1
Cities and Infrastructure: Synthesis and Perspectives

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The subject of this book is infrastructure, the built environment in which we live, the way we use it, and how it may evolve in the future. Cities are the summation and densest expression of infrastructure, or more accurately, a set of infrastructures, working sometimes in harmony, sometimes with frustrating discord, to provide us with shelter, contact, energy, water, and means to meet other human needs. The infrastructure is a reflection of our social and historical evolution. It is a symbol of what we are collectively, and its forms and functions sharpen our understanding of the similarities and differences among regions, groups, and cultures. The physical infrastructure consists of various structures, buildings, pipes, roads, rails, bridges, tunnels, and wires. Equally important and subject to change is the "software" for the physical infrastructure, all the formal and informal rules for operation of the systems.

Reflecting on the history of human endeavor, we are impressed by the creative achievements expressed through the arts, and engineering and science. The infrastructure is a dramatic statement that embodies all of these aspects. Many of the most esteemed, valued, and visible achievements of mankind have been in the domain of infrastructure: the watercourses and gardens of Babylon, the lighthouse at Alexandria, the roads and aqueducts of the Romans, the Suez and Panama canals. The control of water resources constituted the principal problem of early Chinese history, as agriculture was afflicted by frequent floods and droughts. The maintenance and repair of the canals and dikes of the large river valleys were the central administration's main duties and became symbolic of a well-organized and efficient government (Wittfogel, 1958).

Walls encircling towns were once perhaps the most important infrastructure for many settlements. Walls were built to provide security and at the same time served to control access to a city, allowing inspection of incoming travelers and collection of tolls. Gate taxes were a major source of income for medieval towns, and building and maintaining walls required tremendous financial outlay and technical efforts. The greatest engineers, such as Leonardo da Vinci, were extensively employed in the design and construction of walls and fortifications. Remarkably, as reported in the chapter by Lynn Hollen Lees and Paul M. Hohenberg in this book, the population of the cities that built some of the greatest structures was that of a small town by modern standards (see Table 3-1, p. 78). For example, the populations of the great cathedral cities of the Middle Ages—Cologne, Milan, and others—were typically only about 50,000 souls. The populations of the cities of the Italian renaissance—an era unsurpassed in building achievements—were less than 150,000.

Many of the symbols and landmarks of U.S. history, the turnpikes that carried the wagons west, the Erie Canal, the transcontinental railroad, the Brooklyn and Golden Gate bridges, the great dams of the Southwest and Northwest, the interstate highway system, the skyscrapers and subways are infrastructure. Many of the heroes of American history, including Morse (telegraph), Bell (telephone), and Edison (electric power) are fathers of infrastructure systems. Matching the heroic and visible legacy are the little-noticed and often unattributed accomplishments of infrastructure systems, especially improved public health connected to supplies of fresh, clean water and prompt removal of wastes.

Both public and economic welfare have been motives for infrastructure development. Spurred by a severe yellow fever epidemic, Philadelphia was the first large U.S. city to construct a municipal water supply system (1779–1801). The first modern urban sewerage system was constructed in Brooklyn in 1857. According to Joel Tarr (1984), water supply represented a situation in which a number of interests, such as businesses and industries, homeowners, fire insurance companies, and those concerned with public health joined to demand the construction of large public works in order to secure more adequate water supplies at reasonable cost. City boosters considered waterworks crucial in the competition between municipalities for population, trade, and industry.

How vital is infrastructure? One need only think of what life is like when each person is individually responsible for disposal of all wastes, carrying messages, collecting and purifying water, and gathering fuel.

The range, safety, depth, and variety of contacts we commonly now experience are in large part functions of the quality of our infrastructure.

What are "public works" and what are private works? In the United States we sometimes identify infrastructure only with public works. In this book we examine both the conventional public works, such as roads and bridges, and the privately owned or managed infrastructure. The historical and international perspectives developed in this book effectively downplay the differences between the two. In some countries, telecommunications systems are a government-owned utility; in some countries, private. There are private and public water companies. There are private and public power companies. Often, a new, young infrastructure system is introduced by private enterprise and then becomes publicly regulated or owned as it matures into an indispensable "utility."

Infrastructure systems are systems for the delivery of services. As such, the underlying questions are how broadly and explicitly should cost be distributed? Who has ownership and control? Institutional arrangements are a means to an end, and the ends for infrastructure systems are such features as quality, flexibility, adaptability, reliability, and cost-effectiveness. In different countries and regions at different times, one or another form of ownership and governance for infrastructure may be preferable. Some networks and facilities tend more naturally toward monopoly, and so in the United States these have typically come under government management or regulation.

As a society, we should strive for a high level of access for individuals, groups, and organizations for the services available through infrastructure. To generalize the stated goal of the early days of the American Telephone and Telegraph Company, we should strive for universal, affordable service with regard to water supply and wastewater removal, energy, and transport, as well as communications. In part, infrastructure is designed to overcome uneven distribution of natural resources. As Cesare Marchetti points out in Chapter 7, infrastructure enables us to extend our range and control over our lives. Infrastructure is often in the foreground when we speak of the quality of life, and images of infrastructure, whether positive ones of aesthetic structures or negative ones of time spent waiting in queues, are central to our image of healthy cities and societies.

