportation problems arise from the lack of timely and accurate information and from the lack of appropriate coordination among the decisions made by the people in the system. The contribution of information technology is to provide better information to assist people involved in the system to make better coordinated decisions in order to meet the ITS objectives of increasing efficiency, safety, productivity, and air quality.

There is a plethora of existing technologies which can be or have been applied to ITS. As the capabilities of "high tech" continue to increase and their costs continue to decrease in the future, so will the capabilities and costs of ITS functions. In addition, these technologies will build on top of each other to produce synergism. For example, the same information for electronic toll collection may be used also to provide vehicle probe data for traffic management. (Vehicle probe means the use of a vehicle to sense traffic conditions as it reports actual traveling time experienced in real traffic.) However, it is not necessary for any traffic agency to master all the high tech electronics to begin applying ITS to solve some of their most urgent problems. As mentioned previously, traffic adaptive signal controls have been developed and applied to smoothen traffic at intersections for decades.

USER SERVICES AND MARKET PACKAGES

Countries which have established ITS programs in recent years share similar views on the range of possible ITS functions, as represented by the corresponding ITS user services. User services are the functions performed by ITS technologies and organizations for the direct benefit of the transportation users, which include the traveler, the driver, the operator, the manager, and the regulator in the transportation systems. A composite taxonomy of these user services is given in Table 1, based on program information from many countries around the world. Note that the ITS programs in various countries may put emphases on different subsets of the user services. For example, most ITS programs in the United States do not include vulnerable travelers services for pedestrians and bicyclists, which may be very important in some other countries. Moreover, the provision of some user services presumes certain policy decisions. For example, demand management and operations through road pricing and policing/enforcing traffic regulations can certainly be facilitated by ITS technologies but their implementation would require strong policy support in some countries. (Road pricing is the charge of user fees as

Table 1. User Services Provided by Intelligent Transportation Systems[a]

Traveler information (ATIS)	Pretrip information
	On-trip driver information
	On-trip public transport information
	Personal information services
	Route guidance and navigation
Traffic management (ATMS)	Transportation planning support
	Traffic control
	Incident management
	Demand management
	Policing/enforcing traffic regulations
	Infrastructure maintenance management
Vehicle (AVCS)	Vision enhancement
	Automated vehicle operation
	Longitudinal collision avoidance
	Lateral collision avoidance
	Safety readiness
	Precrash restraint deployment
Commercial vehicle (CVO)	Commercial vehicle preclearance
	Commercial vehicle administrative processes
	Automated roadside safety inspection
	Commercial vehicle on-board safety monitoring
	Commercial vehicle fleet management
Public transport (APTS)	Public transport management
	Demand responsive transport management
	Shared transport management
Emergency (EM)	Emergency notification and personal security
	Emergency vehicle management
	Hazardous materials and incident notification
Electronic payment	Electronic financial transactions
Safety	Public travel security
	Safety enhancement for vulnerable road users
	Intelligent junctions

[a] Source: International Standards Organization.

Table 2. Market Packages for Intelligent Transportation Systems (for United States)

ATMS01	Network Surveillance
ATMS02	Probe Surveillance
ATMS03	Surface Street Control
ATMS04	Freeway Control
ATMS05	HOV and Reversible Lane Management
ATMS06	Traffic Information Dissemination
ATMS07	Regional Traffic Control
ATMS08	Incident Management System
ATMS09	Traffic Network Performance Evaluation
ATMS10	Dynamic Toll/Parking Fee Management
ATMS11	Emissions and Environmental Hazards Sensing
ATMS12	Virtual TMC and Smart Probe Data
ATMS13	Standard Railroad Grade Crossing
ATMS14	Advanced Railroad Grade Crossing
ATMS15	Railroad Operations Coordination
APTS1	Transit Vehicle Tracking
APTS2	Transit Fixed-Route Operations
APTS3	Demand Response Transit Operations
APTS4	Transit Passenger and Fare Management
APTS5	Transit Security
APTS6	Transit Maintenance
APTS7	Multimodal Coordination
ATIS1	Broadcast Traveler Information
ATIS2	Interactive Traveler Information
ATIS3	Autonomous Route Guidance
ATIS4	Dynamic Route Guidance
ATIS5	ISP-Based Route Guidance
ATIS6	Integrated Transportation Management/Route Guidance
ATIS7	Yellow Pages and Reservation
ATIS8	Dynamic Ridesharing
ATIS9	In-Vehicle Signing
AVSS01	Vehicle Safety Monitoring
AVSS02	Driver Safety Monitoring
AVSS03	Longitudinal Safety Warning
AVSS04	Lateral Safety Warning
AVSS05	Intersection Safety Warning
AVSS06	Precrash Restraint Deployment
AVSS07	Driver Visibility Improvement
AVSS08	Advanced Vehicle Longitudinal Control
AVSS09	Advanced Vehicle Lateral Control
AVSS10	Intersection Collision Avoidance
AVSS11	Automated Highway System
CVO01	Fleet Administration
CVO02	Freight Administration
CVO03	Electronic Clearance
CVO04	CV Administrative Processes
CVO05	International Border Electronic Clearance
CVO06	Weigh-In-Motion
CVO07	Roadside CVO Safety
CVO08	On-Board CVO Safety
CVO09	CVO Fleet Maintenance
CVO10	HAZMAT Management
EM1	Emergency Response
EM2	Emergency Routing
EM3	Mayday Support
ITS1	ITS Planning

a means to reduce traffic congestion and/or to finance road construction and operations.) Appropriate institutional arrangements are also prerequisite for effective ITS user services. For example, route guidance involving public agencies often requires cross-jurisdictional agreement in traffic diversion from one jurisdiction to another.

The concept of user services is central in ITS deployment so that the ITS implementor would be guided by what the users want ultimately, and not by the application of ITS just for the sake of its technology. Another useful concept in ITS implementation is that of market packages. Each market package includes an assembly of equipment on the vehicle or the infrastructure that can be purchased on the market (now or in the future) to deliver a particular user service in part or in full. A list of 56 ITS market packages for the full deployment of the ITS program in the United States is given in Table 2 (2). Note that ITS market packages are technology independent; that is, each market package may consist of equipment whose capability and cost may change over time as technology advances. For example, network surveillance (the first market package in Table 2) may employ inductive loops, microwave detectors, or closed circuit television, or some combination of them, for the function of traffic surveillance, which in turn supports a number of user services including traffic control.

Note that the market packages in Table 2 are bundled under seven application areas as follows:

1. ATMS (advanced traffic management systems): Adaptive traffic signal controls, automatic incident detection, regional traffic control, emission sensing, freeway management, etc.
2. APTS (advanced public transportation systems): Automatic vehicle location, signal preemption, smart cards for fare collection, dynamic ride sharing, etc.
3. ATIS (advanced traveler information systems): Motorist information, dynamic route guidance, pretrip planning, in-vehicle signing, etc.
4. AVSS (advanced vehicle safety systems): Intelligent cruise control, collision warning and avoidance, night vision, platooning, etc.
5. CVO (commercial vehicle operations): Weigh-in-motion, electronic clearance, automatic vehicle classification, fleet management, international border crossing, etc.
6. EM (emergency management): Automatic Mayday signal, coordinated emergency response, signal preemption for emergency vehicles, etc.
7. ITS (planning for ITS): Automatic data collection for ITS planning, etc.

HISTORY

In the United States, research on automatic control of automobiles began in the private sector during the 1950s (3). In the public sector, US government research on electronic route guidance systems (ERGS) in the 1960s (4) has been cited as the first serious attempt to apply information technologies to ground travel, and has inspired similar programs elsewhere in the world, including the autofarer leitung und informationsystem (ALI) project in Europe (5) and the comprehensive automobile traffic control system (CACS) project in Japan (6). The lack of continuing US Congressional support resulted in only minimum activity in this area in the Unites States until the late 1980s. However, the activities in Japan and Europe continued with both public and private sector support, perhaps as a result of the more pressing needs for congestion relief there, especially in the urban areas, as well as different government policies (7).

The announcements of the billion-dollar DRIVE and PROMETHEUS (8) programs in Europe and the comparable AMTICS and RACS programs in Japan (9) during the mid-1980s, along with extensive prodding by the California Department of Transportation, have jolted the United States, leading to a revival of its activities in applying information technology to ground transportation. In 1986, a small group of federal and state transportation officials, academics, and private sector representatives, under the sobriquet of Mobility 2000, began to meet informally to prepare for enactment of the first major national transportation legislation of the post-Interstate era. As the era of interstate expressway construction drew to a close, study after study showed traffic congestion worsening and traffic safety, environmental, and energy conservation problems increasing as the number of vehicles rose from about 70 million in 1960 to 188 million by 1991. National productivity and international competitiveness also were major concerns, both closely linked to transportation efficiency as manufactured goods frequently were required to move over long distances.

With the passage of time, the revived activities in the United States in the late 1980s took on characteristics which differ, both technically and institutionally, from that seen through the 1960s and 1970s. For example, more emphasis is now put on the nearer term use of information systems for traveler advisory functions than on the longer term use of control technologies for automation purposes due to the rapid progress of computer technology. There is also a wider range of organizations working in concert from both the private and public sectors than in the past to link the vehicles and highways through information technology. These considerations led the researchers at the University of Michigan to give a new name to this broad area, intelligent vehicle–highway systems (IVHS), which connotes the integration of vehicles made by the private sector with the highway infrastructure operated by the public sector into a single system.

