CHAPTER 5

Cross-Cutting Technologies for Infrastructure

Photo credit American Consulting Engineers Council

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CHAPTER 5

Cross-Cutting Technologies for Infrastructure

. . . infrastructure choices [including technologies] are choices of resource allocation [and] must be dealt with in the political arena.[1]

Technologies for public works have come a long way since the days of open sewers and roads made of stones embedded in the soil; and the technologies and materials available to designers, construction engineers, and managers continue to evolve. As the need to maintain and repair the Nation's infrastructure becomes more acute and the value of greater efficiency and higher operating standards grows, advances in technology and materials can provide many opportunities to save time and money for public works. Most technologies are applicable to more than one type of infrastructure, and the most useful of these cross-cutting technologies for public works may be clustered into the following general categories:

- measurement and nondestructive evaluation tools,
- information and decision systems,
- communications and positioning systems,
- field construction technologies, and
- materials and corrosion.

These categories are not new, but a number of technological advances have led to devices and systems of remarkable versatility, precision, and power that can decrease costs and increase reliability. This chapter describes some of the most useful technologies for infrastructure and discusses the reasons that many of them are used today in private industry, but have not yet found wide application in public works.

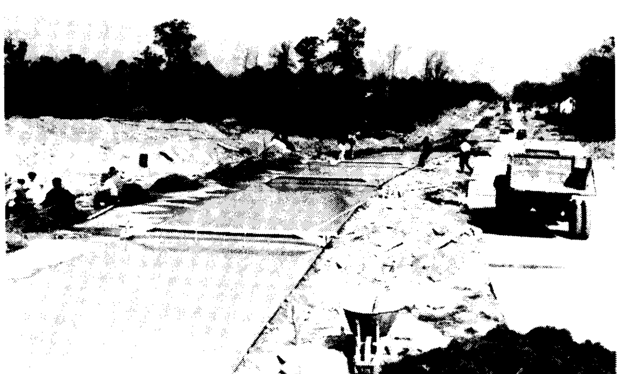

Photo credt: Library of Congress

Today's technologies make this nonmechanized highway construction project of the 1940s look outdated.

Measurement, Instrumentation, and Nondestructive Evaluation Tools

High-speed, noncontact, sensing technologies—radar, infrared thermography, laser optics, ultrasound, and others-make it possible to survey hundreds of miles of pavement, piping, or a number of bridge decks with great accuracy in a single day. The applications already commercially available or under development include radar to detect pavement voids, infrared thermography to identify delamination in concrete bridge decks, automated imaging and image processing for high-speed surveys of pavement surface distress, and lasers for evaluation of pavement profiles and continuous measurement of pavement deflection.[2]

Sensors and Measuring Instruments

Today's advanced sensors, made smaller and more accurate by silicon microchips, include ultrasound, fiber optics, and infrared optics. Radiation, sound, temperature, moisture, pressure, and other phenomena can be measured with a high degree of precision using appropriate sensors.

However, the major areas stimulating new sensor development include advanced manufacturing, power generation, security, waste technology, and environmental protection, rather than public works.[3] Sensitive electronic devices do not function well under the adverse operating conditions-including dirt, humidity, temperature and pressure extremes,

[1]Scott Johnson, comments, in Royce Hanson (ed.), *Perspectives in Urban Infrastructure* (Washington, DC: National Academy Press, 1984), p. 171.

[2]Kenneth R. Maser, "From Guesswork to Guarantee?" *Civil Engineering,* vol. 59, No. 9, September 1989, p. 78.

[3]Kenneth B. Steinbruegge, "New Sensors for Today's Industry," *Design News,* vol. 42, July 7, 1986, p. 109.

and the presence of harsh chemicals-that characterize much of public works. Nonetheless, a number of sensors have been developed that can monitor under such conditions. For example, detecting leakage or the chemical composition of fluids in large public works systems, such as drinking water and wastewater treatment plants, has been made easier by advances in sensor technology for detecting fluid content and flow rates.

Remote sensing, automated control, and measurement instrumentation can enhance marine dredging operations. A position indicator coupled with an automatic control system to orient and position equipment precisely can increase dredging efficiency and reduce the amount of material dredged unnecessarily. Modern instruments used to measure material flows and partial automation of maintenance dredging can reduce annual costs by 40 percent.[4]

Automated railroad track measurement, using equipment mounted on railcars, can give dynamic measurements of track geometry under loaded conditions. Using electro-optical or electromagnetic sensors coupled with inertial sensors, the equipment measures and records such parameters as track location, gage, profile, alignment, and crosslevel. Such systems provide repeatable track geometry measurements at close intervals in a fraction of the time required by track walking crews measuring at longer intervals.[5] These data can be fed into computerized maintenance planning tools, which can identify and set priorities for needed track maintenance. "Smart sensors," which indicate their own breakdown, will enter the market soon, Table 5-1 provides information on other major types of sensing technologies for public works.

Japanese manufacturers have made wide use of pressure sensors on computer-controlled machine tools, hydraulic robot limbs, and vacuum-assisted picking tools.[6] Sensitive pressure sensors, implanted in robot "hands,' can make machines more tactile, while optical sensors enable robots to discriminate among the patterns that are being examined. Research and development (R&D) is under way to develop micromachined sensors that would measure acceleration and vibration of machinery. Although these sensors can be very useful in especially hazardous construction or maintenance activities, much of the public works environment is too harsh to make use of such sensitive equipment reliable and cost-effective.

Nondestructive Evaluation (N DE)

NDE describes any method of examining the physical or mechanical properties of a structure or component (pavement or a machine part) without affecting it permanently or significantly. Human inspection is the most common NDE method. More automated inspection tools include visual, optical, liquid penetrant, magnetic particle, eddy current, ultrasonic, radiography, and leak detection techniques. Widely used in industry, nondestructive testing instruments have become very powerful, especially when coupled with microprocessors. Because they can improve productivity, NDE instruments are becoming indispensable for automated inspection in computerized manufacturing plants. Computers are now being interfaced with NDE instruments from every category, including those used for public works.[7]

No single NDE method is appropriate for all types of materials, structures, and types of damage. Some methods are suitable for detecting surface cracks, others for examining deep within structures, although resolution deteriorates the deeper one looks inside a structure. To minimize error, many methods may be used in combination to determine a structure's condition. Field conditions such as changing weather, moisture content, and shock waves from moving vehicles also make nondestructive testing of public works extremely difficult. Moreover, heterogeneous materials, such as the asphalt and concrete widely used in infrastructure are relatively difficult subjects **for NDE. The judgments of trained experts are still needed to determine infrastructure condition, because NDE, particularly for public works, is not yet a purely scientific process.**[8]

[4]National Research Council, Co remission on Engineering and Technical Systems, Marine Board, Dredging *Coastal Ports* (Washington, DC: National Academy Press, 1985), p. 112.

[5]Public Technology, Inc., "Track Geometry Measurement System,'' *Transit Technology Briefs,* vol. *2, No. 3,* fall 1982.

[6]Steinbruegge, op. cit., footnote 3, P. 30.

[7]John E. Dwight, "NDT Is Changing—Slowly But Surely," *Quality, vol.* 27, No. 1, January 1988, pp. 20-22.

[8]John Broomfield, Strategic Highway Research Program, personal communication, Aug. 9* 1989.

Table 5-l—Measurement Technologies for Public Works

Physical property	Technology	uses	Comments
Surface pressure	Silicon crystal-based sensors	Truck weighing systems for highways; robotic handling devices	Applications limited because sensitive equipment cannot tolerate harsh public works environment.
Temperature	Fiber optics; infrared detectors	Process control if temperature is a factor; pavement inspection equipment; overheating	
Fluid properties	Moisture sensors: electrolytic cell, aluminum oxide, and chilled mirror; pressure wave viscosity sensor	Treatment plants and pipe networks; treatment plants for chemical composition	Limitations in harsh and rapidly changing environments.
	Infrared optical sensors	Detect presence and amount of organic materials in treatment plants	Expense limits use in public works.
	Chromatography	Chemical composition of liquids and gases	Used in various environmental public works testing activities.

SOURCE: Office of Technology Assessment, 1991.

Sound waves are frequently used NDE methods. A simple procedure to determine flaws in relatively thin pavement areas, such as bridge decks, is to drag a set of chains across suspect areas. A loud, drum-like sound results if delamination, or separation of the pavement into layers, has Occurred.[9] More advanced techniques involve transmitting ultrasonic waves through target materials or test structures and measuring the echo response as the waves bounce back.[10] Ultrasonic devices have benefited from advances in circuit design on silicon chips, and portable devices that produce high-frequency sound waves and accurately record the signals from the tested object have become common. A commercially available, ultrasonic instrument tied to a microprocessor is being used for testing corrosion cracking in pipes.[11]

Tagged materials are a promising method for NDE in the future. If detectable particles are embedded in concrete and other materials, inspectors can quickly trace structural changes over time. Magnetic detection devices can be used to examine the density distribution of embedded particles; damaged areas show changes in the average distribution of the particles.[12] Sonic devices emit a sound wave into the structure and measure the vibrations of the embedded particles. The particles in damaged material vibrate more than those in solid concrete, and a different echo is produced.[13] Table 5-2 summarizes a spectrum of current NDE methods suitable for public works.

Photo credit: American Consulting Engineers Council

Nondestructive evaluation methods, such as ultrasonics, help inspectors determine the physical condition of bridges or other structures without affecting them permanently.

Public Works Experience

Measurement and nondestructive evaluation tools are most useful for relatively homogeneous materials and in controlled operating environments. Under other circumstances, including many typical infrastructure environments, the most sensitive NDE

[9] Ron Frascoia, Materials and Research Division, Vermont Agency of Transportation personal communication, Aug. 10, 1989.

[10] Jim Murphy, Materials Division, New York Department of Transportation personal communication, Aug. 9, 1989.

[11] Robert H. Grills and Mike C. Tsao, Nondestructive *Inspection With Portable Ultrasonic Imaging System,* Special Technical Publication No. 908 (Washington DC: American Society for Testing and Materials, 1987).

[12] Ivan Amato, "Making Concrete *Smarter Than* It bolts," Science News, vol. 135, May 6, 1989, p. 284.

[13] "Vibrating Iron Particles to Sound Out Problems," *Engineering News Report, vol. 223, No. 2,* July 13, 1989, p. 15.

Table 5-2-Nondestructive Evaluation Techniques for Public Works

Technique	Use	Comments
Ultrasonic waves	Detect flaws in pavement, voids in materials.	Used for lockand dam inspections, up to 30 foot within a structure.
Impact echo	Detects flaws by measuring structural strength of materials.	Requires access to only one side of structure.
Radiographic (x-ray radiation)	Detects flaws on materials and machinery.	Requires access to both sides of subject material; involves high-energy radiation, well-trained technicians, and safeguards.
Eddy-current method	Detects flaws at or near surface of electrically conducting materials.	
Magnetic particle	Detects surface cracks of ferrous materials.	Very reliable.
Liquid penetration	Detects small discontinuities on a solid surface.	Useful for nonmagnetic materials.
Infrared thermography	Detects surface flaws in almost all materials.	Can detect voids and cavities around sewer pipes as well as delamination and cracks in bridge decks.
Ground probing radar	Detects subsurface voids.	Requires trained specialist to interpret recorded data.
X-ray fluorescence	Analyzes chemicals in solids and liquids.	Commercially available equipment is highly specialized and expensive; not widely used in public works.
Electronic acoustic sensor	Detects leaks in underground pipes or tanks.	Used in New York City, which has an old water system.
Fiber optic probes	Detect leaks, surface flaws, and other conditions.	Monitors provide visual information; machine (or robotic) vision can be used to detect surface flaws.

SOURCE: Office of Technology Assessment, 1991.

techniques are much less precise.[14] Moreover, many newer technologies, such as infrared thermography and laser impulse interferometry, are still too expensive to be used routinely in the field. Furthermore, the expertise required to operate the sophisticated equipment and analyze the test results is beyond the capabilities of most State departments of transportation (DOTS) and municipal water and sewage agencies.