There are choices to be made with respect to infrastructure. Anyone flying over North America and Europe immediately notes the drastically different configurations of settlement. Like the diverse solutions for the design of local area computer networks discussed by Dean Gillette in Chapter 10, each infrastructure system at the outset may be realized in many different forms. But infrastructures also quickly grow rigid and costly to modify. We could benefit considerably from better understanding of the implications of alternative designs from technological and social perspectives.

What in fact is the state of the infrastructure? Is it deteriorating more rapidly than we are restoring or replacing it? Are systems being expanded rapidly enough to accommodate likely demands, for example, for growth in passenger and cargo air transport? The essays in this book suggest that in truth we do not know well the condition of our infrastructure. Simple, partial physical inventories are available for some components of the infrastructure. For many key systems, and for many cities, we are unable to specify much at all. Our diagnosis of the vital systems of cities and the nation remains primitive, and therefore the basis of most forecasts is questionable.

Some claim that the infrastructure of the United States is in a critical stage of decay. Is this so? In our view, the quantitative data and evidence are strong in a few areas and less clear in many others. A need and a question are raised by this judgment. The need is the deceptively simple one for more documentation of the historical and current performance of infrastructure. The question is the relationship between chronological age and quality of service provided. The relationship between age and decay is by no means clear-cut or linear for all infrastructure systems. It depends on several highly variable factors, including quality of original design, defects in construction, climate, and how facilities are used.

Some old infrastructures, whether physically sound or not, simply have no use with respect to their original function. If technological generations come quickly, as in telecommunications at present, designing and building systems and devices for a short life span may be appropriate. The fact that tens of millions of telephones built decades ago could still work today has little value because they lack the features that are now desired by consumers. With some old roads, the problem may not be age but other characteristics, such as width. With power plants, the problem may not be a decline in the quality of service they provide but that we have not determined how to relicense plants for another generation of operation. Moreover, some infrastructure elements, such as churches and many public buildings, given proper maintenance, appear to improve and increase in value with age. Infrastructure may not routinely mellow with age like a fine violin, but we should be cautious of drawing dramatic conclusions from listings simply giving the age of structures.

On the other hand, the mentality of producing goods that are expected to be used for only a short time is almost certainly self-defeating in many infrastructure areas. Why throw away roads or houses? As John S. Adams points out in Chapter 6, new housing for the poor in the United States is usually cheap and thus has built-in susceptibility to early decay and demise. Good engineering and design can change this prospect. To illustrate, some housing that was thought to be cheap when constructed, such as much nineteenth century English working-class housing or the row houses of Baltimore, has proved to be long-lived or at least readily adapted to new uses.

Although we must not assume too much about the link between aging and decay, there is a clear need for more widespread adoption of a life cycle approach to infrastructure systems. In the final chapter of the book, Gregg Marland and Alvin M. Weinberg make a telling case for this approach by asking three fundamental questions about a variety of infrastructure systems: What actually is the characteristic longevity of a given infrastructure? How long *could* it last? How long *should* it last? For all our sociotechnical systems there is birth, growth, development, and then, to varying degrees, senescence and death. As argued by W. Brian Arthur in Chapter 4, we do not appreciate sufficiently the importance of the early life history of systems, the time during which they take on a relatively fixed character. Neither do we appreciate the extent to which the growth of systems, and patterns of substitution among technologies for such infrastructure needs as energy and transport, are predictable. In their chapters, Cesare Marchetti and Nebojsa Nakicenovic provide striking examples of how well-documented life histories of infrastructure systems may enable us to forecast future infrastructure needs and how these needs are most likely to be met.

There is another simple yet compelling reason for taking an approach that emphasizes the full potential of a system through time and not merely the short-term investment decision. As Marland and Weinberg observe, sites for infrastructure are virtually eternal. The process of siting, designing, and building infrastructure facilities, whether airports, sewage treatment plants, incinerators, power plants, roads, or prisons, is characteristically long, often measured in decades. In turn, the function fulfilled at the site endures for generations and, not infrequently, centuries. The needs for infrastructure to supply energy and communications, for example, never end; specific components, systems, and technologies used are of course replaced eventually. It is time to achieve a better balance in our thinking about how to build systems, with an emphasis on both how the systems decay and how to maintain them.

Cities and the systems that serve them suffer both acute and chronic disease. Throughout human history many cities have been abruptly destroyed by wars and natural hazards, such as earthquakes and volcanic activity. We need to understand better the built-in attributes of infrastructure systems that lead to potential vulnerabilities from these forces and such events as power failures and major accidents with hazardous materials. It is possible to build resilience to disasters into infrastructure, although it sometimes requires costly outlays and also foresight about where evolving vulnerabilities lie. Some formerly devastating problems are now largely under control; fire, for example, was once the scourge of cities, but firefighting and improved engineering and design of structures now effectively keeps fire damage at an acceptable level.

The chronic diseases that afflict our roads, pipes, and other facilities should be a simpler matter to treat effectively. Much of the decay is apparent and predictable, and long-term strategies are feasible. We have usually reserved long-term efforts for the building of systems, such as the 30-year plan for the development of the interstate highway system. Such plans should be pursued more frequently for the maintenance and retirement of systems as well.