In May 1990, 200 academics, business and industry leaders, federal, state, and local government officials, and transportation association executives met in Orlando, Florida at the IVHS Leadership Conference. They agreed that a formal organization was needed to advocate the use of advanced technologies in surface transportation, to coordinate and accelerate their development, and to serve as a clearinghouse of information from the many different players already active in the field. They also agreed that a totally new entity would be needed. Then, in July 1990, a House Appropriations Committee report called for "a nationwide public-private coordinating mechanism to guide the complex research and development activities anticipated in the IVHS area."

As a result of this mandate, in August 1990 the IVHS America was incorporated in the District of Columbia as a nonprofit educational and scientific organization. After its formation, IVHS America was designated as a utilized Federal Advisory Committee to the US Department of Transportation, which assured that its recommendations would be heard at the highest levels of government. In the fall of 1994, the organization changed its name to the Intelligent Transportation Society of America (ITS AMERICA) to reflect a broader mission, including all parts of public transportation and intermodal connections, than implied by the term vehicle–highway systems.

For the 35-year period, 1956–1991, America's surface transportation policy was dominated by construction of the National System of Interstate and Defense Highways. But with the enactment of the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991, the interstate construction era ended and a new era in surface transportation began. The law gave much more flexibility at the state and local level in deciding how federal highway and transit funds should be used. To ensure intermodal management of the federal funds, the US Department of Transportation established an ITS Joint Program Office in 1993 to oversee and coordinate ITS program activities in the Federal Highway Administration, the National Highway Traffic Safety Administration, the Federal Transit Administration, the Federal Rail Administration, and other relevant agencies (7).

PROGRAMS AROUND THE WORLD

With the enabling legislation of ISTEA, and the Congressional appropriation of $200–300 million per year, augmented by comparable expenditure in the state/local governments and the private sector, the ITS Program in the United States moved rapidly from research to field operational tests (FOTs), and to deployment since the early 1990s. The purpose of FOTs is to learn from the experience of limited applications of R&D results in real traffic environment before making major investments for deployment. With positive results from many FOTs, the US Secretary of Transportation announced the Operation Time Saver (10), declaring the intention to build intelligent transportation infrastructure (ITI) in 75 metropolitan areas within a decade. The first projects are under the name of Model Deployment Initiatives (MDI) for four metropolitan areas and for a number of commercial vehicle operations in eight states. Each of these projects has featured public–private partnerships to provide a wide array of ITS services. Continuous expansion of ITS deployment is sought through an effort to mainstream ITS by pitching ITS projects against more traditional alternatives in the regular transportation planning process. With the expiration of ISTEA, US Congress is deliberating the National Economic Crossroads Transportation Efficiency Act (NEXTEA), which would include a reauthorization of the federal ITS program under the title of Intelligent Transportation Systems Act of 1997.

In parallel to the ITS movement in North America, corresponding European and Japanese programs, using various names, have forged ahead, involving both public and private sectors. Since 1994, annual ITS World Congresses have been launched to encourage and facilitate international exchange in the field, initiated by ITS America and its European counterpart ERTICO (European Road Transport Telematics Implementation Co-ordination Organization) and its Japanese counterpart VERTIS (Vehicle, Road & Traffic Intelligence Systems). The ITS World Congress has become a meeting ground for all countries around the world to exchange ideas and compare experiences. It is noteworthy that other countries active in ITS are not limited to the industrially mature nations like Australia but also many developing countries or economies in transition such as China and Brazil. In fact, the 1998 ITS World Congress held in Seoul, Korea, signifies that the driving forces behind their programs are the common goal of achieving transportation efficiency, safety, productivity, energy savings and environmental quality through ITS (11).

SELECTED TECHNOLOGIES

Any system using information and control technologies may be broken down into the sub-functions of information collection, storage/processing, dissemination, and utilization (for decision and control support). In ITS, these sub-functions would be applied to traffic, vehicles, and the people involved. Selected ITS technologies and sub-functions described below can be grouped as shown in Tables 3–5. Note that some of the technologies may belong to more than one category. Each of the technologies in the three tables will be discussed in the subsequent sections.

Table 3. Selected ITS Technologies for the Infrastructure Dimension

Information Function	Infrastructure
Information collection	Induction loop detector
	Ultrasonic detector
	Microwave detector
	Infrared detector
	Closed-circuit television (CCTV)
	Helicopter patrol
	Car patrol
	Vehicle probe
Information storage/ procession	Image processing
	Traffic parameter calculation
	Traffic data fusion
	Incident detection
	Traffic optimization
	Centrally determinated route guidance
Information distribution	Wireline communications, including optical fiber
	Wireless communications, including spread spectrum
	Telephone
	Fax
	Radio
	Television
	Teletext
	Desk-top computer
	Internet
	Kiosk
	Traffic display board
	Changeable message sign (variable message sign)
Information utilization	Adaptive signal control
	Ramp meter
	Expressway management
	Incident management
	Road pricing (and congestion pricing)
	Parking management
	Pretrip planning
	Electronic toll collection (ETC)
	Electronic toll and traffic management (ETTM)
	Coordinated rescue operation

TRAFFIC AND ROAD SURVEILLANCE

On the road side, a prerequisite for many ITS services is the collection of timely and accurate information about traffic and road conditions. For many years, traffic surveillance has been achieved by induction loop detectors that can sense the presence of a vehicle as the metallic mass of the vehicle changes the inductance and thus the resonant frequency of the induction loop installed under the pavement. In the simplest application, a single loop buried under the lane pavement can do vehicle counting. However, loop detectors can do a lot more than the pneumatic tubes put across the pavement surface to do vehicle counting. As various vehicles and trailers have different masses and lengths, vehicle classification can often

Table 4. Selected ITS Technologies for the Vehicle Dimension

Information Function	Vehicle
Information collection	Automatic vehicle location (AVL)
	Global positioning system (GPS)
	Differential global positioning system (DGPS)
	Dead reckoning
	Map matching
	Signpost
	Automatic vehicle classification
	Automatic vehicle identification (AVI)
	Tag (transponder)
	Active tag
	Backscatter tag
	Reader (transceiver)
	Smart card
	Weigh-in-motion (WIM)
	Electronic lock
	Vehicle diagnostics
	Tire slippage sensing
	Radar
	Lidar
	Ultrasonic obstacle detector
	Magnetometer (magnetic nail sensor)
	Video camera (lane sensor)
	Vehicle-initiated distress signal
Informaton storage/ procession	Digital map
	Compact disk (CD)
	PCMCIA card (PC card)
	Heuristic algorithms
	heuristics for map matching
	heuristics for route guidance
	Dijkstra's algorithm
	A* algorithm
Information distribution	Car radio (AM and FM)
	Highway advisory radio (HAR)
	Automatic highway advisory radio (AHAR)
	Radio data system (RDS)
	Traffic message channel (TMC)
	Radio broadcast data system (RBDS)
	Subcarriers (FM and AM)
	Cellular telephone
	Cellular digital packet data (CDPD)
	In-vehicle fax
	Pager
	Personal digital assistant (PDA)
	Personal communications system (PCS)
	Special mobile radio (SMR)
	Mobile data terminal (MDT)
	Laptop computer
	Palmtop computer
	Voice and sound alarm and display
	Head-up display (HUD)
	Reconfigurable dashboard
	Arrow display for route guidance
	Countdown visual display for route guidance
	Tinged side-mirror display
	Dedicated short-range communications (DSRC)
	Vehicle-to-vehicle communications
	Satellite communications
	Low-earth-orbit (LEO) satellite communications
Information utilization	Navigation
	Route guidance
	Static route guidance
	Dynamic route guidance
	Freight management
	In-vehicle signing
	In-vehicle traveler information
	Electronic toll collection
	State/provincial border crossings
	International border crossings
	En-route trip planning
	Anti-theft
	Adaptive cruise control (ACC)
	Intelligent cruise control (ICC)
	Lane keeping
	Collision warning
	Collision avoidance
	Automatic highway system (AHS)
	Free agent
	Platoon
	Truck convoy

be deduced from the pattern of the electrical signals that provide inductive loop signatures of vehicles. Double loops in the same lane separated by a fixed distance can measure vehicle speed. As vehicle speed slows below a threshold, loop detectors can give indication of traffic congestion. When used in conjunction with computer software, signals collected from multiple loop detectors placed strategically on the highway and transmitted to the traffic center can do incident detection and alert the center operator about the likelihood of an incident occurrence.

The advantages of induction loop detectors include their low cost as well as usability for many applications. However, their installation under the pavement disturbs traffic and they are difficult to maintain, especially under harsh climate conditions. In addition to their limited capability to classify vehicles, their sensitivity is degraded by the steel in reinforced concrete pavement. These problems can be overcome by the more expensive ultrasonic, microwave, or infrared traffic sensors installed on overhead gantries. Such detectors can ac-

Table 5. Selected ITS Technologies for the Driver/Operator Dimension

Information Function	Driver/Operator
Information collection	Driver monitor
	Driver-initiated distress signal
	E911
	Immigration information
Information storage/ procession	Driver override
Information distribution	Voice and sound display
	Head-up display
	Reconfigurable dashboard
	Human interfaces
Information utilization	State/provincial border crossings
	International border crossings
	Emergency services

curately measure the height and other dimensions of the passing vehicle, thus providing more reliable information for vehicle classification.

