CYBERTECHNOLOGY AND TRANSPORTATION[12]

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Information Technology will be one of the key factors driving progress in the 21st century–it will transform the way we live, learn, work, and play. Advances in computing and communications technology will create a new infrastructure for business, scientific research, and social interaction. This expanding infrastructure will provide us with new tools for communicating throughout the world and for acquiring knowledge and insight from information. Information technology will help us understand how we affect the natural environment and how best to protect it. It will provide a vehicle for economic growth.

President's Information Technology Advisory Committee[13]

Introduction

The domestic and global transportation enterprise is being transformed by widespread and rapid application of technologies associated with the sensing, storage, processing, display and communication of information. These elements are rapidly being incorporated into the many elements that make up the transportation system, and thereby are dramatically altering the interactions of organizations and people (operators, users and others) with the transportation system and with the technology. In this paper, the term *cybertechnology* will be used as a concise way to capture the full spectrum of these technologies, their interaction with users, and their broader integration into human activities.

A particular characteristic of cybertechnolgies is the degree to which they inherently entail or foster new and very broad interactions among specific subsystems, the overall system, and the people and entities using and operating the system. A real technical revolution is occurring, ultimately comparable in importance to innovations such as the automobile and the telephone. The course of this revolution is not predictable, but it clearly is unleashing many opportunities to advance significantly the entire transportation enterprise and greatly enhance the personal mobility of people everywhere.

As was the case for many earlier technological innovations, the initial applications of cybertechnolgies often provide only modest improvements in convenience or localized incremental benefits. However, as they mature, become integrated into business and personal activities, and are linked to other applications and innovations, it is often found that they

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[13] *Information Technology Research: Investing in Our Future*, President's Information Technology Advisory Committee Report to the President. (February, 1999)

transform how the system operates and is used, while also greatly improving performance and enabling new capabilities.

Cumulatively, the changes these technologies bring are already substantial – often dramatic – and cut across all facets of transportation. Beyond yielding benefits in efficiency and quality of service, they are enabling and generating the introduction of new services, products and resources that will significantly affect both the supply of and the demand for transportation.

Transportation and Technological Innovation

To a large degree, the history of transportation has been driven by technology – particularly by the technology of vehicles and propulsion systems. The steam engine, applied to marine and rail transport, was a central factor in the industrial revolution as well as the westward expansion of the U.S. The electric streetcar was a major force in creating early suburbs in the late 19th century. The early years of the 20th century saw the development and vigorous exploitation of the infant internal combustion engine, in both spark-ignition and diesel manifestations, which powered the road vehicles that have shaped life in the United States ever since, and were critical to the practical realization of heavier-than-air flight. More recently, other critical innovations, including diesel locomotives, jet-engine airliners, "mega-ships," and containerized freight have made their appearance. Modern transportation is virtually defined by technologies such as these.

Physical infrastructure has kept pace with the vehicle and propulsion advances. This is most evident in achievements such as tunnels and suspension bridges, railroad lines crossing deserts and mountain ranges, airports that are virtually small cities unto themselves, highly efficient marine ports, and the network of modern highways that comprise the U.S. Interstate System.

The system context within which these elements are used is less obvious, but has similarly evolved. It makes possible global aviation and marine transport, rail operations that reach across continents, and development of practices, procedures, knowledge, and technical standards that yield an unprecedented level of efficiency and safety in the face of steadily increasing volume of passenger and freight traffic.

Several enabling technologies, not exclusively associated with transportation, have also been key to supporting the movement of goods and people. In the 18th century the sextant and chronometer made possible precise global marine navigation. The telegraph was an important part of inter-city and transcontinental rail operations in the 19th century, and in the 20th century radio communications and radar permitted another major step in the ability to control and manage transportation operations in ways that improved safety, economic efficiency and system performance.

Similarly, dramatic advances in cybertechnolgies during the last several decades have come to play such a broad and pervasive role in transportation that it becomes useful to think of them as comprising an "information infrastructure". This has become a new and critical element of the transportation system, largely invisible but increasingly important to the effective use of the vehicles, physical infrastructure and system framework described previously. The full impact of this evolution on transportation will emerge only slowly in coming decades, and often will not be separable from the effect of other societal changes. But the net effect on the desires of Americans for mobility and access, and the means by which those wishes are satisfied, will be great.

Cybertechnology and Transportation

The Role and Impact of Cybertechnology

The mobility of goods and people in the U.S. is being affected ever more strongly by the rapidly expanding incorporation of cybertechnologies into virtually all facets of transportation services. In the closing decades of the 20th century, cybertechnology has become a primary element driving the evolution of transportation supply, and is increasingly affecting demand as well. As a motivator and enabler of innovation in transportation, cybertechnology will ultimately have an impact on system performance and use comparable to that of propulsion system advances such as steam power and the jet engine. Applications of cybertechnologies not only affect individual vehicles, components and subsystems, but also provide an information "overlay" to improve operation, control and management of the physical elements of transportation. This process is transforming virtually every aspect of transportation services.

