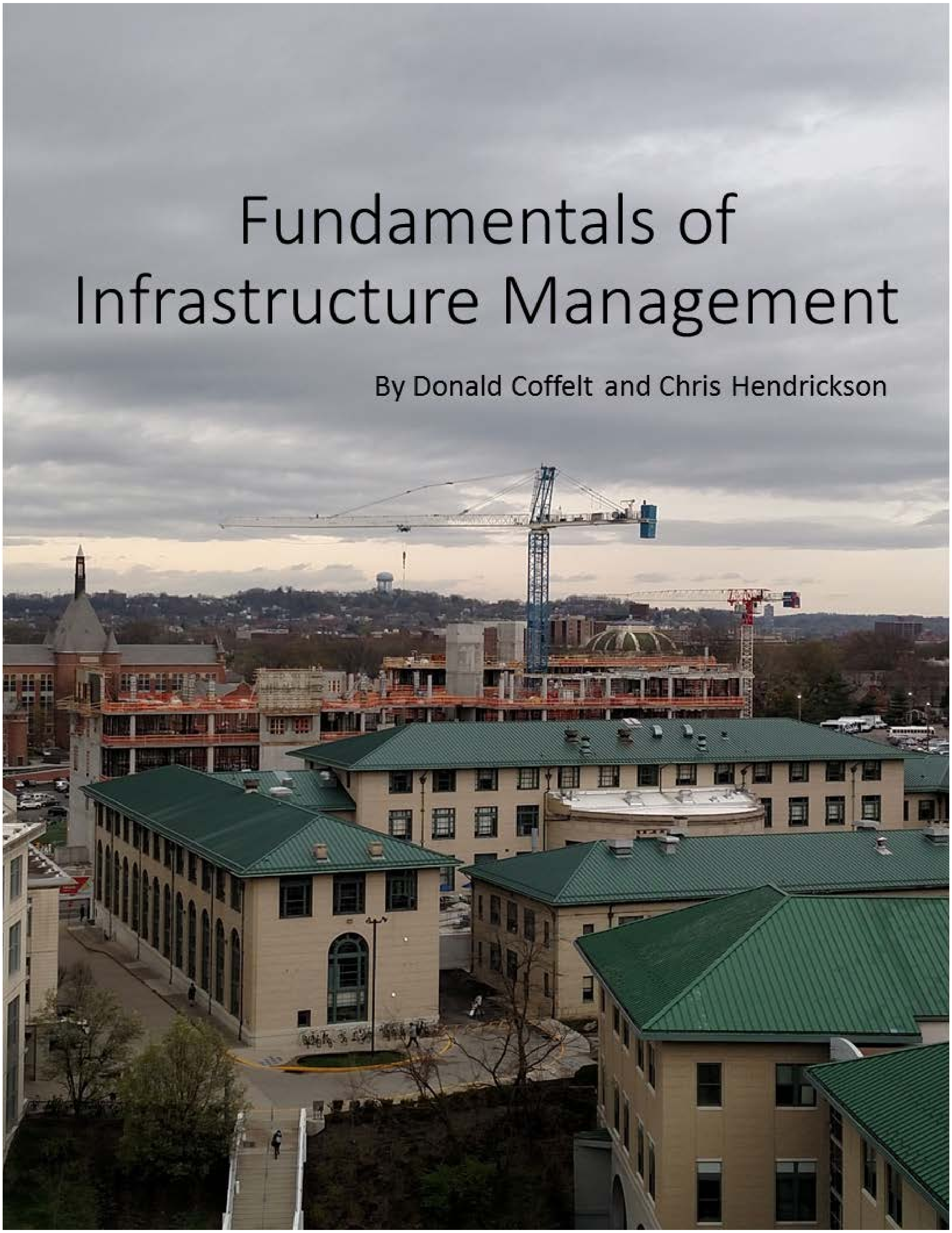
Fundamentals of Infrastructure Management

By Donald Coffelt and Chris Hendrickson



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Cover Photo Credit: Donald Coffelt

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Don Coffelt hiking in Maui, Hawaii. Chris Hendrickson in Switzerland.

Source: Authors

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Introduction by the Authors

This book is provided on the worldwide web as a service to the community of practitioners and students. While we believe that the material in the book could find a commercial publisher and a market, we feel that free of charge availability will expand the impact of the material and help improve the practice of infrastructure management. By 'free of charge,' we mean that the material can be freely obtained, but readers should devote time and effort to mastering the material. We have provided problem assignments for various chapters, and we strongly urge readers to undertake the problems as a learning experience.

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If you find this work helpful or have suggestions for additions or corrections, please email one of the authors: Don Coffelt (dcoffelt@andrew.cmu.edu) or Chris Hendrickson: (cth@cmu.edu). We plan to update the book periodically in the future, although our focus is on fundamental concepts that don't change rapidly over time.

This book grew out of a decade of co-teaching a course entitled 'Infrastructure Management' at Carnegie Mellon University. Our teaching philosophy was to prepare students for work in the field of infrastructure management. We believe that infrastructure management is a professional endeavor and an attractive professional career. Don is a good example of infrastructure management career opportunities. He currently serves as Associate Vice-President for Facilities Management and Campus Services at Carnegie Mellon University, responsible for providing facilities leadership to 350 personnel supporting a campus covering 150 acres and including more than 6M square feet of buildings and associated transportation and utility distribution systems. Don's $100M annual program includes infrastructure planning & management, utility operations, parking, facility operations and various support services.

Of course, there is also a role for infrastructure management research. Both of the co-authors have research interests (and a number of research publications) on various topics of infrastructure management. However, the primary audience for this book is intended to be professionals intending to practice infrastructure management, and only secondarily, individuals who intend to pursue a career of research in the area.

We draw examples and discuss a wide variety of infrastructure systems in this book, including roadways, telecommunications, power generation, buildings and systems of infrastructure. We have found that some common fundamentals of asset management, analysis tools and informed decision making are useful for a variety of such systems. Certainly, many infrastructure managers encounter a variety of infrastructure types during their professional careers. Moreover, due to the functional inter-dependencies of different infrastructure systems, it is certainly advantageous for managers of one infrastructure type to understand other types of infrastructure. For example, roadway managers rely upon the power grid for traffic signal operation.

The first segment of this book presents fundamental concepts and processes, followed by chapters on specific types of infrastructure. In the first segment of the book, we generally use roadways as an example infrastructure application but not exclusively. We have chosen roadways since they are ubiquitous and nearly everyone is familiar with their use (and deterioration!).

We are convinced that a life cycle or long-term viewpoint is essential for good infrastructure management. There are always pressures to adopt short term thinking in making investment and management decisions. Political election cycles and short-term stock performance certainly focus attention on immediate priorities or issues. Nevertheless, many infrastructure investments will last for decades or more, and providing good performance over an entire lifetime is critical for good infrastructure management. Even virtual decisions such as the adoption of a particular performance standard for a facility component are likely to have long-term implications.

Of course, infrastructure managers may face budget limits or other constraints that preclude long-term optimization. A result is the deferred maintenance and functional obsolescence that exist in many infrastructure systems. However, understanding the effects and implications of these constraints is an important task for infrastructure managers.

As a fourth organizational concept, we believe that infrastructure management in a process with multiple objectives (as well as multiple constraints). In particular, infrastructure management should adopt a ‘triple bottom line’ to consider economic, environmental and social impacts. Again, infrastructure managers may be charged with focusing solely on costs of providing services, but infrastructure certainly has implications for the natural environment and for society. For example, infrastructure management typically involves a large number of workers and affects a large number of users, so social impacts are significant. Throughout this book, we will try to address the impacts of infrastructure decision making with regard to these multiple objectives.

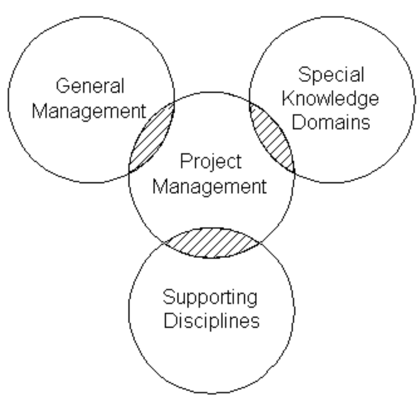
Students in our Infrastructure Management were usually first year graduate students or senior undergraduate students. While most were majoring in engineering disciplines, we also had architects, computer scientists and public policy students successfully complete the course. Indeed, many of our students ended up pursuing a career in some form of infrastructure management, and we are particularly grateful to all our students for their insights, their questions and their feedback on the material.

Our course in Infrastructure Management was a full semester with class sessions for 30 to 35 hours over the course of a semester. The order of coverage of material generally followed the order in this book, except that we usually covered one or two infrastructure chapters early in the course to provide context for examples. The course involved class sessions (with a mix of lecture, discussion, videos and in-class exercises), homework assignments and a group project of the student's choosing. Our textbooks ranged from peer reviewed journal papers to the literal infrastructure "news of the day". We also invited a few practicing infrastructure managers to guest lecture on their own their own activities, problems and successes as practitioners in this sub-discipline. We always included a tour of campus infrastructure, visiting utility tunnels, roof tops, and mechanical rooms – spaces not generally open to students.

An online Instructor's Manual with problem solutions and project assignments is available to genuine instructors. Instructors should email Don Coffelt (dcoffelt@andrew.cmu.edu) or Chris Hendrickson (cth@cmu.edu) with their course details for a digital copy of the Instructor's Manual.

This book has three companion books available on the World Wide Web. Each of these other books grew out of semester long courses at Carnegie Mellon University and may be of interest to some readers. The companion books are:

1. Hendrickson, Chris, 'Project Management for Construction,' http://pmbook.ce.cmu.edu/. This book discusses the fundamentals of project organization, cost estimation, financing, cost control, and quality control. Construction processes are also described. While this book uses construction examples and processes, many of the fundamental methods can be used for other types of projects, including software engineering.