While all of these traffic detectors can provide traffic parameters that are normally sufficient for traffic management, they provide only the symptoms but not the nature of traffic congestion. Furthermore, these traffic parameters do not provide much information to allow important and necessary human comprehension and assessment of complicated situations, such as during a traffic accident, when the traffic center operator may need to call upon fire, police, or medical services for coordinated actions. There is nothing better than live video images to help the traffic center operator monitor complicated traffic situations and make appropriate decisions. Visual images from closed circuit television (CCTV) are therefore obtained by the traffic management center to complement the data acquired from traffic detectors.

As the cost of CCTV is higher than that of traffic sensors, the video cameras are usually installed at critical junctions and curves on the roadways, and at a proper height to provide a rather broad coverage of the roadway. The camera can be controlled remotely from the traffic management center in several degrees of freedom—pan, tilt, and zoom (PTZ), in addition to focus and iris controls—so that the camera can be manipulated to focus on a particular segment of the roadway. Thus, with appropriate installation, CCTV cameras can be spaced about 2 km apart and still be able to provide full surveillance of the roadway.

The video surveillance technology must be versatile to provide video images in bright light (day), flat light (overcast/low contrast), adverse weather (rain, snow), and low light (night) conditions. Color images tend to provide maximum resolution for daylight conditions, while black-and-white images provide the best contrast for low light conditions. Thus, a combination of color and black-and-white video cameras may be chosen, color for bright light conditions, and black-and-white for low light/night viewing. An automatic camera switch could then be used to monitor ambient light conditions and switch over to the appropriate camera.

Image processing through machine vision is one of the latest technologies to be applied to traffic detection. Thus, images acquired by CCTV cameras can be processed to obtain the traffic parameters mentioned previously—vehicle presence, speed, lane occupancy, lane flow rate, etc. Multiple detection zones can be defined within the field of view of the CCTV camera, thus providing multiple lane coverage by a single camera. Multiple cameras can be connected to one processor unit providing wide area coverage, as well as alleviating some of the problems caused by shadows, occlusion, and direct sunlight shining on some of the cameras. Although current machine vision systems require heavier up-front investment, lower cost systems are emerging and have become more cost effective than traditional traffic sensors in a number of situations, especially where multiple zones need to be covered.

Even with a combination of traffic detectors and video traffic surveillance, there are additional inputs that are useful for traffic management. First, there is relevant information from road maintenance authority, police department, and weather bureau. Additional information can come from human observers purposely sent out on helicopters or patrol vehicles, or travelers reporting through telephones or mobile communications (cellular phones and citizen band radios). These inputs are particularly useful for information related to road and weather as well as traffic conditions, and from locations that are not covered by any traffic surveillance devices. Vehicles which are equipped to receive ITS services can also send both traffic and road information automatically through mobile communications to the traffic management center. Such vehicles are known as *vehicle probes,* also known as *floating vehicles.* Traffic analysis and simulation have indicated that statistically reliable traffic parameters can be obtained for traffic management purposes if 10% or more of the vehicles in an adequate traffic flow on a road segment can serve as traffic probes.

In addition to traffic information, road conditions such as icy pavements can be sensed automatically by temperature and humidity measurements or by vehicle probes through such measurements as tire slippage. Anticipatory information such as road closures and major sports events can be obtained directly from pertinent authorities.

With the many ways through which traffic information is obtained simultaneously at the traffic or transportation management center, there is a need to process all the data, verify their accuracy, reconcile conflicting information, and combine them into a consistent set of traffic data before they are distributed or used for traffic control purposes. This process is known as *traffic data fusion.* Within the traffic management center, traffic information is usually conveyed to the operators on a large display board, supplemented by multiple CCTV monitors that can be switched to any camera in the field. The photograph shown in Fig. 1 shows the array of multiple CCTV monitors of a traffic management center. Color code can be used on the traffic display board to indicate the degree of congestion or occurrence of incidents.

Traffic parameters obtained from traffic sensors can be transmitted through wireline communications or relatively low bandwidth mobile communication systems (e.g., packet radio). In contrast, video images include many bytes of information and therefore require a broad bandwidth of communication channel (e.g., optical fibers) for real-time (live video) transmission. Thus, distributed data processing is usually applied to convert video images from CCTV cameras to traffic parameters locally before the information is transmitted to the traffic management center for data fusion. Alternatively, the traffic parameters obtained locally may be used directly for local control (e.g., for ramp metering) or local display (e.g., for vehicle speed). However, for the purpose of providing visual images to the traffic center operator, video distribution at operational resolutions and frame rates, even with data compression, still requires relatively wide bandwidths for each video distribution channel. In contrast, data transmission in the opposite direction, from the traffic center to the CCTV cameras for PTZ controls, requires only very low bandwidths and presents no particular communications problems. Operators at the traffic management center also maintain voice communications with patrols and operators in other centers, which is important during emergency situations as timely, accurate, and interactive information acquisition is required for coordinated rescue operations.

Information picked up by traffic sensors need not be transmitted to the traffic management center to become useful. This is the case with adaptive traffic signal controls which can create green waves of traffic signals to let a group of vehi-

Figure 1. A typical traffic management center. The most visible equipment includes the array of CCTV traffic monitors and the computer consoles for the human operators. (Source: Federal Highway Administration)

cles on a major arterial pass through intersections by sensing the presence of vehicles upstream from the intersections (e.g., SCOOT (12)) as well as at the intersections (e.g., SCATS (13)). In general, traffic signals are controlled by the length of their split (relative duration between green and red), cycle (duration between the beginning of green lights), and offset (duration between the beginning of green light at one intersection and that at the following intersection). By sensing traffic parameters at both the arterial and the side streets within an area of street network, the information may be fed to a local computer in the area. The algorithm in the computer, based on certain traffic optimization model, is then used to control the split, cycle, and offset of the traffic lights in the area. If all the relevant traffic information is brought to the traffic management center, traffic optimization through a whole region is potentially feasible even though traffic prediction models and rigorous algorithms for traffic optimization have been a continuing subject of research and development.

Another example of using traffic information either locally or regionally is the control of *ramp meters,* which control the rate of vehicles flowing into expressways through varying duration of red lights at the on ramps. The idea behind ramp metering is to control vehicle density on the expressway. Traffic theory, which has been verified empirically, predicts that flow rate (measured in numbers of vehicles per unit time) increases with vehicle density up to a threshold value beyond which the flow rate decreases as vehicles move in a stop-and-go mode, wasting travel time and fuel, and increasing pollution and frustration. Vehicle density measured by loop detectors near the on ramps can be used to control the red duration of the local ramp meters to keep vehicle density on the expressway below the threshold. The more advanced ramp metering system would send upstream vehicle density information to the traffic management center which can then control the downstream ramp meters in an anticipatory mode on the basis of a computer model. Communications for traffic information and ramp meter control can be accomplished through wirelines or narrow band wireless channels since the required bandwidth is rather limited.

DISTRIBUTION OF TRAFFIC AND RELATED INFORMATION

Traffic and other relevant information (road and weather conditions, parking availability, etc.) may be distributed by public authorities in order to improve transportation efficiency, safety, and environmental quality. Similar information may be distributed by information service providers in the private sector who collect revenues through advertisement or charges to the end user. In such cases, traffic-relevant information distribution services are sometimes bundled with other information services (e.g., paging service) for business reasons.

Public–private partnerships have also been formed in recent years in which the public and private partners share the tasks of traffic information collection and distribution, including the possible bundling with other services.

There are two broad categories of technical means for distributing traffic and other relevant information: fixed terminals and mobile terminals. Fixed terminals include regular telephones, radios, television, desk top computers, fax machines, kiosks, and changeable message signs. Mobile terminals include car radios, special mobile radios, cellular telephones, laptop computers, pagers, and hand-held digital devices.

The most common ways for the general public to receive traffic information is through their television at home and their radios, both at home and in the vehicle. In the United States, there are commercial radio and television stations that broadcast traffic information provided by the traffic management center or information service providers who collect traffic information with their own helicopter and car patrols and collect their revenues through advertisement. Many modern traffic management centers provide special booths for radio and TV stations staffs, who can look at the same traffic display board as the center operators and make their live broadcast accordingly (although this function is performed off-site mostly by exchanging data).

Traffic information is usually broadcast within certain time slots during the day as such information competes with other programs for air time. One way to alleviate this conflict is to use *teletext* to transmit brief traffic reports superimposed onto the television signal, utilizing the narrow time slots between the transmission of consecutive TV frames.

While the broadcast traffic information is free, the traveler does not get the traffic information of specific interest without much delay. On demand traffic information services have been made available, sometimes at a cost, through interactive telecommunications. For example, telephone call-in may be used with options to specify location of interest through push buttons or through conversation with a human operator, who can fax a hard copy of the information upon request if the facilities are available. Similarly one can get more specific traffic information through interactive cable television. Traffic maps of cities around the world (color coded to indicate congestion and incidents) have become available through computer access to the Internet, and the user can focus on a segment of the road network to get detail information.

Kiosks have been installed in public places, such as bus stations, for travelers to get interactive traffic information. The same kiosks are often sources for other transportation information, such as transit fare, routing, and schedule, sometimes with dynamic information about expected departure and arrival times and delays, similar to the display monitors at the airport for air travelers. In the case of the kiosks, yellow page information such as lodging and food could also be available, sometimes with equipment arrangements on or near the kiosk to make potential reservations and payments convenient.