It appears that there are opportunities to be more systematic in the study and management of waning infrastructures. Marland and Weinberg (see p. 191) propose a framework for succinctly characterizing the causes of decline of bridges, dams, roads, and power plants. Could this framework also be applied to harbors, canals, railroads, post offices, and lending libraries? What are the relative roles of misuse, overuse, abuse, crime, neglect, and obsolescence in the decline of systems?

We should not underestimate the possibility of finding pleasing new uses for old infrastructure. Most harbors no longer serve the purposes for which they were designed in the nineteenth or early part of this century; movement of cargo is being widely replaced by housing and parks as the main waterfront uses. Canals in the United States are now largely used for recreational boating. Railroad tracks have been superseded by bike paths, and railway stations by restaurants. The Gare d'Orsay in Paris, a monumental infrastructure achievement of the railway era, has become France's museum of the nineteenth century. What will become of post offices, public libraries, and, eventually perhaps, airports?

An interesting trend in transport and energy technologies evident in several chapters in this volume is that infrastructures appear to be decaying or losing their share of the market for which they compete at progressively lower rates. Is this because each new system is larger in its fullest realization than the previous dominant mode, and thus more lives must be changed each time we abandon, decommission, or reduce a system? Alternatively, are we as a society tending toward preserving all systems in parallel as a form of sociotechnical insurance?

This book queries whether we are asking the right questions about the waxing infrastructures as well as about those that are waning. Nakicenovic and Thomas Craig present compelling evidence that we are not yet adequately coming to grips with the likely dimensions of the air transport system, not only today, but as envisioned 10 or 30 years in the future. Harvey Brooks and Dean Gillette outline a comparable series of issues about the communications infrastructure, which continues to grow vigorously but perhaps without sufficient careful checking against social goals.

Demographers emphasize the need to take into account demographic and behavioral considerations in infrastructure planning. The changing age profile of the U.S. population is predictable with considerable accuracy extending decades into the future. We know, for example, that the greatest percentage growth in U.S. population will be in those who are very old, that is, over 85. Our planning should reflect this and other demographic trends. We also need to understand better the mutual influence of behavior on infrastructure and of infrastructure on behavior. What should be done about "crimes" against the infrastructure: misuse, abuse, vandalism, and destruction? To what extent can we educate people to use the infrastructure more respectfully? In turn, what is the influence of infrastructure on antisocial and criminal behavior? Is it true that beauty defuses anger? How much stress might be relieved by more efficient and reliable provision of services such as transport?

The topic of behavior also raises the most fundamental question: what are the objectives of infrastructure? What is being maximized, minimized, or made adequate? Leonard Duhl (1986) has argued that we should examine the city from the point of view of human requirements. He urges us to build the "healthy city," defined in large part as one that learns from its experiences and uses the experiences to create a better quality of life. Many of our cities fail this test.

It is clearly a continuing challenge to represent the interests of users with regard to quality, safety, and satisfaction in the design and operation of infrastructure systems. The builders and operators of systems tend to provide the dominant vision, often with goals of maximizing system efficiency or size in ways that may not match users' preferences. A difficulty in this regard is the lack of detailed information on performance. However, there are vexing questions about how even to measure the economic productivity or social contribution of, for example, a bridge or a road system. In addition, how do we measure the quality of infrastructure services, such as air transport? It is universally agreed that we would like the time spent engaged with the infrastructure to be of a high quality, but how is this quality defined, measured, and denominated? The quality of a system is the result of an intimate interdependence among the various parts of the system itself, the provider, and the user. We have examples of infrastructure services, such as water supply, for which quality is generally uniformly high to all customers, even in the poorest urban areas. In the same jurisdiction, however, waste removal services may be highly variable in quality.

We tend to characterize infrastructure too little in terms of the individual. How do those in different segments of the population view infrastructure? Infrastructure for transportation appears quite different to the young, the old, and the handicapped. Access to water and sanitation remains a problem for the homeless. At what cost can high-quality infrastructure be made more friendly and accessible to larger fractions of the population and remain so? What are the social implications of alternative designs of infrastructure systems? Infrastructure, whether a village well or domed stadium, can be an organizing element in social life, and we would benefit from seeking to understand the transformations that will accompany shifts in infrastructure.

It would be helpful in allocating resources to infrastructure to have better and more readily available quantitative information on the interaction between infrastructure and individuals. For example, what is the time budget of individuals with regard to various forms of infrastructure? What fraction of the population at different times of day on average is in the air, in automobiles, on the telephone, or directly using water? How do these patterns of use vary from city to city and culture to culture? It would be informative to know the distribution of the labor force over the various infrastructure systems, how it differs between societies and how it changes over time. How is the labor force in infrastructure in different societies divided between construction of systems on the one hand and operations and maintenance on the other? Have there been changes over time in the proportion of the labor force working in communications, sanitation, water supply, energy, or transport?