Nevertheless the technologies hold great promise for many public works applications. Highway researchers envision an NDE system combined with information technology to record dynamic changes in structures and predict reliably when bridges and roads need repair or rehabilitation. Cost-effective, nondestructive life prediction systems may be available within the next 5 years to help less experienced inspectors predict structural life and plan for operations and maintenance costs. However, the initial costs of these new technologies will be relatively high.

State Programs

New York State has one of the most advanced nondestructive testing programs in the United States,[15] but it is not linked to an advanced information system. To detect flaws in metal structures, the New York DOT has used. eddy current, magnetic particle, and x-ray radiography techniques and is experimenting with thermography, radar, and ultrasound for checking pavements. Bridge decks are subjected to electrochemical analysis to detect corrosion, and the agency uses the chain drag method to determine delamination. However, the State DOT cannot afford to purchase and maintain the necessary NDE equipment, so it contracts with private firms to perform the tests, and it does not have total cost estimates for its NDE activities.[16]

The Vermont agency for transportation does its own inspection of transportation infrastructure, and contracts out as well. The agency estimates that its direct cost for conducting an in-house, predominantly manual, bridge deck evaluation is 5 cents per square foot, compared with 15 to 20 cents per square foot for infrared evaluation done by a private firm. However, bridge traffic is not interrupted during the infrared evaluation, justifying its higher costs.

The Pennsylvania Department of Transportation's (PENNDOT) NDE program includes visual inspection, friction and skid testing, electrochemical corrosion detection, thermographic and radar testing, and underwater sonar testing. PENNDOT also

[14] Broomfield, op. cit., footnote 8.

[15] Ibid.

[16] Murphy, op. Cit., footnote 10.

utilizes information technology, maintaining computer databases of over 100,000 road segments and 54,000 bridges, and creating models to evaluate different management plans. Their software is available to other DOTS. The cartographic division at PENNDOT is developing techniques to use the TIGER geographical information system (GIS) for sustaining and expanding the infrastructure. Finally, PENNDOT is researching machine vision techniques and expert systems for pavement inspection and management.[17]

Information and Decision Systems

Management information and decisionmaking systems are already proving valuable tools for public works agencies where they have been implemented. The categories of these tools range widely and include artificial intelligence systems and decision models. Public works managers have found maintenance management systems and GIS particularly useful in their activities.

Maintenance Management Information Systems

Maintenance Management Information Systems are essentially database management systems that allow managers to set priorities and schedule preventive maintenance. The systems can track all maintenance activities (both scheduled and unscheduled) and work crews, materials, and time to repair data, permitting planning for future activities. Such systems are not new, but their application to public works infrastructure was slow until microcomputers became commonplace, and appropriate, user-friendly, and cost-effective software was developed.

Geographic Information Systems

GIS are computer systems designed to manage information related to geographic locations. They can also store, analyze, and retrieve large volumes of nongraphic data from other systems and display graphic map images and tie them to descriptive (nonnumerical) data from a specific location. The systems allow the user to enter, store, retrieve, manipulate, and display geographic information quickly and accurately; these decisionmaking aids are particularly valuable. See box 5-A for more details on these powerful and versatile tools.

Artificial Intelligence

Artificial intelligence uses computers configured to provide automated reasoning. Examples of technologies that use artificial intelligence are expert systems, computer vision, and robotics.

Expert Systems

Expert systems are computer programs that attempt to duplicate an expert's reasoning process to solve problems in a given field. Unlike conventional computer programs that process algorithms, expert systems use heuristics ("if-then" rules) to advise and guide users. Since they can be programmed to explain their reasoning, expert systems can be used as training tools to expand the expertise of a few specialists to a larger group of individuals.

Systems that could be useful to a public works manager include a computer model used in Canada to determine whether a contaminated industrial site can be cleaned up or whether the contamination poses enough of a health hazard to require permanent abandonment.[18] The expert system asks prospective users of the site a series of questions, such as what type of construction is planned for the site. The database includes information on the land users, possible land uses, more than 30 organic compounds, physical characteristics of soil types, and the underlying geological formation.[19] Prototype systems have been developed to assist in such areas as highway and bridge design, traffic operations and control, tra.file incident detection, urban sewer system design, and highway noise barrier design.[20]

Although organizations see expert systems as a substitute for trained or experienced specialists, very few sophisticated systems are routinely used today. The systems that are in use are devoted to training people about complicated procedures and to diagnosing complex equipment and system problems. Moreover, current systems address clearly structured conditions, and experts recognize that human

[17] Gary Hoffman, Pennsylvania Department of Transportation, personal communication Aug. 9, 1989.

[18] Dianne Daniel, "AI Decides Safety of Contaminated Sites," *Computing Canada*, vol. 15, No. 15, July 20, 1989, pp. 1-4.

[19] Ibid.

[20] U.S. Army Corps of Engineers, "Survey of the State-of-the-Art Expert/Knowledge Based Systems in Civil Engineering," USA-CERL Special Report P-87/01, October 1986.

Box S-A-Geographic Information Systems

A geographic information system (GIS) is a computer-based system designed to manage information with a spatial or geographic element. With geographic location as a basis, information (spatial and nonspatial, or attribute) pertaining to a particular location can be stored, analyzed, and retrieved A multipurpose GIS can meet many different local government needs and provides automated tools to enter, store, retrieve, manipulate, and display geographic information quickly and accurately. Scanning technology allows rapid capture of everything from old engineering drawings to recent aerial photos. Once entered into a GIS, information can easily be updated and redrafted by the computer in different scales and in different combinations as needed for day-to-day decisionmaking.

Related systems, computer-aided design and drafting (CADD) programs, also produce graphical displays, but are primarily used to create dimensional drawings, such as street plans and profiles, and nondimensional drawings, such as architectural renderings. CADD systems have links for database attributes, such as those of a GIS.

Photo credit: American Consulting Engineers Council

Computer-aided design and drafting (CADD) program speed the work of infrastructure planners designers, and structural planners. CADD programs can be used to create dimensional drawings, such as street plans, and nondimensional drawings, such as architectural renderings.

Automated mapping/facilities mapping (AM/FM) systems, also related to GIS systems, evolved from the need for numerous mapping products within local agencies. The needs include parcel maps at different scales, park and planning maps, tax assessment maps, real estate maps, water and sewer department maps, and street and bridge department maps. These systems have proven useful for operational decisions, inquiry response, land development planning decisions, resource planning decisions, management decisions, and policy decisionmaking. GIS, AM/FM, and CADD differ in user interface, discipline-specific procedures and terminology, data models, and applications; however, they share the same fundamental technology and the same enabling technologies, computer graphics, and database management

Computer graphics systems linked to AM/FM systems enable survey data to be processed at a speed comparable to electronic data collection. State-of-the-art computer mapping systems offer great flexibility in the

expertise cannot be replaced in every complex decisionmaking context.[21]

Computer Vision

Machine or computer vision refers to the automated analysis of visual images and can provide a reliable method for analyzing images in real time. For example, in a current highway application, video cameras are linked to computers that analyze the images to generate traffic flow and congestion information, which then serves as input for signal timing algorithms.

Research is currently being conducted to look at the applications of machine vision to analyzing facility condition. Highway cracking, patching, and potholes are distress types best captured by visual devices, but developing an automated system to identify pavement problems presents significant challenges. A complete inventory of distresses for asphalt or concrete pavements may exceed 20 types; current automated systems rarely cover more than 5 or 6 types and must perform their tasks quickly and reliably. Once perfected, however, such systems will provide highway authorities with cost-effective,

[21] Arno Penzias, vice president of research, AT&T Bell Laboratories, unpublished lecture, American Iron and Steel Institute Annual Meeting, May 31, 1990.

way information is presented; a library of symbols can be developed. If survey crews assign the symbol name in the field relevant map symbols can be automatically placed as the graphics software processes the data.

GIS information that is common to most uses of a map can be located in layers within the same file; information used less frequently can be placed in separate files. For example, all information required for project site selection, such as existing facilities, property boundaries, services, elevation contours, and buildings, can be stored in separate layers and manipulated independently, yet viewed and analyzed as a single, comprehensive map.

GIS information includes spatial, or location, data and attribute data. Spatial data is based on a geographic coordinate system; items can include land parcel, area and district, facility, and natural features. Attribute data is traditional database information that can be referenced geographically, such as by addresses, and can include location by events, conditions, demographics, construction permits, or police reports. (For examples of data see table 5-A-l.)

Geographic information serves a broad constituency, because information about land parcels and geographically related data are needed regularly by many different agencies for a variety of purposes. Moreover, the ability to combine land-related attributes from many different sources is a vital support for many government and nongovernment activities. However, while raw data are usually available, they often cannot be used effectively in making complex decisions because of variations among agencies in data format, quality, and organization. For multipurpose systems, information stored in property record books, paper files, microfiche, maps, charts, or computer databases must be input into a GIS in a consistent form and updated regularly. These can be time-consuming and costly tasks. Nonetheless, GIS, linked to the appropriate computer tools for specific purposes, will become a valued aid in many public works offices. With the installation of a computerized data system, the database can be shared and duplication of effort can be minimized, if organizational issues, such as system access authorization, data use, quality control, and validation of the automated record are addressed.

Table **5-A-1-Selected Geographic Information System Data Capabilities**

Planimetric and topographic features:	Area/district features:
Property parcel features	Current land use
Zoning boundaries	City boundaries
Stormwater drainage facilities	Neighborhoods
Water facilities	Planned land-use areas
Sanitary sewer facilities	zoning
Traffic control facilities	Planning/policy areas
Geodetic control	Tax rate areas
Reference grid	School service areas
Soils	Traffic analysis zones
Flood p!ains	Fire/rescue areas
All area/district map layers	sheriff ballwick areas
Census geography	Lgislatlve districts
Road network	Councilman districts
Road, water, and sewer master plans	School board districts
Depth to groundwater	Zip code areas
Facility features:	sanitary inspection districts
Parks	Solidwaste collection dlstrlcts
Solid and hazardous waste disposal sites	Sewer service areas
Sludge disposal sites	Stormwater service areas
Public transit routes	Natural features:
Snow emergency routes	Noise contours
Historical sites	Environmentally critical areas

SOURCE: Office of Technology Assessment, 1991,

objective, repeatable assessments of pavement condition.[22] See chapter 3, box 3-B and chapter 4, box **4-C** for other examples of public works uses of this technique.

Robotics and Automation

While the use of mechanized equipment to apply large forces or lift heavy loads in public works construction and maintenance is widespread, more advanced forms of automation are still largely in the R&D stage. The sophisticated sensing and electronics needed for autonomous operation in the public works environment have been installed in some test vehicles. For example, a multipurpose vehicle for a variety of road maintenance tasks is under development in France. Its intended uses include mowing grass around curbs, sowing, ditch excavation, road marking and cleaning, surface cutting, brushwood cleaning, and salt dispensing. Other machines are being developed for such tasks as curb and gutter construction, road surface patching, bridge cable/beam inspection, and paint removal/surface preparation. A system to help repair runways by removing rubble, filling cracks, and performing nondestructive testing is under development at the University of Florida and the Tyndale Air Force Base.[23]

[22] *Haris* Koutsopoulos, "Automated Interpretation of Pavement Distress Da@' *Construction,* newsletter of the Center for Construction Research and Educatiom Massachusetts Institute of Technology, winter 1989, p, 10.

[23] Miroslaw Skibniewski and Chris Hendrickson, Carnegie-MelonUniversity, ''Automation and Robotics for Road Construction and Maintenance," unpublished paper, n.d., pp. 3-5.

Simulation Models

Simulation models have been developed over the years by public works officials to examine various aspects of flow and movement patterns.