Discussion of the many ways in which transportation is being affected by cybertechnology is thus aided by considering two related but basically different types of application:

- Local & Autonomous Applications: uses that provide useful functions and capabilities independent of their incorporation into a larger or external system.
- System-Level Applications: situations in which the primary value of cybertechnology arises from the incorporation into a broader system, generally based on sharing of information among different elements of the system or between the system and its users and external resources.

Local & Autonomous Applications

As for most other technological advances, implementation of cybertechnology has generally begun with modest incremental applications, relatively independent of the system as a whole, and often intended to serve a relatively narrow and specific function. Only with time, as experience is gained and technologies mature and become integrated into daily activities, do the broader system innovations take place. This is well illustrated by the evolving role of the desktop personal computer in both business and home life. However, as for the PC, cybertechnologies can have great impact even in purely individual, localized or autonomous applications.

Applications to the private motor vehicle provide a clear and important example. Several decades ago electronic components began to replace or greatly change key components, such as the distributor and carburetor and the dashboard instrumentation. With time, digital sensing and controls have been applied to many components and functions, and have come to represent a substantial portion of the cost of an automobile[14]. This evolution was partially shaped by the necessity in the 1970's and 1980's to meet much more stringent fuel economy and emission standards, and was critical to success in these areas, for both cars and other road vehicles. But it has continued as the rapidly declining cost of the technology has made many other applications feasible.

In terms of safety and comfort, there are now systems that continually adjust suspension parameters to accommodate changing road surfaces, and that sense accelerations and direction of travel to provide appropriate braking, traction and power control to assist the driver in dealing with loss of control. Use of radar to detect impending collisions has been considered for many years, with some applications already in place for buses and trucks. The concept of providing a wide range of driver alerting and assistance functions has been much broadened and brought closer to practical realization, now holding promise of identifying and avoiding or mitigating a wide range of incipient crash situations. Infra-red sensors coupled with head-up displays projected on the windshield may come to provide a major advance in the of safety night travel, particularly for older drivers. "Mayday" systems combine cellular phone and GPS technology to issue an alarm to a central office if airbags are triggered or the driver reports an emergency situation.

Convenience features abound, including sophisticated security systems, smart cruise control, and radios and climate control systems that respond to voice commands. Sophisticated GPS-based navigation systems based on on-board digital maps are becoming available to provide not only continual instructions to reach a specified location, but also other real-time information such as traffic conditions, weather, and listings of potential destinations.

Automobiles are evolving toward an integrated approach, based on use of a powerful microprocessor – equivalent to those in desktop computers – "networked" to virtually every operational component in the vehicle. A logical next step, already occurring, is the extension of these links to the external world, making the automobile as "connected" as any home or office. As capabilities and installations expand and costs come down, this platform will provide the foundation for continued inclusion of new features and capabilities that are limited only by the creativity and market responsiveness of the manufacturers. It is easy to imagine a large "automobile peripheral" after-market enabling individuals to tailor their automobile cybertechnology mix just as they now do for their home or office computer.

The introduction of cybertechnology into commercial aviation has already been even more fundamental and of greater impact than for road vehicles. The term often used to summarize this innovation is "glass cockpit," referring to the replacement of individual gauges and dials by color liquid-crystal displays (originally CRTs) that can provide a wide range of information as needed by the crew. However, the real change was not the displays, but rather the incorporation of computer-based flight management systems and automated controls, such as those for throttle,

[14] The Computer Aided Life Cycle Engineering Electronic Packaging Research Center at the University of Maryland estimates that approximately 20% of the value of modern vehicles is associated with electronic components, controllers and sensors, and electrical machines.

brakes and spoilers. Many modes of automated and semi-automated flight are now available to the flight crew, accompanied by tools and information resources that have permitted the safe reduction of crew size from three to two people. This is an area in which debate and research continues as to how best tasks and responsibilities should be allocated between people and automated systems, as well as assuring that crews maintain proficiency to deal with abnormal situations that may occur very rarely. However, the issues reflect the complexities of determining and applying human-centered design principles, rather than the concept itself, and the future application of more sophisticated functional capabilities, 3-D displays and software will surely continue.