Changeable message signs (CMS), also known as variable message signs (VMS), are another means for traffic and road information to be distributed and utilized. Although these signs are fixed on the highway, the messages on them are intended for travelers on the move. These are road signs with messages that can be changed locally, such as from traffic and road sensors nearby to warn about hazardous conditions ahead, or from parking garages to show the number of available spaces. However, most often the messages are changed remotely from the traffic management center and their displays are monitored by the center to assure accuracy, and therefore require two-way narrow-band wireline or wireless communication links. Messages are made up from a mosaic of mechanical plates or electrical illuminators such as light emitting diodes. The latter is more flexible than the former for displaying graphics and color-coded messages. Although any arbitrary message can be composed by the traffic center operator to be shown on the CMS, the common practice is to show only a limited number of messages, normally predetermined for a particular traffic situation. This is to ensure that both appropriate and comprehensible messages are displayed under urgent situations.

The most common mobile terminals to receive traffic and other relevant information are those in the automobiles. For years motorists rely on car radios (both AM and FM) to receive traffic relevant broadcasts. However, the broadcast information covers a large area and often has little relevance to the route taken by the motorist. In order to provide traffic information at the time and location where the motorist needs it, highway advisory radio (HAR) is installed along the road segments for wireless transmission limited to the local area (i.e., localcast), as often done along highways surrounding airports to advise motorists about parking situations. Typically HAR is a low power, under 10-W, standard AM broadcast band transmitter with a planned reception range of 2–3 km. In case of safety related information, it is important to alert motorists who may not have turned on the radio or may be engaged in entertainment listening. There are prototypes of special radio receivers, known as Automatic HAR (AHAR), that can turn on and tune to the HAR program automatically to be localcast.

In order to broadcast traffic information on a more frequent or continuing basis, FM subcarriers can be used to multiplex relatively low-bit-rate (about 1,000 bits per second) traffic data for text display on car radios, analogous to brief traffic reports via teletext on televisions. In Europe, radio data systems have been developed for such purposes as station identification and program type indication. This is accomplished by providing coded messages on a subcarrier of 57 kHz (which is the third harmonic of the standardized pilot tone for stereo FM broadcasting.) The Europeans have agreed to use some of the coded messages for transmitting traffic information. The codes transmitted through this radio data system traffic message channel (RDS/TMC) can be converted into any language understandable to the motorist for display. Similar systems have been developed in Japan and in the United States (under the name of radio broadcast data system, or RBDS) with higher bit rates than the European system, by taking advantage of the wider spacing between the FM stations in those countries and by using more sophisticated modulation techniques (14). For those motorists who have cellular phones or special mobile radios, powered by batteries in the car or in the communication device, they can get traffic information by calling an operator or an electronic message distribution center where traffic advisory messages are stored for retrieval, just like what they can do from home or office using a regular telephone. With two-way interactive communications, cellular phones and personal communication systems (PCS) can be used to query traffic situations in specific locations and yellow page information, and can be used to make reservations and payments such as for parking and lodging. These cell-based technologies have their own communication infrastructure that can provide roaming capabilities so that relevant traffic and other types of information can be multicast to specific individuals with special interests no matter where they happen to be within the coverage area.

Wireless digital information communications have been used to provide ITS functions. For years, mobile digital terminals (MDT) have been used on police cars, trucks, and other special vehicles for data communications, with the advantages of information precision, data storage for record keeping and asynchronous communications, graphical image transmission capabilities, and convenient interfacing with computers. In-vehicle fax machines have been demonstrated also for similar purposes. Personal communication systems (PCS) mentioned previously are all digital. Data communications via analog cellular systems have been made feasible by cellular digital packet data (CDPD) and a number of proprietary packet-switched wireless data communication techniques. New digital cellular services based on TDMA (time division multiple access), CDMA (code division multiple access), as well as the European GSM (global system for mobile communications) standards have already been introduced to the market. With the ever-expanding development of technologies, widespread wireless data communications can be expected to become more capable and less costly in all urban and suburban areas. The advent of low earth orbit (LEO) satellite communication systems (which require much less power than geostationary communication satellites) will also reduce communications costs in rural areas.

Portable digital terminals are becoming widely used for a number of purposes, and can be used by travelers on the ground or in the vehicle. Pagers are becoming more sophisticated so that traffic information can be transmitted in both text and graphical forms on these terminals. A number of hand-held digital devices, sometimes known as personal digital assistants (PDA), have emerged on the market for a variety of functions including traffic information. Pagers and PDAs are particularly useful to pedestrians seeking traffic and related information. Laptop and palmtop computers are being equipped with modems that can be used to access Internet and information service providers for many purposes, including interactive communications related to traffic information and decision support.

Another important way to communicate traffic and other relevant information to the motorist is through dedicated short range communication (DSRC), which links road infrastructure to equipped vehicles in its close proximity, as will be discussed in a later section.

VEHICLE LOCATION RELATED FUNCTIONS

Information about vehicle location is important for ITS functions. Two key questions are: “Where am I?” and “How far am I from other vehicles and obstacles?” The answer to the first question is the vehicle’s absolute location which is needed for navigation, fleet management, and determination of what specific information becomes relevant to the motorist. These functions are discussed in this section. The answer to the second question is the vehicle’s relative location (with respect to other vehicles, road edges, and obstacles) which is needed for vehicle control and collision avoidance, and which will be discussed in a later section on Vehicle Control Related Functions.

One of the most common automatic vehicle location (AVL) systems for determining absolute vehicle location is Global Positioning System (GPS), a system developed and maintained by the US Department of Defense (USDOD). The satellite-based radio navigation system, fully deployed in the early 1990s, consists of a constellation of 24 satellites orbiting 12,600 miles above the earth. The receiver’s three-dimensional coordinates (longitude, latitude, and altitude) can be determined, based on the time of arrival (TOA) principle, when 4 or more satellites are in line of sight from the receiver. The USDOD allows and guarantees the use of Standard Positioning (SPS), which is deliberately degraded from Precise Positioning (PPS) for military use. SPS has an accuracy of 60–100 m for civilian applications, including all modes of transportation around the world. However, by installing a transmitter at a known location on the ground to provide corrections, one can use differential GPS (DGPS) to improve the performance of the degraded GPS and get vehicle location accuracy in the order of 30 m.

Since the normal functioning of GPS requires the observation of at least four satellites, vehicle location needs complementary systems that would still work while the vehicle is under a bridge, under dense tree foliage, or in an urban canyon surrounded by tall buildings. One of the commonly used systems for this purpose is *dead reckoning,* which uses gyroscope or related inertial guidance principles to deduce vehicle location in reference to a known starting point. However, dead reckoning cannot function alone since the cumulative error needs to be corrected from time to time, preferably done automatically. This correction can be done through the radio signal from a beacon at a known location passed by the vehicle as well as by GPS when enough satellites are in sight. Such a location indicating beacon is known as a *signpost.* Another approach to correct cumulative errors in dead reckoning is *map matching,* which takes advantage of the fact that vehicle location is usually restricted to the road network except during temporary deviations when the vehicle is in a parking lot or on a ferry. As the name implies, map matching would require the presence of a digital map on the vehicle and the use of heuristic algorithms to deduce where the vehicle should be on the map.

There are other methods for determining vehicle location, using angle of arrival (AOA) or time difference of arrival (TDOA) principles. For example, the location of a vehicle with its car phone turned on can be determined on the basis of its direction from two or more cell sites of known locations. Such methods can be important for emergency calls from mobile phones (extended 911 or E911 service in the United States) with automatic indication to the rescue team where the caller or vehicle needing help is located, especially if the vehicle is not equipped with GPS. Note that either the vehicle or the dispatch center for a fleet of vehicles can be the host for vehicle location functions, depending on the specific ITS function to be performed. In either case, the output of the system will need a map to convey the vehicle location(s) to the user.

Digital maps are a prerequisite for any advanced traveler information system, including vehicle location and navigation. There are two types of digital maps: raster-encoded maps and vector-encoded maps. The former are basically video images of paper maps and used mainly for display purposes such as for vehicle tracking in fleet management. Vector-encoded maps require less memory, intrinsically relational in nature, and thus easier to manipulate—such as zooming, suppression of details, and expansion of attributes. They are also more expensive to make as the process is labor-intensive. Generally the making of vector-encoded maps includes three steps. First the raw data need to be collected from paper maps, aerial photographs, and other information sources. Then, the information needs to be digitized, with the aid of software. Finally the digital maps need verification and updating from time to time. With advanced storage technology, the digital map showing all the major roads in the United States can be stored in a single compact disk. For detail information needed for route guidance, the digital map of a single metropolitan area may be put in a PCMCIA card (also known simply as PC card).

Among the most common ITS functions accomplished with digital maps are navigation and route guidance. For navigation, the vehicle location determined from GPS and other complementary means would be displayed as icons superimposed on the digital map. For route guidance purposes, the digital map would need to include such attributes of road segments as distance, travel time according to speed limits and time of the day, turn restrictions, toll charges, and so forth. Given any origin and destination, software based on dynamic programming principles can be used to compute the optimum route. Various constraints or modified objective functions may be applied to the optimization problem: no expressway on route, least toll charges, most scenic route for tourists, etc.

Dijkstra's algorithm for shortest path (or cost) computation has been the most common basic algorithm for route guidance. However, in order to save computation time and memory space, the basic algorithm may be modified to include heuristic search strategies (e.g., the A* algorithm). The heuristic approach is particularly important in dynamic route guidance. Unlike static route guidance which is based on historical traffic data, dynamic route guidance would provide timely advice to the motorist that takes into account the real-time traffic situation (congestion, incidents, road closure, etc.) whether the motorist is still at the origin (pretrip planning) or is already en-route (en-route planning). In the latter case, the allowable computation time for optimum route could be quite limited.