It would be interesting to have more comparative data on effort and expenditure with regard to various infrastructure areas. How many worker-hours does it take to supply a gallon of fresh water in different cities and countries? How has the time and human effort required to secure and distribute water changed over the years? How many cubic feet of trash are removed by a given amount of individual effort in different countries? How many square feet of building area exist per person in different countries? How many communications of all kinds are transmitted per unit time by each person in different cities and societies? How do per capita water and energy use and travel vary? Data responding to several of these questions exist, but it is our impression that these data have not been effectively applied in many infrastructure studies or designs. A comparative, quantitative social science of infrastructure could be useful in indicating paths to improved performance.

Improved performance will certainly also come from technology. Probably the most widely appreciated cluster of technological innovations for infrastructure came in the second half of the nineteenth century. Such breakthroughs as steel building skeletons, elevators, electric lighting, indoor plumbing, central heating, telephones, and underground transportation had a profound influence on the built environment. Will there be a comparable burst of innovation in coming years? "Hard" technological advances might be foreseen in transport (larger and faster aircraft, magnetically levitated trains). Hazardous waste is an area in which there is a desperate need for technical solutions that could be widely accepted with a high level of confidence. The "utilidor" for infrastructure elements has been proposed as an interesting extension of a packaging concept that is widely and effectively used on a smaller scale in modern building design. But perhaps the current era will be remembered more for advances in enabling technologies, such as synthetic materials for a full spectrum of specifications, and applications of operations research to a range of systems from auto and air traffic control to elevators.

Just as integration of technological and behavioral aspects of infrastructure is critical, so too is examination of interactions of various infrastructure subsystems. In designing, building, repairing, or researching portions of the system, we too often forget the important interactions among system elements. Sometimes financial, political, or technical constraints lead to compartmentalized thinking and management of portions of the system. How tightly interlocked are different infrastructures? Railroads, coal use, and the telegraph grew together. So did autos and highways, oil use, and telephones. Could air transport have developed without radio and other high-speed telecommunications? In fact, it appears that transportation and communications systems may advance in tandem.

There is a complex and changing mix of competition and dependency among infrastructure systems. The airplane and the automobile compete for intercity passengers but are also jointly necessary to make most trips between given pairs of destinations. We have numerous instances of specific solutions—for example, siting of airports without appreciation of landside needs—that are put in place in a way that inevitably creates problems that surface later to haunt us. We are confident that research on specific infrastructure problems will be improved considerably when performed in the broader context, and a series of such efforts will eventually provide deeper insights and vision into the complex overall problem.

Institutional, legal, and political issues are never remote from systems so central to social organization and power. Technically feasible "fixes" such as interbasin transfers of water and development of nuclear power in the United States are either simply not socially acceptable or are blocked by political and economic concerns. Several authors, especially Brooks and Royce Hanson, stress issues of authority and legitimacy. Indeed, the concept of a "public utility" is at the intersection of all social interests.

What conclusions can we draw about the infrastructure from the chapters in this volume and the efforts associated with their production?

- In the near term, the preference for incremental improvement will almost always be dominant, and, in fact, the question of how to attain higher levels of efficiency within the existing system should always be asked. However, the challenge of infrastructure is more one of "portfolio management," and the corresponding need is to make investments that will generate yield on all time scales, from months to generations and centuries.
- Some major systems are clearly inadequate to meet current or projected demand. The most obvious are air and road transport and waste disposal. Adequate steps are not being taken to accommodate even conservative projections of increases in air travel. Other transport problems, such as parking, are almost totally overlooked. We have 120 million cars in the United States today and may have twice that many in several decades. Where will they all be housed? Are there ways to prevent the levels of congestion and delays in suburbs and outlying areas from approaching those of center cities? Vision is also lacking in waste disposal. Will there be a national infrastructure for hazardous waste? Will water supply and waste disposal be safely and effectively integrated?
- The organization of research and development in infrastructure is deficient. The emphasis is too heavily on solving narrow problems; inadequate efforts are going into research that embeds specific problems in an intelligently defined context or that looks at connections between various elements and problems. Much could be gained by linking the research and development systems for different modes within areas such as transportation and energy, as well as between areas, for example, transportation and communications. Experimentation by practitioners is also not used as it might be. In wastewater management, for example, there may be as great a need to encourage knowledgeable practitioners to experiment as there is for academic research. A major question is how to do meaningful, fundamental research on large, real systems. The importance of the development and understanding of historical data about infrastructure must also be emphasized.
- Several areas of research in engineering and science offer promise for many infrastructure systems. Operations research can be especially

significant in the areas in which there are questions of traffic and transportation. Materials research and associated fields, such as sensors and nondestructive evaluation, may contribute to better and less costly system construction, performance, and maintenance. Telematics is both an infrastructure and—through the use of such concepts as the global positioning system and intelligent highways—a means for improving the use and operation of other infrastructures.

- Finally, we wish to stress not only the social and engineering challenges but also the tremendous intellectual excitement available in studies of cities and infrastructure. The chapters of this book demonstrate that this is a rich field for creative thinking. Paradigms, perspectives, and methods from many fields, including several areas of engineering, physics, operations research and systems analysis, economics, geography, sociology, demography, law, and history are represented in the book, and every author ends with fascinating, unanswered questions.

Let us now turn to a review of, and commentary on, the contributions that follow.