Other aviation innovations include diagnostic systems to improve maintenance efficiency, GPS and inertial guidance systems for navigation, and sophisticated in-flight entertainment systems. Topics currently being researched include greater incorporation of systems to monitor aircraft status, performance and condition (the Boeing 777 already records information on 700 flight parameters eight times per second) and software to permit greater assistance in dealing with component failures. Another goal of both government and industry is to achieve similar capabilities for general aviation at an affordable price.

In the world of marine transportation, as well as in general aviation, perhaps the most visible innovation has been the availability of precise position determination through the Global Positioning System (GPS). A valuable aid for the weekend flyer or boater, this system, coupled with digital charts, provides a dramatic increase in accuracy over previously-used systems for commercial shipping. Coupled with the high degree of operational automation now found on large ships and convenient satellite-based global communications capability, the result is a significant gain in efficiency and safety.

There are other localized applications of cybertechnology, now benefiting greatly from increased computing power, that are finding widespread use in the transportation sector as well. These includes computer-aided design and manufacturing systems, and various types of simulation. These tools are of great value in the design and preliminary analysis of new vehicles. Boeing linked 1,700 individual workstations and four mainframe computers to support the design of the 777 airplane, with additional connections to suppliers in a dozen countries. A similar approach has been widely adopted in the automobile industry, contributing to a substantial shortening of the time required to bring out new models. Tomorrow's computers will be able to perform structural and biomechanical crashworthiness analyses of sufficient reality to reduce significantly the number of cars sacrificed in crash tests. And highly sophisticated simulators for operator training and research are being used to enhance safety and reduce cost across the modes–aviation, marine, rail and highway.

System-Level Applications

Autonomous cybertechnology applications during several decades have already significantly affected the safety, efficiency, convenience and performance characteristics of many elements of the transportation system. But the real impacts, only now beginning to be realized, lie with effective linkage and use of these technologies to integrate and manage the use and operation of transportation systems. Many preconditions and challenges delay the rate at which the system-level applications can be implemented. Among these, four particularly important factors are: (1) widespread (if not universal) deployment of the technology and a basic level of user familiarity; (2) a comprehensive understanding both of how the organization or system operates, as well as of how functions and processes should be changed in order to exploit the capabilities of the technology; (3) goals which are realistic in terms of current technologies and organization or system characteristics; and (4) an organizational infrastructure to maintain the technology and databases, support users, and provide the continual software-based refinement and evolution that is one of the strengths of cybertechnology. To a growing degree, successful system applications also require that the users and customers possess sufficiently mature and compatible systems, data definition and transfer standards, and security protocols.

The story of GPS in civil transportation suggests how cybertechnology-based systems often evolve from initial autonomous applications. Implementation of the Global Positioning System was carried out by the Department of Defense to meet its mission responsibilities. This resulted in the virtual universal availability of satellite signals that could provide to anyone position information considerably more precise than any other general-coverage system, with no cost to users. As equipment manufacturers were able to bring down the initially-high price of receivers, driven by the growing market as well as advances in digital technology, GPS was rapidly adopted in general aviation and the boating community at large as a highly beneficial tool for navigation. From their perspective, it is a stand-alone (autonomous) system.

At the system level, trucking and delivery firms began to couple GPS with satellite or cellular communications systems and apply it to fleet management, which could then be better coordinated with overall logistics systems as well. State highway and transportation departments are now using GPS linked to Geographic Information Systems (GIS) to maintain necessary facility databases and other functions. The Federal Aviation Administration is currently developing augmentations such that GPS, along with advanced communications capabilities, can form the basis of the nation's air traffic management system. This concept includes links to airline operations units, detailed localized weather information, and other resources and entities. When completed, it will be a single overarching system, coupled to an even broader global system, that enables safer and more efficient air transportation operations shaped cooperatively by air traffic controllers, flight crews, and airline dispatchers.

This story is merely one illustration of a process that is recurring in an almost unlimited number of variations. One of the characteristics of the early 21st century will be the near universal evolution of objects of all kinds into "smart" objects. It will be possible, at low cost, to incorporate substantial digital memory, processing power, sophisticated algorithms, communications capability, and many sensors, including GPS, into almost anything. Insofar as vehicles, transportation infrastructure, and individual travelers or purchasers of transportation services are concerned, this development holds the promise of improving the performance, efficiency, safety and convenience of transportation. Highway and transit system traffic management centers, drawing on various technologies for comprehensive monitoring of system status and performance, will similarly be able to achieve substantial improvements in capacity and uncongested flow.

The "bottom line" in transportation generally represents a balance between cost and service. Cybertechnology can affect both strongly. The acquisition and processing of operational and financial data coupled with direct links among all elements of the organization and externally to suppliers and customers yields productivity gains, greater efficiency, better resource allocation, and tighter integration among the many processes and activities that cumulatively produce transportation services.