Source: Chris Hendrickson

2. Civil Infrastructure Planning, Investment and Pricing (co-authored by Chris Hendrickson and H. Scott Matthews). Again, either search for the book title or look at the website: http://faculty.ce.cmu.edu/textbooks/cspbook/). This book covers the fundamentals of infrastructure demand and usage, private and social benefits, infrastructure cost functions and pricing strategies. The material has a large overlap with economic benefit/cost analysis, but the focus is upon additional objectives than cost minimization and applications are made to infrastructure decisions.

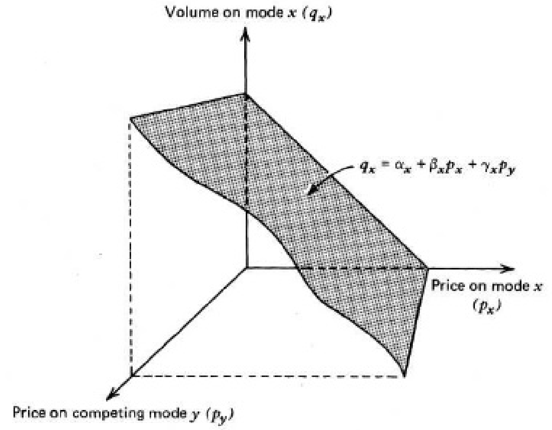
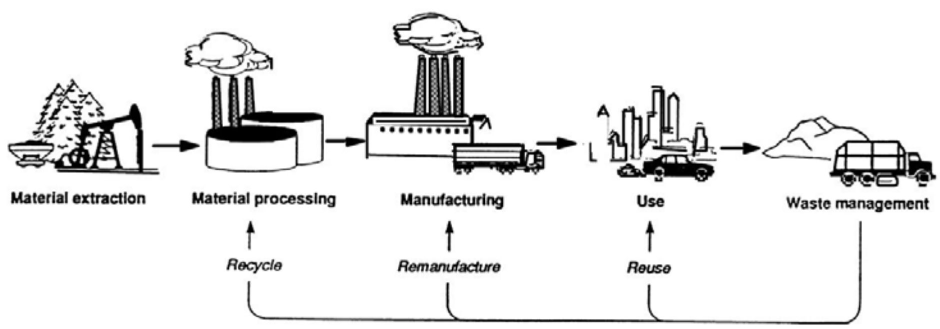


Figure 3-3. Illustrative demand function for a binary mode choice situation.

Source: Chris Hendrickson

3. Matthews, H. Scott, Chris T Hendrickson, and Deanna Matthews, 'Life Cycle Assessment: Quantitative Approaches for Decisions that Matter,' http://www.lcatextbook.com/. This book provides a comprehensive introduction to methods for cost and environmental life cycle assessment.



Source: Chris Hendrickson

Author Biographies

Donald (Don) Coffelt is the Associate Vice President for Facilities Management and Campus Services at Carnegie Mellon University. His 350-member team is responsible for the facility services, infrastructure management, utility operations and campus services required to support the university's 150-acre Pittsburgh campus. Reporting directly to the Vice President for Operations, Coffelt is also responsible for university-wide sustainability practices. Dr. Coffelt holds an appointment as an Adjunct Professor in Carnegie Mellon's Department of Civil and Environmental Engineering with an expertise in Infrastructure Management and a focus in promoting student and faculty access to university facilities for education and research – "The University as a Lab".

From 1995 to 2003, Coffelt managed a nation-wide portfolio for a Pittsburgh area facilities and technology firm. From 1985 through 2013, he served in a variety of leadership assignments across the United States as an officer in the U.S. Coast Guard and Coast Guard Reserve completing his 28-year career in at the rank of Captain.

In addition to his doctorate from Carnegie Mellon University, Coffelt is a graduate of the United States Coast Guard Academy and the University of Illinois. He is a Fellow of the American Society of Civil Engineers and a licensed professional engineer in Alaska, and Pennsylvania. He is a volunteer board member for the Andrew Carnegie Society.

Chris Hendrickson is the Hamerschlag University Professor of Engineering Emeritus, Director of the Traffic 21 Institute at Carnegie Mellon University, member of the National Academy of Engineering and Editor-in-chief of the ASCE J. of Transportation Engineering. His research, teaching and consulting are in the general area of engineering planning and management, including design for the environment, project management, transportation systems, finance and computer applications.

Chris co-authored three additional available freely on the internet: Life Cycle Assessment: Quantitative Approaches for Decisions that Matter (2014), Project Management for Construction (Prentice-Hall, 1989, now available on the web) and Civil Systems Planning, Investment and Pricing (2011). He has also published several monographs and numerous papers in the professional and public literature.

Prof. Hendrickson is a member of the National Academy of Engineering, the National Academy of Construction, a Distinguished Member of the American Society of Civil Engineering, an Emeritus Member of the Transportation Research Board and a Fellow of the American Association for the Advancement of Science. He has been the recipient of the 2002 ASCE Turner Lecture Award, the 2002 Fenves Systems Research Award, the 1994 Frank M. Masters Transportation Engineering Award, Outstanding Professor of the Year Award of the ASCE Pittsburgh Section (1990), the ASCE Walter L. Huber Civil Engineering Research Award (1989), the Benjamin Richard Teare Teaching Award (1987) and a Rhodes Scholarship (1973).

Chapter 1: Introduction to Infrastructure Management

1.1 Importance of Infrastructure

Human society depends crucially upon a series of infrastructure investments that have been made over centuries of time. We have constructed water, wastewater and power systems, as well as buildings, roads, ports, railways and other facilities. More recently, we have built complex telecommunication systems. In the process, humans have profoundly altered natural landscapes and ecological systems. The result has been a large number of inter-dependent infrastructure systems to support economic activity and social welfare. Without our infrastructure, society would not function in anything like its current state. We all have come to depend upon electricity from our power grid, goods delivered from our transportation systems, clean water from municipal water supplies and sewage services. In effect, infrastructure investment is a major social commitment, but it enables a great variety of economic and social activities.

With our dependence upon infrastructure, it is not surprising that the management of our infrastructure is a critical economic and social task. Infrastructure wears out during use, deteriorates over time due to aging and weather effects, and can fail due to extreme stress from event such as earthquakes or floods. Maintaining, rehabilitating and renewing our infrastructure systems are a major undertaking for any society.

Figure 1.1 - Example Infrastructure Facility: A Geothermal Power Facility in New Zealand

Source: Photo by Chris Hendrickson. Water is heated underground and the resulting steam is used in turbines to generate electricity.

There is no widely accepted enumeration of the number and extent of infrastructure systems. Some analyses focus solely on publicly owned infrastructure, but this omits major systems in many countries, such as railroads in the United States. The American Society of Civil Engineers provides 'grades' of the condition of 16 different types of US infrastructure (ASCE, 2016), while the U.S. Department of Homeland Security's National Infrastructure Protection Plan identifies 18 types of infrastructure (DHS, 2016). The National Resource Council defines five 'critical infrastructure systems:' power, water, wastewater, telecommunications and transportation systems (NRC 2009).

Defining the extent of infrastructure is difficult also due to the complexity of components within any type of infrastructure. For example, roadways have a variety of constituent infrastructure systems themselves, including:

- Pavements and pavement markings;
- Tunnels and bridges;
- Drainage and foundation support;
- Sidewalks and
- Signage and traffic control infrastructure.

Each of these roadway components can be treated as its own infrastructure system to be managed. Similarly, buildings have a variety of sub-components and systems to be managed.

For the purposes of this book, we will take a broad view of infrastructure systems, including both critical and mundane facilities and components. Infrastructure managers will certainly vary in the extent of their interests and management responsibilities, so taking a broad viewpoint on what constitutes infrastructure is appropriate.

1.2 Goals for Infrastructure Management

Just as the number and extent of infrastructure systems are complex, so are the goals that are pursued for any particular infrastructure system. One common goal suggested is to insure 'sustainable' infrastructure. One interpretation of sustainable is simply to have facilities with great longevity. However, this is often not a realistic goal. First, managers must be sensitive to the amount of resources required to construct and maintain any particular facility. Longevity requires greater capital investment for initial construction. Second, the requirements for facilities are likely to change over time. For example, the legal size and weight of trucks can change over time (usually with an increase), which may make existing bridges functionally obsolete since they cannot support larger trucks. Third, the usage of facilities may decline to such an extent that maintaining an existing facility is not beneficial.

For most infrastructure systems, managers adopt a planning horizon for longevity decision making. Such planning horizons can vary from a short period (such as a year or two) to decades (for infrastructure such as ports or buildings). Each organization involved in infrastructure management may have their own planning horizon for such decision making.

In practice, the goals for infrastructure management are complex and multiple. Most critically, facilities are expected to provide acceptable performance to a variety of users. For example, a local roadway might accommodate a variety of motorized vehicles (such as buses, cars and trucks - moving or parked), bicycles and pedestrians (particularly at intersections). Deterioration of the facility can affect acceptable performance, as with the development of potholes, uneven surfaces and cracking for pavement. Extreme events such as earthquakes, hurricanes, flooding or terrorist activities can require immediate attention and response.

Figure 1.2 - Example of Flooding Requiring Infrastructure Management Responses

Source: By The National Guard (Maryland National Guard Uploaded by Dough4872) [CC BY 2.0 (http://creativecommons.org/licenses/by/2.0)], via Wikimedia Commons. https://commons.wikimedia.org/wiki/File%3AHurricane_Sandy_flooding_Crisfield_MD.jpg (accessed 9/16/2017)

Typically, goals for infrastructure management can be categorized as economic, environmental and social. Economic impacts include the direct and indirect costs of managing and operating the infrastructure system, the economic development potential for the system (including employment) and any user or non-user benefits stemming from the system. Environmental impacts are associated with ecological system uses, emissions to the environment (especially toxic chemicals and greenhouse gas emissions), and non-renewable resource use. Social impacts pertain to equity of benefits, social justice and individual development (including employment). This 'Triple Bottom Line' of goals is common for many social investments.

