INFRASTRUCTURE OBSOLESCENCE AND DESIGN SERVICE LIFE

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ABSTRACT: Infrastructure facilities generally have long service lifetimes. Major action is nevertheless eventually needed to overhaul, renovate, or sometimes demolish a facility that no longer provides satisfactory service. Sometimes obsolescence, brought on by changes in demands or technologies, motivates such action. Obsolete facilities—antiquated, old-fashioned, out-of-date—impose heavy burdens on their owners and users. Obsolescence, a concern throughout a facility’s entire life cycle, reflects changed expectations regarding the function, profitability, or other dimension of performance that a facility is expected to provide. While such changes are primarily external, a facility’s initial capabilities (e.g., durability of materials, flexibility of mechanical equipment) and how it is maintained influence the likelihood or timing of the onset of obsolescence. Obsolescence reduces the facility’s service lifetime and for infrastructure may be the only meaningful technical basis for selecting a design service lifetime. This paper characterizes obsolescence as a concern for facility design and management, explores its sources, analyzes its impacts on infrastructure performance, and discusses how consideration of obsolescence might influence key infrastructure design and management parameters such as design service life and maintenance policy. The study of obsolescence can yield strategies for more effective infrastructure management, but warrants a multifaceted blending of theoretical analyses and practical observations.

INTRODUCTION

"Always remember that someone, somewhere, is making a product that will make your product obsolete," said Georges Doriot, who directed American Research & Development (a near-legendary venture-capital firm) for its first 28 years and taught at the Harvard Business School. His early support of the fledgling Digital Equipment Corporation made him and his shareholders wealthy. Forbes magazine wrote of him in 1982: "Anyone looking for the roots of professional capitalism in the U.S. need search no further" ("Flashbacks" 1992).

Doriot was speaking of industrial products, but might as well have been commenting on cities and their infrastructure, where obsolescence is widespread. In the city of Detroit, for example—ironically, the home of "planned obsolescence" in the automobile industry—scores of structures sit vacant and crumbling, abandoned to economic and social change. The streets, water lines, sewers, and other public works built to support the economic activities these buildings once housed risk becoming derelict as well, as scarce maintenance dollars are devoted to better-used facilities. The costs make demolition an unattractive option for a financially constrained local government, while an oversupply of office space in the regional real-estate market makes it unlikely that the private sector will be moved to act. One observer has proposed that the ruins be converted to an "American Acropolis" (Vergara 1995).

Detroit's case is extreme but not unique. Across the nation, bridges have been restricted or closed because they cannot safely carry the increasingly heavy load of vehicles. New York's Williamsburg Bridge may be the most famous case, but the U.S. General Accounting Office concluded in 1991 that about 40% of the nation's bridges were deficient ("Bridge" 1991). Water utilities and sewer authorities face huge costs to upgrade treatment facilities to meet new and more stringent environmental regulations. Electric utilities must sometimes replace still-functional equipment with new high-efficiency generators simply to stay competitive when fuel costs change. These are all problems of infrastructure obsolescence.

Yet the impact of obsolescence has been largely neglected by infrastructure designers and managers. The real-estate industry recognizes the problem (e.g., Downs (1995), Khalid (1995), Pilzer (1989)), but the term does not appear in the indexes of engineering- and building-economics texts and can scarcely be found in the scholarly literature of civil engineering or architecture. Obsolescence is nevertheless important to decision makers responsible for infrastructure design and management, particularly because its onset answers the question: "How long should infrastructure last?"

The purpose of the paper is to propose a framework for the analysis of infrastructure obsolescence and to suggest some conclusions this analysis would offer about infrastructure design service lifetimes. The discussion includes both symbolic and graphical presentations of the concepts of infrastructure obsolescence, in an effort to attract both theoretical and practical consideration of the topic among readers. While there is considerable literature on technological innovation that offers insights on matters of obsolescence, the writer's studies indicate that little attention has been given to this issue as it pertains to infrastructure. The topic warrants research and changes in infrastructure design and management practice.

INFRASTRUCTURE OBSOLESCENCE AND ITS SOURCES

Obsolescence, dictionaries tell us, is a condition of being antiquated, old-fashioned, or out-of-date. An obsolete item is not necessarily broken, worn out, or otherwise dysfunctional, although these conditions may underscore its obsolescence. Rather, the item simply does not measure up to current needs or expectations.

Obsolescence results when there is a change in the requirements or expectations regarding the use of a particular object or idea. The danger of earthquakes, for instance, motivates changes in structural design standards to reduce the risks of failure and mitigate the consequences of such a disaster. These changes, in turn, render many older structures effectively obsolete since they no longer comply with the most recent safety requirements.