Dynamic route guidance takes the current location of the vehicle as the origin and computes the optimum route to any given destination repetitively. The computation could be done on the vehicle in vehicle-based systems, or at the traffic center or at the information service provider in center-based systems. Choice between these options depends on the tradeoff between computation and communication costs, and other considerations such as the need to update digital maps—there are some map changes almost everyday in a typical metropolitan area. In either case, travel time experienced by vehicles equipped with route guidance systems would be collected as probe data to complement other sources of link times. The communications between the center and equipped vehicles can be done through general-purpose wide area wireless systems (e.g., CDPD) or through dedicated short range communications (i.e., beacons). The latter provides communications only when the vehicle is within the proximity of a beacon and requires investment of dedicated infrastructure that might not be cost effective for dynamic route guidance unless the DSRC is used also for a number of other ITS services.

LINKAGE BETWEEN VEHICLE AND ROAD THROUGH BEACONS

Most ITS services require the functioning of the vehicle and the road infrastructure as an integrated system. Since beacons are installed at fixed locations on the road infrastructure, they not only provide mobile communications between the vehicle and the road infrastructure, but also provide information about the vehicle location. Thus, the information transmitted by dedicated short range communications (DSRC) through beacons can be location relevant or location selective. The ITS services that are prime users of DSRC are shown in the following list:

- Electronic toll and traffic management (ETTM)
- Commercial vehicle operations (CVO)
- Parking management
- Signal preemption
- In-vehicle signing
- In-vehicle traveler information
- Individual route guidance (in selected systems)

The earliest DSRC investment in the United States has been for electronic toll collection (ETC). Since the beacons for ETC can be installed along the road infrastructure as well as at the toll plazas, the travel time of individual vehicles (or vehicle probes) can be obtained for traffic management purposes as well. Thus the broader term electronic toll and traffic management (ETTM) is used to include both services.

An ETC system, shown in Fig. 2, consists of a vehicle with an on-board unit, a two-way microwave link, and roadside (or tollgate) equipment. The in-vehicle equipment is a transponder, which is usually a tag, an integrated circuit card with a card holder, or a combination of the two. It stores the information needed for toll transactions, such as vehicle type, account identification, and balance. The roadside equipment consists of (a) transceiver (transmitter and receiver), also known as reader, the main functions of which are to verify the functionality of the in-vehicle equipment and to conduct the transaction; (b) a lane controller, which monitors activities occurring in a toll lane; and (c) a primary processing computer system, used to access account information and process the transaction requests (15).

There are several taxonomies to classify ETC systems. The two basic types of DSRC technologies used in current ETC applications are active tags and backscatter tags. Active tags contain a battery or external power source to power the internal circuits and transmissions. They contain internal electronics capable of communicating with the reader through its own transmitter. Active tags operate over a larger range, generally 20 to 50 m, than backscatter tags. Backscatter tags send information back to the reader by changing or modulating the amount of RF energy reflected back to the reader antenna from a continuous-wave RF signal beamed from a reader. The RF energy is either allowed to continue traveling

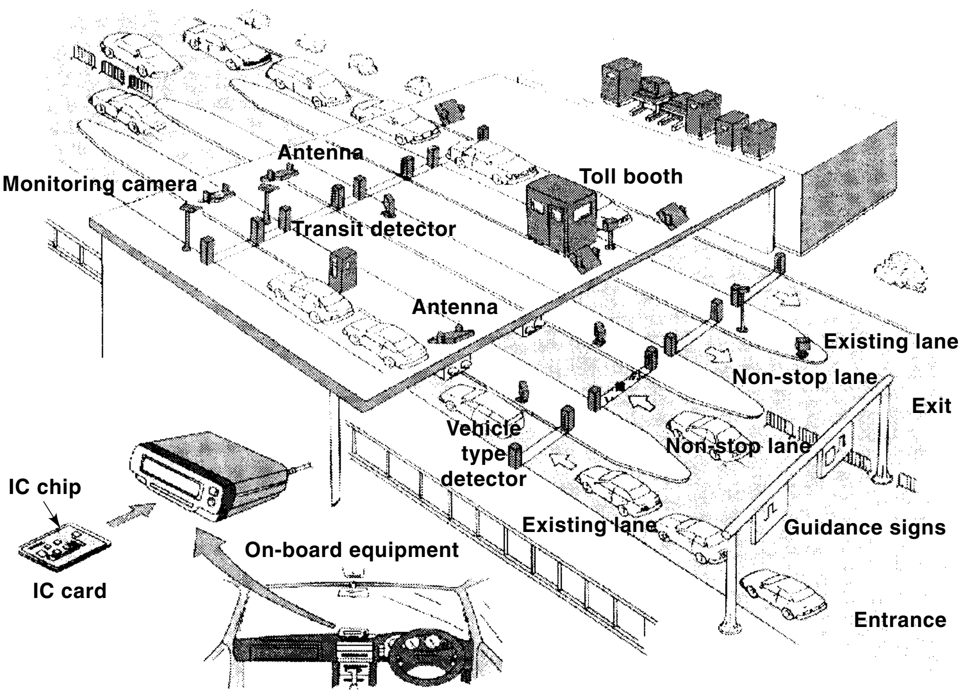

Figure 2. Schematic diagram of an electronic toll collection (ETC) system. The heart of the technology is dedicated short range communications (DSRC) between the readers on the infrastructure (connected to the antenna in the figure) and the tags on the vehicles (connected to the on-board equipment in the figure). (Original source: Highway Industry Development Organization in Japan. Modified by Post Buckley Schuh & Jernigan, Inc.)

past it or is intercepted and "scattered" according to the tag's antenna pattern back to the reader antenna. This operation of switching the scattering on and off can be done with very little power so that it can be powered with an internally integrated battery or with power derived by rectifying the RF signal intercepted from the transceiver. At present, the active and backscatter tags are not compatible or interoperable. Efforts are being made to come up with a standard that can accommodate both technologies. Meanwhile, super readers (that can read both kinds of tags) and super tags (that are interoperable with both kinds of readers) may be installed during the transition period toward the ultimate standard DSRC system (16).

Another way to classify DSRC tags is according to their levels of technical communications capabilities. Type I tags are read-only tags. When interrogated, these tags transmit their unique identification code to the roadside unit. They are factory programmed with their identification code and other data. For Type I tags, a tag database must be kept on a centralized computer to process and record activity. Type II tags are read–write tags. They have the capability to store and transmit other information. They are commonly called *transponders* because they can perform two-way communication with the roadside unit. Data are read from, modified, then sent back to the tag. These tags can allow for the creation of decentralized processing systems. Type II+ tags provide feedback to the driver using lights or buzzers to convey information. Type II++ tags use LCD and buzzers to provide feedback to drivers. Type III tags are also read–write tags, but feature an external interface that is used for transferring information to other on-board devices, such as computers or driver information displays. These tags are particularly useful for fleet management applications, where drivers are required to track and receive large amounts of data from a variety of sources. Type IV tags are also read–write tags with many of the same features as Type III tags, but these tags have an integrated smart card reader, rather than simply an interface to an on-board computer or smart card reader. *Smart cards* are plastic credit cards that include a small microelectronic circuit that allows memory and simple logic functions to be performed, such as requirement for correct personal identification numbers to be entered into the reader for financial transactions.

Still another way to classify ETC systems is according to the way toll payment is calculated. In an open system, each time a vehicle passes a toll lane, the roadside unit instructs the transceiver to debit the vehicle's account. In a closed system, a roadside transceiver reads the memory content of the in-vehicle equipment unit at the point of entry. The computer then verifies the vehicle identification and account number, and whether sufficient funds are available in the account. The transceiver then writes a date, time, location, and lane number stamp in the appropriate fields of the unit's memory. When the vehicle exits the system, the transceiver reads the on-board unit's memory and the computer calculates the toll and debits the vehicle's account. This information is then written back to the unit's memory.

Finally, ETC systems may be classified according to the configuration of the toll collection zone. The single-lane ETC systems operate only if the equipped vehicles are allowed to pass through specific lanes, such as in situations where toll plazas have been installed for manual toll collection previously or for mixed (manual and electronic) toll collection. In such situations, vehicles usually slow down from mainline speeds and barriers may be installed to stop those vehicles without tags or without sufficient funds in their accounts. The multilane ETC systems operate in situations where vehicles may crisscross between lanes and traveling at mainline speeds. The technology and process for accurate toll operation and for catching violators are more complicated in such situations. These situations arise where the roadway was designed originally without toll plazas, such as in the case of electronic toll collection on former freeways. However, ETC technologies have progressed to the state that reliable operations (accurate toll collection according to vehicle types and catching violators) can now be achieved in multilane configurations with a variety of vehicles (including motorcycles) traveling at mainline speed (over 100 miles per hour). Of course, the complexity of ETC systems may add to their costs.

ETC systems are being applied around the world, including many developing countries where toll collection has become a necessity for financing road construction. The number of ETC tags issued worldwide by the end of the 20th century has been estimated to total up to ten million. All major interurban expressways in a number of industrialized countries, including Japan and Southern European countries, have traditionally been toll roads. Some Northern European countries are in the process of converting their free expressways to toll roads. Even in the United States, the first private toll road was constructed after over a century in Southern California as a way to relieve congestion. In this case, the principle of *road pricing* (also known as *congestion pricing*) has been applied to vary the toll rate according to the time of day, and ETC has been found as a technical means to facilitate its implementation. From an institutional perspective, it was not surprising that ETC has turned out to be one of the earliest widespread ITS applications since it has helped all the major stakeholders with vested interests. The toll agencies have reduced costs through ETC automation, the drivers of vehicles equipped with ETC save time as they do not need to stop to pay tolls manually, and even the drivers of nonequipped vehicles save time since the queues at the toll plaza for manual toll collection have become shorter without the equipped vehicles.