Suppose a Martian geographer or sociologist came to Earth and wanted to develop a taxonomy of human settlements and to describe the general characteristics of their temporal evolution. The chapter by Robert Herman et al. is such an effort to develop an objective, dynamic characterization of cities. It is an empirical attempt to use basic principles to find sets of small numbers of objective variables to describe actual cities in space and time. These variables in turn are used to generate a taxonomy of cities whose features follow similar tracks in time and that may thus be useful in prediction.

Herman and coworkers develop a history of the infrastructure of the city of Austin, Texas, and perform a comparison among contemporary features of eight U.S. cities. Some remarkable and intriguing facts emerge: water consumption per capita in Austin has remained constant since 1950; energy consumption per capita continues to grow exponentially; and the number of residents for each restaurant has held steady at roughly 600 since the turn of the century, notwithstanding the much-discussed emergence of a service society. A second area of discovery is that there are underused data resources for infrastructure studies. Quantitative examination of such sources as city directories and yellow page telephone books are one pleasing example. It would be fascinating and valuable to extend the analyses undertaken by Herman and coworkers to other cities in the United States and to cities in other countries to understand what is truly invariant, what is culturally dependent, and what is inherent in different stages of city development.

Lees and Hohenberg provide historical and sociological perspectives on how cities have grown in the Western world. They stress that cities are open systems, whether their main role is as the dominant central place of a system of settlements or as one among equally significant cities in a network. In fact, the single best descriptor of a city is dependence; a city cannot be a closed self-sustaining entity. Connectedness is thus the essence of systems of cities, and the systems may take various forms. They can be maritime empires or urban leagues united in trade. Leicester, for example, was one link in a chain of cities stretching from the north of England to central Italy that was organized in the Middle Ages around the production, processing, and marketing of wool.

Lees and Hohenberg illustrate that city growth is neither uniform nor automatic, but consistent patterns are linked to structure and function. Urban systems do not require compactness or symmetry, since transportation and communication technologies allow many feasible configurations. There may be some boundary conditions, however. In his chapter, Marchetti proposes that the ability to travel between any two points in roughly one hour defines the limits of a city. This does not accord with the traditional city planner's definition of a city based on administrative or geographical boundaries. Lees and Hohenberg, in turn, note that the distance—measured in time of travel—between cities of a given size or rank tends to be more or less uniform.

Lees and Hohenberg also discuss the dynamics of growth and change of cities and their infrastructure. Growth is not uniform in time; there are periods of explosive growth. An interesting example is the development of capitals, for example, in Spain and Italy. Capitals can continue to be oversized because of their political dominance, well after economic justification has declined. Indeed, the desire for glory or the need to maintain public order in crisis often leads to physical improvements. The economically paradoxical size of political capitals may be explained by viewing them as capitals of information.

Arthur asks how history affects the pattern of cities. Do chance events, including seemingly small occurrences, play a significant role, or does necessity determine what unfolds? For example, is it accidental that Silicon Valley developed as it has, or was it inevitable based on certain natural resources and other endowments? Arthur argues that cities become according to what they are; a mixture of economic determinism and historical chances, not either alone, forms the evolving patterns we see.

Arthur also proposes that cities exist in large part because of agglomeration economies. Most firms need to be near other firms in their own and other industries for supplies or as consumers of their products and services. Thus, there is a self-reinforcing attraction to existing and growing agglomerations.

Cities we have inherited depend partly on needs for services that arise at particular geographical locations, but also result from where skilled people happen to go. Determinism alone cannot explain city patterns without reference to chance events, coincidences, and past events. Without knowledge of these circumstances or those yet to come, Arthur argues that we cannot predict with accuracy the shape of urban systems in the future.

Thus, our infrastructure both records our past and shapes the present and future, except that early events or fluctuations act to push us into particular states or structures that the system eventually "locks into." With regard to infrastructure, we become locked into both particular spatial configurations and also technological choices. Sometimes we may settle to our later regret on local optima found with respect to restricted boundary conditions. For example, early historical competition among railroads in England resulted in adoption of narrow gauges that were better in handling turns but inferior in speed and comfort. The main reason for the eventual dominance of narrow gauge was not technological superiority; rather, George Stephenson simply built more narrow gauge in the early competition with the wide gauge of Isambard Brunel, and conversion from broad to narrow gauge was easier than the reverse. In the mid-1950s a series of minor circumstances appears to have acted in favor of light-water nuclear reactors over potentially superior competing alternatives. Arthur's argument about the importance of early decisions in the life history of systems has profound implications for infrastructure.

Martin J. Beckmann presents an economic model of urban growth. Consistent with Arthur, Beckmann argues that cities are characterized by increasing rather than constant or diminishing economic returns as the scale of an organization or operation grows. His conclusion is that under reasonable assumptions, the prediction of economic theory is that the urban sector must always grow relative to the agricultural sector and that this process will continue in the future. Substitution of services for industrial production as the main function of a city does not change this. The implication is that there is no end in sight to the increase in city size. The growth of "giant cities" such as Mexico City may confirm Beckmann's theoretical viewpoint.