In most cases things that are obsolete continue to function but at levels below contemporary standards. In doing so, they may still fulfill a useful function but not precisely that for which they were designed. For example, a road passing through a small town will still serve local traffic even after construction of a bypass. (The bypass was probably constructed, in turn, because the through road was unable to serve heavy traffic loads without imposing unacceptably high safety,
maintenance, or environment costs on road users, agency budgets, and town residents.)

The factors that can cause obsolescence can be grouped into four broad categories:

1. Technological changes influence the scope or levels of services infrastructure is to provide, e.g., when a newly introduced aircraft cannot be served at existing airport terminal gates

2. Regulatory changes impose new requirements on infrastructure, e.g., when transit vehicles had to be retired or retrofitted to make them fully accessible to mobility-impaired passengers

3. Economic or social changes in the markets within a region can substantially alter the demands placed on infrastructure, e.g., when residential construction aimed at satisfying demand for new suburban houses necessitates upgrading of inadequate rural roads and village water supplies

4. Changes in values or behavior of the people who use and own the infrastructure can similarly alter demands but are more difficult to foresee, e.g., when a societal commitment to private auto travel spurred removal of street railways in most urban areas

These changes occur for the most part outside of the boundaries of the infrastructure system, but system design or management may be influential. The high capital cost and typically long service lives of infrastructure facilities—30–70 years and more—make the spread of technological innovation a slow process, for example, as compared with automobile safety features. Thus, when standards imposed by the Safe Drinking Water Act effectively made many local water-supply treatment plants obsolete, the high costs of upgrading spurred complaints from local government authorities. Consequent debate in the 103rd Congress considered whether those standards should be relaxed. In the absence of substantial public outcry, one could reasonably conclude that relaxation of the standards would relieve many plants from the need for immediate upgrading of no-longer-obsolete equipment.

This case exemplifies the broader idea that agencies that use and manage infrastructure sometimes find it necessary to modify otherwise-satisfactory facilities, to bring them up-to-date or to remedy features that no longer meet user’s demands. Often, these modifications are especially costly because the designs of older structures are not adapted easily to new applications and services. In extreme cases of obsolescence, it is more cost-effective to abandon and replace facilities rather than renovate them. This occurs particularly with buildings expected to house new equipment (e.g., hospitals) and bridge structures that are too narrow or undersized to carry contemporary loads.

**CHARACTERIZING OBSOLESCENCE**

Obsolescence then is a matter of inability to meet performance requirements that are changing. “Performance” means the facility’s ability to provide the service for which it is intended, and can be measured by any of a variety of parameters, depending on the particular facility type or subsystem being considered. For example, highway pavement performance is typically measured in terms of roughness of ride and skid resistance, while for water-supply systems, purity and clarity of water are important. The complexity of infrastructure systems defies definition of any single parameter adequate to measure all aspects of performance. Performance measurement, a subject that goes well beyond the scope of this paper, typically includes financial, economic, and sociological factors as well as more traditional engineering parameters. [See *Measuring* (1995) for a recent comprehensive discussion.] Some researchers [e.g., Ben-Akiva and Gopinath (1995)] argue that performance is only indirectly observable in terms of indicators of distress or other aspects of deteriorating performance.

**Characterizing Performance**

The concept of performance of infrastructure has been a recurring research subject for more than 20 years. [For example, see *Proceedings* (1972), “Building” (1986), *Performance* (1990)]. The framework used here for characterizing performance is essentially that suggested by Lerner (1971, 1992), based on concepts from consumer theory in economics. In mathematical terms, performance may be represented as follows:

\[
\text{Performance} = P(S_j, D_j, t)
\]

where \(S_j = \text{supply vector of services } j \text{ that the infrastructure facility or system provides to various groups (e.g., users, owners, neighbors)}; D_j = \text{demand vector of services } j \text{ that the infrastructure facility or system provides to various groups (e.g., users, owners, neighbors)}; \text{and } t = \text{time, measured from the completion of construction and start of commissioning.}

In general, the supply of services, \(S_j\), is characterized or predicted as a function of design and operational characteristics of the facility and its management, i.e.

\[
S_j = S(X_i)
\]

where \(X_i\) = a vector of descriptive and functional characteristics \(i\) of the infrastructure facility or system (e.g., pavement thickness, pipe diameter, steel modulus of elasticity).

The aspects of “service” that infrastructure provides include access and mobility (e.g., transportation infrastructure), shelter, safety, comfort (e.g., highway ride), purity (e.g., water supply), and the like, as well as less desirable consequences of infrastructure, such as noise (e.g., airports), air and water pollution, and others. The formulation is essentially an adaptation of Lancaster’s (1966) approach to consumer demand, an application of utility theory.