The second most important DSRC application, at least in the United States, is for commercial vehicle operations (CVO), including weigh-in-motion and (interstate and international) border crossing. The objective and major benefits are in time savings by substantially reducing the need for trucks to stop for inspection. It has been estimated that every minute saved by a large commercial truck is worth $1 to the trucking company, as well as reduction of stress and frustration on the part of the driver.

A number of systems for weigh-in-motion (WIM) systems are currently obtainable from manufacturers. They are based on stress and strain measurements as a function of the total weight or axle weight of the vehicle—bending plate, electric capacitance variation, piezo-electric load sensors, etc. Those commercial vehicles which do not violate the weight limit are given a signal through DSRC by the inspector to bypass the weigh station.

In the United States, every state has its own regulations regarding licensing, fuel tax computation, and safety requirements for commercial vehicles. This situation has caused inspection delays for trucks traveling between states. The purpose of CVO application to this situation is to reduce all state border inspections to only one stop. Once cleared, the commercial vehicle can then travel nonstop from state to state, with passing signals through DSRC at the state border crossings as the data from the single-stop inspection can be sent ahead to all the downstream states on the route traveled by the truck. In this case, the tag (transponder) on the truck needs to carry only the identities of the vehicle, the owner, and the driver.

Once the DSRC system is in place, many other kinds of information may be transmitted to the truck driver, including freight management information between the driver and the fleet dispatcher. Vehicle diagnostic data (e.g., defective brakes and excessive emissions) can also be downloaded at the maintenance station through the same DSRC tag on the vehicle. In the case of international border crossing, the situation is much more complicated since customs and immigration information also need to be transmitted to the border in order to reduce inspection delays and transmitted back for record keeping. For example, the cargo on a truck may be inspected before it arrives at the international border. Once cleared, an electronic lock is used to seal the door and the truck can be instructed to bypass further custom inspection at the border after a simple check is made to assure that the electric lock has not been opened. Multiple government agencies from two or more countries will need to agree and coordinate with one another, making the institutional aspects more complicated.

Other current DSRC applications include parking management and signal preemption. The operational concept of parking management is quite similar to that for a closed ETC system. The parking agency can positively identify the location and entry time of the vehicle, both at the time of the payment transaction and when the vehicle enters the parking area, ensuring that the driver is correctly billed. The system can assign access to vehicles by specific lots and for various time periods. Some systems can electronically report attempts to use an invalid tag to parking managers, giving the location of the attempted entry and the name and card number of the violator. An anti-pass-back feature can require the smart tag to exit before reentering the lot, making it impossible for one user to pass a tag back to another.

DSRC technology can be used to allow for signal preemption for transit and emergency vehicles, as well as transit vehicle data transfer (similar to CVO data transfer). In this case, the transit and emergency vehicles use DSRC technology (either at microwave or infrared frequencies) to communicate with traffic signal control systems to request priority signal treatment (usually through extended green times or reduced red times but no sudden change of signal for safety reasons).

DSRC applications to other ITS services have been tested and are expected to be widely deployed. These include in-vehicle signing to bring road sign information (speed limit, cross street names, etc.) for continuous display on vehicle dashboards. Such displays can also be in large characters to help those with eyesight impairment. Portable transmitters may be put on school buses to warn drivers around the corner. Location-relevant yellow-page information would help motorists and travelers as well as commercial interests. These applications have already been implemented by some private toll road agencies (e.g., Cofiroute, a private highway concessionaire in France) to deliver value-added services to their customers. Location-relevant route guidance system has also been deployed in certain countries (e.g., in the Japanese VICS system) where the traffic authorities have both the financial capabilities to install the dedicated infrastructure and the desire to maintain control of the route guidance system. In other countries, such as in the United States, dynamic route guidance usually leverages on the wide-area mobile communication systems already invested by the telecommunications industry rather than relying on any new DSRC infrastructure.

VEHICLE CONTROL RELATED FUNCTIONS

Solid-state electronics, which has been applied increasingly for vehicle control since the 1960s, has gone through three generations. Vehicle electronics was first used in open-loop control at the component level such as for engine ignition. Then, it was applied in closed-loop control at the subsystem level such as in anti-lock braking system (ABS), in which the vehicle is prevented from skidding through a number of rapid braking pulses applied automatically on the basis of tire slippage sensing. The third generation was at the system integration level such as for control of the entire power train to optimize economy, performance, or emission. While these vehicle control electronics may not be very visible, most drivers today interact with cruise control which has provided comfort and convenience in long-distance travel. It has been suggested that ITS services for vehicle control and safety call for the fourth generation of vehicle electronics which integrates the vehicle and the roadway into a total system, a basic feature of ITS (17).

Concerns about vehicle safety have led to vehicle design and new devices that give the driver and the passengers in the vehicle more protection upon impact. These include seat belts, air bags, and crash-proved bumpers. However, these are passive safety approaches that improve safety only after collision. Vehicle control and safety under ITS emphasize active safety approaches that try to avoid collision.

The basic aspects in *active safety* or *crash avoidance* are longitudinal control and lateral control of vehicles, and their combinations in various circumstances. Statistical data show that most vehicle accidents involve rear-end collision resulting from erroneous longitudinal vehicle control, and most fatalities result from loss of lateral vehicle control. Both longitudinal and lateral controls can be improved within the individual vehicle autonomously, or with the help of communications between vehicles, or communications between the vehicle and the infrastructure.

The most common sensors used for longitudinal control are radar and laser devices that can provide measurements of distance from the vehicle in front, gap closing rate between vehicles, and detection of obstacles on the roadway. In general, laser (Lidar) has limitation of range in the order of 50 m and operates only within line of sight. Radar has more difficulty in distinguishing roadway clutter from desired target, and may get confused by radar signals from vehicles in the oncoming traffic. Sonic and ultrasonic sensors are also used, especially for detecting people and objects in the back of the vehicle as it backs up. These devices generally operate at short distance and low vehicle speed, and have problems with beam displacement by cross wind.

In spite of various limitations, sufficient technological progress in both hardware and software has been achieved to make adaptive cruise control (ACC), also known as intelligent cruise control (ICC), reliable enough for market introduction. These systems can automatically reduce vehicle speed, which has been set by the driver through cruise control, to keep safe headway from the vehicle in front and to resume the set speed when the headway is sufficiently long. Speed reduction in ACC can be accomplished through automatic closing of the throttle, gear down shifting, or braking. Driver intervention is still needed under abnormal circumstances, such as driving along sharp curves and detection of large animals crossing the roadway. However, the remaining barrier to widespread application of ACC is no longer the technology but concerns about legal liability in certain market areas.

From the safety perspective, ACC assumes that the speed set by the driver is safe when the vehicle in front is sufficiently far ahead. However, this assumption is not necessarily true even if the set speed is within legal limits under normal circumstances. The real safe speed depends on many other factors, including weather and road conditions, traffic around the vehicle, and the load on the vehicle and the condition of the vehicle itself. External conditions communicated to the vehicle (through both wide area and short-range mobile communications), and internal conditions sensed within the vehicle, can be used to provide real-time advice to the driver what maximum speed is safe to set. In fact, if the set speed is unsafe, the system can provide a series of steps beginning with warning, followed by deceleration as in ACC if necessary, but with the option for driver override.

The most basic need for lateral vehicle control is lane keeping, that is, keeping the vehicle in the middle of the lane. Various approaches to lane keeping have been tested and demonstrated. The most common approach to lane sensing and lane keeping is through video image processing of the white edge, and the lateral control strategies must take into account of the growing uncertainty in lane edge positions as the video camera looks farther ahead the road. Low-cost off-the-shelf video cameras have been shown to be sufficient for lane sensing purposes. The use of GPS and digital map for lane keeping has also been tested, taking advantage of the vehicle location accuracy provided by GPS, especially if differential GPS is available. Both video and GPS approaches to lane keeping do not require modifications of the existing road infrastructure.

Other types of lane keeping approaches rely on new devices put on the road infrastructure. These include the installation of guide wires along the lane pavement carrying electrical signals and the installation of magnetic nails buried under the lane pavement. The latter not only has the advantage of being completely passive but also provides digital preview information of the road geometry through the deliberate polarity arrangement of multiple magnets along the road path. The lateral positions of the magnets and the preview information are picked up by magnetometers under the vehicles for lane-keeping purposes.

From the perspective of vehicle safety, much of the benefit from longitudinal and lateral controls can be realized without full automation. In fact, beginning with reliable sensors, the automotive industry has taken an evolutionary approach to begin with warning first, followed by partial automation, and eventually perhaps to full automation. Warnings are provided not just when the vehicle is getting too close to another vehicle ahead or when the vehicle begins to veer off the lane, but also when another vehicle is nearby in the neighboring lane or in the blind spot so that the driver would not attempt an unsafe lane change. Partial automation is provided only to assist the driver, who can, in most cases, override the automatic assistance. For example, a small torque may be applied automatically to the steering wheel to keep the vehicle on a particular lane. However, driver override can be achieved by manually applying a larger torque to avoid an obstacle in front.