A detailed understanding of system operations also enables the design and implementation of innovative operational concepts and practices. The overnight package delivery service, for example, could hardly exist on its present scale without myriad computers, digital tags, and extensive communications links. It is difficult to conceive of operating the Nation's commercial aviation system – with well over one million airliner seats to be filled daily at market-driven prices for several thousand origin-destination city pairs – without the technology that underlies and links modern computer reservations systems.

More recently, cybertechnologies have begun to transform the interface between the service provider and the customer or user. The implementation of Intelligent Transportation Systems (ITS) includes as a basic component the provision of real-time status information for local highways and transit systems, potentially with guidance on optimal choices for any particular trip. Any individual with access to the World Wide Web can find the status of an overnight package in seconds. With a highly controlled and visible transportation system, manufacturers can safely integrate their suppliers into "just-in-time" production systems and tailor their outputs to short-term customer needs. The FAA plans an air traffic control system in which all parties – controller, crew, and airline dispatchers – have full access to the same information and can work collaboratively for efficient operational tactics, with the decision process supported by powerful automation aids having detailed information on current and projected system status.

Tagging of freight-carrying vehicles, containers, and of the cargo itself is revolutionizing logistic processes, as tags become capable of storing situation-specific data (such as container contents and destination) and of being interrogated over long distances – via satellite in some cases. A truck with an GPS-enabled tag and cellular or satellite communications capability can be tracked anywhere in the country, reporting the status of the vehicle and cargo wherever they go.

Cybertechnology and the Demand for Transportation

Consumption of transportation services is not generally an end in itself. The demands placed on the transportation system are shaped by the aggregation of the needs and desires of individuals and organizations for personal mobility and for the movement of goods and resources. How and to what degree those demands are met depends on cost, performance, convenience, availability and other attributes of the system, as well as various characteristics of the user. As noted above, cybertechnology will continue to have a major impact on the workings of system itself, and how users relate to it, thus generating continuing adjustments in travel demand. Less direct, but of potentially great long-term impact, are the myriad ways in which cybertechnologies are altering the need and desire to travel or transport goods, as well as the type of transportation utilized.

Telecommunications services are also playing another, potentially even more fundamental role: replacement of physical transportation. Telecommuting, teleshopping, video conferencing, and other "tele-substitutions" are already beginning to be a significant factor in shaping mobility and access needs and how they are met. The power of an individual to communicate readily with far distant organizations and services can provide access that otherwise would depend on the physical mobility of transportation.

There are several ways to view a film: by traveling to a theater, accepting what is available from television broadcasters, traveling to a video rental store, or staying home and ordering a specific choice for direct cable delivery. A trip for a business meeting may be replaced by a joint telephone call or video conference, and personal purchases may be made by traveling to a store, or by ordering (over telephone, TV or Internet) and relying on a delivery service. A trip to the bank, long since replaced in many instances by visiting a local ATM, may soon be eliminated by "smart cards" reloaded with electronic cash on a home personal computer.

Aided by Internet-linked computers, fax machines, and on-line services, a growing segment of the population is finding it feasible and preferable to work from home, either as a telecommuting employee or as a contractor proprietor of an independent business. (On the World Wide Web, one can hardly distinguish between a large multi-national corporation and a one-person enterprise.) Many other types of "tele-substitution," ranging from tele-medicine and tele-education to nation- or globe-spanning videoconferences, will likely have a significant cumulative impact on the amount and nature of transportation demand. "E-commerce" – the purchase of goods ranging from books to automobiles over the Internet – is expected to continue its current rapid growth for many years to come. One can easily imagine that in just a few years a large portion of the public will have constantly available to them – presumably in only one or two devices – the functions of cellular phone, pager, electronic book, digital and personal calendar and database, GPS location-determination, and e-mail and other Internet access.

The consequences of these and many other economic and societal changes partly enabled or stimulated by cybertechnology can only be guessed at. As perceived by individuals, the transportation implications of each new capability will generally be secondary to convenience, economic or business considerations. But the associated continuing societal adaptations and changed behaviors will almost certainly be reflected in significant impacts on transportation. Many of these changes are not of a type that is readily captured in traditional transportation measures and indicators. Assessment of what is happening is still subjective and largely anecdotal and speculative. Many projections of the future offer a possibly exaggerated or misleading picture of a coming "cyber-society." But there is an underlying reality to the magnitude and pervasiveness of these changes that suggests a future world which will look significantly different, in its transportation characteristics as well as other areas.

Digital Building Blocks - The Key Elements of Cybertechnology

Information is coming to exist almost entirely in digital form – captured in strings of zeros and ones, thereby permitting levels of precision and freedom from transmission error unattainable with the analog technologies of earlier years. Exploitation of the power of digital communication and information processing is an essential characteristic of many cybertechnology applications.