The performance function \(P\) in general has dimensions of effectiveness, reliability, and cost (*Measuring* 1995). Effectiveness is the degree to which the infrastructure accomplishes the tasks its owners, users, and neighbors set for it, i.e., meeting the demands \(D_j\). Maximum effectiveness is achieved when the supply of services \(S_j\) at least equals demand relative to all services \(j\). Note: in microeconomic theory, optimum market conditions occur when supply and demand are just equal; supply of a service \(j\) in excess of demand—e.g., water quality better than the required standard—is an uneconomic use of resources. However, inability to measure all aspects of service in monetary terms and a variety of market “imperfections” generally defy economists’ efforts to be precise when applying theory to actual transactions involving infrastructures.

Designers and managers of infrastructure seek generally to assure that characteristics of a facility or system, \(X_p\), are such that effectiveness is adequate. The strategy is what Simon (1957) termed “satisficing” rather than optimizing. Demand in excess of supply is often accepted as a provision for future growth, a contingency or safety factor for unknown aspects of demand, or simply a higher “quality” than the functional minimum required by standard or custom.

Reliability is the probability that effectiveness will be sustained at acceptable levels for an extended period of time, generally throughout the design lifetime of the facility. Cost—sometimes termed “life-cycle cost” in the literature—encompasses the resources required to plan, design, construct, operate, maintain, and sometimes convert or demolish facilities such that their effectiveness is sustained throughout the design lifetime.

154 / JOURNAL OF INFRASTRUCTURE SYSTEMS / DECEMBER 1996
Characterizing Failure

Failure occurs if performance falls below levels that decision makers judge to be unacceptable, i.e., the infrastructure is ineffective or too likely to become so within the near future, or costs are too high. The condition is shown symbolically as

$$P(t) < P^r$$  \hspace{1cm} (3)

where $P^r = \text{minimum acceptable performance}$. Planners and designers generally seek to assure that effectiveness, reliability, and cost are balanced to achieve "optimum" performance during the design lifetime, i.e.,

$$P(t) \geq P^r$$  \hspace{1cm} (4)

where $T^O = \text{design service life}$. Optimum in this context generally means reliably effective service at the lowest possible cost. In practice, however, optimum may imply lowest construction cost, tolerance of what some users will view as excessive congestion or unreliable service, and other compromises.

Design service lives for infrastructures are set typically at 30−70 years for benefit-cost and other design calculations, often with very limited rationale. Definitions of design service life (and optimum performance, normal maintenance, and operating policies) are, in principle, choices to be made by designers and owners, based on analysis of life-cycle costs and benefits. Most typically, no such analysis is conducted, and these definitions are adopted implicitly from so-called standard practice. Actual service lives achieved, as we will discuss further, vary widely from these abstract targets (Marland and Weinberg 1988).

Fig. 1 illustrates conceptually and in simplified form the progression of a facility’s performance during its service life. As shown in the figure, performance immediately following the completion of construction, i.e., at commissioning, is typically less than the design ideal. Generally, a modest "shakeout" period of operation is necessary for the facility—and its operating personnel—to raise performance from the facility’s initial capability to the anticipated optimum level of performance. Care during commissioning can reduce the likelihood that early problems will have lasting impact on peak longer-term performance levels.

Assuming that the facility’s performance does approach the optimum, and the new facility will continue to deliver that performance at a reasonably steady level for some years—barring catastrophe and with proper operations and normal maintenance—a slow decline eventually (and inevitably) begins, owing to wear and aging. Eventually, performance falls to a level judged to be the minimum acceptable.

Users or maintenance personnel are typically the first to notice the decline. Because of the performance drop, the users may change their patterns of use (i.e., take alternative routes for travel, purchase water from alternative sources). For most infrastructure, the conclusion that performance is truly unacceptable often involves political decisions. Once the conclusion is reached, owners may take actions to renovate their facilities (i.e., resurface a highway, reline pipes, reduce prices), or the facilities may be retired or replaced. Neglect of maintenance or conditions of use more demanding than anticipated will generally spur earlier onset and speed up the rate of performance deterioration. As Fig. 2 illustrates, the performance curve declines more steeply and the minimum acceptable performance level is reached sooner. Thus, the service life is reduced. Such a reduction in service life—below design levels—is typically judged a failure by users or owners, although sometimes a maintenance effort above normal levels can extend the service life beyond its design target.

![FIG. 1. General Representation of Performance and Service Life](image)

![FIG. 2. Maintenance Practices Influence Service Life](image)

![FIG. 3. Expectations or Standards May Change with Time](image)

Failure through Obsolescence

For the sake of simplicity, Figs. 1 and 2 show unchanging levels of performance judged to be optimum or the minimum acceptable throughout the period of the facility’s service life. This is seldom the case in practice, except perhaps regarding a few very basic aspects of performance, such as structural stability. More typically, peoples’ expectations change over time as a result of the development of newer facilities, the introduction of new products, and increased experience. The change is more frequently toward higher rather than lower expectations and can cause performance to reach minimum acceptable levels much sooner than they would otherwise (see Fig. 3). (On the other hand, some older structures may achieve historic importance, and the public accepts aspects of performance that would be judged unacceptable in a new facility. This effect reflects a change in the services provided by the infrastructure.)