Transportation

Planning models attempt to model consumer route and mode choice to assist planners in road and transit development plans. Road traffic models examine traffic patterns at intersections, traffic flows in networks, and aggregate system performance to provide information about traffic delays, bottlenecks, and aggregate vehicle performance. Researchers from the Federal Highway Administration (FHWA), State DOTS, and universities have developed numerous models; current efforts focus on models that process real-time information about traffic demand and use it to determine signal timing plans. The *Automated Traffic Surveillance and Control System (ATSAC) in Los* Angeles is based on the Urban Traffic Control System developed by FHWA. (For additional information, see chapter 3.)

The Federal Aviation Administration (FAA) makes use of a number of models to provide analytic and management information. *SIMMOD* is a detailed model that tracks individual travel times, delays, and fuel burn for a given airport, as well as airspace and traffic configuration. It is useful for measuring the delays at a specific location caused by airspace or procedural changes, but is difficult to use for systemwide analyses, as capacity must be estimated by trial-and-error.[24]

NASPAC provides delay and utilization statistics for entire networks based on simulation and queuing models, incorporating the national airspace and airways structure, and selected airports, arrival and departure fixes, and weather conditions.[25] Best suited for strategic analyses, NASPAC can estimate the benefits across the system of a new airport, such as **that in** Denver, Colorado, now under construction, or identify which elements of the air traffic system are limiting factors. However, since the model uses average traffic demand data, based on published airline schedules, it cannot analyze the transient behavior that characterizes daily operations.

Environmental Models

Simulation models are important to environmental studies for examining the way contaminants are dispersed in the various media and determining the impact of contaminants on groundwater, for example. Numerous models have been developed by the U.S. Environmental Protection Agency (EPA) and other agencies to assist in regulatory and decisionmaking activities.[26] The Bureau of Reclamation is developing a model that combines artificial intelligence, policy analysis, systems analysis, and risk analysis to yield a tool for river basin planning, operations, and management.[27] River basin planning in the Western States involves environmental concerns as well as irrigation, hydropower, and water rights considerations, and such a model can be of considerable help to decisionmakers at all levels of government.

Communications and Positioning Systems

Communications and positioning technologies are essential elements of traffic management and control and remote infrastructure monitoring. Public works managers and transportation users rely on communications, navigation, and surveillance systems, some developed and supplied by the Federal Government and others by private providers. Comparable technologies to locate and identify vehicles and craft, and to relay traffic instructions and other information, are now practical for each transport mode. See chapter 4, box 4-C for a related use in environmental public works.

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[24] U.S. Congress, Office of Technology Assessment, Safe *Skies for Tomorrow: Aviation Safety in a Competitive Environment*, OTA-SET-381 (Washington DC: U.S. Government Printing Office, July 1988), p. 136.

[25] Federal Aviation Administration, "Plan for Research, Engineering, and Development-Volume II: Project Descriptions," Conference Review Draft #4, Sept. 21, 1989, p. 49.

[26] See, for example, the following OTA reports: *Protecting the* Nation's *Groundwater From Contamination,* vol. I, PB 85-154 219/AS (Springfield, VA: National Technical Information Service, 1985); *Use of Models for Water Resources Management, Planning, and Policy,* PB 83-103655 (Springfield, VA: National Technical Information Service, 1983); and *Catching Our Breath: Next Steps for Reducing Urban Ozone, OTA-O-412 (Washington* DC: U.S. Government Printing Office, July 1989).

[27] U.S. Department of the Interior, Bureau of Reclamation, "Advanced Decision Support Systems," Progress Report, June 30, 1989.

Signal Systems

Signals transmitted over various portions of the electromagnetic spectrum form the basis of the many types of navigation and surveillance systems, which generally depend on one- or two-way communications. The increasing power, reliability, and cost-effectiveness of microprocessing technology have made advanced communications and positioning functions available to a wide range of users.

Systems that support information transfer are considered to be communications technologies. High-frequency radio and visual signals are commonly used in line-of-sight communications for transportation vehicles, while waveguides, such as cables and fiber optics, are used to link ground facilities. The low-frequency radio spectrum permits over-the-horizon communications; however, interference and low data transfer rates pose problems.

Navigation technologies include radio signal systems that provide bearing, distance, or other reference to fixed transmitters. Widely used in aviation and maritime navigation, these are now finding increased application in surface transportation. Inertial navigation and dead reckoning systems compute vehicle position relative to an initial fixed location based on vehicle heading, speed, and time en route, also without communication links. However, small measurement errors can accumulate, causing problems over long distances.

Surveillance includes determining the position and other characteristics of a remote vehicle, usually through communications technologies, and in civilian transportation, cooperative vehicle-based systems and procedures are often used. For example, air traffic control radar information is augmented by automatic transponder replies from aircraft, which strengthen the signal returning to the radar, identify the aircraft, and provide other data. Position reports from vehicles transmitted to a monitoring facility is another type of cooperative surveillance, and is commonly used by commercial operators in all transport modes.

Satellites

Satellite-based systems offer the greatest potential for enhancing worldwide communications, navigation, and surveillance, because they have the key advantage of altitude. Operating thousands of miles above the Earth, satellites have direct line-of-sight over entire continents, permitting the higher frequencies of the radio spectrum to be used for communications and positioning. Satellites can support and augment existing communications and positioning systems, and serve as passive communications relays, as reference positions for navigation, or as interrogation and monitoring devices for surveillance. Although satellites are expensive to install and operate, a few satellites can replace an extensive ground-based infrastructure. However, potential users must consider ways to ensure that satellite systems can be reliably maintained and replaced.

Three decades of telecommunications industry experience and increasingly affordable mobile receivers and transmitters have enabled industry and public traffic managers to use communications satellites as linchpins in traffic surveillance and control. For example, truck companies have found satellite-based services to be cost-effective, because drivers on long haul routes do not have to stop en route to telephone their locations to dispatchers. FAA is considering using automatic dependent surveillance (ADS) for air traffic control over remote areas without radar coverage. Under ADS, onboard navigation systems would relay the aircraft's identification and position via satellite to a central monitoring facility to display screens similar to current radar-based ones.

The United States and the Soviet Union are each deploying constellations of satellites, which, although funded for military purposes, will allow civilian receivers to determine their positions to accuracies of around 100 meters.[28] The U.S. Global Positioning System (GPS) is expected to be available for worldwide navigation in late 1993. Each satellite serves as position reference by broadcasting its location and a precise time signal, and a receiver calculates its position by measuring the time delay of signals sent from three or more satellites. FAA is investigating whether a single navigation device using both GPS and Soviet satellite signals could provide greater redundancy and precision.

A different approach for obtaining position information is by radio-determination satellite systems,

[28] Military users will have access to encrypted signals unavailable to civilian users, permitting positioning accuracies roughly on an order of magnitude greater than civilian systems.

which unlike GPS requires that each participating vehicle transmit as well as receive. Signals sent from the vehicle must be relayed by at least two satellites to a central location, where the vehicle's location is computed by noting the time difference in the signals.

Automatic Vehicle Identification (AVI)

AVI systems commonly use vehicle radio- or microwave-based transponders, which can be "read" by fixed or mobile equipment. The readers can be placed along a route or at a facility where information needs to be exchanged or billing needs to take place, such as bridge or toll road entrances and exits (see chapter 3, box 3-E for further information), weigh stations, and ports of entry. FAA regulations require commercial carriers and all aircraft flying near the busiest airports to be equipped with radar transponders, which can transmit aircraft identification and altitude to ground controllers. Additional AVI technologies include optical and infrared systems, inductive loop systems, and surface acoustic wave systems.

Long-Range Radionavigation

Long-range radionavigation systems, LORAN and OMEGA, provided by the Federal Government and originally designed for marine operations, permit navigation in remote locations. OMEGA's coverage is worldwide; LORAN's is up to 1,000 miles. Positions are determined by measuring the difference in signals from precisely synchronized transmitters, using time difference for LORAN and phase difference for OMEGA. Low-cost/low-weight microprocessors can automatically perform these measurements, making widespread use possible. LORAN reception is presently concentrated in coastal areas, but FAA is providing funds to the Coast Guard to install four additional LORAN stations for complete coverage across the continental United States.[29] Combined with an automatic dependent surveillance link, LORAN and OMEGA allow enhanced low-altitude and remote-site traffic monitoring.[30]

Photo credit: PortAuthority of New York and New Jersey

Automatic vehicle identification and billing systems could significantly lessen traffic delays at toll faclities.

Automatic Meter Reading

Various communications technologies are being used to develop automatic meter reading systems (see box 5-B) for utilities that set rates on the basis of usage. System customers are provided with a meter and a device that collects information from the meter, packages it into a data stream, and sends it to a central location, where the data are received and stored in a computer. Systems can be developed for water, sewage, and other utilities, and the opportunity for computerized operational management may be the biggest advantage of such systems.[31]

Field Construction Technologies

The tasks necessary to complete a capital facility after a final design has been chosen comprise the field construction process. Although construction usually refers to building anew project, methods and techniques for rehabilitating existing infrastructure are equally, or perhaps more, important to today's public works officials. Nonetheless, engineering education and most related R&D emphasize con-

[29] U.S. Department of Transportation, Federal Aviation Administration, *National Airspace System Plan: Facilities, Equipment, Associated Development and Other Capital Needs* (Washington, *DC:* September 1989), p. IV-58.

[30] U.S. Department of Transportation, Federal Aviation Administration, "Federal Aviation Administration Plan for Research, Engineering, and Development" vol. II, draft manuscript, September 1989, p. 258.

[31] Donald Schlenger, United Water Resources, personal communication, 1990.

Box 5-B—Automatic Meter Reading Systems

Meters are used by utilities to measure consumption of their product water, gas, or electricity. A utility metering system usually consists of meters and local devices to collect information from the meter, package it into a data stream, and send it to a central computer. In contrast, traditional metering systems use collection personnel to read meters individually at the point of service. Automatic meter reading (AMR) systems can eliminate the extra work and costs involved in ''lock-outs,' estimates, call backs, and premature cancellations and can shorten read-to-bill turnaround,

The development of integrated circuitry and the restructuring of the Nation's telephone system now enable AMR systems to use telephone lines or a radio transmitter to send consumption data to the utility's computer system. An AMR system can be configured in one of several ways, including: 1) telephone dial-inbound which uses an electronic meter interface unit (MIU) on the customer's premises through the telephone company's test equipment without ringing the customer's telephone; 2) telephone dial-outboundin which the MIU dials the utility's computer and transmits the latest meter reading, usually at a preset time; 3) a cable TV-based system in which the utility communicates with individual MIUs over the cable to obtain the meter reading; and 4) a radio system in which the MIU transmits to a utility receiver. In a variation of the radio system, the utility queries the MIU for information. About 50 percent of the existing systems are telephone systems although these are restricted by court rulings relating to AT&T; cable systems area very small part of existing and potential systems.

AMR systems are part of a larger field, termed "computerized operations management." In addition, since most customers are served by more than a single utility, the information collection and transmission components needed by each utility could be integrated in a single metering system. Major issues must be resolved, however, including:

- who installs and maintains the equipment;
- telephone line use limitations and radio frequency use limitations;
- the way regulations affect or restrict utility activities; and
- standardization of the electronic equipment for compatibility of communications signals and data interchange and transmission issues.[1]

[1]Typical of the standards is the High Level Data Link Control model of the International Standards Organization that is designcd to facilitate synchronous code transparent transfer of user data. Japan has adopted its standarddata exchange format for automatic meter reading.

struction of new facilities rather than the special problems involved in rehabilitation.[32]

Construction activities require considerable planning and organization, as well as management of materials, personnel, and time. Many of these early processes are crucial to design and management, and take place primarily in an office. These and other phases of construction projects have been greatly aided by advances in computer hardware and software, new materials, and technologies related to structural design, corrosion protection, and robotics. Virtually all the construction technologies discussed here have already found some applications in public works.