Most transportation uses of cybertechnology depend upon the often-transparent and inseparable integration of multiple specific technologies and functionalities. Cost and performance improvements in any one such technical area often enable a broad range of new applications or services. The potential for cybertechnology to affect mobility and access in modern society is rooted in a small set of building blocks, both technical and institutional:

- Telecommunications
- Computer Hardware and Software
- Navigation and Positioning Systems
- Sensors, including Monitoring, Surveillance and Tagging Technologies
- Data Exchange and Fusion Capabilities
- Standards–Interoperability, Security, Transactions
- Principles and Knowledge to Guide Design of the Human Role and Interface

Telecommunications

One of the most visible aspects of the information revolution is the ease and economy of using telecommunication services. The advent of satellite-based and fiber optic communications channels, cellular telephone systems, and network linkages epitomized by the Internet have made a reality of "anywhere-to-anywhere" high-bandwidth communications, often at a remarkably low cost. Global exchange of voice conversations or virtually any kind of digitized information are typically as convenient and almost as inexpensive as the local telephone calls of a generation ago. The explosive growth of the Internet, in terms of both users and total usage, illustrates on a global scale how readily individuals and organizations can exploit the ability to communicate and tap diverse information sources. Making real-time operational information available throughout a transportation system, no matter how geographically dispersed, and combining it with data from other sources carries powerful benefits for operators, managers and users.

While communications functions are generally thought of in terms of long distances, a very important subset of this function is electronic data interchange (EDI). This can occur over a very short-range: between trucks and wayside inspection stations, highway vehicles and toll collection stations, or cargo containers and port logistics systems.

Computer Hardware and Software

In the half-century since the invention of the transistor, the field of solid state electronics has produced minuscule devices having processing power comparable to that of the supercomputers of only a short while ago. The building blocks described here all have their roots in highly sophisticated data processing. The technology is still advancing at a pace that often exceeds the ability to apply it. Both microprocessor power and circuit density continue to double every eighteen months, with comparable growth in the storage capacity of memory devices. The Defense Advanced Research Projects Agency has estimated that computational power per unit cost, which increased by about 20% annually during the first half of the 20th century, is now more than doubling every year, growing 4000-fold in a decade[15].

This many-orders-of -magnitude reduction in the cost of computing power already permits the inclusion or embedding of highly sophisticated sensors and computer-based control systems in "smart" consumer items from automobiles to washing machines. "Smart cards" that can include the functions of credit and ATM card, identification card, transit pass, and even "digital cash." are now becoming common. Incorporation of GPS receivers, pagers, cellular phones, and other communication functions (including those based on stand-alone satellite links) is increasingly practical and affordable.

The immense processing power can be used for complex functions such as pattern recognition, generation of speech and images, data storage and retrieval, use of highly sophisticated algorithms for traffic control and management functions, and complex simulations of operational systems. Enormous data bases can be already accessed directly using compact disc storage technology, with dramatic further advances anticipated in the near future. Concepts of artificial intelligence, expert systems, automated language translation and fuzzy logic have long been a source of exaggerated claims, but these expectations are becoming more realistic as processing power increases, and are likely to yield very powerful innovations.

Navigation and Positioning Systems

Navigation has always been central to long-distance transportation, particularly for marine and aviation modes. From the sextant and chronometer to the radio-based systems of the present (e.g., RADAR, radio beacons, OMEGA, and LORAN), improved means of determining position have been critical advances in transportation. Other techniques used singly or in combination – such as automated beacons, gyroscope-based inertial navigation, and even sophisticated dead reckoning – increase the tools from which the system designer can choose. Navigation has been transformed by operational availability of GPS, which now makes convenient real-time three-dimensional position information available throughout the world with great accuracy and at low cost.

As the practical precision of these technologies has improved – dropping from hundreds of meters or more down a meter or less – and prices fall, new transportation and other applications become potentially feasible. Examples include route navigation for highway vehicles and

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[15] Quoted in *The Road to 2015,* by John L. Peterson, Waite Group Press, 1994.

landing aircraft under zero-visibility conditions. Many applications involve position determination equipment on the vehicle communicating (often via satellite links) to a central computer for fleet or traffic management functions. Precise knowledge of location can support functions as disparate as placing and retrieving containers in a port storage area, identifying the whereabouts of a stranded motorist for response vehicles, and assuring safe separation of trains on shared tracks.