Referring to (3), the effect can be characterized by projecting the failure level of performance

$$P^r = P^r(E_x, t)$$  \hspace{1cm} (5)

where $E_x = \text{exogenous or environmental factors such as overall levels of technology, economic conditions, and cultural setting that influence expectations about infrastructure performance}$; and $t = \text{time}$. This rise in expectations and failure criteria is generally the source of obsolescence. Service life reduction because of these

JOURNAL OF INFRASTRUCTURE SYSTEMS / DECEMBER 1996 / 155
ranging expectations is the basic measure of obsolescence. Obsolescence occurs when \( P^* \), the failure criterion, increases quickly enough that the actual service life is reduced below design expectation, i.e., when the expected performance at age \( T^* \) (i.e., when \( t = T^* \)) is

\[
E[P(t = T^*|X, D)] < P^*(t = T^*|E), \text{ such that } T^* < T^0
\]

where \( T^0 = \) age at obsolescence.

The function \( P^*(E, t) \) may be termed the "expectations function." The rate of increase of the expectations function can be very rapid, as Fig. 4 illustrates. Obsolescence associated with regulatory change, for example, could be represented almost as a step function, although extended public discussion and debate often precede the regulatory change. Passage of the Safe Drinking Water Act (SDWA), for example, initiated imposition of a succession of new regulatory standards that have rendered the water-supply systems of many communities effectively obsolete. However, obsolete systems may continue to be used. If they are not replaced or refurbished, these systems impose a variety of disbenefits on infrastructure’s users, owners, and neighbors, including losses in productivity, environmental degradation, and elevated operation and maintenance expenses. Failure to comply with the SDWA, for example, presumably threatens public health and certainly risks legal sanctions and large fines.

Other factors likely to be included in the vector of exogenous or environmental factors, \( E_{\text{env}} \), include level of economic development or industrialization (e.g., per capita incomes), location, and availability of alternative sources of services (e.g., competition). A few studies in the infrastructure-related literature (e.g., Khalid (1995), Karni and Schmeidler (1990)) address such matters directly, but the literature of technological innovation offers many useful insights (e.g., Stoneman and Ireland (1983), Silverberg et al. (1988)).

**SERVICE LIFE PREDICTIONS**

The long service life of infrastructure is often considered one of its defining characteristics (e.g., In Our (1993)). Some facilities do fail quickly (the Tacoma Narrows Bridge and Tetons Dam are famous examples), but most infrastructures endure for many decades, and sometimes for centuries. Ancient Rome’s Cloaca Maxima is still in service, more than 10 centuries after its construction, and the Brooklyn Bridge has served for more than a century, becoming one of New York’s most treasured landmarks.

In this sense, infrastructures’ service lives often differ from their physical lives, the actual time it takes for the facility or one of its major subsystems or components to wear out or fail, i.e., the “time period after which a facility can no longer perform its function because increasing physical deterioration has rendered it useless” (Kirby and Gargas 1975). The end of the physical life comes as parts exposed to the weather need replacing, mechanical equipment breaks down, metals corrode, and sealants erode, regardless of users’ demands, economic factors, or technological advances. These conditions are not obsolescence, because they do not stem from changed expectations about performance. (The repairs or replacements may, however, incorporate materials or parts that use new technology and thereby defer or redress obsolescence.)

**Design Service Life**

While service lives may differ from physical lives, expectations about physical lives for the most part determine the design service life. U.S. highway pavements, for example, are typically designed for 20-year lives (but often wear out or break down sooner). Many of the German autobahns were designed to serve Hitler’s 1000-year Reich and still are serviceable, more than 50 years later (albeit with regular maintenance). Power plants have typically been expected to last 25–30 years because history has shown them to become non-competitive by then, although that perception is said to be changing—and lifetimes lengthening—as designers reach the ceiling of thermodynamic efficiency in conventional generation technology (Marland and Weinberg 1988). The service life of housing similarly seems to be increasing in areas where new home construction is unable to keep pace with growing demand (Meikle and Connaughton 1994). In sharp contrast to infrastructure, some companies find the lifetime of desktop computers to be less than two years, as new microprocessor chips hit the market at about 18-month intervals, each with twice the power of the preceding generation.

Experience and testing are the two principle sources of information on which expectations of service life—and design service lives—are based (Sjöström 1985). Efforts to predict infrastructure service lives (and the shape of the performance-deterioration function) face a number of obstacles, including our limited knowledge of the mechanisms of deterioration, uncertainties of climate and other factors influencing deterioration, lack of data, and inherent complexities of the problem. Among these complexities are the challenges of characterizing the service lifetime of a whole facility or system—e.g., a bridge or a sewer network—as distinct from the lifetime of its repairable or replaceable components.