Fully automatic longitudinal and lateral vehicle controls will eventually lead to automated highway systems (AHS), which is defined as hands-off and feet-off driving. Even though the deployment of AHS may be further away, feasibility demonstrations have been held in several countries, including the one in San Diego, California in early August 1997 (18). Among the different concepts demonstrated are the free-agent scenario and the platooning scenario. Free agents are vehicles equipped with sensors and automatic control mechanisms operating autonomously without any assistance from the infrastructure. Free agents can therefore operate in non-automated traffic on all existing roadways. Platoons are multiple vehicles traveling in a single-file formation with very short headway (in the order of one or two meters). Vehicles in the platoon are guided by magnetic nails in the pavement and communicate with one another. The short headway implies the potential of increasing highway throughput by several times. Since the very short headway is beyond human capability to maintain, full automation is required and human errors are virtually eliminated. Figure 3 shows a smart car fully equipped for most ITS functions, including AHS.

An evolutionary approach to AHS emphasizes near-term applications of some of the AHS technologies without full automation. These applications include collision warnings to individual vehicles, hazard warning passing down a group of vehicles, computer-assisted merging and overtaking among cooperating vehicles, warning to snowplow operators about lane departure and vehicles buried under snow banks, and truck convoys in which a single driver will operate a train of trucks coupled to each other electronically.

HUMAN SIDE OF ITS: TRAVELERS AND OPERATORS

Fully automated driving is only a small part and a long-term goal of ITS. Most ITS services center around the driver/traveler and the traffic operator. Human factors and human interfaces with ITS terminals and devices are therefore an important part of ITS technology. Human-factors research in ITS includes all the domains of human physiology (ergonomics), perception, comprehension, and decision making. Some or all of these domains need to be included in the specifications and designs of ITS human interfaces, depending on the specific applications.

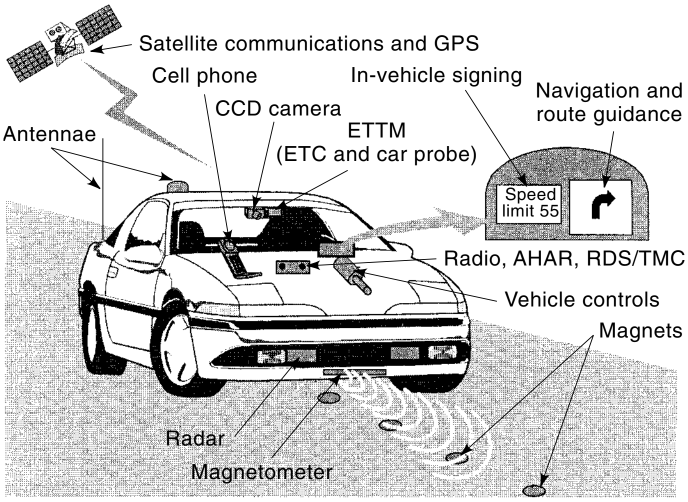

Figure 3. Selected components of a smart car. This figure shows the essential components for vehicle location and vehicle control related functions. (Source: Kan Chen Incorporated and Post Buckley Schuh & Jernigan, Inc.)

In general, human interfaces with ITS terminals for non-drivers are better understood since they are extensions of traditional computer, communications, and consumer electronics technologies—television, home computer, office telephone, and so forth. Traffic management centers enhanced by ITS technologies include many more displays and communication terminals than previous centers without ITS. In case of multiple serious highway accidents, the challenge in providing the most critical (highest priority) information simply, accurately, and in a timely manner for coordinated operator decisions is not unlike that in a nuclear plant accident. Lessons learned from the latter experience and other similar emergency situations can be helpful to ITS-oriented traffic management center design.

Human interfaces with ITS terminals for drivers present new and relatively unique challenges as the reception and digestion of new traffic-relevant information from ITS can distract or add substantially to the driving tasks. Although the situation is not unlike that in the cockpit of an aircraft, the human factors challenge in ITS is more difficult partly because a car driver generally has not gone through the rigorous training and selection process of an airplane pilot, and that the air traffic environment is generally more forgiving in that it allows more time for human decision making.

On the infrastructure side, location, size, and brightness of changeable message signs (CMS) must be chosen so that the display can attract drivers' attention easily in busy traffic and cluttered urban environment. The displayed messages need to be composed for brevity and ease for accurate comprehension since drivers cannot be counted on to read more than two short lines at high speed. Icons have been found to be helpful in conveying meanings of signs quickly (analogous to the shape of stop signs) and color codes have been suggested for CMS in multiple languages where bilingual signs are needed.

Inside the vehicle, driver's use of car phones has already caused public concerns, and manufacturers have offered memory dialing and voice dialing options to ease the situation. The challenge in text display of RDS/TMC is similar to that in the display of CMS. Since voice displays are less distracting than visual displays to the driver, voice displays in the driver's preferred language have been offered for RDS/TMC. On the other hand, voice displays could be drowned out by traffic noise. Thus, for safety warnings, both voice and visual displays are frequently used.

With the space behind the dashboard of most vehicle models becoming extremely scarce, various ITS driver information has to compete for presentation. A re-configurable dashboard display has been offered as an option. While OEMs generally install their navigation system monitor in the dashboard, navigation system displays purchased after the market are usually retrofitted to the dashboard through a goose-neck connection. Route guidance information itself can be displayed either on a digital map or as arrows showing direction to turn or to go straight ahead at the next intersection. In the latter case, the arrows are usually accompanied by voice displays, and a countdown visual display is used to provide comfortable time for the driver to do lane change and other maneuvering to make safe turns at the intersections.

Human factor considerations have also led to innovative product designs and technology transfers for locating visual displays. For example, head up displays (HUD) are used to put images of speedometer information and warning signals on the windshield, just above the hood in front, so that the driver can see them without taking the eyes off the road. This technology was originally developed for fighter pilots using a set of mirrors or a holographic system. Another example is to display a red tinge on the side mirror display when the side-looking radar detects a vehicle in the neighboring lane, in order to warn the driver intending to change lanes.

From safety standpoint, driver monitoring is also desirable. Two general approaches are taken to detect drivers who get tired or drowsy, or are under the influence of alcohol or other controlled substance. One approach is to monitor the driver directly, especially the driver's eye movement. The other approach is to monitor the driving behavior such as the swerving or drifting of the car movement. For the sake of privacy, the warning is usually fed back to the driver, although suggestions have been made to provide the same information to other drivers and to regulatory bodies.

Another safety related ITS service is driver-initiated distress signal. The combination of automatic vehicle location and mobile communications on the vehicle makes it possible for the driver to seek help from public or private agencies when needed (for example, when the driver gets stranded or when a truck is hijacked). The distress signal can also be automatically triggered by an airbag in case the driver becomes disabled or unconscious in an accident, or by a burglar alarm system when the vehicle is entered by an unauthorized party. This kind of service represents one of the earliest ITS markets involving the private sector.

EVOLUTIONARY DEPLOYMENT

The plethora of ITS technologies has offered many possible strategies for different communities and countries to get into ITS according to their local priorities and policies. Most public agencies and private companies with ITS deployment experience have chosen evolutionary strategies that would begin with information collection and dissemination on the infrastructure side for traffic management, and that would leverage on the existing and expanding communications infrastructure which serves as common carriers for many information services beyond those for ITS. Thus, initial ITS investments tend to put emphasis on traffic surveillance hardware and software and on cooperative agreements among relevant jurisdictions for information sharing and common standards for data exchange.

Beginning with existing computer control of traffic signal and loop detectors at busy intersections, advanced traffic management systems (ATMS) would move to adaptive traffic control, ramp metering at the entrances to expressways, changeable message signs to inform drivers of current traffic situation and advise them to divert from incident sites, and upgrade their traffic surveillance technologies (expanding CCTV coverage or installing video image processors). Eventually they build new traffic management centers to fuse traffic data from multiple sources, coordinate traffic control across multiple jurisdictions on a regional basis, and couple traffic management infrastructure with information superhighways and with information service providers in the private sector.

Building on the comprehensive database at traffic management centers, advanced traveler information systems (ATIS) usually would move from informational stage to advisory stage, and eventually to coordinated stage. Tourist information, real-time traffic information (including multimodal transit and rail information), and static route guidance are the key services provided in the informational stage. Dynamic route guidance and multimodal guidance are the key features in this stage. In the coordinated stage, the operations of ATMS and ATIS would be coordinated so that, for example, dynamic route guidance and adaptive signal controls would be coordinated.

ETTM usually begins with conversion of existing manual operation at the toll plaza to automatic ETC. Then, additional readers would be added to collect travel time information for traffic management purposes and new toll roads are built with tolls to be collected only electronically. A common standard for DSRC will then be established for both CVO and ETTM services. The toll agencies using ETC will use their beacons (readers) to provide additional user services through in-vehicle traveler information systems. Eventually a DSRC standard would be established at least within each continent, if not for the entire world, so that multiple ITS services proliferate, using DSRC as a communications medium that complements wide-area mobile communications network services.

Advanced vehicle control and safety systems would begin with the existing ABS and cruise controls and expand into adaptive cruise control and collision warnings in both longitudinal and lateral dimensions. Driver assistance and advisory systems (for safe speed, lane change, merging, etc.) would probably come next. Then free-agent AHS applications would allow equipped vehicles (especially special vehicles like buses, trucks, and military vehicles) to drive on any existing roadways with practically complete automation. Eventually other AHS concepts based on cooperative vehicles or supportive roadways will be deployed to maximize throughput, safety, and environmental benefits.