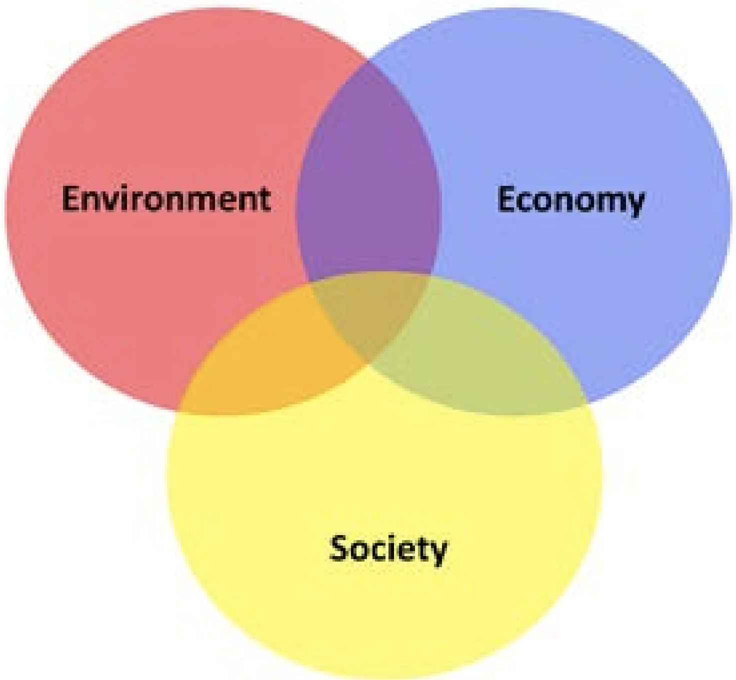


Figure 1.3 -Triple Bottom Line Goals for Sustainable Infrastructure

Source: US Environmental Protection Agency, Public Domain, http://archive.epa.gov/region4/p2/web/html/sustainability.html (accessed 2/17/2016).

1.3 Role of Infrastructure Managers

Infrastructure managers are becoming increasingly important in the agencies and owners of infrastructure. Throughout the world, centuries of infrastructure investment have resulted in complex, multi-layered systems of existing infrastructure. Maintaining this infrastructure investment is a major task as noted above.

The skills required of infrastructure managers will vary from place to place but have some common elements. Managerial skills for setting priorities, communication with multiple stakeholders, building effective teams and proactive problem solving are always desirable. Technical familiarity with information systems and infrastructure systems is highly desirable, although managers can often rely upon their management team for relevant technical expertise. Developing rapid and effective responses to component breakdowns and extreme events such as floods or earthquakes is also a major role for infrastructure managers.

The background and career paths of infrastructure managers can also vary. Traditionally, many managers rose through the ranks of skilled tradesmen such as mechanics or construction workers. More recently, professional backgrounds in architecture, engineering, or business have become more heavily represented among infrastructure managers. With any background, it is imperative for infrastructure managers to stay current with new technologies and issues affecting their work.

Rather than a holistic overview for infrastructure management, many managers are charged with responsibility for single components or even single attributes of components. For example, Infrastructure systems along a neighborhood street might include:

- Roadway pavement
- Electricity
- Tele-communications
- Potable Water
- Natural Gas
- Wastewater Sewer
- Storm Sewer

Each of these systems may have separate owner organizations and managers. One system might have multiple managers. For example, the roadway pavement may have different managers for snow removal, routine cleaning and rehabilitation and maintenance. As might be imagined, co-ordination in the management of these different systems may be difficult. The infrastructure managers involved should make special efforts to insure information sharing and co-ordination. For example, roadway rehabilitation could be usefully coordinated with work on other underground utilities to avoid repeated excavations.

1.4 Organizations for Infrastructure Management

A variety of industrial and professional organizations have emerged to provide a forum for infrastructure managers and indeed to support the notion that the discipline itself represents a discrete field of study within the engineering profession. These organizations provide a means of spreading relevant information, such as best practices and job availability. However, these organizations often are limited to particular types of infrastructure or specific regions or countries. A partial list of related professional organizations associated with the practice of infrastructure management in the United States is listed below:

- APPA (www.appa.org) Association of Physical Plant Professionals
- ASCE (www.asce.org) American Society of Civil Engineers
- ASME (www.asme.org) American Society of Mechanical Engineers

- SAME (www.same.org) Society of American Military Engineers
- BOMA (www.boma.org) Building Owners & Managers Association
- IFMA (www.ifma.org) International Facilities Management Association
- AFE (www.afe.org) Association of Facility Engineers

1.5 Exercises

P1.1 **(6 pts)** The ASCE produces a periodic report card on the nation's infrastructure system (See the ASCE readings) Pick 2 of the following infrastructure systems: Bridges, Dams, Drinking Water, Energy (Electricity), Hazardous Waste, Public Parks & Recreation, Roads, Solid Waste, Transit, and Wastewater.

> (a) Provide a grade for the local systems at in Pittsburgh using just three categories for grading: condition, capacity, and adequacy of funding. (Note that the ASCE methodology includes seven categories).
>
> (b) Document a justification for your grade (in a fashion similar to that in the ASCE report card site listed above). If you have no data for a particular category, just say so.
>
> (c) Contrast your local grade with the national ASCE grade in the reading.

P1.2 **(10 pts)** Provide a critique and summary of one paper published in a refereed ASCE (or other professional society) Journal in the past ten years pertinent to infrastructure management. Your critique and summary should be no more than three pages long. ASCE journals are listed at:

http://ascelibrary.org/action/showPublications?pubType=journal

Feel free to pick a journal that reflects your own interests. Good starting points are the Journal of Infrastructure Systems or the Journal of Architectural Engineering. This assignment is intended to introduce you to the professional literature as a resource for infrastructure management.

Your summary should include:

1. the full reference for the paper (authors, title, journal, volume, number, pages, publication date),
2. a summary of the content of the paper,
3. the implications and usefulness of the results for infrastructure managers,
4. any problems you see with the paper (such as needed further work), and
5. the contribution of the paper with regard to other published work, including the references cited and any citations to the chosen paper.

Paper citations can be tracked through the Web of Science database (if that is available to you) or through Google Scholar (scholar.google.com) search. Please consult both and report the results. In many cases, your chosen paper may be too recent (or too obscure) to have had citations.

1.6 References

(ASCE 2016) American Society of Civil Engineers, 2013 Report Card on America's Infrastructure, http://www.infrastructurereportcard.org/ (accessed 1/5/2016).

(DHS 2016) Department of Homeland Security, 'National Infrastructure Protection Plan,' http://www.dhs.gov/national-infrastructure-protection-plan (accessed 1/5/2016).

(Hendrickson 2016) Hendrickson, Chris, 'Project Management for Construction,' http://pmbook.ce.cmu.edu/ (accessed 1/6/2016).

(Hendrickson 2016b) Hendrickson, Chris and H. Scott Matthews,' Civil Infrastructure Planning, Investment and Pricing', http://faculty.ce.cmu.edu/textbooks/cspbook/ (accessed 1/6/2016).

(Matthews 2016) Matthews, H. Scott, Chris Hendrickson and Deanna Matthews, 'Lifecycle Assessment: Quantitative Approaches to Decisions that Matter,' http://www.lcatextbook.com/ (accessed 1/6/2016).

(NRC 2009) National Resource Council, 'Sustainable Critical Infrastructure Systems: A Framework for Meeting 21st Century Imperatives,' National Academies Press, 2009, DOI: 10.17226/12638).

Chapter 2: Asset Management Process

2.1 Introduction

Actively managed infrastructure systems typically have a structured process for asset management. Such processes are usually planned for regular time intervals such as annually or every five years. Asset management does require resources of various types. But with an asset management process, owners can reduce the risk of unexpected infrastructure failures and plan for preventive maintenance to reduce lifetime infrastructure costs.

In many cases, owners are required to have an asset management process in place by lenders or regulators. In such cases, the lenders or regulators may be interested in estimates of the value of infrastructure assets in addition to appropriate management actions. An example is the standards recommended by the Government Accounting Standards Board (FHWA 2000). Since sale of infrastructure assets happen only sporadically, the ‘value’ of infrastructure is usually estimated as either the original acquisition or construction cost less depreciation over time, the cost of replacement, or the cost of preservation for the infrastructure.

Depreciation is an accounting term that represents a loss in value over time and is usually considered a cost of business. For many infrastructure systems, depreciation is calculated as a linear loss of value over the expected lifetime of the system. So if the original construction cost was C, the expected lifetime is n years, then the depreciation in each year is C/n and the estimated value of the system in year t (counting from the time the infrastructure is constructed or acquired) is C – t*(C/n). For example, if C is $ 10 million, n is 50 years, depreciation in each year is $ 10,000,000/50 = $ 200,000 and the ‘value’ in year 10 is $ 10,000,000 - 10*$200,000 = $ 8,000,000.

While we focus on infrastructure assets here, assets to a particular enterprise will often comprise a wide range of resources. Employees are assets whose value can improve with experience, education or training. Likewise, inventories of goods and real estate are assets. Even reputations are viewed as assets and can be subject to an asset management process.

2.2 Usual Elements of an Asset Management Process

Figure 2.1 illustrates the typical steps in an asset management process. These steps would often be undertaken on an annual basis, although many of the elements might not change from year to year such as goals and policies. In the remainder of this section, we will comment upon the various components in the generic asset management systems in Fig. 2.1. Later chapters will examine these process steps in greater detail.