There has been some success, nevertheless, in infrastructure performance and service life prediction, notably with regard to highways. The boom in U.S. highway system expansion in the 1950s and 1960s coincided with rapid advances in computer technology and applications of systems analysis techniques in civil engineering. At the same time, work by development economists at The World Bank and elsewhere began to demonstrate convincingly the direct impact that pavement-surface conditions have on vehicle operating costs and, in turn, on economic efficiency of a region’s transportation system. These developments combined to motivate research that led to establishment of practical pavement management systems. After two decades of development, these systems are now used routinely by many state and local transportation agencies to monitor highway performance and schedule maintenance (Hudson et al. 1979). Researchers in the field are looking toward evolving present systems into larger, integrated, “total facilities management” systems useful to public facilities administrators responsible for underground services and parks and recreation facilities, as well as for road pavements (Haas and Hudson, unpublished paper, 1987).

Another area of relative success is in development of climatological data used in the design of hydraulic structures and flood-control schemes. Bolstered by years of storm records, researchers have devised sophisticated statistical models to predict frequency and sizes of storms, which seem to give a rational basis for making design decisions. Large storms in the
Mississippi Valley and northern California have nevertheless exceeded designers’ expectations and caused extensive damage. Residents who have chosen to move their towns out of the floodplain rather than rebuild what was lost have, in effect, decided that new experience has made their previous location and flood-protection facilities obsolete.

**Obsolescence as the Only Effective In-Service Failure**

In general, past experience, custom, and rules of thumb are still the primary sources of estimates for infrastructure service life. Design decisions and owners’ investment decisions typically are based on an assumption that adequate performance can be delivered for a design service life of 20, 30, 50 years, or some other convenient number. In some cases, the tax code rather than engineering or other technical judgement is the best source of a number.

Such sources may be the only sensible response to the complexities of finding theoretically correct measures. One could argue that trying to predict physical life is irrelevant, if not impossible, at least at the level of whole infrastructure facilities or systems. First, the assumptions that must be made to support prediction—e.g., the quality of construction, future maintenance practices, weather conditions—cannot be assumed to hold over several decades of service. In the case of maintenance, in particular, any assumption other than “no maintenance” is almost certain to be violated at one time or another. Second, infrastructures are seldom taken completely out of service until some competing device can provide the same service less expensively or the service is no longer needed, that is, until the infrastructure is obsolete. While maintenance may be neglected, repairs will be made when they can no longer be postponed. New York’s Williamsburg Bridge, closed to traffic for months because corrosion had reached crisis proportions, is an extreme but by no means unique example. Finally rising expectations will almost surely cause performance to fall below acceptable levels before infrastructure wears out or is used up.

**EXPECTATIONS FUNCTION**

In other words, the concept of a “design service life” is meaningful only if it is defined in terms of obsolescence. Design service life cannot be meaningfully described in terms of performance deterioration alone. Referring to (6), one must consider the expectations function $P^e$ as well as the performance deterioration function $P$ to develop a useful estimate of service life. What then do we know about the expectations function?

First, one may presume, almost by definition, that the function originates at a level of performance comparable to what is achieved in current practice at the time of planning and design. This level of current experience represents the designer’s minimum expectations. As the planning and design of a new facility progress toward construction, these expectations are embodied in drawings, specifications, and then concrete and steel. The ordinate of the expectations function, the level of performance that will be judged the lowest acceptable, may be measured with reference to these designer’s expectations. Fig. 5 is drawn with this convention.

As explained, expectations of performance will typically rise; the slope of the curve is greater than zero. While there is little solid data on which to base analysis, one could argue that rates of changes that cause obsolescence (technological, regulatory, economic or social, and values or behavioral) are generally steady or accelerating over time periods comparable to the service life of infrastructure (e.g., 20–200 years), so that the second derivative of the expectations function is equal to or greater than zero. That is, with

$$\frac{dP^e}{dt} \geq 0, \text{ and } \frac{d^2P^e}{dt^2} \geq 0$$

Sometimes, as some of the examples in this paper have illustrated, the expectations curve may turn downward; that is, both derivatives will be less than zero (see Fig. 5). This condition denotes a period when the owners of infrastructures are essentially consuming their capital or assets. The condition may occur because of fiscal constraints, as is the case frequently with school buildings. It may occur in times of political instability, such as civil Insurrection or war. It may occur when large-scale shifts in an area’s economy are causing basic changes in the demands infrastructure is meant to serve. Such is the case in many older U.S. inner-city areas. Whatever the cause, the condition represents effective disinvestment, a consumption of assets accumulated by previous generations of infrastructure builders. If the condition continues for an extended period, it inevitably leads to abandonment of the infrastructures.