Just as 18th and 19th century navigators needed astronomical almanacs in order to use a sextant and chronometer to derive their position, GPS and other modern systems fulfill their potential only in concert with digital maps of high precision, based on a standardized geodetic reference system. More generally, Geographic Information Systems are finding many applications in transportation, where they support operational, maintenance, planning, system analysis and other functions used by individuals, commercial users, and public agencies. In some applications multiple technologies are combined to achieve satisfactory positional precision, reliability and integrity, as GPS is coupled to inertial techniques.

Sensors, Including Monitoring, Surveillance and Tagging Technologies

Many cybertechnology applications in transportation depend upon a vehicle being able to characterize its environment, or on the ability of some element of the fixed infrastructure to identify and exchange information with vehicles, cargo or individuals. High performance computer chips and sophisticated pattern recognition software can increasingly carry out complex sensing and surveillance tasks. For example, closed circuit televisions connected to pattern-recognizing computers are monitoring freeway traffic to detect incidents and congestion and identifying tagged freight cars. Aircraft are continually exchanging identification numbers, altitude and other information with the air traffic control system.

Another aspect of surveillance is the use of vehicle-mounted sensors such as radar coupled to computers and displays to detect potential hazards, provide warnings, and suggest responses. Collision-avoidance systems of this type have been used in aircraft for many years. Federal and corporate research programs are currently applying the same concept to highway vehicle crash prevention.

Standards–Interoperability, Security, Transactions

As more and more human activities are based on a pervasive digital information and communications infrastructure, the need for standards – whether industrial or governmental, voluntary or binding – becomes greater. Many apparently attractive transportation applications can be thwarted, or substantially reduced in impact, if there are delays in establishing agreements addressing such topics as operating frequencies, data exchange protocols, digital tag characteristics, and spatial data references.

Data Exchange and Fusion Capabilities

Above and beyond supporting specific transportation functions, one product of cybertechnology is a much more "knowledge-rich" system in which both users and providers can make decisions and perform tasks on the basis of a greatly enhanced understanding of the likely consequences. The effective combination of often-disparate information from diverse sources is central to many cybertechnology applications, including real-time operations, inventory and process management, system characterization, and other user services. This has led to the new discipline of "data fusion"– the design of computer systems that can facilitate convenient, flexible and adaptable blending of information from a wide range of independent sources.

Technology of the Human Role and Interface

Most cybertechnology applications ultimately involve direct interactions with humans in entering instructions or requests and receiving and acting on outputs. The performance and ultimate success of cybertechnology applications depend very strongly on the effectiveness of their link to the humans interacting with it. The presentation of information to operators and users, the partitioning of roles among humans and automated systems, and the overall ease, convenience and flexibility of operation all can be critical to system safety, performance and acceptability.

While most often thought of in terms of graphical display of text and images, either printed or on a screen, this interface function now includes speech recognition and synthesis devices, head-up displays for vehicle operators, simulated three-dimensional presentations, and interfaces to facilitate use by visually handicapped individuals. Emerging technologies include various types of biosensors, such as those that check user identity by fingerprints or retina patterns, and systems that detect and act upon indications of user inattention, impaired performance, or other characteristics. Graphical displays can now provide strong three-dimensional effects, and "virtual reality" systems enable a direct linking of user motions to the image displayed.

Some of the less visible advances in the relationship between system and user involve software, such as the powerful search engines found on the Internet and elsewhere, context-sensitive help functions, and adaptive displays of suggestions or options based on prior experience with a particular situation or person.

Special Characteristics of Cybertechnology

The application of cybertechnologies differs in important respects from the traditional means by which new propulsion, vehicle and physical infrastructure technologies have been incorporated into transportation operations. This is in due part to the inherent nature of cybertechnology, and in part to its role in transportation. Special characteristics that shape the evolutionary process include the following:

- *Rapid Technical Evolution.* Driven by very broad markets across all economic sectors, information technology is developing very rapidly–dropping sharply in cost while simultaneously increasing in performance. While these tendencies are currently present in many areas of technology, the rate has been far greater for cybertechnology. Not only are the basic information technologies advancing, but understanding of how best to use them is also a significant continuing source of improvements in itself.

- *Rapid Implementation.* Implementation or application of cybertechnology in transportation focuses largely on the ways in which the existing physical system, such as vehicles and infrastructure, are used, and what services are provided. The physical elements of cybertechnology can be introduced relatively rapidly in comparison to the typically very lengthy lifetime of vehicles and structures.

- *Process Re-engineering.* Cybertechnology generally involves changes in how a system operates. Thus, realization of significant benefits from the introduction of hardware or software typically calls for redesign of operational processes throughout the enterprise, accompanied by a substantial redefinition of work functions. As for all innovations, the pace of change is determined primarily by the ability to incorporate the new technology. But cybertechnology is so pervasive and cross-cutting that the required level of organizational change is particularly great – as widely experienced in the more general infusion of cybertechnology into business activities of all types during the last two decades.