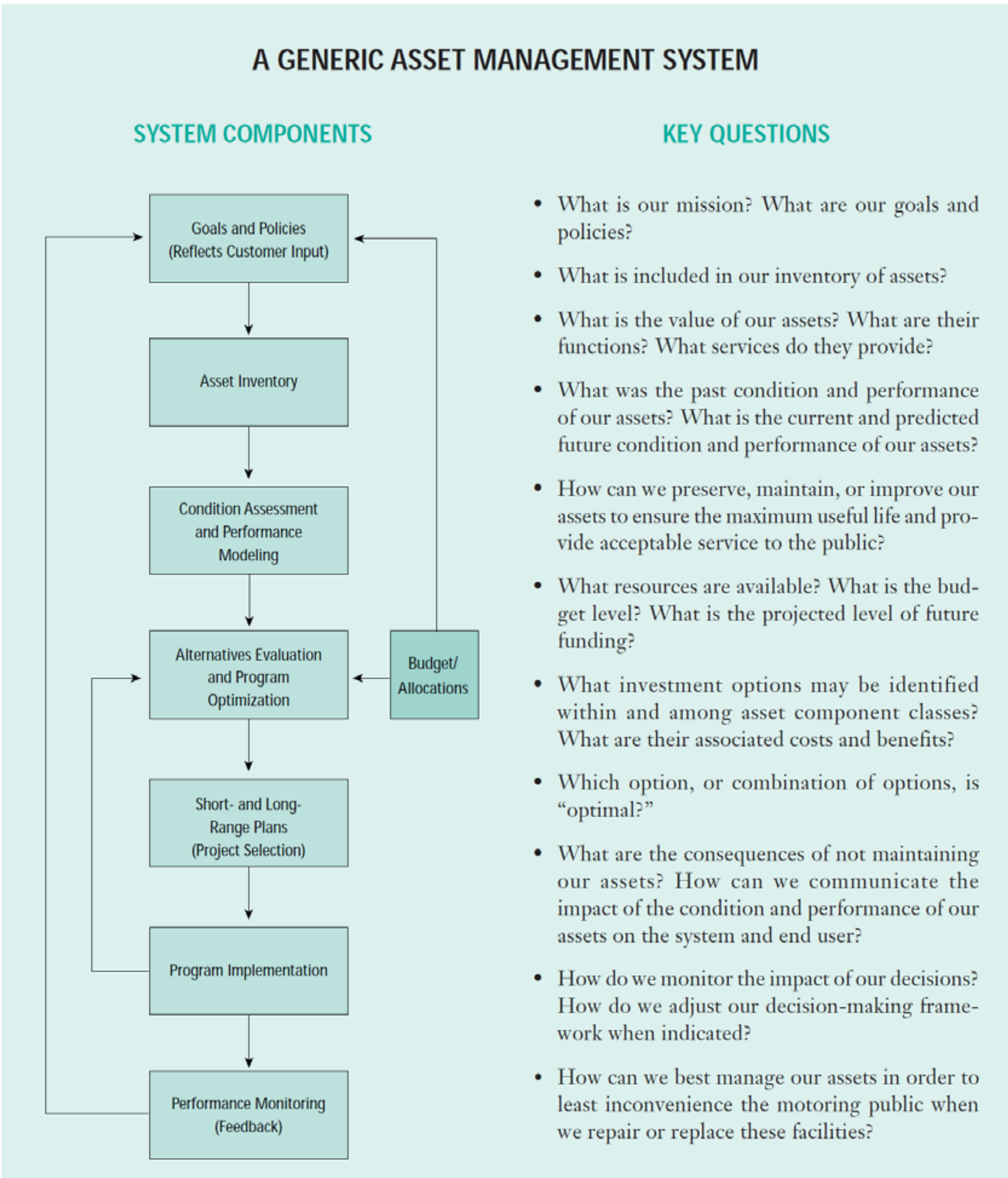


Figure 2.1 - A Generic Asset Management Process

Source: FHWA 1999, Public Domain.

Goals and policies will differ among enterprises. For example, a water provider (e.g., a water utility) might have goals to provide a certain quantity of water within defined quality standards. Further, the water provider might have goals to preserve its physical infrastructure at a certain quality standard. A major difference in policies concerns corporate taxation. For private corporate owned assets, the tax implications of depreciation and maintenance expenses may be important in the overall profitability of the corporation. Infrastructure managers must assess the specific goals and policies pertaining to their own enterprise.

Asset inventory identifies the numbers and types of assets available. For example, a roadway agency might keep track of the numbers and types of roads in their system, but also assets such as road signs and lane markings. Inventory is often hampered by the absence or loss of historic records, such as the exact locations of old underground pipes. Inventory changes over time as assets are created (through construction or purchase) or disposed (through retirement or sale).

Computer aids are available for asset inventory. For fixed in place assets, geographic information systems may be quite helpful, showing the location and types of assets visually on a computer screen (Figure 2.2 provides an example of such a GIS inventory). For these aids, a standardized labelling or numbering system for assets is required. These identifiers are usually stored in an inventory database of asset information, but also installed on pieces of infrastructure themselves. For example, railway cars will have a standardized ‘reporting mark’ to indicate the owner of the car and its number. The identifiers may be written on the assets or stored in readable digital form by technologies such as radio frequency identifier (RFID) tags or bar codes. In many cases, computer aids pertain to individual assets such as bridges or roadway segments, and some form of ‘data gateway’ may be required to provide a holistic view of enterprise assets.

Figure 2.2 - Geographic Information Systems Inventory of California Roads

Source: By RandomlyAdam - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=35868125. Note the density around Los Angeles and San Francisco.

Condition Assessment and Performance Modelling requires an assessment of the current functionality of each asset and often involves a forecast of asset deterioration. Condition assessment can be done mechanistically by assuming a standard deterioration with use and time, but more often involves active survey and/or sensing along with models of performance and deterioration. In many cases, condition assessment is summarized in a numerical rating score based on survey, sensing or testing. Figure 2.3 shows a pavement segment having less than perfect condition as an example.

Figure 2.3 - Example of longitudinal cracks affecting condition rating on a roadway segment

Source: FHWA Distress Identification Manual for The LTPP, 2003, Public Domain, https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/ltpp/reports/03031/03.cfm#fig92.

Alternatives Evaluation and Program Optimization is a process step to plan asset maintenance, rehabilitation or replacement for the planning horizon. In this step, managers need to formulate reasonable alternatives for asset improvement. For a roadway segment, alternatives might include various maintenance activities (such as crack sealing or pothole patching), repaving (such as milling off the top layer of asphalt and placing a layer of smooth, recycled asphalt), or reconstruction. Of course, any asset management plan will have to be modified over time in response to changing conditions or priorities.

Computer aids can also be useful in the process of alternatives evaluation and program optimization. Databases of possible alternative actions (and their costs and other characteristics) are helpful. Optimization programs to minimize costs may be employed. Alternatives evaluation can also involve multiple stages, with preliminary investigation followed by detailed analysis of a final set of possible actions.

Budget and Allocations define the resources available for asset management and will influence selection of management alternatives. In effect, most infrastructure managers are constrained by the allocation of resources and budgets available in any particular period. As shown in Figure 2.1, budget and allocations may also influence the goals and policies defined for the entire process.

Short and Long Range Plans (Project Selection) develops a plan of action for selected alternatives over periods of time. 'Short range' typically is a yearlong planning horizon, although it might be as short as scheduling activities over the course of a day or week. Long range plans usually involve major projects and may involve a significant planning process. For discussion of long range planning, see Hendrickson (2016). Plans usually involve the infrastructure management organization itself, but often include provisions to contract out for specific projects.

A component of most infrastructure management short range plans is a process for responding to routine maintenance requests. For example, a building manager might have a systematic plan for replacing light bulbs in the building, but would also respond to reports of burnt out or broken lights.

Program Implementation is the process of actually completing the selected projects. For example, a City might plan to repave 200 kilometers of designated roadway segments over the course of a construction season. Program implementation involves actually doing the repaving work.

Performance Monitoring (Feedback) is a means of providing continuous feedback information on asset management performance. While Fig. 2.1 shows this feedback as a flow into goals and policies, the feedback can influence all stages of the asset management process. For example, the performance of particular maintenance or rehabilitation alternatives may inform alternatives evaluation and project selection. Performance monitoring often involves measures of infrastructure usage and quality of services provided in addition to direct information on asset management actions.

2.3 Example Asset Management System: Commercial Roof Management

Commercial roofs represent a substantial asset that is often subject to an asset management process. Of course, roofs would only be one component of a building asset management process, but since roofs have special design characteristics, construction and maintenance, they often receive special attention. Figure 2.4 illustrates the various components of a typical low slope commercial roof. A reflective cap for energy conservation is the top layer, with a waterproof membrane, insulation (varying in thickness with design decisions relative to the local climate) and a roof deck below.