The rate of decline in expectations may vary under this disinvestment condition. The writer finds no basis for hypothesizing more than the single, first-order criterion for characterizing this condition

$$\frac{dP^e}{dt} < 0$$

**RATES OF CHANGE AND AGE AT OBSELESCEENCE**

Experience demonstrates that expectations are almost always increasing, but there is little information to support estimation of either the rates of increase or the consequences in terms of onset of obsolescence. Observation and anecdotal evidence do, however, provide some insight, for each of the four principal sources of obsolescence-inducing change: technological, regulatory, economic or social, and values or behavioral.

**Technological Change**

In his study of technological change in transportation, Grubler (1990) concludes that it is taking longer and longer to phase out outdated infrastructures. He draws this conclusion within a long-range perspective, noting also that a relatively long time period is required, on the order of 100 years in the case of rail and road, to make a transition from one infrastructure technology to the next. Grubler suggests that we are undergoing a major technology shift with respect to goods transportation. The transition of advanced national economies toward services and information brings with it a proportionate reduction in

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**JOURNAL OF INFRASTRUCTURE SYSTEMS / DECEMBER 1996 / 157**
goods movement. Economies of scope (that is, general-purpose carriers rather than specialization in one type of cargo) and quality of service (such as “just in time” delivery) rather than lowest tariff are becoming primary characteristics of successful competitors. (Federal Express is a primary example.) Such changes are making older modes of transport infrastructure obsolete.

Fig. 6 illustrates obsolescence in the transport infrastructure network as a whole. The 19th-Century advent of rail transportation led to decline of the relative share of canals as an element of the national infrastructure of the United States and former USSR. Growth in road transportation and highways has similarly overtaken rail. The data suggest that airways will continue to grow for some time, resulting in a relative decline in highway’s share of the total network.

The progress of obsolescence is apparent in highway pavements as well. After the mid-1850s, when increased levels rendered cobblestone streets virtually obsolete, cities began to experiment with granite (Belgian) blocks, a “cheaper and smoother alternative.” (Moehring 1982). Gravel and macadam, popular in the 1860s and 1870s, were in turn made obsolete by the automobile, and by 1920 many urban public works departments had switched to more durable, smooth-riding, and dust-free asphalt and concrete surfaces. (Of course, gravel and penetration asphalt remain popular for low-volume and low-cost roads in less-developed regions of the world.)

Another historical example is the “celebrated battle” (Moehring 1982) in the late 18th Century between sanitary engineers George Waring and Rudolf Hering on the construction of separate or combined storm water and sanitary sewers. Herings’s dominance within the professional community swayed the decision of many cities, and by 1909 places with populations more than 100,000 people had built seven times as many miles of combined sewers as separate ones (Tarr 1979). Greater understanding of the limitations of dilution as a pollution-treatment technology made these decisions and the resulting systems obsolete. Those cities that have not already done so are replacing these combined systems with separated ones, sometimes under federal mandate. The age to obsolescence was about 70 years.

A review of the performance of 68 long-span bridges built in New York state between 1801 and 1993, for example, revealed that only four of the 14 bridges from the 19th Century were still in use. The causes of bridge closure included winds, ice, and fire, but half were closed because of “insufficient load capacity or general deterioration” (Purt et al. 1994). A review of the nation’s highway bridges found that the number of structurally deficient or obsolete bridges on rural arterial roads (both on and off the Interstate system) was increasing steadily between 1982 and 1988, from 10,000 to 12,800 (“New” 1990). Federal Highway Administration standards provide the basis for making this assessment. Adopting proposals to increase the size and weight limits for trucks traveling the nation’s highways would substantially increase these numbers. These bridges were built for the most part to Interstate-era standards, and so have served about three decades before the onset of obsolescence. Maintenance practices presumably had something to do with this onset as well.

While performance expectations normally increase with time, housing provides a particularly noteworthy case where declining expectations (i.e., disinvestment) are assumed as an article of public policy. U.S. housing-policy analysts in the 1960s adopted the trickle-down theory as a basis for meeting shelter needs of low-income groups in urban areas (Grigsby 1967). Dwelling units constructed to serve higher-income market segments are expected, with time and use, to decline in desirability and market price (i.e., rent level or sale price). These older units then trickle down to those who can now afford them, while more affluent households move on to newer dwellings. The service standards of infrastructure serving these dwellings may also be expected to decline, but the subject is not addressed explicitly in typical discussions of the theory. The theory does have an ability to rationalize what is observed to occur in urban housing markets, and works well in large-scale dynamic models of the sort that were popular in the 1960s and 1970s [see Forrester (1969), for example].