- *Incremental Implementation and Continuous Evolution.* The rapid technical evolution of cybertechnology, and its primary role as an enabler rather than a replacement for existing hardware, implies that systems not only can evolve continuously, but are also virtually required to do so. This is in contrast to the spurts of innovation typically associated with periodic injections of new technology, such as the diesel locomotive or jet aircraft. It is often misleading to think in rigorous terms of an "end state" system, or to seek to introduce new technology on the basis of sequential requirement analysis, design, and implementation. A better model is the rapid prototyping approach found in the software world, and an iterative process of "design a little, build a little." Indeed, major changes based on cybertechnology often occur incrementally and almost unintentionally, as when specific technology elements – often introduced as a minor conveniences – evolve into critical tools or business necessities.

- *Ubiquitous Applications.* The information technologies applied in the transportation sector are generally those also used across the economy and society for an enormous range of purposes. This characteristic has provided the broad markets that sustain the observed high rate of improvement in cost and performance characteristics, and also facilitates the large-scale integration and optimization across the transportation enterprise and with other sectors.

- *Unpredictability of Consequences.* Attempts to predict the rate at which various cybertechnology capabilities will be incorporated into personal and commercial life have often fared badly. Issues of cost, technical challenge, and absence of a true market need have often disappointed the advocates of presumed advances. Video telephones and personal-service robots have been waiting in wings for decades. Major corporations have suffered grievously from unrealized expectations about the relative roles of mainframes, mini-, and desktop computers. On the other hand, the cellular telephone, the fax machine and the Internet represent areas that – after hitting a threshold of capability, cost and installed base and infrastructure – surprised many observers by the suddenness with which they became virtual necessities for many people and organizations. The long-term growth of tele-work –

employees or self-employed individuals working primarily from home or a remote work-center – remains as difficult to predict as it is to measure.

Cybertechnology impacts can arise in circuitous ways. The initial focus of the ubiquitous bar code – the Uniform Product Code – was simply improved speed and accuracy in accomplishing retail sales transactions. Success in this effort led to linkage of point-of-sale computers (no longer simple "cash registers") to price and inventory data bases (which may be at a distant central location) and supported a shift to greater reliance on "just-in-time" logistic practices. The next step was sophisticated individualized marketing strategies based on the combination of purchase data with information about the specific consumer. Parts of this information infrastructure now can also facilitate development of remote computer-based ordering via Internet, coupled to home delivery – a step that, if commercially successful, has significant transportation implications.

Trends, Challenges and Issues

Trends and Outlook

The consequences of cybertechnology will ultimately be determined by a complex merging of societal forces, markets, and personal preferences and needs which renders specific predictions highly uncertain. However, some clear trends are apparent:

- *Better Technology.* Cybertechnologies will continue to be characterized by steadily improving performance and declining prices, spurring aggressive development of wider applications, accompanied by a steady stream of new products, services and capabilities.
- *Maturing User Community.* User familiarity with explicit and embedded cybertechnology in products and awareness of information resources will continue to increase, including access to the Internet and other communication media. This will enable a continued high pace of innovation.
- *Universality of Cybertechnology.* Cybertechnology elements are likely to become so universally used and deeply embedded in "smart" products and systems as to be almost invisible to users and no longer identifiable as separate items. The distinction between "technology" and "cybertechnology" will have little meaning, and may well fade from use.

Challenges

Change is inherently difficult, whether at the level of the individual, organization or society. Within the broader challenges of dealing with a rapidly changing world, the effective and efficient application of information technologies to meet mobility and access needs will require resolution of a wide range of difficult institutional, economic and technical issues:

- *Technical Interfaces and Institutional Coordination.* The ubiquitous nature of cybertechnology and its applications ultimately involves links among virtually all elements of the transportation system and even society. Establishment of technical and procedural interoperability and ready exchange of data across applications, technologies, economic sectors, national borders and other interfaces, remains an enormous challenge. The relentless advance of these technologies exacerbates this problem, which often occurs more rapidly than can be dealt with by means of existing institutional arrangements.

As straightforward a task as the creation of a cellular telephone system in which the same unit can be used throughout the country has proven to be very challenging. The ultimate benefits of transportation applications such as vehicle-based traveler information systems, paperless crossing of state and national borders, or electronic toll collection depend on the universality of their application. Always a difficult subject, standardization becomes particularly complex when technology is developing rapidly and affects a wide range of applications.