Trench less Construction Technologies

Trenchless excavation construction (TEC) refers to installing of water supply, sewer pipes, or any other structural components, below grade without digging an open trench. Trenchless construction avoids much of the disruption and traffic delay associated with digging up streets, sidewalks, and yards and eliminates the need to excavate around other utility equipment and tunnels, particularly in dense urban areas.[33] It differs from construction of large diameter tunnels primarily in size--TEC openings range from 2 inches to 12 feet and permit the installation of pipes to transport fluids, while tunnels are much larger and transport vehicles. Table

[32]American Society of Civil Engineers, Task Committee on Water Supply Rehabilitation Systems, ***Water Supply System Rehabilitation,*** Thomas ***M.*** Walski (ed.) (New York, NY: American Society of Civil Engineers, 1987), p. 1.

[33]Natioal ResearchCouncil, U.S. National Committee on Tunneling Technology, ***Micro- andSmall-Diameter Tunneling*** (Washington,DC: National Academy Press, 1989).

Table 5-3—Types of Trenchless Construction and Rehabilitation Technologies

Type	Variations	Comments
Trenchless construction technologies:		
Horizontal earth boring	Boreholes can be produced by augering, drilling, ramming, and water jets.	Does not require workers in the borehole; some equipment is laser-guided and remote-controlled.
Pipe jacking	Excavation processes vary from manual to highly sophisticated tunnel boring machines; pipe can be prefabricated concrete, steel, or fiberglass.	Requires workers inside the pipe during the excavation and/or spoil removal process.
Utility tunneling	Excavation methods may be identical to pipe jacking methods; most widely used lining systems are tunnel liner plates, steel ribs with wood lagging, and wood box tunneling.	Smaller than transportation tunnels.
Rehabilitation technologies:		
Cured in place lining	Curing process includes inserting a resin impregnated hose into an existing pipe; liner materials include polyester felt, woven glass/ felt, and woven polyester; liner is cured by heat or ultraviolet light.	Requires that cuts be made in the liner for lateral connections.
Sliplining	Existing pipe is lined with a new pipe, possibly polyolefin, with spirally wound profiled pipe, or with pipe that reaches its final shape and size after insertion into the original pipe and an expansion process.	Joining pipe sections is critical; grouting between liners and original pipe maybe needed.
Spraying	Cementitious or polymeric coating reinforced with steel is sprayed onto the interior walls of pipe; cementitious coatings are limited to man-entry sewers.	Sources of water infiltration must be removed before lining is applied; can utilize manual spray equipment or remote-controlled spray equipment.

SOURCES: For construction technologies—D.T. Isley, Department of Civil Engineering, Louisiana Teeh University, "Trenchless Excavation Technologies (TEC) Methods: A Classification System and an Evaluation," unpublished paper, Second Annual Alumni Appreciation Seminar, Ruston, LA, Nov. 3, 1989. For rehabilitation technologies-K. Reed, *The Development of a Framework for the Evacuation of Sewer Renovation Systems,* Report No. 539 (Huntingdon Valley, PA: Water and Wastewater Technologies, October 1989).

5-3 summarizes the primary trenchless construction and renovation technologies.

Trenchless construction R&D has focused on smaller structures-generally less than 42 inches in diameter-because this size range includes the majority of piping networks used for water supply, petroleum product, and sanitary and storm sewer systems. Rapid development of new techniques and innovations in traditional methods underscore the importance of having installers, designers, and regulatory agencies be familiar with TEC capabilities. Installation of TEC systems requires a high degree of accuracy and increases the need for monitoring and control systems, because if trenchless construction is done incorrectly, it can be more destructive than trenching work.[34] Contractors have been slow to adopt these techniques because of the complexity of installation and because they prefer simple methods that provide fewer chances for technical problems.[35] Supporting technologies that can speed the application of TEC methods include active guidance systems, improved cutting equipment to handle large cobbles and boulders, and obstruction sensing equipment.[36]

Tunnels

Tunneling consists of excavating a hole in the ground and supporting the hole as the tunnel advances, if necessary. Conventional tunneling includes a systematized drill and blast cycle for excavating and tunnel support by timbering, masonry arches, or steel ribs. Tunnel boring machines (TBMs), introduced in the United States in 1954, provide a continuous excavation process that is fast and relatively inexpensive, although use of TBMs is largely restricted to ground with predictable, constant geology.

The New Austrian Tunneling Method (NATM), one of the most recent innovations, was developed

[34] D.T. Iseley, Department of Civil Engineering, Louisiana Tech University, "Trenchless Technology: Alternative Solutions to Complicated Underground Utility Network Problems," seminar notes, Second Annual Alumni Appreciation Seminar, Ruston, LA, Nov. 3, 1989.

[35] James B. Gardner, "Trenchless Technology: A Quiet Revolution," *The National Utility Contractor, vol. 12, No. 12* (Arlington, VA: National Utilities Contractors Association, December 1988), p. 18.

[36] National Research Council, op. cit., footnote 33, pp. 20-21.

in the 1950s for construction of road and water tunnels in the Alps. The technique met the demands of extremely variable geology and the need for flexible construction methods to meet changing ground conditions. NATM includes drill-and-blast excavation; extensive use of shotcrete, a light coat of concrete sprayed on the tunnel walls to seal the newly exposed rock from the atmosphere and to support unstable rock; extensive instrumentation to measure ground deformation; and frequent use of waterproofing membranes. NATM also requires contracting arrangements that permit decisions on construction methods and the extent and timing of structural support systems to be made jointly by the engineering and contracting staff as excavation progresses. While NATM saves money on materials because it uses no shield and less lining, the savings realized by the sheer speed of TBM excavation may offset the extra material costs of conventional tunnel linings.

A flexible, waterproof, asphalt-based material recently developed in Japan offers potential as a backfill material for tunnels, particularly in earthquake-prone areas. Consisting of an asphalt emulsion, cement, and a water-absorbing polymer, the components are liquid at ambient temperature and can be pumped, but form a waterproof gel when mixed. This material has lower strength but higher ductility than other materials used as tunnel backfill. The ductility is important because it allows the material to cushion the shock from earthquakes. Because the material is more viscous than standard backfill material, it can fill the space between tunnel segments and the surrounding rock more completely and make the tunnel more waterproof.[37]

Soil Improvements and stabilization

Earth can be strengthened and stabilized by steel reinforcing bands that are used to form a cohesive wall or embankment from sand, gravel, and other fill material. Other reinforcement techniques include fibro-compaction, compaction grouting, dynamic compaction, and wick drains.

Soil nailing, or drilling a hole into a slope and filling it with a steel rod and grout, usually concrete,[38] is an alternative method for constructing retaining walls for construction projects. Although the technique has been used in other countries for nearly 20 years, U.S. experience has been limited. A design manual under preparation for FHWA will provide specific design information and allow more widespread use of soil nailing for highway projects.

Jet grouting is a versatile technique for underpinning existing foundations, but other applications are evolving as the technique becomes better known. Grout slurry is pumped under high pressure down a drill pipe 2 to 3 inches in diameter and forced out of lateral jets at high velocity. The grout shatters the surrounding earth, mixes with it, and dries, after the removal of the drill pipe, to form a column up to 48 inches in diameter of grouted soil. The soil and jetting conditions determine the physical properties of the column.[39] Jet grouting has also been used as temporary shoring for open cut and shaft excavation, to construct tie-backs for anchoring reinforced concrete retaining walls, and to construct nails for soil nailing.

Dredging Technology and Capabilities

There are two basic methods of dredging—mechanical and hydraulic-and the particular application depends on sediment type, water depth, sea conditions, and the location and proximity of the disposal area. Mechanical dredges employ buckets, grapples, or other containers to cut and scoop material and transport it to the surface; they are generally less efficient for U.S. waterway conditions than hydraulic dredges, which work like vacuum cleaners. The pump/suction elements of hydraulic dredges are often coupled with mechanical devices to loosen material from the bottom.

Improvements in automation and instrumentation, rather than changes in fundamental dredging equipment and techniques, offer the best potential for reducing excavation costs for channel maintenance and construction in the near term. Short-term dredging contracts, the vast majority of U.S. work, favor use of older, less-sophisticated equipment and discourage new investment and R&D.[40] The last wholesale introduction of new private dredge equip-

[37] Akihiro Moriyoshi et rd., ''A Composite Construction Material That Solidi.ties in Water, " *Nature,* vol. 344, Mar. 15, 1990, pp. 230-232.

[38] Reinhard Gnilsen, ''Soil Nailing Debate,'' *Civil Engineering,* vol. *58, No. 8,* August 1988, P. 61.

[39] Paul Pettit and Clayton Wooden, ''Jet Grouting: The PaceQuickens,'' *Civil Engineering,* vol. *58, No. 8,* August 1988, p. 65.

[40] National Research Council, op. cit., footnote 33, p. 113.

ment followed the retirement of the Corps' hopper dredges in the late 1970s.

Rail Track Construction and Rehabilitation

Track maintenance has been highly mechanized with complete rail-mounted machines capable of total track rehabilitation in one operation. These sophisticated technologies are, in general, used by the more affluent railroads; smaller railroads tend to use more traditional manual maintenance methods.[41] For example, one class I railroad is testing a mechanized tie renewal system designed to replace 400 ties per hour. The system carries its own ties, spikes, anchors, and plates, and consists of several units, each responsible for a different part of the tie renewal process (rail anchor removal, spike pulling, tie removal, tie insertion, and tamping). It travels along the track at roughly **0.5 mile** per hour as it renews the ties, reducing the labor and track occupancy time normally needed for tie renewal.[42] New equipment designs have also been introduced for automated ballast tamping operations, ballast cleaning, rail laying, and aligning and gaging.[43]

Materials and Corrosion

Concrete and steel will continue to be primary construction materials for infrastructure for quite some time. Recent research has identified new additives, coatings, and uses for these materials to improve their durability and resistance to operating stress. Corrosion has plagued all elements of infrastructure for decades, and many technologies exist to combat this problem at both the design and maintenance levels. However, convincing State and local officials to invest limited funds in preventive methods is difficult.

Concrete

Concrete is one of the most widely used construction materials in the United States; it is found in public works structures ranging from bridge decks to railroad ties, highways to runways, and structural supports to water pipes and storm drains. The principal advantages of concrete include the availability of component materials throughout the country, its low cost, workability at time of installation, and durability. Concrete is a strong, workable material, made up of aggregate, cement, water, and controlled amounts of entrained air. Sand, gravel, and crushed stone are the most commonly used aggregates; clay, shale, slate, and slag are more lightweight, but less frequently used. The lightweight aggregates can reduce initial costs and produce better acoustic and thermal insulation than stone aggregate. The trade-off is some loss in structural strength. Concrete can be recycled, but the process is difficult, because the old pavement must be crushed to retrieve the aggregate.[44]

Cement is the "glue" that binds the aggregate together. The one most commonly used in construction is Portland cement, a dry powder, consisting of silica, alumina, lime, and iron oxide, which react chemically when water is added to form a glue-like binder. Any excess water not used by the chemical reaction improves the workability of the cement and aggregate mixture. However, excess water increases the porosity of the concrete, which in turn reduces its strength, and engineers and construction workers must choose between strength and workability .45

In addition to the basic ingredients, various additives to concrete mixtures can achieve certain properties. Air entraining admixtures increase the amount of air in the concrete material, increasing the concrete's resistance to the cracking associated with freezing and thawing. Accelerators, such as calcium chloride,[46] sodium chloride, sodium sulfate, sodium hydroxide, sodium sulfite, potassium sulfate, and potassium hydroxide can speed up the hydration process to make the concrete set faster, but this may reduce the materials' effective lifetime. Organic materials, such as sugar and lignosulfonates, act as retarders to slow the hydration process. Under certain conditions, increasing the time required for

41 Federal Railroad Administration, informational document, n.d.

42 "Continuous Action Tie Removal/Insertion," *progressive Railroading,* November 1989, pp. 43-44.

43 Federal Railroad Administration op. cit., footnote 41.

44 Hal Friedland, Aviation Consultants, personal communication, Nov. 8, 1989.

45 U.S. Congress, Office of Technology Assessment, *Advanced Materials by Design*, OTA-E-351 (Washington, DC: U.S. Government Printing Office, June 1988), pp. 48-49.