Adams discusses the evolution of urban infrastructure at national and local scales. He identifies a series of epochs characterized by different transportation technologies: wagon and sailing vessel; steamboat and early railroad; long-haul trains; automobiles, trucks, and airplanes. Adams stresses the complementarity and synergy among modes of transport, in contrast to Nakicenovic and Marchetti, who stress the struggle for survival among them. At any given time, a city or individual is dependent on several modes, and in combination they provide services that could not be offered by a technological monoculture.

An interesting question is whether communication will become the next "epochal" infrastructure. In fact, communication has traditionally been associated with transportation, though it now may receive greater attention in its own right. Letters and packages have been carried by wagons, sailing vessels, pony express, trucks, and airplanes. Is there a qualitative difference between traditional and modern means of carrying information, that is, between the mails, telegraph, radio, and new lightwave communication? Is the epochal designation earned by the growth of infrastructures that are dedicated exclusively to transport of information and not goods?

Adams points out the difficulty faced by planners in the transition periods between epochs. "A group of urban planners in 1880 might have been fairly successful at outlining growth patterns for the ensuing 20 or 30 years, but how would such a group have fared in 1920, when their experience with the characteristics of a rail-dominated transportation network was about to become obsolete?" (p. 111)

Like Hanson and Brooks, Adams faces the question of who should pay for infrastructure. One issue is the extent to which one mode of transport or one sector should subsidize another. More generally, there are questions of distributive justice and fairness. In this context, he raises the key question of how we can take the economic temperature of a city: Do we look at bond ratings? Should we measure the change in number of jobs within its boundaries?

Adams also reviews the availability, condition, and cost of housing units in the largest cities and urban/suburban dynamics. Housing, unlike some other infrastructural elements, is never obsolete in a broad sense, though it may be dated in style, deteriorated in quality, or lacking some modern technological features.

Marchetti approaches the question of infrastructure at both its most global and most fundamental levels. From biological thought, he borrows the notion that the goals of infrastructure are range and control. The final objective must be to have the whole earth comfortably and efficiently as one's territory, and this requires a hierarchy of complementary infrastructures for transportation and communication. Marchetti argues that there is limited range for substitution between transportation and communication. Rather, each feeds the growth of demand for the other.

In the area of transportation, time and money are allocated by individuals to different means of travel to maximize range. People in all societies in fact travel on average about 75 minutes per day, hence Marchetti's notion of a city as a spatial configuration that can be traversed in about one hour. Ancient cities satisfied this definition, and the majority of modern cities do as well. Naturally, means adequate to distances are required. Ancient Athens was a pedestrian city, whereas Peking had public wagon transportation from a remarkably early date. Indeed, any agglomeration that cannot be traversed in about an hour must fragment into several entities, according to Marchetti's view. The introduction of air shuttles in many corridors like Boston-Washington and San Diego-San Francisco is coagulating these into a functional unity. To make genuine cities of the megalopolises that are developing in various urban corridors in Japan, the United States, and Europe, Marchetti suggests that very rapid magnetically levitated trains will come into commercial operation around the year 2000, providing a sort of super-subway. To achieve the true global village, aircraft that can travel between major cities in one hour are a necessity, and indeed research efforts are under way on hypersonic airplanes that could in three or four decades provide an "Orient Express" shuttle service between, for example, Tokyo and New York.

Marchetti emphasizes the extraordinary regularity and universality, and hence predictability, of infrastructure development. The growth of the network of telegraph wires in the United States (Figure 2 in Chapter 7) is one of many examples of a perfectly consistent process; the smooth curve shows none of the social, political, and industrial conflict that must have accompanied this growth. The spread of railroads and subway systems throughout the world can also be successfully analyzed as a single, global process, with each city or country falling into line with military precision. Marchetti also discerns pulses of growth arising from technological innovation, "long waves" that have periods of about 50 years and characterize the transformation of infrastructure.

Nakicenovic provides a complementary characterization of the evolution of infrastructure systems for transportation and energy in the United States. A logistic substitution model organizes the data on these systems according to market share and overall growth into a set of patterns that have probably not been appreciated in the past for their remarkably steady behavior. The successive roles of horses and automobiles mesh with astonishing precision, as do the life cycles of canals, railroads, roads, and air routes (Figures 14 and 15 in Chapter 8). His analyses also bring out the parallel and interdependent evolution of the systems for transport and energy.

Extrapolating Nakicenovic's analyses leads to significant predictions. On the one hand, no breakthroughs in transport are required for the rest of the century, rather improvements must be made in those systems and technologies currently in place. On the other hand, to handle predicted increased demand for air transport, around the year 2000 stretched jumbo jets carrying 1,000 people will be needed. Alternatively, supersonic or hypersonic aircraft carrying about 300 passengers could contribute significantly toward meeting the projected demand for intercity transportation. Nakicenovic also concludes that in the United States only about half of the eventual number of road vehicles that will saturate the country are currently in use. In 50 more years some 300 million road vehicles are projected for the United States. Like Marchetti, with whom Nakicenovic developed the theoretical underpinnings of the approach presented in Chapters 7 and 8, Nakicenovic argues that natural gas will be the fuel of choice for a new pulse of growth in the world economy; considerable expansion and extension of the gas pipeline network thus lies ahead.