- *Security and Reliability.* New technologies and operational concepts inevitably contain within them new vulnerabilities. It is rarely possible to anticipate and characterize these risks sufficiently to avoid or mitigate them totally in advance. Cybertechnologies raise many challenges such as protection against malicious attacks on critical information technology, data security, and software reliability. Complex challenges arise in the establishment of security processes that will ensure the confidentiality and validity of digital transactions. The economic forces that drive transportation can function only with effective mechanisms for paperless on-line commercial transactions.

- *Continuous Technical Evolution.* Rapid technological advances pose a severe challenge in the development of large systems, which can easily become technically obsolete by the time final implementation occurs, and for which upgrading to incorporate new technologies can be very difficult. The long service life typical in transportation vehicles and infrastructure exacerbate this problem. While cybertechnology offers the potential to achieve continuous system evolution through ongoing software upgrades and replacement of electronic modules, it is still difficult to achieve design and development processes that effectively accommodate the on-going insertion of improved technology and software rather than focusing on discrete periodic major upgrade and replacement programs.

- *Centralization vs. Decentralization of Control.* The application of cybertechnology to transportation systems generally results in the availability of detailed real-time operational status information, powerful data processing capabilities, and immediate communication throughout the system in question. The allocation of roles and responsibilities between centralized controllers, vehicle operators and others then becomes a conceptual design choice, rather than an automatic consequence of technical constraints. It is possible to have (1) a highly centralized system, (2) relatively autonomous behavior by system elements (such as aircraft, ships or road vehicles), or (3) a combination. For example, infrastructure managers (e.g., air traffic controllers), vehicle operators (flight crews), and fleet dispatchers (airlines) might work collaboratively to make joint decisions. In doing so, each party could have full access to the same comprehensive database and an array of tailored automated decision aids.

- *User Interfaces.* A widespread dilemma for users of information technology is extracting the key information needed from a vast data reservoir. Presentation of the right information at the right time, in an easily perceived form, can be critical to safety and to operational efficiency. Whether serving an airliner flight crew, a transit system rider, or someone seeking road condition status or making travel reservations on the Internet, achievement of user interfaces that take full advantage of the value inherent to the information will be critical to the success of many cybertechnology applications.
- *Workforce Skills.* As the technologies upon which transportation depends expand, bringing with them new services and operational concepts, significantly different skills and knowledge will be required of the people who plan, operate, maintain and manage the system. A high rate of technological evolution will severely stress the conventional processes by which workers have always adapted to change.
- *Benefit-Cost Analyses.* An innovation principally characterized by direct cost or performance improvements – e.g., a more efficient engine, a shorter route, or a less labor-intensive process – is reasonably amenable to estimation of the likely costs and benefits associated with its introduction. However, many cybertechnology applications in transportation involve new services or different ways of using the system, and the string of deployment requirements and practical consequences becomes substantially more difficult to quantify. For example, the decision to invest in creating an urban traffic management, user information or container tracking and asset visibility system could be delayed by uncertainties over the magnitude of attainable benefits or difficulties in defining suitable performance specifications to support an acquisition process.

Issues

Innovation brings not only challenges, but also true issues – topics for which the choices depend not only on technical and quantitative factors, but also on the perspective and values of the people involved. The pace and completeness with which these issues can be resolved will play an important role in shaping the nature, pace and effectiveness of cybertechnology applications in transportation. Some of the more general issues to be faced are as follows:

- *Allocation of Costs.* Significant costs are entailed in providing several critical and widely used elements of the transportation information infrastructure. Examples include the Global Positioning System, comprehensive weather information, and the Internet. To the degree that a small number of entities is responsible for their funding while many users share the benefits, investments in advancing the technology and its use may be less than warranted and not optimally directed. Although this is partially a question of developing cost allocation mechanisms, parties can differ widely over the value of the services and their willingness to pay.
- *Information Access vs. Privacy.* The value to the transportation enterprise and public agencies of many types of operational and economic data, including results of automated sensing and surveillance, can conflict with the desires of businesses and individuals for confidentiality and privacy.

- *Equity*. Individuals with access to information technology, very often by virtue of wealth or education, could have a growing advantage over those without such access. The net effect, in terms of mobility as well as other areas of life, is likely to be an intensification of inequalities.
- *Federal Role*. To a large degree, the introduction of information technology into transportation is the responsibility of the private sector and state and local governments, and market forces are often the best mechanism for determining the value of new technologies. However, some elements – GPS, for example – inherently have a large Federal component. There also is a clear need for a facilitation and stewardship role – objective analysis, support for standard setting, stimulation of invention and innovation, and prototype demonstration of concepts with substantial potential for public benefit but of uncertain market success – that might best be realized at the national level. In an age of tight public sector budget constraints and lean businesses, where is the line to be drawn?