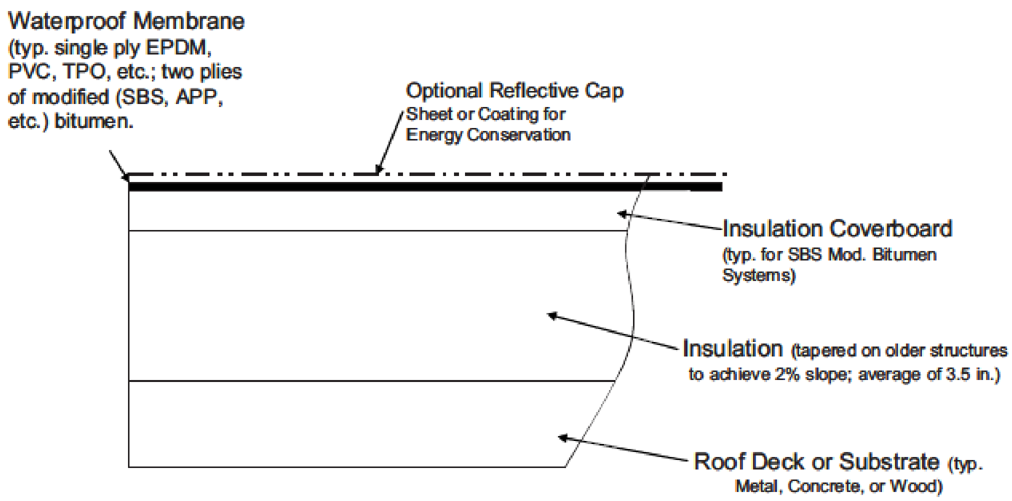


Figure 2.4 - Typical Low Slope Roof Cross Section

Source: Coffelt and Hendrickson, 2010

The goal of managing commercial roofs is often long term (or life cycle) cost minimization. In addition to roof maintenance and replacement costs, this cost minimization should consider user costs either directly or as a constraint (such as perform maintenance or replace if leaks begin to occur). A direct forecast of user costs would require assessment of the costs associated with roof failures (notably leaks) multiplied by the probability of such failures (Coffelt and Hendrickson 2010 and 2011). Introducing other goals for use of roof space or water retention might motivate adoption of different roof types, such as green roofs with a soil and plant layer (Blackhurst 2010).

Inventory of roofs is based upon building blueprints, maps, and inspection. A database record of a building roof characteristics and records is illustrated in Figure 2.5. The area of the roof is recorded as well as roof characteristics. The location of the roof can be found from the (unique) building name.

In this case, the roof has a record of manual inspections roughly every six months from 1997 to 2005. The inspection rated the condition of the overall roof, the membrane, the roof support and flashing using a five point rating scale from 1 (new) to 5 (failed). Flashing is a metal strip to prevent water intrusion between a roof and another component such as a vent. In addition to roof inspection and rating, the biannual inspection can be used to perform minor maintenance such as clearing debris on the roof. Note that the roof was generally deteriorating in years 1997 to 2001, and then was in stable condition after the replacement of the old roof.

Building	**Warner Hall**		
GSF	45917	2005 Gross	
Roof GSF	6,600	approx	
Floor Plate	6078	Upper Occupied Floor	
	Original	Roof#2	
Slope	Flat	Flat	
Type	Builtup	Modified	
Manufacturer			
Ballast	River Stone	Cap Sheet	
Underlayment			
Underlayment2			
Date	1970		2002
Expected Life	30		30

Rating System	
Condition	**State**
Excellent	7
Very Good	6
Good	5
Fair	4
Poor	3
Very Poor	2
Failed	1

Inspection Date	Overall	Support	Membrane	Flashing	Miscellaneous	Asset Maintenance	Asset Renewal
November 1997	5.50	6	5	6	6		
March 1998	4.00	6	4	4	6		
November 1998	4.50	6	4	5	6	$ 2,778	
March 1999	4.00	6	3	5	6		
November 1999	3.50	6	3	4	4	$ 836	
March 2000	2.00	6	2	2	5		
November 2000	2.50	6	2	3	5	$ 852	
March 2001	2.50	6	1	4	5	$ 196	95988
March 2002	6.00	6	6	6	6	$ 194	
March 2003	4.50	6	6	3	6		
November 2003	5.50	6	6	5	6	$ 852	
March 2004	5.50	6	6	5	5		
November 2004	3.50	6	4	3	6	$ 242	
March 2005	4.50	6	5	4	5		
November 2005	4.00	6	6	2	5	$ 1,200	

Figure 2.5 - Illustrative Database of a Commercial Roof Management System

Source: Don Coffelt – Carnegie Mellon University Asset Management System

In any particular year, the roof asset manager would review the roof condition, forecast roof conditions and costs for the next year or so, formulate alternatives (such as replace the roof or perform maintenance as recorded in the data record) and make decisions about treatments to the roof.

Performance monitoring could also be accomplished annually as the roof asset manager evaluates last year's decisions.

Roof asset management has the advantage of reducing the risk of catastrophic losses that might occur with sudden roof failure. By systematically rating conditions and considering management alternatives, the roof asset manager avoids such failures. Of course, natural hazards such as tornados or hurricanes might still result in roof failures, but even there design decisions such as tying roofs down can reduce the risk of failure.

2.4 Asset Condition, Level of Service and Performance

Asset management systems can focus upon improving condition, performance (often called level of service) or some combination of these characteristics. For infrastructure asset management, condition relates to the functionality of a particular infrastructure component and its deterioration process. Performance and level of service refer to the user experience and use of the infrastructure itself. Performance and level of service can also be defined and measured for processes that are not infrastructure, such as patient waiting time on visiting a hospital emergency room. Facilities management processes can also have process performance measures, such as response time and communications adequacy to repair requests.

Figure 2.6 illustrates levels of service for four different transportation modes as originally defined by the Florida Department of Transportation. Automobile level of service is usually defined by the volume of traffic relative to the roadway capacity. As volume increases, congestion and delay also increase with a progression from level of service A (free flow traffic) to F (traffic jam). For bicycles, the level of service is defined by the separation from the dangerous vehicular traffic stream. For pedestrians, sidewalk amenities, provision of sidewalks and separation from vehicular traffic influence level of service. For buses, level of service is defined with respect to frequency of service and crowding on the buses.

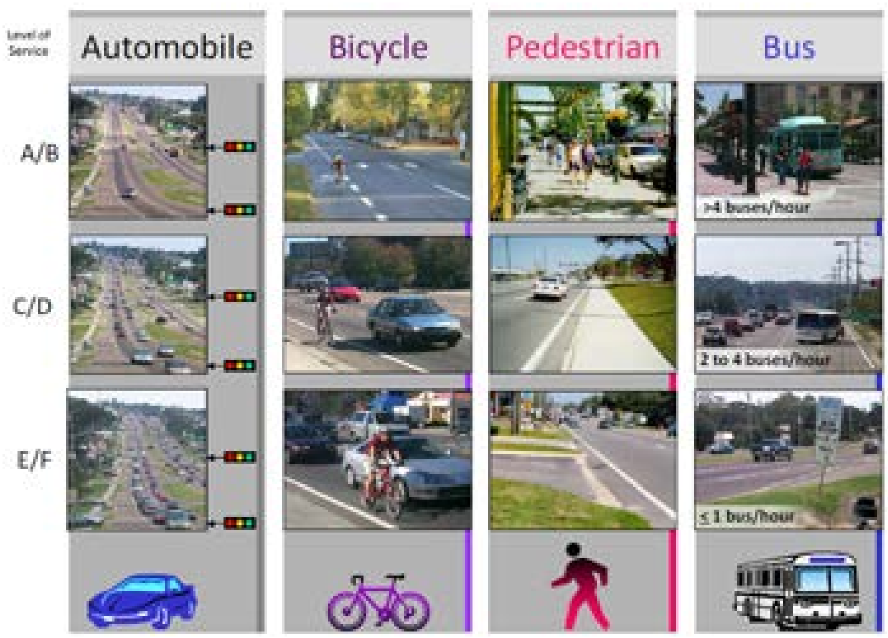


Figure 2.6 - Pictorial Examples of Level of Service A to F for Multiple Transportation Modes

Source: FHWA, Public Domain, https://ops.fhwa.dot.gov/publications/fhwahop12035/chap10.htm.

Individual components of infrastructure systems can also have level of service and performance measures. Figure 2.7 shows the levels of service for intersections with traffic signals defined by the California Department of Transportation. In this case, the level of service and performance is related to the average delay per vehicle at the intersection. Note that the factors affecting level of service relate to the intersection infrastructure (such as traffic signal and geometric conditions) as well as the traffic volumes (such as numbers of pedestrians and trucks).