Craig discusses air traffic congestion in a detailed case study. All transportation analysts are predicting growth in the volume of air traffic accompanied by continued and often worsening congestion. Indeed, the major problem with travel infrastructure for the rest of the century will be in aviation. As Craig points out, innovative engineering and management will be required in relation to both air and ground traffic control. The so-called landside problems of the air transport system create massive and largely unresearched issues of how to process astonishingly large numbers of people through hubs, and how to connect the air transport system to other modes of transport. The airport can be regarded as essentially the location at which autos meet aircraft, and these "intermodal" connections are generally ignored by research organizations and funding agencies that tend to focus on the pure problems of each mode, like highway paving and air traffic safety, rather than the links between modes.

What will be the great cities of the air? Historically, cities have always emerged with each new infrastructure. The growth of Chicago and Berlin, for example, was intimately connected to the growth of railways. What cities will emerge as the highest-level hubs in the continuing expansion of aviation? Amsterdam? Singapore? Brasilia, which, like a 1951 Buick LeSabre, has an automotive heart but a shell designed to look like an airplane? We also wonder when airports will begin to be recognized as the new city centers, as they become central places for more and more socioeconomic activity.

Gillette examines the conjunction of computers and telecommunication devices that makes up the telematics infrastructure. The integration of these systems became possible for widespread applications in the 1970s. It is a metaphor for the entire structure of society: to what extent are processes and knowledge centralized or distributed? What are the topologies and flows of data? Gillette points out that this system is still in the early, turbulent stage of growth that we recognize as the subject of Arthur's analysis. Alternatively, this is the variable, undetermined part of the growth curve in the Marchetti-Nakicenovic perspective. Telematics is a system in which many variants are competing. In time, certain structures will emerge and dominate for better or worse.

Can the pace of innovation in telematics be maintained by existing institutional arrangements? In contrast to areas such as water supply, in which it is generally held that progress toward better systems will be costly, in this instance it is believed that better systems will cost less. Components of greater capacity and lower cost are certainly in the offing. Although telematics will develop primarily on the basis of technology, Gillette also raises a number of social issues, such as privacy and intrusion, that may be created by or constrain the technology.

Brooks points out that telecommunications infrastructure is a different problem from all of the others addressed in this book. It is not a problem of decay or lack of investment. The problem is the shortening of the life cycle of the technologies and what to do in the face of the richness of opportunities. Moreover, substitution among communication technologies does not seem to be as significant as symbiosis. The question is how the technologies fit together. Indeed, customers are interested in the service and do not concern themselves with whether their voice is carried by copper or silicon. Yet, certainly there is competition within communication technologies, with copper wires, satellites, and optical fibers—or electrons and photons—battling for niches and market share.

Distributive effects are of central importance. What is the relation between high technology for a few and the service available to the many? Is there a trickle-down effect? Are developments in communications technologies a force for hierarchy or equality? Will they allow or encourage dispersion over forces for centralization and economies of scale? Will telecommunications attain a pattern of hubs and spokes similar to air travel and tend to reinforce the hierarchy of urban centers? In turn, what will be the impact of modern telecommunications on the configuration of the city itself?

Brooks reports that Japan is experimenting with regional development centered on the telecommunications infrastructure. The Japanese are building experimental cities of about 200,000 people with wideband communication, videotext, and interactive systems. An interesting question raised by Brooks is whether there are meaningful ways to assess the volume of service in telecommunications. Is saturation in the offing? Do we have insatiable appetites for transmission of information in contrast to areas such as water, energy, or transport in which saturation appears to be a valid concept, albeit at high levels?

Hanson stresses the importance of the changing context in which our infrastructures operate. In the case of water supply, we need to be as alert to problems arising from outside the systems as we are to internal ones. Hanson emphasizes that at least two external factors, the pollution of groundwater and the climatic changes caused by man-made emissions of greenhouse gases, may be critical. By expanding an energy infrastructure for burning coal, oil, and gas, the main sources of greenhouse gases, we may be undermining our planning for the water infrastructure.

At the same time Hanson notes that forecasts of water demand have not been reliable; estimates have often been overblown. We noted earlier the finding of an almost constant level of per capita demand over four decades in Austin. In addition, estimates of costs to replace water supply systems based largely on age have been unreliable. The age of water mains is not firmly correlated with failures, as Marland and Weinberg also discuss.

Water was perhaps the first infrastructure around which civilizations were built, for example, the hydraulic civilizations of Mesopotamia and China. Water is unique and of primary importance. It has often been a reason for, and an instrument of, war. Hanson proposes that there must be real progress in technology (for example, desalinization) and in institutional arrangements for its distribution or there will be conflict. In the United States there is enough water overall, but not locally and everywhere. In many other parts of the world, especially where watersheds are divided between two or more nations, the outlook for adequate and equitable distribution of water in the context of a changing and perhaps deteriorating global or regional environment is not encouraging.

In the area of wastewater, Bernard B. Berger similarly stresses the need for a systems view. Planning needs to be more and more comprehensive. There are some extraordinary successes in this area, for example, Chicago's Tunnel and Reservoir Plan (TARP)—a sewer and water overflow system that makes use of underground storage reservoirs. We speculate that such systems will be adopted by other cities over the next century so that, like subways, they are integral components of most major cities. There are enormous political and financial obstacles to constructing such systems, however, and in the meantime there is an urgent need to work on various related aspects incrementally.