Public policies and regulations are also needed to support implementation of ITS technologies and services. As a minimum, multi-agency coordination is required to support regional traffic information collection and utilization, and to support effective and efficient operations to rescue drivers in distress. Such coordination becomes more important, and also more difficult, as multimodal ITS user services are implemented. Enabling legislation is needed to support national program planning and implementation, especially ITS public–private partnerships. Road pricing or congestion pricing as an effective means for congestion relief has often failed due to public objection on the ground of double taxation. Implementation of demand management as an ITS user service must go hand in hand with strong policy support. The advantage of using smart cards for both transportation and non-transportation applications, entailing in great convenience to the end users, cannot be realized without policy support from both financial and transportation authorities at the policy level.

SYSTEM ARCHITECTURE

The amalgamation of the many technologies requires that all the current and future ITS technologies work in concert with one another. System architecture is a framework for ensuring the interoperability and synergistic integration among all the ITS functions, regardless of the specific technologies to be deployed. Interoperability may be exemplified by the capability of a vehicle using a single set of antenna and in-vehicle unit to receive a host of ITS user services (e.g., toll payments, in-car signing, and international border crossings) no matter where the vehicle is operating. As to synergistic integration, there are in general four sources in ITS: (1) mutual reinforcement of ITS technologies, such as those for toll collection and vehicle probe mentioned previously; (2) shared database such as the common use of data between traffic and transit management centers; (3) exchange and coordination between organizational units such as between highway patrol and emergency services; and (4) synergism between transportation and communication infrastructures. Thus, the benefits of integration include cost savings, enhanced capabilities, easier user acceptance, and faster and fuller system completion (19).

System architecture also helps local and regional ITS planning by providing a big future picture for all stakeholder to see (20). To be practical, the system architecture must be flexible enough to accommodate a variety of local needs, including some of their existing systems. There are two kinds of mutually consistent architectures: the logical architecture which describes the information data flow and data processing needed to provide ITS user services; and the physical architecture which allocates specific functions to physical subsystems, taking into account of the institutional responsibilities. Figure 4 portrays the national ITS physical architecture developed for the United States through a three-year consensus building process among a wide spectrum of stakeholders.

Note that the interfaces between subsystems are clearly depicted in Fig. 4. Data flows between subsystems are through four kinds of communications media, the choice of which has taken into account the rapid changes in telecommunications, partly due to deregulation, a general trend in many countries. Although the US national architecture may need adaptation to other countries (e.g., to include ITS services for pedestrians) the architecture appears flexible enough to accommodate many national needs around the world as well as many regional needs within the United States.

STANDARDS

ITS system architecture, such as the one given in Fig. 4, provides an important basis for setting standards as each interface between subsystems implies the need for standards and protocols to allow smooth information flow among the subsystems. Data dictionaries defined in the architecture also imply standard message sets that must be defined and mutually accepted for the subsystems to exchange meaningful information.

ITS standards have been a subject of international discussion and cooperation through such organizations as the International Standards Organization (ISO). For years, international standards setting within Europe has been coordinated by the European Committee for Normalization (CEN) and that for the whole world has been coordinated by ISO. For ITS, CEN has set up the technical committee CEN/TC278 on RTTT (Technical Committee on Road Traffic and Transport Telematics) corresponding to the worldwide committee ISO/TC204 on TICS (Technical Committee on Transport Information and Control Systems). The duplicate effort between CEN and ISO is considered necessary by the Europeans not only for historical reasons but also because, within Europe, the compliance to CEN standards is mandatory while the compliance to ISO standards is only voluntary. For the sake of inter-

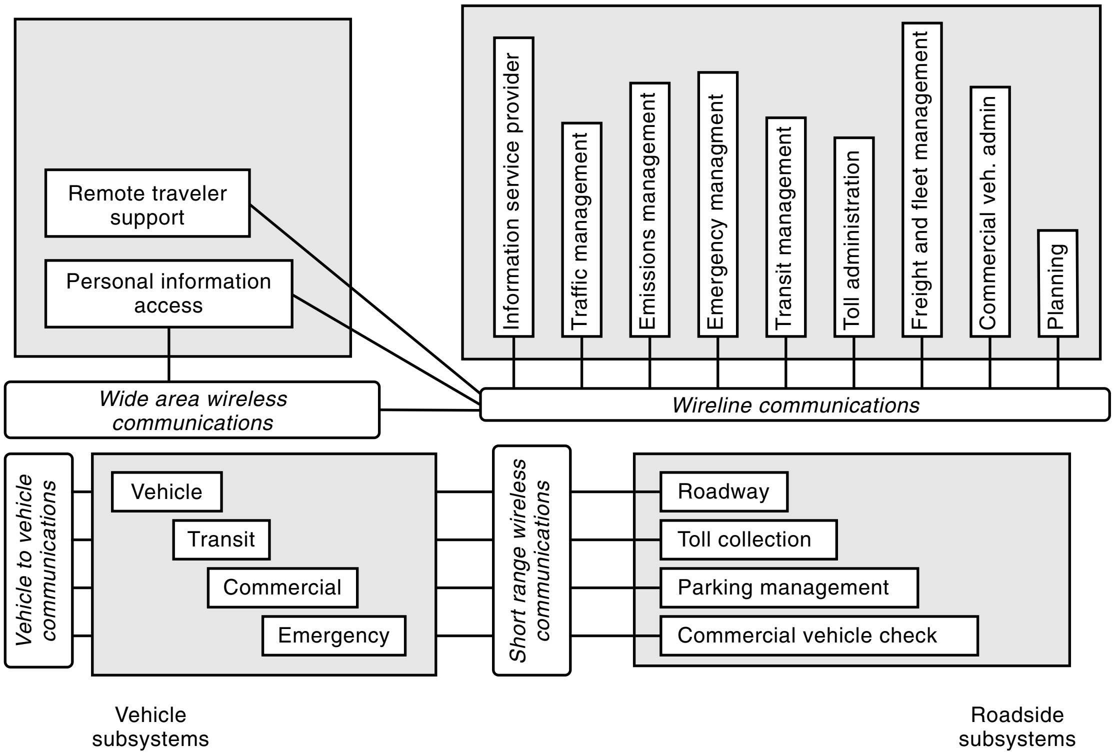

Figure 4. National ITS architecture for the United States. All ITS user services (except those related to the pedestrians) are captured by the four sets of subsystems (in the shaded blocks) interconnected through four types of communications (in the sausage-shaped boxes).

national harmonization for ITS standards, CEN and ISO have agreed to cooperate through a number of working groups (WGs).

Standards setting may or may not be critical at the local, national, and international levels, depending on the specific ITS user service. In general, ITS users want standards not only for the sake of interoperability but also for the advantage of being able to acquire components and systems from multiple vendors. ITS suppliers want standards for the sake of market size and economy of scale in production. However, standard setting often runs into difficulties as suppliers with proprietary standards or with established market position do not wish to change their products. Users already invested in specific systems are reluctant to switch to new standards before they realize a reasonable return to their sunk investment. Premature standards setting may also stifle innovation. Thus, the timing of standard setting is important. Even after standards are established, practical considerations must be given to acceptable migration paths for existing systems to move toward the standards over a reasonable period of time. Considerable energy has been, and will be, focused on developing ITS standards in the US and internationally.

MARKET AND EVALUATION

The worldwide movement in ITS since the mid-1980s has created a new ITS industry. A 1997 study for the US situation has produced the following findings of quantitative benefits and costs on the basis of the national ITS goals of the United States (21):

- ITS infrastructure will generate an overall benefit–cost ratio of 5.7 to 1 for the largest 300 metropolitan areas, with even stronger returns to the top 75 most congested cities (8.8 to 1).
- Present value of ITS benefits should exceed $250 billion over the next two decades.

Comparable results have been reported from Europe, Canada, and Japan. The markets for ITS products and services have grown and matured rapidly over the last five years in the United States. This growth is expected to continue and even accelerate as end-user (consumer) technologies move from early trial applications to adoption. Other relevant conclusions include (22):

- Over the next 20 years, the market for ITS products and services is expected to grow and cumulate to approximately $420 billion for the period.
- Building on public investments in basic ITS systems, the private market is projected to represent a smaller share initially, eventually growing to represent approximately 80 percent of all sales in the market through the year 2015.
- Public infrastructure-driven markets in the US metropolitan areas are projected to exceed $80 billion cumulative over the next twenty years.
- Private markets, including those for consumer- and commercial-driven ITS products and services, are estimated to exceed $340 billion cumulated over the next two decades.

Results from comparable market studies for other parts of the world are not available. However, more focused studies, such as on ETC products and services, have suggested that the global ITS market is at least three times as large as the US market.

Another study in the United States has compared the traditional solution of building roads to accommodate transportation demand growth versus the new alternative of investing in ITS infrastructure to help in building the same traffic handling capacity (21). The total cost for road construction to accommodate expected transportation demand growth in the United States for the next decade is about $86 billion for 50 US cities, based on the average cost of $3 million per lane-mile for urban freeways. With full ITS deployment for these cities, only two-thirds of the new roads are needed to provide the same traffic handling capacity. In other words, one-third fewer new roads are needed. Even accounting for the much higher operations and maintenance costs for 24-h operation of ITS, the United States can still save 35% of the total cost to provide enough capacity for the expected growth through an appropriate mix of ITS and new road construction. The same can be said on the vehicle side. That is, with ITS, it is possible to reduce the capital needs for buses and trucks because a smaller number of these vehicles would be needed to carry the same amount of cargoes or passenger trips. Similar results are probably applicable to other countries, assuring the continuation and expansion of the worldwide ITS movement.

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