Regulatory Change

The example of bridges and housing both represent regulatory as well as technological change, in that design standards and government codes define criteria for obsolescence. Design standards evolve through a complex process of professional consensus within the context of industry and professional organizations such as the ASTM and the American Concrete Institute (ACI). For those concerns considered to be valid targets of government regulation—primarily threats to life safety and public health—these consensus-based standards then pro-

FIG. 6. Example of Impact of Infrastructure Obsolescence: Substitution of Transport Networks in the US and Former USSR, Measuring Shares by Length of All Transport Infrastructures [Source Grüber (1990), p. 197]
vide the basis for local- or state-level legislation that give them force of law in local building codes, government agency design guidelines, and similar forms. The process generally is slow-moving and often makes provision for older structures to be "grandfathered in" when standards change, that is, to be excused from meeting newer, more stringent restrictions on use and occupancy. In such cases, obsolescence still occurs but its consequences are deferred. The impact of environmental regulations has already been noted. The number and impact of such regulations as the Safe Drinking Water Act and Clean Water Act have been increasing for several decades, even before the sharp increase in public awareness of environmental issues that began in the 1970s. Smoke-control ordinances for example, the oldest air-pollution laws, have been on statute books for two to three centuries ("Impact" 1972). While we feel confident that such regulatory change will continue to cause obsolescence in infrastructure, we have no data on which to base an analysis of scale or rate of impact.

Economic or Social Change

As already noted, Detroit and other older cities are experiencing obsolescence-inducing economic and social change. Migration of business and resident population to the sprawling suburban fringes of many metropolitan areas has changed the scale and scope of demand for infrastructure serving these older cities and bankrupted the companies or agencies responsible for infrastructure operations. Shrinkage of the nation's railroad network and widespread abandonment of branch lines in the 1970s are among the more spectacular examples of this form of change and obsolescence. (U.S. government regulatory policies certainly influenced the timing of branch-line abandonment, just as they have the radical reorganization of the passenger air transportation route network following deregulation of the airline industry.)

Many of these economic and social changes have long gestation periods. Historians trace suburbanization, for example, to the work of 19th-Century landscape architects or even further back to the agrarian ideals of Thomas Jefferson [e.g., Barlow (1972)]. The "edge cities," while only recently named (Garreau 1991), have been growing in parallel with the interstate highways and many have roots anchored more deeply in earlier metropolitan settlement patterns. Transportation and communication technologies certainly played a role in these economic and social changes and have sometimes, in turn, been made obsolete.

Values or Behavioral Change

The decades-long trends of economic and social change reflected in urban settlement patterns are tightly intertwined with people's basic values and resultant behavior. In the United States, these values tend toward embracing the new and discarding the old. Visitors to Europe and Japan, for example, often remark on these nations' greater apparent commitment to facility maintenance; consequently obsolescence seems to be held longer at bay. The writer has found no firm data or definite studies that support these impressions, and although this is an area of study somewhat removed from typical engineering views of infrastructure, it warrants engineers' attention.

Architects Denise Scott Brown and Robert Venturi wrote 20 years ago, for example, that the highway "has rammed itself through our lives and we shall never be the same again. The new technology insinuates so deeply and broadly into our culture that no aspect of it is left untouched. When our freeway network becomes as technologically obsolete as the walls of the medieval city, remnants of streamlined toasters, split-level ranchers and A&P supermarkets will testify to its pervasiveness as a cultural artifact and as a symbol of a way of life" (Brown and Venturi, unpublished exhibition paper, 1970). One might as well expect that changes in our living styles—e.g., many people whose economic circumstances permit them to do so are moving to smaller, more remote communities—will bring about relative obsolescence of highways as people switch to air or new modes for longer-distance transport (e.g., refer again to Fig. 6).

IMPLICATIONS FOR INFRASTRUCTURE DESIGN AND MANAGEMENT

One of the most important questions facing decision makers responsible for infrastructure design and management is "How long should infrastructure last?" Conventional answers typically would range from "several decades" to "indefinitely." These answers would be based for the most part on individual judgement, experience, and values.

Planners and designers need to assume values for the service life of infrastructures, to compute such parameters as the number of loadings a pavement must endure or the probability that a storm sewer will be called on to accommodate certain quantities of rainfall runoff. The assumed service life is then used in estimating the aggregate benefits and costs of an infrastructure project to determine whether the investment to undertake the project should be made and to compute the prices that must be charged if the costs of infrastructures are to be recovered from their users. In the writer's experience, the various assumptions regarding service life (which are not necessarily always the same, even for a single project) have little basis, primarily because the physical life of structures and materials are substantially longer. Indeed, it is for this reason that many infrastructure professionals argue that very long service lives should be presumed.

Assuming a longer service life helps to justify higher initial facility development costs, because benefits accrue over longer periods. However, current practices of economic analysis discount the value of these future benefits to the extent that those anticipated more than about 50 years in the future have almost no present worth or influence in the computations on which decisions are based. A by-product of this effect is that infrastructures surviving beyond this period appear to their inheritors to have no capital cost (or at least very low cost—repairs may still be needed from time to time). In the absence of some financial mechanism (e.g., a sinking fund or trust indenture) to require owners to set aside funds for their eventual replacement, the infrastructures are likely to be used heavily until a precipitous performance failure demands attention.