46 While calcium chloride is the most common accelerator employed by the construction industry, excessive use can cause serious corrosion Of steel-reinforced rods. See corrosion section in this chapter.

Photo credit: American Public Works Association

Concrete's low cost, durability, and workability at the time of installation make it one of the most widely used construction materials.

the concrete to set can produce concrete that can maintain its strength for longer periods of time.

Concrete is considerably stronger under compression than under tension and works well for structures such as gravity dams, footings, and heavy foundations. To compensate for its low tensile strength, concrete is generally reinforced with steel. Because it changes volume at different temperatures and moisture levels, concrete is subject to cracking. Joints between slabs of concrete can accommodate volume changes, but often allow moisture to seep in, which eventually causes further damage. Proper design and maintenance can minimize these problems.

Brittleness is another disadvantage of concrete, which is able to bend only slightly to absorb stress and may crack as a result. Researchers are studying the chemical reactions of cements in order to improve the strength and durability of concrete. Some aggregates contain silica in a form that reacts with sodium or potassium in cement, absorbing moisture and expanding to crack the concrete.

Because of the many advantages of concrete, the construction industry continues to use it regularly. Government and university researchers are working to overcome its limitations. (See table 5-4 for further information.)

Asphalt

Asphalt is an inexpensive material, processed from petroleum byproducts, and used primarily as a cementing and waterproofing agent. Although asphalt's public works applications include lining cards and reservoirs, waterproofing and facing dams and dikes, and coating pipes, more than 70 percent of asphalt produced in the United States is used as a cementing material for asphaltic concrete (AC), for paving roads and highways. Hot asphalt is mixed with hot graded stone aggregate. The mixture is spread over a gravel base and subbase and rolled, while still hot, to produce the desired density and smoothness.[47]

The problems associated with AC pavements include rutting, stripping, fatigue cracking, thermal cracking, and aging, and may result from improper installation and maintenance and unexpected traffic wear. AC pavement's ability to withstand heavy loads is a function of both its design and the strength of the subbase. It can be designed to support the same loads as concrete pavement, but care must be taken when it is laid. The Strategic Highway Research Program (SHRP) (see chapter 6 for details) will monitor over 800 sections of pavement over the next 15 years to compare performance with design in order to improve the design method. These evaluations of design methods are important because engineers rely heavily on the performance histories of concrete composed of specific aggregates under certain environmental conditions.[48]

Resurfacing an AC pavement is relatively simple; the top inch of the pavement is scraped off and remixed; then anew layer is added on top of the old. The remix method gives an excellent seal between the old surface and new layers and serves as a form of instant recycling. If surface cracking is too severe, a fiber mat impregnated with asphalt material can be laid over the old surface; when the new layer is placed on top, the mat distributes stress around the cracks of the old pavement, preventing them from affecting the new layer.

Current research is focusing on ways to improve performance of AC pavement. SHRP is studying the chemistry of the asphalt binder so as to develop guidelines for State and local engineers to follow

[47] *McGraw Hill Encyclopedia of Science & Technology* (New York, NY: McGraw Hill Publishing, 1987), vol. 2, @I ed., pp. 111-112.
[48] John Broomfield, Strategic Highway Research Program, personal communication, June 21, 1990.

Table 5-4--Concrete Types Used in Infrastructure

Type	Characteristics	Uses/comments
Steel reinforced concrete	Steel reinforcing bars are implanted into concrete for increased tensile strength.	Pavement, buildings, dams, parking decks.
Prestressed concrete	High-strength steel wire is stretched inside a concrete member prior to hardening process; increases tensile strength.	Bridges and buildings where heavy weights must be supported.
Post tensioned concrete	High-strength wires are stretched after the concrete has hardened to increase tensile strength.	Bridges and buildings where weight must be supported.
Blended cements; cement substitutes	Current substitutes are used to reduce overall cost while increasing strength and reducing permeability of concrete; depends on local availability of substitutes.	Reduces costs.
Blended cements; fast setting or high early strength	Additives are used to achieve faster curing times or yield higher early strength.	Permits quicker use of finished product; more costly. Long-term performance of some mixtures needs to be evaluated.
Fiber reinforced concrete	Small, discontinuous fibers are added (steel, glass, carbon, nylon, polyethylene, and polypropylene) to concrete mixture.	Adds impact resistance and ductility to the concrete.
Roller compacted concrete	Concrete using less cement and lower quality aggregate is rolled after put in place.	Dam construction and low-speed heavy-weight vehicle pavements; problems can occur due to poor binding between layers and random uncontrolled cracking.
Polymer concrete	Polymers are added to aggregates.	Sets quickly and has low permeability; costs are high.

SOURCE: Office of Technology Assessment, 1991.

Photo credit: American Society of Civil Engineers

Resurfacing an asphaltic concrete pavement is a relatively simple procedure. The top inch of the pavement is scraped off and remixed; then anew layer is added on top of the old.

when building a road, runway, or parking lot. These specifications will describe performance results for both the asphalt binder and the aggregate selected and will take into account variations in weather and temperature.[49] Private sector research to develop more durable, and more crack-resistant AC products includes experimentation with a sulfur modifier, which lowers cost, reduces the amount of petroleum needed to produce asphalt, and makes the pavement less susceptible to temperature variations.[50]

Steel

Steel's great strength, elasticity, durability, and ductility make it a valuable material for public works, where it is used in bridges, building structures, storage tanks, and pipelines. However, steel's vulnerability to corrosion requires that coatings or other protective techniques be used. Galvanized and polymeric-coated steel, which represent two types of corrosion protection, are widely used for culverts, bridge spans, retaining walls, revetments, and underground piping.

Any exposed steel surface will develop a protective oxide layer in the presence of moisture and oxygen, which isolates it from the environment and retards corrosion.[51] However, if conditions are hostile enough, this protective layer is not sufficient,

[49] Ed Harrigan, asphalt program manager, Strategic Highway Research Program, personal communication Dec. 7, 1989.

[50] Ibid.

[51] N. Dennis Burke and James Bushman, *Corrosion and Cathodic Protection of Steel Reinforced Concrete Bridge Decks*, FHWA-IP-88-007 (Washington, DC: Federal Highway Administration, 1988).

and once the steel structure is corroded, the alternatives are costly—shoring up the structure or replacing the affected members. Currently, the best way to protect a new steel structure in a highly corrosive environment is to coat it with some type of material, usually paint. A cathodic protection system can be used if the steel is in an electrolyte such as soil or water.

Weathering steel forms a hard, protective, oxide coating that prevents additional rust. Under the right combination of moisture, sunlight, and fresh air, it stands up to corrosive environments better than conventional steel.[52] However, if weathering steel is not used properly, the formation of the protective rust film stops, and normal corrosion proceeds instead of slowing to a negligible rate once the oxide layer is formed.[53] Prolonged exposure to deicing salt and water, such as might occur in bridges in cold climates or marine environments, is very harmful to weathering steel. FHWA has developed guidelines to aid local officials in designing structures using weathering steel.[54]

Geotextiles

Geotextiles, woven or nonwoven fabrics, are made of long chains of polymeric filaments or yams formed into a stable network. Geotextiles became widely available in 1975, when 3 million square yards were sold. Because the fabrics are inert to commonly encountered chemicals, sales of 400 million square yards were expected in 1990, driven by demand for geotextiles for industrial hazardous waste landfills. Infrastructure needs have also spurred the geotextile industry, and forecasters see an annual growth rate for infrastructure applications of 5 to 10 percent in the near future.[55] Geotextiles have a wide variety of uses in infrastructure maintenance, rehabilitation, and new construction for drainage; erosion control; materials separation; soil reinforcement; and blocking moisture seepage. For example, when used on a road running through a swampy area, geotextiles can help reinforce the surrounding banks and prevent soil erosion.

Despite their utility, these relatively new products have problems that need to be resolved before this technology gains full acceptance. Uniform quality standards are lacking, and geotextile manufactures currently set their own strength and durability standards. Techniques for working with geotextiles are not commonly taught in engineering schools, and the engineering community is consequently reluctant to use geotextiles, because trial-and-error methods have often failed. FHWA, the American Association of State Highway and Transportation Officials, the Associated General Contractors, and manufacturing industry representatives plan to form a task force to establish performance standards for silt fences, drainage, erosion, separation, and paving fabric. Other groups working on standards include the California DOT, the Army Corps of Engineers, and the U.S. Forest Service.[56]

Plastics

Recent advances in plastics, primarily in the area of polyvinyl chloride (PVC) pipe manufacturing have benefited public works infrastructure. PVC pipes had long been banned from most wastewater projects, because the pipes did not conform to standards set by the American Society for Testing and Materials for compression resistance, tensile strength, and other loading factors. Manufacturers of PVC piping assert the pipes can now meet the standards for pipes up to 60 inches in diameter, large enough for most water and wastewater applications.[57] PVC piping can attain the same strength as standard metal or masonry piping, but is more resistant to corrosion in hostile environments such as acidic soils or exposure to stray currents and is generally lighter, making it easier to handle

Advanced Composites

Advanced composites have been used in the aerospace industry for years with great success, but little advanced composite technology has been transferred to infrastructure needs. The main hurdle is a fragmented construction industry, with few

[52] Rita Robison, "Weathering Steel: Industry's *Stepchild," Civil Engineering,* vol. 58, No. 10, October 1988, p. 42.

[53] Broomfield, op. cit., footnote 48.

[54] Ibid.

[55] Jerry Dimaggio, senior geotechnical engineer, Federal Highway Administration, personal communication Nov. *9, 1989.*

[56] Michael Lawson, "Geosynthetics Winning New Respect," ***Engineering News Record,*** vol. 223, No. 17, Oct. 26, 1989, pp. 36-38.

[57] U.S. Congress, Office of Technology Assessment, "Construction and Materials Research and Development for the Nation's Public Works," staff paper, June 1987, sec. 7, pp. 4-5.

incentives to innovate or move away from traditional materials, such as concrete and steel. Other obstacles include high initial costs and lack of manufacturing equipment, uniform design codes, data on long-term performance, and understanding of advanced composites by public works designers and engineers and construction and maintenance officials. Moreover, composites often degrade on exposure to water, oxygen, and light, leading to changes in color, size, mechanical properties, and occasionally to crazing or propagation. The rates of degradation can be significantly reduced by using expensive additives that are justifiable for high-performance aircraft, but much less so for public construction projects.

Advanced composites have many advantages over traditional building materials. Most are more durable, lighter, and less costly to maintain, and can form strong interlocking bonds without rivets or welds. Composites are not affected by corrosion and do not require much inspection during the design life. Many deliver the same strength as traditional materials, but at much lower weight, a potentially large advantage for the design of heavy structures, such as bridges. The largest load that must be supported by a long span bridge is the dead weight of the bridge itself, rather than the traffic on the bridge deck. Therefore, lightweight advanced composites can save money by reducing the amount of material required to support both the dead weight and a given traffic density, or the same amount of material can support much heavier traffic.[58]

In England, a 7-year advanced bridge project led to the construction of a 250-ton, corrosion-resistant, glass fiber bridge, with decks that latch together. Japan is also researching infrastructure applications for advanced composites; a 4{ story office building in downtown Tokyo contains ,0,000 wall segments made of pitch fibers.[59] ‘

Maintenance: Protecting Against Corrosion

Corrosion of infrastructure components costs billions of dollars (one major study estimated that costs total about 4 percent of the Nation’s GNP annually) in repair, replacement, and lost productivity; approximately 15 percent of these costs are avoidable with current technology.[60] Corrosion most often affects metal structures, such as bridges, concrete reinforcing bars, and pipelines, and even problems invisible to the casual observer can lead to structural failure, lost lives, the loss of investment, and damage to the environment. As the average age of facilities and structures continues to rise, corrosion problems will inevitably worsen, although expenses can be minimized if proven technologies and techniques that account for corrosion in all phases of construction (design, installation or fabrication, maintenance, and repair) are utilized.