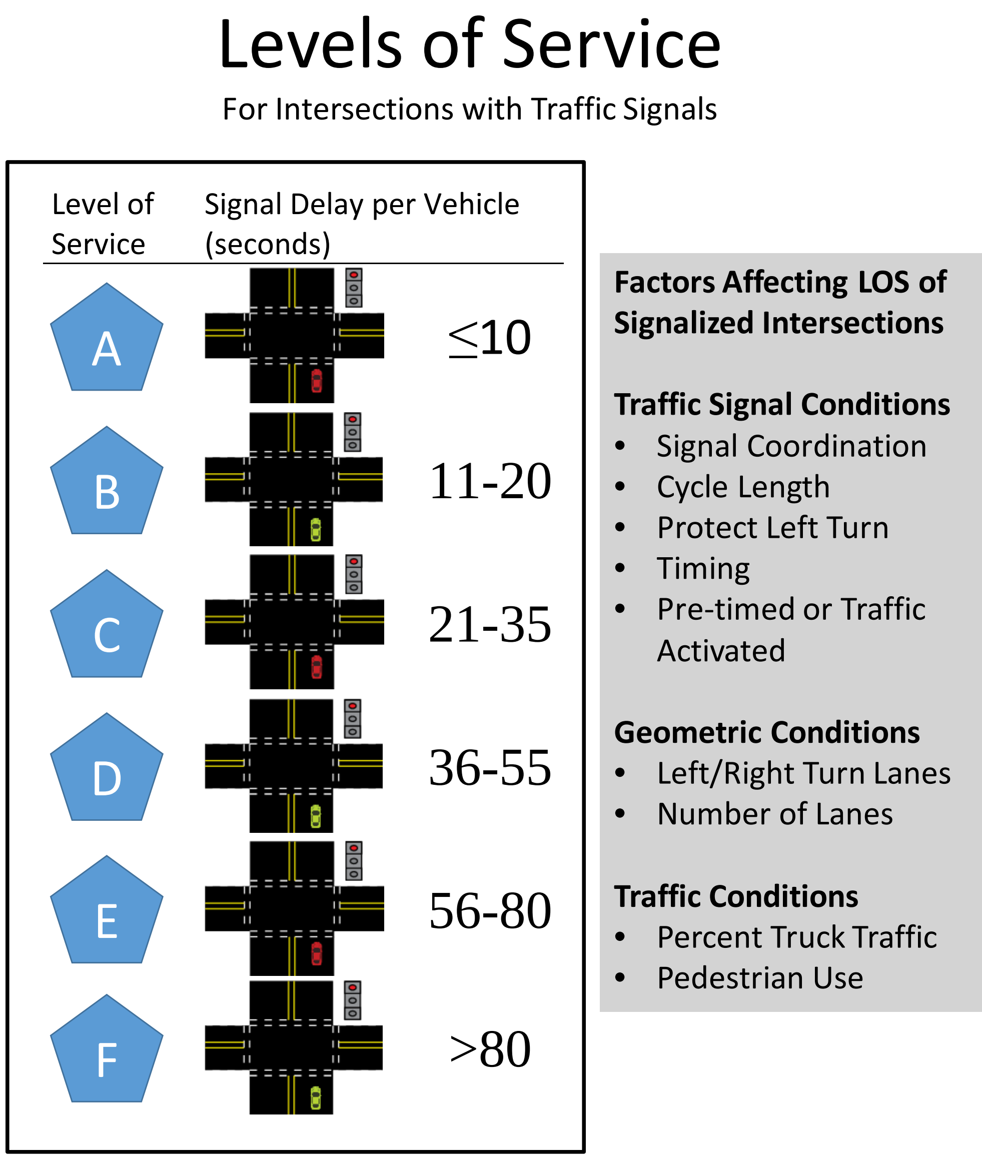


Figure 2.7 - Example of Level of Service for Signalized Intersections

Source: California Department of Transportation, http://www.dot.ca.gov/ser/forms.htm. Redrawn and altered by Authors.

Infrastructure performance can be a multi-dimensional consideration. For example, telephone service performance includes aspects of coverage (for cellular phones), dropped calls (again for cellular phones), sound quality and user costs.

For nearly all infrastructure systems, performance and level of service depend upon the infrastructure condition. For example, unreliable cellular telephone routers will degrade the service performance. Leaky roofs are both a condition and a user problem. Rough and potholed roadway surfaces reduce the speed of traffic flow even at low traffic volumes. Moreover, the infrastructure conditions can be influenced directly by maintenance or rehabilitation activities initiated by an infrastructure manager, so condition of infrastructure is often emphasized in infrastructure asset management.

The measures of infrastructure performance differ from system to system. Some typical performance measures would include:

- Asset condition assessed in processes of inspection and modelling of deterioration. Index scales are often used to summarize condition as described in later chapters.
- Asset value is closely tied to condition as well as use.
- Cost for both owners and users of the infrastructure. Owner costs include maintenance, operations and rehabilitation. User costs include waiting or delay times.
- Customer service related to communications and response to requests.
- Safety measured by the numbers and extent of injuries or risks.
- Reliability measured by the availability of infrastructure services both in normal service and in extreme events such as hurricanes.
- Sustainability related to overall economic impact of the infrastructure, environmental emissions and resource consumption, and social impacts.

Fortunately, infrastructure managers can generally use organizational or well-established metrics of performance for asset management. Obtaining user costs can be more difficult, and may require special data collection efforts or surveys. For example, traveler delays on roadways may be assessed by measuring the speed of vehicles travelling over the network.

In later chapters, we will discuss the individual processes and approaches to condition assessment and infrastructure performance.

2.5 Exercises

P2.1 (**5 pts**) Suppose we decided to implement an asset management process for information technology in small (100 person) office. What steps would be needed to do so?

P2.2 **(10 pts)** Describe why asset management is such an important process for state and local authorities that are in charge of infrastructure. Be sure to consider economic and social impacts. Include references as needed.

P2.3 **(10 pts)** Appearing below is Note 9 from the Carnegie Mellon University Annual Report for 2013.

a. Why would Carnegie Mellon go to the trouble of estimating the value of land, buildings and equipment?

b. What is accumulated depreciation? What fraction of the value of buildings, moveable equipment, utilities and leasehold improvements has been depreciated? Why isn't land in the same category as these other assets?

c. Carnegie Mellon hasn't sold a building in a very long time. How might these values be estimated?

9. Land, Buildings and Equipment

Land, buildings and equipment at June 30 consist of the following (in thousands of dollars):

	2013	2012
Buildings	$ 970,789	$ 944,057
Moveable equipment	253,248	248,340
Utilities and building-related assets	57,750	56,585
Land improvements	12,664	12,664
Leasehold improvements	14,457	13,847
Subtotal	1,308,908	1,275,493
Accumulated depreciation	(683,696)	(654,917)
Subtotal	625,212	620,576
Land	45,682	45,411
Construction in progress	28,744	24,511
Land, buildings and equipment, net	$ 699,638	$ 690,498

Included in the cost of buildings is $40.9 million for the Collaborative Innovation Center (CIC) and its tenant improvements for the years ended June 30, 2013 and 2012. The CIC building was constructed on land owned by Carnegie Mellon. This land is subject to a ground lease agreement between Carnegie Mellon and the Regional Industrial Development Corporation (RIDC). The ground lease term concludes on March 20, 2038, but is subject to an additional four year renewal period exercisable at the RIDC's option.

Included in moveable equipment is unamortized computer software cost of $9.9 million and $8.1 million for the years ended June 30, 2013 and 2012, respectively. Amortization expense of $3.1 million and $2.6 million was charged to expense for the years ended June 30, 2013 and 2012, respectively.

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Chapter 3: Inventory, Inspection and Condition Assessment

3.1 Introduction

As discussed in Chapter 2 Asset Management, asset component inventory and condition assessment are important steps in any infrastructure management process. They provide essential information for maintenance and rehabilitation decision making.

For immobile and long lasting physical assets with explicit geophysical locations, inventory can be relatively simple. Data records for asset location, size, age and other pertinent information can be created. As new assets are added or retired, the data records need to be updated, either as transactions occur or on a periodic basis. Computerized asset facilities management (CAFM) systems and computerized maintenance management systems (CMMS) systems with or without mapping capability are often useful for these inventories.

For linear and network physical assets (e.g., pipelines, electrical distribution systems, etc.) inventory is increasing complex. Like fixed location systems, data records can be created and updated; however, accurate inventories for the systems are specifically dependent on management systems with geospatial capabilities (e.g., geographic information systems (GIS)) that include a mapping capability so that these assets can be displayed on a two, or even three dimensional map.

Mobile assets may be more difficult to inventory since their locations might not be known at any given time. However, records of acquiring and retiring mobile assets provide a means of keeping an inventory listing. Manual inspection or bar code readers provide a means of identifying the locations of the various assets. Figure 3.1 illustrates a typical mobile asset in the form of a postal truck used for carrying mail and parcels. Replacement parts for infrastructure such as elevators represent another class of potentially mobile assets that might be inventoried by an infrastructure manager.

Figure 3.1 - Postal Services have fixed and mobile asset inventories

Source: Public Domain,
https://commons.wikimedia.org/wiki/File:United_States_Postal_Service_Truck.jpg

3.2 Manual Inspection and Condition Assessment of Infrastructure

Manual inspection and condition assessment of infrastructure components is a common practice. These inspections require a knowledgeable individual and can include visual inspection, hearing (for motor sounds for example) and touch.

Good manual inspections have a defined rubric and a focus on completeness and consistency of condition assessment. A rubric is a guide for condition assessment based upon a set of rules or text descriptions. A wide variety of rubrics for infrastructure components exists. Figure 3.2 summarizes a rubric for pavement condition assessment as an example. In addition to this pavement condition assessment, other consideration for conditions might be skid resistance and structural capacity. Chapter 2, presents the results of a series of roof inspections with indices for roof components and an overall condition assessment.

Pavement Serviceability Index Guidelines

- 4.0 – 5.0: Only new (or nearly new) superior pavements are likely to be smooth enough and distress free (sufficiently free of cracks and patches) to qualify for this category. Most pavements constructed or resurfaced during the data year would normally be rated in this category.
- 3.0 – 4.0: Pavements in this category, although not quite as smooth as those described above, give a first class ride and exhibit few, if any, visible signs of surface deterioration. Flexible pavements may be beginning to show evidence of rutting and fine random cracks. Rigid pavements may be beginning to show evidence of slight surface deterioration, such as minor cracks and spalling.
- 2.0 – 3.0: The riding qualities of pavements in this category are noticeably inferior to those of new pavements, and may be barely tolerable for high-speed traffic. Surface defects of flexible pavements may include rutting, map cracking, and extensive patching. Rigid pavements in this group may have a few joint failures, faulting and/or cracking, and some pumping.
- 1.0 – 2.0: Pavements in this category have deteriorated to such an extent that they affect the speed of free-flow traffic. Flexible pavement may have large potholes and deep cracks. Distress includes raveling, cracking, rutting and occurs over 50 percent of the surface. Rigid pavement distress includes joint spalling, patching, cracking, scaling, and may include pumping and faulting.
- 0.1 – 1.0: Pavements in this category are in an extremely deteriorated condition. The facility is passable only at reduced speeds, and with considerable ride discomfort. Large potholes and deep cracks exist. Distress occurs over 75 percent or more of the surface.

Figure 3.2 - Pavement Serviceability Index Rubric

Source: FHWA, 'Present Serviceability Rating', Public Domain, http://safety.fhwa.dot.gov/tools/data_tools/mirereport/29.cfm.

Manual inspectors usually compare and discuss their results as a means of inculcating consistency and accuracy in condition assessments. For some types of inspections, formal classes and certifications may be required, such as the certification required for roadway bridge inspections.

Numerical indexes for condition assessment are also common, as with the .1 to 5.0 scale shown in Figure 3.2. Integer indexes are the most common for manual inspections. However, there is no consistency in the range of defined ratings among different infrastructure systems: inspectors may employ 0 to 3, 1 to 5, 1 to 10 and others. The best ratings also differ, with some systems having higher numbers for better conditions (as in Figure 3.2) and some indexes having lower numbers for better conditions.