Large, bold solutions for waste disposal are not only expensive but inappropriate in some situations. In addition, the technical ''solutions'' of one generation may not be acceptable, scientifically or otherwise, for succeeding generations. For example, Berger reports that the view that ''dilution is the solution'' is no longer held; neither is it acceptable to use sewage sludge as fertilizer, because of fears about toxic substances.

Cities have been the innovators in waste disposal. One concern is how the increasingly dense but less politically organized populations that are filling so many areas, for example, coastal regions, will address problems of wastewater treatment. Will higher levels of systems integration, for example, regional plans, become necessary?

C. William Ibbs and Diego Echeverry describe the need for and examples of technological progress in the construction industry. There is tentative evidence that productivity growth in construction industries is lower than in other industrial sectors in the United States. Factors such as complexity, uniqueness, and size of projects, managerial complacency, poor labor–management relations, and governmental regulations have contributed to the absence of an innovative environment.

At the same time there has been an explosive growth of competition among firms from many countries for infrastructure projects in all parts of the world, including the United States. A large number of vendors are available to do infrastructure work on a global scale. Historically, certain technologically advanced countries have designed and built (or supervised the building of) infrastructure systems. The British, for example, were responsible for building railroads all over the world, from India to South America, in the nineteenth century. Now many more nations appear to have skilled construction enterprises, and it may not be necessary to be a world economic power to compete for such contracts.

Ibbs and Echeverry identify several promising areas for research that could contribute to improved infrastructure in many modes: materials, monitoring and sensing technologies, nondestructive evaluation and testing, construction methods, robotics, management approaches, and data bases for management.

Marland and Weinberg discuss the longevity, mortality, and morbidity of infrastructure systems. Rather than dwell on the decay and death of systems, they point out that a surprising number of systems live longer than anticipated and thus give free benefits to future generations. This is true of some dams, power plants, bridges, and roads. Their chapter is a first attempt at a deeper demography of infrastructure. Many more such studies are needed. Marland and Weinberg identify three factors that determine the lifetime of infrastructure. Systems wear out. They become too expensive to maintain so that maintenance and replacement are not feasible. They are superseded by better alternatives.

Marland and Weinberg also note the permanence of routes and the eternity of sites. Even if roads and plants decay, their routes and the sites on which they are located appear to have immortality. It is easier to widen roads or add to sites than to obtain territory for new infrastructure. The man-made backbone of our society is probably well established and unlikely to change.

Marland and Weinberg hypothesize that immortalization and future uncertainty make for smaller, more decentralized units. If the perception of obsolescence is strong, then the amount that is worth spending in the first place is limited. Research and development in materials should lead to longer life without additional capital investment. In what cases should we design for immortality? Marland and Weinberg conclude with the fundamental observation that we should design in a way that structure and life expectancy are optimized for an evolving role, incremental change, and periodic replacement.

The chapters in this book show vividly that the overall problems of the physical infrastructure and the human activity associated with it present both an overwhelming and an inviting task for researchers and practicing engineers. We are confident that creative inroads can be effectively made immediately in thinking globally about the area. It is also imperative to move toward a style of infrastructure research in which more effort goes to thinking about the meaning of specific questions concerning smaller problems considered in broader contexts. The infrastructure appears as a system with fractal qualities, reproducing its essential features in a hierarchy of levels ranging from the global to the individual. Ultimately, we would like to attain a unified appreciation of the functioning of the entire infrastructure system and understand where it is headed. To use the phrase employed by Lees and Hohenberg, we would like to understand cities as systems and the systems of cities.

Such an appreciation requires a broader and deeper education for many more individuals who study, design, build, operate, and manage infrastructure systems. More of our engineers must also be historians and sociologists, and more of our city planners must understand fundamental trends and insights deriving from technology and the behavioral sciences.

It is our belief that the stronger forces in U.S. culture continue to move our society in directions that emphasize self-reliant, and sometimes atomized, structure. Our overriding goals are often to provide great autonomy and higher levels of consumption for the individual. Inevitably, much of our group character derives from the summation of the resulting individual behaviors. There are many positive features to this trend. For example, it contributes to the development of an infrastructure that provides considerably better for the aged and the handicapped. At the same time, to use Thomas Schelling's (1978) phrase, there are unwanted macroconsequences from micromotives. Indeed, we believe this is the essence of the problems of the infrastructure systems that are in crisis in the United States. For example, everyone is free to have a car and drive where they choose, and at liberty to make traffic jams. The central challenge is to improve the imagination and effectiveness with which we address longer-term, collective needs and retain a balance with individual possibilities.

The infrastructure is us. Like a seashell or a coral reef, it is an expression of the organism, a history of our lives and the technological and social evolution of our societies. It is a genetic reminder that we are what we were and will be what we are. We should not allow the infrastructure to develop only on the basis of individual utility and short-term measures of cost and benefit, or narrowly measurable attributes that are tractable with current analytic tools. We require longer-range goals of a creative and inspirational kind that blend technological and aesthetic considerations. The future quality of life is to some considerable degree in our hands when we debate decisions about infrastructure. Are beautiful structures ever obsolete?

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