A natural phenomenon, corrosion is an electrochemical process through which metals are oxidized in aggressive environments, such as moist salt air in a marine environment,[61] wastewater in pipelines or wastewater treatment plants,[62] soils in contact with buried structures or pipelines,[63] or where a structure is subjected to pickup and discharge of stray currents from such sources as direct current rail systems.[64] Material selection, use of coating systems, consideration for corrosion in the design of a facility, and cathodic protection are options for controlling corrosion. It is important that engineers and other design professionals be aware of the many available corrosion control techniques and of the benefits of incorporating them into initial designs to extend the service life of structures.

Corrosion of reinforcing steel in buried, submerged, and atmospherically exposed concrete structures including bridge decks and substructures, piping for water and wastewater, water treatment

[58] U.S. Congress, Office of Technology Assessment, *Advanced Materials by Design: New Structural Materials Technology*, OTA-E-351 (Washington, DC: U.S. Government Printing Office, June 1988), pp. 87-88.

[59] “Can New Technologies Save Our Public Works?” *Civil Engineering*, vol. 59, No. 12, December 1989, pp. 26-28.

[60] National Bureau of Standards, *Economic Effects of Metallic Corrosion in the United States: A Report to Congress by the National Bureau of Standards, NBS Special* Publication 511-1 (Washington DC: 1985). Costs are extrapolated from a 1975 study by the National Bureau of Standards.

[61] R.J. Kessler and R.G. Powers, “Conductive Rubber as an Impressed Current Anode for Cathodic Protection of Steel Reinforced Concrete,” *Corrosion/89* (Houston, TX: National Association of Corrosion Engineers, April 1989).

[62] J.L. Villalobos, ‘ ‘Corrosion of Reinforcing Steel by Hydrogen Sulfide Induced Corrosion in Wastewater Facilities,” *Corrosion/90* (Houston, TX: National Association of Corrosion Engineers, April 1990).

[63] K.C. Garrity et al., “Corrosion Control Design Considerations for a New Well Water Line,” *Materials Performance*, August 1989.

[64] A.W. Peabody, Control *of Pipeline Corrosion* (Houston, TX: National Association of Corrosion Engineers, 1967).

Photo credit: American Society of Civil Engineers

Corrosion of public works infrastructure costs several billions of dollars annually for repair, replacement, and lost productivity.

Photo credit: Marsha Fenn, OTA Sfaff

Using properly protected steel bars for concrete provides defense against corrosion.

facilities, and parking garages has become a significant problem in the United States for many types of public works facilities.[65] Concrete is porous, and acts like a sponge in the presence of water or other liquids. It normally provides a protective environment for reinforcing steel, because its chemical constituents and highly alkaline nature help create a protective film on the surface of the steel. However, if the water contains chloride ions and these penetrate to the surface of the reinforcing steel, the protective film will be disrupted and corrosion of the reinforcing steel will begin.[66] As corrosion of the reinforcing steel progresses, rust products which have a larger volume than that of the original steel will accumulate around the corroding area. This eventually causes cracking and spalling of the concrete due to forces that can exceed 5,000 pounds per square inch. Corrosion may also occur when the protective film does not develop uniformly, as may happen when calcium chloride is added to concrete during mixing to accelerate the set of the concrete.

Protection

Techniques to protect concrete structures against chloride contamination include high-quality, dense concrete, epoxy-coated reinforcing bars, liners, and corrosion inhibitors added to concrete mixtures (see table 5-5 for details). Regardless of the choice of protective method, ongoing maintenance is essential and replacement may eventually be necessary .[67]

Maintenance and Rehabilitation

The principal technologies now available for corrosion prevention during rehabilitation are cathodic protection, waterproof overlays, epoxy sealers, and local patching. Once concrete has been contaminated with chloride ions, engineers have several options depending on how long the repairs must last and how much money can be spent (see table 5-6).[68] For example, if a bridge has a functional life of only 3 to 5 more years before replacement, a quick fix method is most cost-effective.

Cathodic protection, used by the Navy for more than 50 years to protect the integrity of ship components, provides longer term safety. Cathodic protection is not now widely used on bridge decks, because placing a new layer of concrete can also be

[65] Office of Technology Assessment and National Association of Corrosion Engineers, Materials Technology and Infrastructure Decisionmaking Workshop, unpublished remarks, Oct. 14, 1989,

[66] M.L. Allan and B.W. Cherry, ''Mechanical Simulation of Corrosion Induced Cracking in Reinforced Concrete,' *Corrosion/89* (Houston, TX: National Association of Corrosion Engineers, April 1989).

[67] John Broomfield, Strategic Highway Research Program, personal communication Nov. 30,1989.

[68] National Association of Corrosion Engineers, "Steel Reinforced Concrete Structures Corrosion Control Considerations," unpublished report, November 1989.

Table 5-5-Corrosion Reduction Techniques

Method	Characteristics	Comments
High-quality dense concrete	Less permeable than ordinary concrete; reduces the likelihood of chloride ions contaminating steel reinforcement.	Increases weight and production costs; traditional protection method in high-risk environments.
Epoxy-coated reinforcing bars (rebars)	Protective sleeve prevents corrosion even in presence of chloride ions.	Now widely used for bridges in United States and Canada; requires careful handling during construction.
Penetrating sealers	Thin layer of sealer is applied to surface to reduce ion penetration.	Frequently used on roads and highways.
Waterproof overlays	Layer is bituminous, covered with layer of asphalt.	Used successfully in European countries.
Corrosion inhibitors	Admixtures to concrete mixture.	New technology; test results are inconclusive.

SOURCE: Office of Technology Assessment, based on Federal Highway Administration, "Time-to-Corrosion of Reinforcing Steel in Concrete Slabs," FHWA-RD-88-165, unpublished report, September 1988.

Table 5-6-Rehabilitation Techniques for Corroded Bridge Decks and Substructures

Method	Characteristics	Comments
Cathodic protection	Current passed through the steel reinforcing bar stops the electrochemical corrosion activity.	Current must continue or corrosion can begin again.
Waterproofing membranes	Pavements and bridge decks resurfaced with asphaltic-type concrete.	Membrane can crack soon after installation.
Epoxy sealers	Surface sealed with epoxy or other polymer products to prevent more chlorides from entering or to change internal moisture content.	Effective in short term; sealer often needs to be replaced.
Patching	Deteriorated concrete replaced.	Not effective in the long term unless all the chloride-contaminated concrete is removed.
Conductive polymer concrete	Bridge decks and structural supports overlayed with sprayable conductive concrete to prevent electrochemical corrosion.	Still under development; experimental testing shows promise.

SOURCE: Office of Technologv Assessment. based on Federal Highwav Administration. "Sprayable Electrically Conductive Polymer Concrete Coatings," FHWA-RD-85-102~ unpublished report, July 1987.

successful in preventing corrosion. However, cathodic protection is a preferable method of protecting contaminated concrete substructures, because the removal of a significant layer of contaminated concrete in preparation for an overlay could result in structural collapse. Missouri, one of the few States to turn to extensive cathodic protection for bridges, did so because its bridges had relatively thin layers of support, and the degree of corrosion made State DOT officials concerned about their structural integrity.

Coatings

Because it is simple and cost-effective, paint is the most common coating for preventing corrosion. However, environmental concerns have created new complications for public works officials and for the paint industry. Regulations governing lead contamination require measures to ensure that lead does not escape into the atmosphere during paint removal and that paint debris is disposed of safely. In North Carolina, DOT officials have turned to sandblasting off old paint and then using the sand-lead mixture in asphalt pavement.[69] States that do not find such alternatives face hazardous waste disposal problems.

The air pollution caused by volatile organic compounds (VOCs) in paints also poses an environmental dilemma. VOCs are hydrocarbon-based solvents that evaporate during application, drying, and curing and create lower atmospheric ozone in the presence of nitrogen when catalyzed by sunlight. While paints without VOCs have been developed, they do not yet adhere as well or last as long.

Some 224,000 steel bridges in the national inventory need protection from corrosion. Officials responsible for their maintenance must find ways to protect them with coatings that conform to new environmental regulations.[70] In some cases, local

[69] William G. Krizan, "Regulators Putting the Lid on Paint,'' *Engineering News Record,* vol. *223, No. 14,* Oct. *5,1989,* pp. 30-33.

[70] Ibid.

officials have found it cheaper to replace a bridge than to strip the paint for coating replacement.[71] Since costs for R&D to develop new materials are prohibitively high for State and local agencies, FHWA is doing research on protective coatings for steel as well as how to dispose of contaminated, removed paint.[72]

Water and Wastewater Facilities

The pipe systems for water and wastewater facilities are particularly subject to corrosion. Acidic and moist soil attacks the outside of the pipe, while materials in the water or the wastewater corrode from the inside. Stray currents from such sources as nearby high-voltage mass transit power supplies, or grounding systems from electrical distribution systems, and oil and gas pipelines, also cause corrosion.

Three available methods protect pipes from the effects of corrosion: material selection, coating selection, and cathodic protection. Advances in materials and coatings have done much to mitigate against corrosion and prolong the useful lives of pipes, making the additional initial investment well worthwhile. However, the most effective method to protect a water/wastewater distribution system is cathodic protection. Gas and oil pipelines are required by law to have cathodic protection, because leaks caused by corrosion can lead to explosions. In contrast, penalties are rarely assessed for a water or wastewater leak, giving local agencies little incentive for protecting their piping systems. Yet a simple protection system can extend the life of a piping network indefinitely, and since corrosive materials in effluent from wastewater facilities are common, corrosion protection considerations should be a routine part of planning a pipe network.[73]

Technology Management

The complex and fragmented process for Federal, State, and local public works decisionmaking, the requirements for community participation in large projects, environmental impact statements, and complicated permit processes make public works project timetables extraordinarily lengthy. Numerous organizations and interest groups committed to preserving the status quo affect technology choice, and legal, social, economic, and political considerations usually outweigh technology-related factors. It is hard to imagine a decisionmaking framework less adaptable to change and to innovation. Politics often determine what gets built, by whom, and how, and somehow elected and appointed decisionmakers must find an appropriate balance among competing needs and technology alternatives.

Designing the Project

Every large construction project goes through similar stages before completion, with preliminary design activity beginning even before a decision is taken to start construction. Project design, which has a major impact on the final outcome, can be carried out by agency staff or by a design consultant. In either case, designers pay close attention to existing design standards and previous projects to ensure the success of the project and to reduce the financial, political, and professional risks involved with the project. Neither agency engineers nor design firms have an incentive to introduce new technologies unless directed to do so by the owner, and many public officials are not interested in being the first owner of a new technology.[74] Thus, technologies developed offshore are not easily introduced into the United States because designers are not familiar with them, operating experience is often under different conditions, and handbooks and manuals describing their implementation and use are not readily available.[75]

After a design is completed and accepted, bid documents are prepared, which include the project design, specifications for materials, parts, and equipment, and contract provisions. Designers rely on engineering standards and specifications to prevent unexpected failures, and since the design determines what the contractor will construct, opportunities for introducing promising new methods or technologies are limited. Flexibility in certifying what is acceptable to meet specifications, such as allowing proprietary and sole source technologies, might spur the

71 Don Fohs, chief of materials, Federal Highway Administration, personal communication Nov. 28, 1989.

72 Ibid.

73 National Association of Corrosion Engineers, "Water and Wastewater Corrosion Considerations Offered by the National Association of Corrosion Engineers," unpublished paper, November 1989.

74 Rudolf Nothenburg, chief administrative officer, City and County of San Francisco, personal communication, Feb. 10, 1989.

75 Victor Elias, private consultant, personal communication, May 2, 1990.

use of innovative technology.[76] Legal restrictions often prevent a designer and contractor from working together to develop a better or less costly project.