Contemporary infrastructure designers and managers must explicitly consider obsolescence as a basis for making decisions. As long as technological innovation and changing economic conditions continue, infrastructure obsolescence and its costs are ultimately unavoidable. It might be effectively argued, in fact, that obsolescence plays a valuable role in speeding up the introduction of new infrastructure technology into systems of long-lived facilities. While some of the Roman's centuries-old roads and aqueducts may still be intact and usable, it is difficult to imagine how modern commerce could exist with the quality of service such facilities would provide in current use. As White (unpublished speech, 1991), then president of the U.S. National Academy of Engineering pointed out, "Rapid obsolescence . . . generally . . . deployed as evidence of a wasteful society . . . does have virtues. The twin goals of environmental protection and economic growth can both be advanced by rapid obsolescence of capital stocks." Obsolescence allows new, more productive and less
polluting infrastructure technologies to be put in place, which might otherwise be blocked by long-lived facilities.

Regardless of its values in opening the way to innovation, obsolescence provides a rational basis for establishing an appropriate set of service-life assumptions. The writer's experience suggests that these service-life assumptions should in many cases be shorter than is currently common practice. The pace of technological, economic, and social change makes it increasingly difficult to justify commitments of resources that are both long-term and limit the choices available to future generations. As a society, we are finding more frequently that our large-scale infrastructures are having precisely that effect, i.e., limiting future choice rather than providing a valuable legacy.

Successfully predicting the course of technological innovation, regulatory requirements, and the other changes that produce obsolescence is difficult, if not simply impossible. Stories abound of notoriously wrong forecasts by even famous inventors and business leaders (e.g., Ken Olson, founder of Digital Equipment Corp., is said to have judged in 1977 that "There is no reason anyone would want a computer in their home."). Reducing the design service life of infrastructure reduces society's commitment to decisions that may be found later to have faulty premises.

Of course, there are at the same time strong incentives to extend the service life of existing infrastructures as long as possible. The difficulties of mobilizing capital, achieving sufficient social and political consensus, and simply completing development of major projects make it worthwhile to avoid unnecessary new infrastructure development. If infrastructure professionals are alert to the onset of infrastructure obsolescence, they may to some degree take action to delay the end of the service life. There are four strategies that may be pursued for delaying or mitigating obsolescence:

1. Plan and design to provide the flexibility to respond to obsolescence-inducing change, for example, through reservation of extra right-of-way or construction of foundations to accommodate a second deck on a bridge; in effect, target higher levels of optimum performance (see Figs. 1–5).

2. Construct to assure that the facility does not fall short of the required characteristics of performance anticipated during planning and design; that is, assure the targeted optimum performance is realized.

3. Monitor change during operations and maintenance, and act to increase performance or slow its degradation, thereby deferring obsolescence; in effect, increase "T".

4. Refurbish and retrofit early to accommodate change, thereby reducing the likelihood of early occurrence of unsatisfactory performance and reduced service life; in effect, raise the optimum-performance target level and thereby maintain the difference between current performance and the expectations function $P^t$.

QUESTIONS FOR RESEARCH AND PRACTICE

As this discussion has highlighted, there are many practical questions to be answered about obsolescence and its onset, before meaningful estimates of expectations functions and time to obsolescence can become routinely useful to infrastructure decision makers. This research must for the most part be based in empirical studies of the life cycles of infrastructures.

How quickly is change progressing? How great are the costs of obsolescence to an infrastructure's users, owners, and neighbors? Are we consistently overinvesting in infrastructures bound to become obsolete before an adequate return on our investments can be realized?

Practitioners have an important role to play in this work. It is often the experienced judgement of practitioners that will first recognize the onset of obsolescence. Research on obsolescence, undertaken primarily by teams that combine researchers and practitioners, could take full advantage of the measurable but seldom documented knowledge these latter participants have to offer. The subject demands a blending of historical reports and theoretical technical analysis, which this paper has sought to demonstrate.

APPENDIX I. REFERENCES


APPENDIX II. NOTATION

The following symbols are used in this paper:

\[ D_j = \text{demands for infrastructure's services } j; \]
\[ S_j, S_j[X_j] = \text{supply of infrastructure's services } j; \]
\[ E = \text{exogenous or environmental factors that influence expectations about performance}; \]
\[ P, P[S_h, D_h, t] = \text{performance of a facility or system}; \]
\[ P^*, P^*[E_n, t] = \text{minimum acceptable performance, failure criterion}; \]
\[ T^o = \text{design service life}; \]
\[ T = \text{age at obsolescence}; \]
\[ t = \text{time}; \]
\[ X_r = \text{descriptive and functional characteristics of infrastructure}. \]