Through the application of various manual rating systems condition indices, the following general guidelines emerge with respect to condition indices: it is difficult to differentiate between more than 7 condition states; a condition state of zero (0) may cause difficulties in derivative calculations; rating systems that equate a higher value with a better condition tend to graph more intuitively. Regardless, users of condition indexes should always check the index definitions to avoid misinterpretation of conditions!

Numerical condition indexes are often used in deterioration models as discussed in Chapter 3. They are also useful for developing comparisons and metrics of overall infrastructure conditions. For example, Figure 3.3 shows a map of pavement conditions in a region of central Massachusetts.

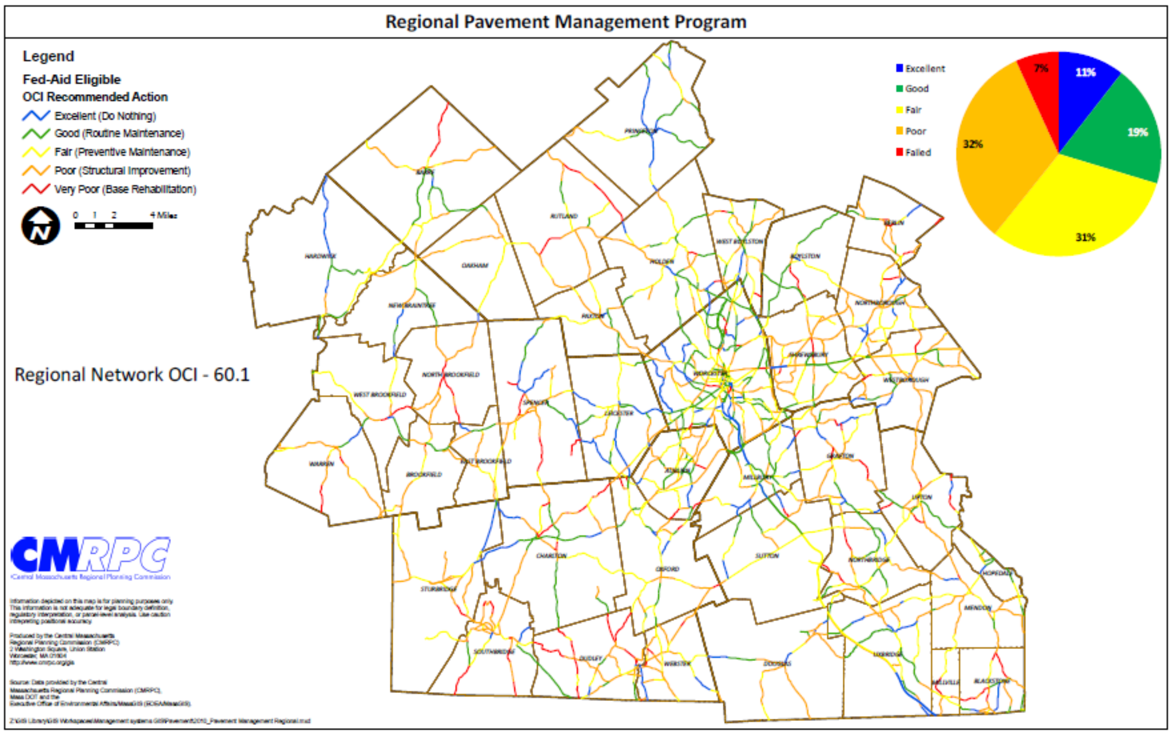

Figure 3.3 - Example Display of Pavement Conditions

Source: Central Massachusetts Regional Planning Commission, Public Domain, 'Pavement Management,' http://www.cmrpc.org/transportation-data-and-maps.

While condition assessments are usually numerical, they may also take the form of a condition grade, such as the scale A – excellent; B – very good; C – good; D – passable and F – failing.

Infrastructure 'grades' are also regularly prepared, but they generally involve a broader range of considerations than a simple condition assessment. These grades might include functional compliance with particular goals, adequacy of capacity relative to demand, infrastructure resilience and other considerations as well as the infrastructure condition. As an example, the criteria used in assigning infrastructure grades by the

American Society of Civil Engineers (2016) includes condition rating but a variety of other criteria:

- Capacity – Evaluate the infrastructure's capacity to meet current and future demands.
- Condition – Evaluate the infrastructure's existing or near future physical condition.
- Funding – Evaluate the current level of funding (from all levels of government) for the infrastructure category and compare it to the estimated funding need.
- Future Need – Evaluate the cost to improve the infrastructure and determine if future funding prospects will be able to meet the need.
- Operation and Maintenance – Evaluate the owners' ability to operate and maintain the infrastructure properly and determine that the infrastructure is in compliance with government regulations.
- Public Safety – Evaluate to what extent the public's safety is jeopardized by the condition of the infrastructure and what the consequences of failure may be.
- Resilience – Evaluate the infrastructure system's capability to prevent or protect against significant multihazard threats and incidents and the ability to expeditiously recover and reconstitute critical services with minimum damage to public safety and health, the economy, and national security.
- Innovation – Evaluate the implementation and strategic use of innovative techniques and delivery methods.

3.3 Devices to Aid Manual Inspection

The previous section outlined procedures for conducting manual inspections of infrastructure components. There are a variety of devices that can be used to aid such manual inspections.

Rulers and gauges are often useful for measuring lengths and depths of components or cracks. Mobile (battery) powered drills, wrenches and wire brushes also can be useful.

Devices to aid visual inspection in difficult or impossible to reach vantage points can be particularly useful. Hand held mirrors and lamps are a simple example of such an aid, but devices that are more elaborate exist. Figure 3.4 shows a video camera that suited for use in small pipe that can provide pictures of the interiors so that corrosion or root intrusions may be identified. More elaborate pipeline 'pigs' can be stabilized in a desired location within the pipe and can have self-locomotion.

Figure 3.4 - A Video 'Pig' for Pipe Inspection

Source: Wikipedia Commons, By The original uploader was Leonard G. at English Wikipedia - Transferred from en.wikipedia to Commons by IngerAlHaosului using CommonsHelper., CC SA 1.0, https://commons.wikimedia.org/w/index.php?curid=9015505. The Pig is pulled through the pipe of interest.

Unmanned flying vehicles (commonly called 'drones') provide another means of aiding manual inspections (Figure 3.5). These devices can simplify inspection of a variety of infrastructure components such as bridges or power lines. Drones are regulated for safety reasons and inspectors using such devices must determine the acceptable use of drones in any particular location. In addition to unmanned flying devices, underwater aids for visual inspection are also available, but visibility for such devices may be an issue.

Figure 3.5 - An Unmanned Aerial Vehicle or 'Drone' used for Visual Inspection of Power Lines

3.4 Sensors for Inspection Condition Assessment

A variety of tests can also be used to assist or to replace manual inspection. For example, infrared images may be obtained to aid roof inspection, with areas of high heat flux indicating insulation issues. Water samples can be tested for a variety of trace elements. These test results can be considered in arriving at a particular condition assessment rating.

An example of automated, sensor based condition assessment is the widely used International Roughness Index (IRI) for pavements. This index is based upon the vertical variation on a pavement surface over a particular length of pavement. More vertical variation represents rougher and worse condition pavement. The International Roughness Index is calculated from laser depth measurements and reported in units of length (of vertical variation) divided by length of measurement, such as millimeters per meter. Figure 3.6 shows typical International Roughness Index values for different types of pavements and for different pavement distress types. Also shown on Figure 3.6 is a typical use speed for pavements of different conditions.

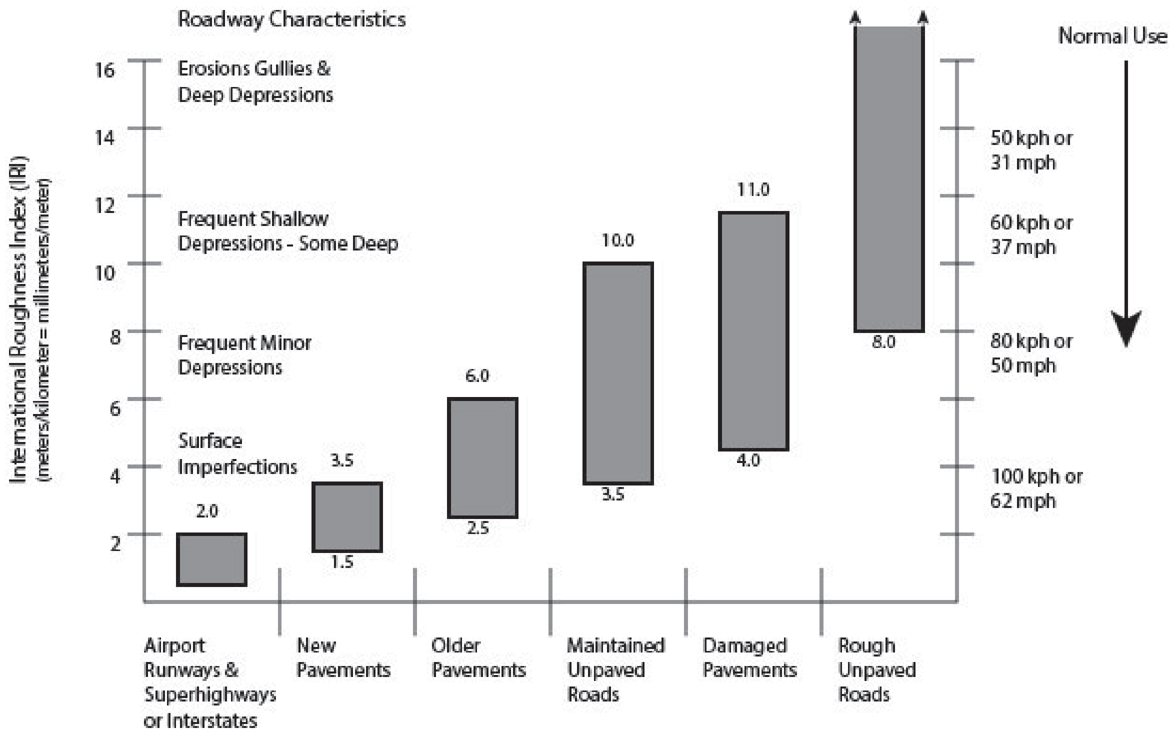

Figure 3.6 - International Roughness Index

Source: Sayers, 1986. Redrawn and altered by Authors.