Long-term maintenance requirements of new designs must be considered, since an improved design may reduce capital costs but require additional inspection and maintenance efforts. Because responsibility for design, construction, operations, and maintenance is divided in most organizations, opportunities during design for improving operations are often unknown to, or overlooked by, designers. Maintenance managers are not always consulted in the development of specifications for a facility or equipment for which they will be responsible, even though their suggestions can result in cost savings.[77]

One possible improvement to the process is holding a competition for preliminary designs; this would allow evaluation before detailed development of the preferred design and weighing of alternatives on a basis of more than low cost.[78] Although examining alternative designs can bring long-term savings, the costs of funding more than one design may be hard for public officials to justify. Costs are incurred early in the process, benefits are accrued only in the future, and there is no guarantee that the benefits will be as estimated. Projects can be procured through a design-build contract (see below), but in some States this approach is not considered protective of the public interest, and legal restrictions prohibit it for public projects.[79]

Design on the basis of system performance is another way to develop less costly designs. Good performance specifications require a thorough understanding of the problem and the technological ways to solve that problem.[80] Even when officials have such understanding, evaluating alternative designs to meet performance objectives is difficult, because comparisons are based on a range of criteria that have different definitions and measures. Evaluating designs that include new or innovative technologies is also difficult, particularly if operating experience is lacking. Despite these complications, performance-based design competitions can open the path for innovative problem solving.

Value engineering (VE) is a very specific cost control methodology for examining a design on the basis of its functional purpose and capital, operating, and maintenance costs, so as to identify cost items unnecessary for the proposed function of the facility. EPA mandates VE for projects greater than $10 million and currently reports an $18 return per dollar spent on VE.[81] Some design firms perform an independent in-house VE of all their design projects.[82] Some DOT programs, especially in the Urban Mass Transportation Administration, also require VE for capital grant-funded facilities.

Procurement Options

Most public works projects are purchased under a system of competitive bidding that offers those who are qualified an opportunity to prepare a bid or proposal. Procurement procedures and regulations have been developed over time to ensure fairness and accountability and to protect the large sums of public money involved. Some procurement regulations, such as Buy America and minority set-asides, have been established to achieve specific economic and social goals, but they also can affect technology choice.

Selection on the basis of lowest cost or ‘low-bid’ is most common for public works projects, even though the lowest bid price rarely accounts for quality, performance over time, and maintenance. Contractors compete against one another in the bidding process, and often the winner subsequently competes with the locality to further minimize costs and maximize profit. However, choices on the basis of lowest initial cost ignore options that could have higher quality and long-term economy. Since operating and maintenance costs are not the same for different designs, a purchase decision that ignores

[76] Russell Vakharia, Congressional Research Service, ‘‘Productivity in Public Works Construction: Options for Improvement” report 88-97, Jan. 29, 1988.

[77] Robert Contino, ‘‘Employee Participation: The Blue Collar Edge,” *Public Works*, June *198’7*, pp. 81-82.

[78] Vakharia, op. cit., footnote 76.

[79] H. Gerald Schwartz, vice president, Sverdrup Corp., personal communication, May 4, 1990.

[80] Thomas Richardson chief, Engineering Development Division, U.S. Army Engineering Waterways Experiment Station, remarks at the OTA Workshop on Transportation Infrastructure Technologies, July 25, 1989.

[81] William Jakubic, private consultant, personal communication, Apr. 30, 1990.

[82] Thomas Moran, U.S. Environmental Protection Agency, personal communication, May 4, 1990.

them can result in high expenses in the future. Some public officials, while recognizing the difficulties of administering alternative procurement approaches, characterize low-bid procurement as "penny wise and pound foolish."[83]

One alternative to low-bid procurement is based on life-cycle cost, which takes into account capital, operations, and maintenance costs of equipment or facilities over their expected life. Bidders must work closely with the purchasing agency to fully understand the performance needs of the owner. A disadvantage of life-cycle cost procurement is that promising technologies seldom have life-cycle cost data to support the analysis, and uncertainty over future cost prevents wider use.

Federal agencies have successfully used alternative methods of procurement for construction, particularly when time was limited or the project was complex, unusual, and initially difficult to define.[84] These nontraditional methods include:

- cost-reimbursable contracts that permit payment of allowable costs plus a fee or profit that is fixed or variable based on performance;
- competitive negotiations that involve face-to-face negotiations with a number of potential contractors;
- a two-step bid process, with evaluation of technical proposals followed by submission and evaluation of cost proposals;
- concurrent design-build, which allows the start of the construction phase before the design is completed; and
- turnkey construction, in which a firm assumes the responsibility for design and construction and hands the keys over to the owner upon completion. In a variation of the turnkey approach, the contractor would also have responsibility for operations and maintenance.

Each of these approaches involves additional contract administration effort; and legal, administrative, or political considerations can make them difficult to implement.[85]

The design-build approach in which a single firm is awarded the contract to design and build a facility has been used successfully for private construction projects. Combining the design and construction steps with a contract to operate and maintain is another possibility, one that is currently being used for the Channel Tunnel project linking England and France. The contractor won the right to develop the tunnel at its own expense and the concession to operate the tunnel until 2042 with freedom to set tolls.[86] Variations of this approach are possible for other revenue generating projects where private financing is available, although approval by a legislative body is often required.

Standards and Specifications

Design standards help the designer achieve a safe and reliable design and serve to protect the owner's investment from inferior products.[87] The process for establishing standards and specifications is lengthy, and once developed, standards are difficult to change. Thus while providing substantial protection to the owner, they limit the opportunity for introducing product improvements. Standards can range from theory-based, structural design standards to mandated water quality standards for treating municipal wastewater. They are usually conservative in nature and include a safety factor that is a reminder that our understanding of risks, materials, and designs is not always complete;[88] as just one example, EPA regulations have been described as requiring wastewater to be treated so that it is cleaner than the receiving stream without addressing the need to protect the stream from other pollution sources.[89]

[83] Henry W. Wedaa, vice chairman, South Coast Air Quality Management District, remarks at the OTA Workshop on Transportation Infrastructure Technologies, July 25, 1989.

[84] Federal Construction Council Consulting Committee on Procurement policy, *Experiences of Federal Agencies With Nontraditional Methods of Acquiring Real Property,* Technical Report No. 83 (Washington, DC: National Academy Press, 1986).

[85] Vakharia, op. cit., footnote 76.

[86] "Managing a Megaproject," *Civil Engineering,* vol. 59, No. 6, June 1989, p. 45.

[87] Michael Krouse, "Workshop Report-Engineering Standards Versus Risk Analysis," *Risk-Based Decision Making in Water Resources,* Yacov Y. Haines and Eugene Z. Stakhiv (eds.) (New York, NY: American Society of Civil Engineers, November 1985).

[88] Forrest Wilson, "Doctors for Building," *Technology Review,* vol. 89, No. 4, May/June 1986, p. 49.

[89] Whit Van Cott, commissioner of water, Toledo, Ohio, remarks at the OTA workshop on Environmental Technologies, Sept. 14, 1989, p. 64.

Construction contracts include many specifications and provisions that go beyond the actual project design. They include general provisions regarding legal issues such as liquidated damages, project change orders, terms of performance, and methods and schedule of payment; special provisions dealing with system or equipment verification, quality assurance, and contractor deliverables; and technical provisions that describe all the specifications that must be met.

Risk and Liability

Each new technology is surrounded by risk due to uncertainty. The risk is multifaceted and includes:

- technical risk (will the system do what it is designed to do?);
- health risk (will it control disease as effectively as other technologies?);
- safety risk (will it reduce injury and death?);
- financial risk (will the investment be justified?);
- political risk (will the technology provide desirable results?); and
- liability risk (will the potential for failure be financially bearable?).

Public decisionmakers are reluctant to purchase new technology; their basic decision guideline is that technology should be proven in the field or in revenue service before being considered for their jurisdiction. While it maybe an exaggeration to say that administrative agencies ". . . anguish over new technology and the possible effects on society . . ."[90] it is true that public works are not ". . . well-suited for trial-and-error management; the cumulative operating experience is not long enough to provide a good database on what the risks are."[91] However, if opportunities for introducing new technologies are limited by various risks, the value of seeking better methods for testing and evaluating new technologies is great.

Risk-sharing arrangements, which recognize that no one party can afford to accept all the risk, represent one way to overcome bias against new technology. Risk sharers can include all levels of government that would benefit from successful application, local investors and developers who could gain financially, and manufacturers and contractors who anticipate future sales contracts. The need to spread the risk in the United States results from governmental unwillingness to establish a recognized authority to test and approve new technologies.[92] Efforts such as EPA's Innovative and Alternative Technology Program (see box 5-C) were designed to provide an increased Federal match to localities for construction grants.[93] Demonstration projects that help bridge the gap between a developed technology and Ml-scale implementation in an operating environment are an effective way to encourage the use of advanced technologies.

Repair and Rehabilitation

Although numerous studies have documented the value of good maintenance practices, maintenance funds are highly vulnerable to budget cuts.[94] Easy to overlook and defer and with little or no political constituency, maintenance has been compared to visiting the dentist because, ". . . it's painful and costly . . . and it doesn't get done unless it is absolutely necessary or catastrophic."[95] Because maintenance budgets are limited, small repairs are often made with low-grade materials to eliminate an immediate problem and to delay a more costly, longer lasting repair.

Inventories, inspections, and evaluation are all needed to avoid costly repairs and rehabilitation. A recent study of New York's bridges stressed the importance of preventive maintenance, recognizing that if maintenance is stopped, even for short periods, deterioration accelerates.[96] The study also concluded that although modem methods are helpful, some of the best steps are the simplest. Cleaning,

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[90] Peter Huber, "Don't Innovate: It's Dangerous," *Civil Engineering*, vol. 58, No. 4, April 1988, p. 6.

[91] Walter Diewald, "Risk Analysis and Public Works Decision-Making," Engineering *Applications of Risk Analysis*, F.A. Elia, Jr., and A. Moghissi (eds.) (New York, NY: The American Society of Mechanical Engineers, 1988), pp. 39-43.

[92] National Council on public Works Improvement, *Fragile Foundations: A Report on the Nation's Public Works*, Final Report to the President and the Congress (Washington, DC: February 1988), p. 128.

[93] American Public Works Association, "Structuring Demonstration Projects of New Technologies," *Proceedings, Aug. 3*, 1987, p. 7.

[94] Apogee Research, Inc., "Maintaining Good Maintenance," technical memorandum prepared for the National Council on Public Works Improvement Sept. 30, 1987.

[95] Van Cott, Op. cit., footnote 89.

[96] "Fixing What Ain't Broke," *Civil Engineering*, vol. 59, No. 9, September 1989, p. 69.

Box 5-C—The Environmental Protection Agency's Alternative and Innovative Technology Program

Americans' zest for innovation and the drive to build a better mousetrap fades rapidly when it comes to public works. The history of the Environmental Protection Agency's (EPA) efforts to promote nontraditional technologies for wastewater treatment highlights the conservatism of State and local officials' attitudes toward public works innovation.

Disturbed that the construction grant program established by the Clean Water Act of 1972 was funding predominantly large regional facilities using conventional technologies, Congress authorized the Innovative and Alternative Technology (1/A) Program in 1977 to absorb the financial risks of local experiments with nontraditional system design and construction. If a community used an EPA-approved alternative treatment or innovative technology, EPA covered an extra 20 percent (or 75 percent) of project costs, even if they were as much as 15 percent higher than conventional methods. Communities that chose new technologies were eligible for 100 percent grants to corrector replace systems that failed. States were required to set aside 4 percent of their total Federal construction grant allocations to fund the required bonuses for new technologies.

While providing a proving ground for experimental technology was a prime program goal, only 600 out of the 2,700 I/A-funded projects meet EPA's definition of innovative--using developed, but not fully proven technologies.[1] This category includes, for example, new aeration and mixing processes and innovative kinds of clarifiers and disinfection for wastewater treatment, and aerobic and/or anaerobic digestion of sludge. The vast majority of I/A projects use more orthodox methods EPA classifies as alternative; these include land treatment of wastewater and sludge, aquifer recharge, and methane recovery—well known, if not widely used, techniques that are low cost and emphasize environmental preservation and energy conservation. Despite the relatively low participation in innovative projects, EPA reports that the acceptance of ultraviolet disinfection as an alternative to chlorination and technical improvements in sequencing batch reactors for small communities are direct results of I/A-funded projects.[2]

Most I/A grants have gone for alternative projects in capital-short, small communities more interested in money and low-cost operations than cutting-edge technology. Over two-thirds of I/A projects serve communities with populations under 10,000, many of which would have had low priority for Federal or State funding outside the I/A program.[3] Between 1979 and 1985, over one-half of the States failed to appropriate all their State I/A set-aside, foregoing millions in Federal funds.[4]

Funding for I/A projects ended in 1990 when the Construction Grant Program expired. Innovative wastewater treatment projects are eligible for State Revolving Fund loans, but for most communities, loan repayment is likely to be a further disincentive to innovation and risk-taking.

[1] u.s. Environmental Protection Agency, Office of Water, *Effectiveness of the Innovative and Alternative Wastewater Treatment Technology Program (Washington DC:* September 1989), p. 66.

[2] Ibid., p. 67.

[3] Ibid., p. 64.

[4] Ibid., p. 45,

painting, patching, and sealing need to be performed regularly.

Proprietary Technologies

When the private sector develops a better mousetrap, the rights to it are important because of the competitive advantage they bring. Selling the improved mousetrap to the public sector may be difficult, because public authorities want to protect themselves against price changes or supply problems associated with proprietary technologies.[97] Furthermore, the private sector may have to forego some proprietary rights on a product purchased by the public sector, thereby sacrificing its competitive position. Sole source procurement is possible where a one-of-a-kind product is available, but procedures built into the procurement system to protect against favoritism make sole sourcing difficult.

[97] Vakharia, op. cit., footnote 76, p. 21.

Personnel Training, Education, and Recruitment

As promising as many new technologies appear, they cannot be used properly without trained managers and technicians, and there is much evidence that the public works field is losing its well-trained people to the private sector and to retirement much faster than they are being replaced. Many new technologies require new skills; in some cases jobs must be redefined or job assignments combined, so that qualified people can be hired at a competitive salary .[98] Some public works departments are providing special training for entry-level employees to help them qualify for jobs and for additional technical training.[99] The current need for repair and rehabilitation in public works increases the severity of these problems, because very little engineering training and education focuses on emerging methods or technologies.

Small systems have particular difficulty in finding trained personnel to operate and maintain the complex treatment systems necessary to meet current EPA standards. The National Rural Water Association with funding from EPA has developed a circuit rider program (see chapter 4, box 4-E) to alleviate some of the problems created by the lack of trained personnel, but more help is needed. Qualified circuit riders soon leave the program for more money and greater opportunity in larger systems. Thus while it is important to develop special technologies for small systems, helping find the people to staff them is even more crucial.

Improved training and education are necessary for many reasons. If procurement procedures are changed to allow promising technologies to be introduced more quickly, public works staffs must be capable of adjusting to the improvements. Procurement decisions based on performance standards, for example, will require abilities that are not now generally available. As one expert puts it, "We cannot have performance specifications if all we have are a bunch of contract monitors. ''lWNontraditional procurement procedures will also require more contract administration and greater coordination between the technical and administrative staffs of public agencies.[101]

The construction industry and its labor unions have recognized the need for additional well-trained personnel and have initiated a national training program, spending about $400 million last year alone.[102] DOT's university centers, too, are focusing on attracting students to stay in the civil engineering field in public works. (See chapter 6 for further details.)

Conclusions

Although many innovative technologies are available to help infrastructure managers use staff more productively and improve system operation and maintenance, institutional, management, and financial constraints prevent their adoption by most public works organizations. Moreover, since many of these originated in fields other than infrastructure, successfully applying them to public works requires additional analysis, development, and field testing and evaluation. Yet, despite a multitude of Federal technology transfer programs, efforts to implement cross-cutting technologies with application across a range of public works have no institutional home.

Acceptance and use of new technologies is closely tied to legal requirements and management and procurement policies that inhibit consideration of alternatives without an extensive record of operational experience. Although caution is necessary when public funds are used, Federal leadership would be invaluable in developing appropriate safeguards and evaluation procedures that allow a broader set of technology alternatives to be considered.

[98]U.S. Congress, Office of Technology Assessment, *Making Things Better: Competing in Manufacturing*, summary (Washington, DC: US. Government Printing Office, February 1990), p. 22.

[99]Carolyn H. Olsen, commissioner, Atlanta Department of Water and Pollution Control, personal communication, Feb. 7, 1990.

[100]Thomas Richardson, chief, Engineering Development Division, U.S. Army Engineering Waterways Experiment Station, remarks at the OTA Workshop on Transportation Infrastructure Technologies, July 25, 1989.

[101]Federal Construction Council Consulting Committee on Procurement Policy, *Experiences of Federal Agencies With Nontraditional Methods of Acquiring Real Property*, Technical Report No. *83* (Washington DC: National Academy Press, 1986).

[102]C. James Spellane, The Kamber Group, personal communications, May 101990.

Promising Technologies

Computers for scheduling work tasks, monitoring equipment use, ordering and tracking supplies, tracking staff requirements, organizing and tracking documents, and performing many other routine functions in public works projects have brought enormous benefits. Public works organizations are most likely to be using computers; the degree to which other electronic or advanced decisionmaking tools are used depends on the skill levels of personnel and the agency's financial resources.

Communications and Decision Tools

Advances in solid-state electronic technology have fueled the development of low-cost reliable tools to assist public works managers in assessing their systems. These sensing and measuring devices, especially when coupled with information management systems, can provide extensive infrastructure condition and performance data for many decisionmaking and management tasks. They can also reduce long-term maintenance costs by helping managers to identify problems when they are less costly to correct and to set maintenance priorities when funding is tight. However, budget processes make it difficult for public works officials to purchase items designed to reduce future expenditures or those not directly related to current needs, and most current Federal grant categories preclude use for this sort of equipment.

Computer-based inventory and decision support systems provide efficient means of storing and accessing infrastructure condition and performance data. Expert systems and artificia1 intelligence programs show promise as training and engineering tools. Computer systems coupled with appropriate technical skills and decisionmaking tools can help public works authorities faced with expanding inventories of facilities and limited operating budgets operate more productively and efficiently.

Advances in communications and positioning technologies may make large-scale traffic management and control, common today in aviation, practical for other modes of transportation. Surface traffic flow gains on the order of 10 percent are possible, and in congested areas this might result in large reductions in delay. Off-the-shelf urban traffic signal control systems can reduce delay by up to 10 to 20 percent.

Construction and Materials

Considerable research is under way on materials for highway construction to yield longer life and lower maintenance costs. Improved methods and techniques for construction and preventive maintenance are as important as materials to prevent premature failure. Construction methods that do not physically disrupt normal operations and minimize the tra.file delays of traditional methods of construction are available for wider use in public works. Such methods are particularly cost-effective in congested areas and for heavily used facilities, and are also important for repair and rehabilitation projects.

Advanced tunneling technologies provide opportunities for lower cost construction for transportation and water projects. Combined with electronic guidance and monitoring equipment these technologies can make completing such projects easier and less costly.

Techniques such as soil nailing and jet grouting and using geotextiles make it easier to utilize existing soils and terrain conditions, lowering construction costs. Such techniques also can be used for cost-effective repairs and rehabilitation and deserve further exploration and development.

Although their initial cost is higher, advanced materials, such as polymers and composites, can yield higher strength, longer life, and improved durability to public works, making them good long-term investments. In addition, regular, preventive maintenance and using known techniques can save the costs and prevent many of the losses due to corrosion of infrastructure facilities and equipment.

Technology Management

Probably the greatest gains in public works productivity and efficiency will be made by focusing on changing management practices. Table 5-7 provides a summary of issues and alternatives.

Changes in the Federal Role

Federal policies could be shaped to encourage public officials to make greater use of procurement approaches that have proven successful for public projects. Using life-cycle costs and value engineering in making procurement decisions can help lower long-term costs without affecting project performance.

Table %7—Alternatives for Technology Management

Subject	Issues	Alternative
Project design	Engineers and designers have few incentives to introduce innovative technologies; designers and contractors are often legally prohibited from working together on public projects. Project designs direct contractors as to what to construct so they have no incentive to innovate except in construction techniques.	Design competitions, performance specifications, and value engineering furnish opportunities for innovative approaches.
Procurement	Low-bid procurement does not account for quality, performance over time, and future maintenance requirements. it encourages adherence to the status quo and stifles the opportunity for innovation.	Alternative procurement methods have proven successful in delivering higher quality products, often at a lower cost. Design-build procurement has been used to advantage in the private sector for many years.
Standards and specifications	Design standards are vaiuabie but they are difficult to change and hinder innovation. The scope of project specifications has expanded to include many provisions that address legal and administrative areas.	Streamlining design standards and contract specifications would be helpful. A materials testing laboratory could hasten new technology introduction.
Risk and liability	Public decisionmakers have little or no incentive to introduce a new technology; risk aversion is widespread in the public sector. industry is highly protective of proprietary technology.	Risk-sharing arrangements are necessary for the public sector to embrace new technology. Demonstration projects can encourage innovative technologies. Funding tied to performance may provide an additional incentive.
Repair and rehabilitation	Poor and deferred maintenance are known to lead to premature failures and deterioration of capital facilities, and yet decisionmakers often discount the long-term value of good maintenance,	inventories, condition assessment data, and preventive maintenance programs together with capital funding that is tied to these can force appropriate actions.
Personnel training, education, and recruitment	New technologies require new technical skills and too few engineers are entering the field to meet the need. improved training and education is needed so that innovative technologies can be put into use quickly and effectively.	Efforts to educate and train engineers and technicians that include the engineering profession, universities, consultants, and unions need private and public support to address the severe staff shortages.

SOURCE: Office of Technology Assessment, 1991.

Acceptance of new technologies requires a sharing of the financial and technical risks among designers, manufacturers or builders, and government agencies that finance and operate these technologies. Projects designed to evaluate, refine, and demonstrate innovative technologies in an operating environment would help promote new technology and provide a basis for determining their value. Such demonstration projects will require considerable public-private cooperation, and Congress could consider focusing a few R&D programs on promising technology areas and encouraging public-private arrangements.

The establishment of an authoritative institution for testing and approving new technologies would help avoid some of the current problems associated with risk and liability. Such an institution will require considerable support from the Federal Government (see chapter 6 for a discussion of the National Institute of Standards and Technology). An independent, national testing laboratory and national technology demonstration program **sponsored by the Federal Government could encourage researchers and facilitate the introduction of new products and technology.**

Even though preventive maintenance is an important component in protecting the investment in capital facilities, the value of maintenance is often discounted when the competition for limited budgets increases. Congress could consider ways to recognize deferred maintenance as a cost item and to hold the capital grant recipients accountable for premature deterioration of facilities and equipment due to improper and deferred maintenance.

Personnel Training, Education, and Recruitment

The complexity of much new technology places high demands on the technicians, operators, and maintenance personnel involved. The need for additional training of such personnel and their managers is very great if new technology is to be used effectively. Consultants, manufacturers, professional organizations, unions, and universities all can help provide training. Mentor programs that provide help to small systems would be particularly helpful.

The average age of infrastructure managers increases, and the numbers of young graduates in relevant fields to take the place of the retiring infrastructure work force are insufficient. The United States faces a serious shortage of qualified personnel to operate public works. Directing additional funds to programs that support university **research in transportation and environmental infrastructure could attract students back to transportation and civil engineering and alleviate the worsening shortage of qualified engineers to design, build, operate, manage, and maintain infrastructure systems. Congress could address the need for more engineers and for engineering curricula that includes attention to maintenance and rehabilitation.**