For an automated index such as the International Roughness Index, a manager would like to know how the index might compare to manual inspections and how the index might correlate to user costs (or in this case, traveler comfort). Fortunately, for the International Roughness Index there is good correlation with both manual inspections and reported ride quality as long as roughness measurements are made for the full width of the pavement surface.

Other automated approaches for pavement condition assessment are also possible.   In particular, video images of pavement surfaces can be analyzed by software for a direct condition assessment. These methods make use of less expensive sensors in the form of video cameras and rely on pattern recognition approaches for pavement distress. In many cases, a combination of different approaches can be employed, with manual inspection often used for maintenance alternatives assessment.

A variety of other non-destructive sensors can be used for infrastructure component inspection. Visual inspection is described above, but others can include: Liquid

Penetrant, Magnetic, Ultrasonic, Eddy Current and X-ray sensors. Figure 3.7 illustrates the use of ultrasonic sensors for identifying potential structural flaws hidden within a component such as a steel building beam or rail.

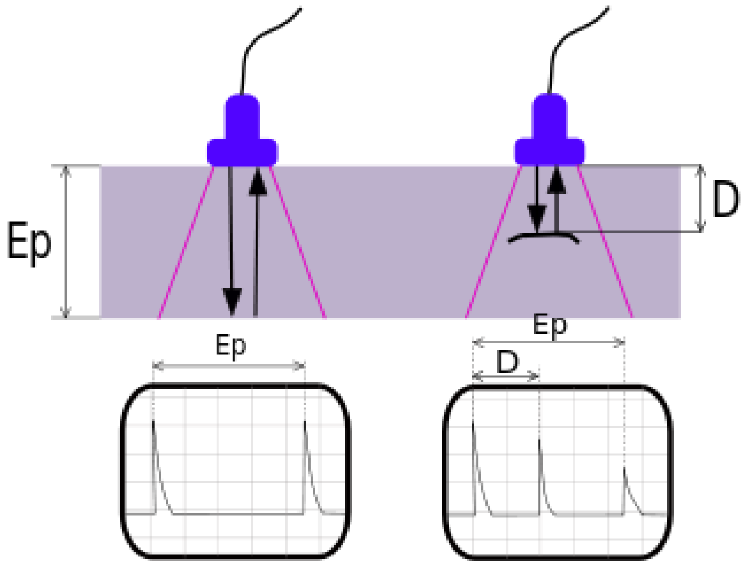

Figure 3.7 - Ultrasonic Structure Inspection

Source: Wikipedia Commons, 'Principle of Ultrasonic Testing,' By No machine-readable author provided. Romary assumed (based on copyright claims). [GFDL (http://www.gnu.org/copyleft/fdl.html), CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/) or CC BY 2.5 (http://creativecommons.org/licenses/by/2.5)], https://upload.wikimedia.org/wikipedia/commons/thumb/a/ae/UT_principe.svg/330px-UT_principe.svg.png). An Early Echo identifies a possible flaw such as a crack inside the structure.

We will close with a few examples of devices and sensors used for different types of infrastructure inspections.

- Power plant equipment and facilities can be visually inspected, but hard to reach elements and corrosion identification require special sensors. Eddy current probes, crawling robots and flying drones may all help inspectors.
- Periodic wire rope inspection for aerial lifts and transmission lines is always recommended (and often required by regulation). While visual inspection is the traditional method of inspection, drones, measuring devices and sensors for internal flaws can all be used.
- Storage tank inspection is routinely performed. Above ground tanks can be observed manually, with crawlers or with drones. Below ground tanks can be inspected from the inside (as with pipes), but exterior inspection below ground is difficult.
- Rail inspection can be performed manually, but specialized sensors are usually employed to assess geometry or hidden defects. Dedicated vehicles

are commonly used, but there is already equipment available that can monitor rail condition from regularly running trains.

- Natural gas leaks have specialized sensors that may be handheld or designed for vehicles. Since natural gas (or methanol) is a potent greenhouse gas, new emphasis on inspection for leak identification and repair is becoming more prevalent and important.

3.5 Exercises

P3.1 **(5 pts)** What is best way to measure flow on a river every hour?

P3.2 **(5 pts)** What is best way to estimate stormwater run-off from:

a. A building?
b. A neighborhood?
c. A city?

P3.3 **(15 pts)** Descriptions and color photos are attached at the end of this exercise section for seven types of asphalt pavement distress. Your assignment is to walk around the local area and identify as many of the seven types of pavement surface distress as you can. List a specific location for each type you find, describe the distress, including an estimate of the size of the distressed area, and either take a photograph or produce a sketch of the distress. You may do this problem with one or more colleagues.

Important Note: Watch out for traffic! Work during daylight hours and do not expose yourself to traffic. Parking lots and sidewalks can be used for this exercise!

3.6 Pavement Distress Examples

Alligator Cracking

Alligator cracking is a series of interconnecting cracks caused by fatigue of the asphalt concrete surface under repeated traffic loading.

Alligator cracking is considered a major structural distress and is often accompanied by rutting

Figure 3.8 - Alligator Cracking in Asphalt Pavements

Source: FHWA, 'Selection Of Pavement For Recycling And Recycling Strategies', Public Domain, https://www.fhwa.dot.gov/pavement/recycling/98042/03.cfm.

Block Cracking

Blocks are interconnected cracks that divide the pavement into rectangular pieces. Block cracking usually indicates that the asphalt has hardened significantly.

Figure 3.9 - Block Cracking in Asphalt Pavements

Source: FHWA, 'Selection Of Pavement For Recycling And Recycling Strategies', Public Domain, https://www.fhwa.dot.gov/pavement/recycling/98042/03.cfm.

Distortions

Distortions are usually caused by corrugations, bumps, sags, and shoving.

They are localized abrupt upward or downward displacements in the pavement surface, series of closely spaced ridges and valleys, or localized longitudinal displacements of the pavement surface.

Corrugation

Shoving

Figure 3.10 - Distortions in Asphalt Pavements

Source: FHWA, 'Selection Of Pavement For Recycling And Recycling Strategies', Public Domain, https://www.fhwa.dot.gov/pavement/recycling/98042/03.cfm.

Longitudinal and Transverse Cracking

Longitudinal

Transverse

Longitudinal cracks are parallel to the pavement's centerline or lay down direction while transverse cracks are perpendicular.

Longitudinal cracks may be caused from poorly constructed paving lane join, shrinkage of the asphalt concrete surface due to low temperature, or a reflective crack caused by joints and cracks beneath the surface course.

Figure 3.11 - Longitudinal and Transverse Cracking in Asphalt Pavements

Source: FHWA, 'Selection Of Pavement For Recycling And Recycling Strategies', Public Domain, https://www.fhwa.dot.gov/pavement/recycling/98042/03.cfm.

Patching and Utility Cut Patching

A patch is an area of pavement, which has been replaced with new material to repair the existing pavement.

A patch is considered a defect no matter how well it is performing.

Figure 3.12 - Patching in Asphalt Pavements

Source: FHWA, 'Selection Of Pavement For Recycling And Recycling Strategies', Public Domain, https://www.fhwa.dot.gov/pavement/recycling/98042/03.cfm.

Rutting and Depressions

A rut is a depression in the wheel paths.

Rutting stems from a permanent deformation in any of the pavement layers or sub grade, usually caused by consolidated or lateral movement of the materials due to traffic loads.

Figure 3.13 - Rutting and Depressions in Asphalt Pavements

Source: FHWA, 'Selection Of Pavement For Recycling And Recycling Strategies', Public Domain, https://www.fhwa.dot.gov/pavement/recycling/98042/03.cfm.

Weathering and Raveling

Weathering and raveling are the wearing away of the pavement surface.

This distress indicates that either the asphalt binder has hardened appreciably or that a poor quality mixture is present.

Figure 3.14 - Weathering and Raveling in Asphalt Pavements

Source: FHWA, 'Selection Of Pavement For Recycling And Recycling Strategies', Public Domain, https://www.fhwa.dot.gov/pavement/recycling/98042/03.cfm.

3.7 References

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Sayers, M.W., Gillespie, T. D., and Paterson, W.D. Guidelines for the Conduct and Calibration of Road Roughness Measurements, World Bank Technical Paper No. 46, The World Bank, Washington DC, 1986

Chapter 4: Deterioration Modeling

4.1 Introduction

As soon as infrastructure is newly built or rehabilitated, it begins to deteriorate. The decline in overall infrastructure condition may be slow, but it is inevitable. The decline may be mitigated by preventive maintenance or even reversed by major rehabilitation actions such as repaving, but deterioration will again proceed without continuing interventions that are likely to be expensive.

The common 'Deterioration Hypothesis' posits that infrastructure will deteriorate over time due to use and other factors. The strict form of the 'Deterioration Hypothesis' assumes that conditions cannot improve over time unless there is an intervention by infrastructure managers and workers. Typical factors causing deterioration are weathering, corrosion, use-related stress, and general wear-and-tear. Figure 4.1 illustrates the deterioration hypothesis with slow condition degradation for a period of time, then a more rapid deterioration as the infrastructure ages and its condition degrades. As shown in the figure, interventions for asset preservation can improve the asset condition rating, but the deterioration then resumes.

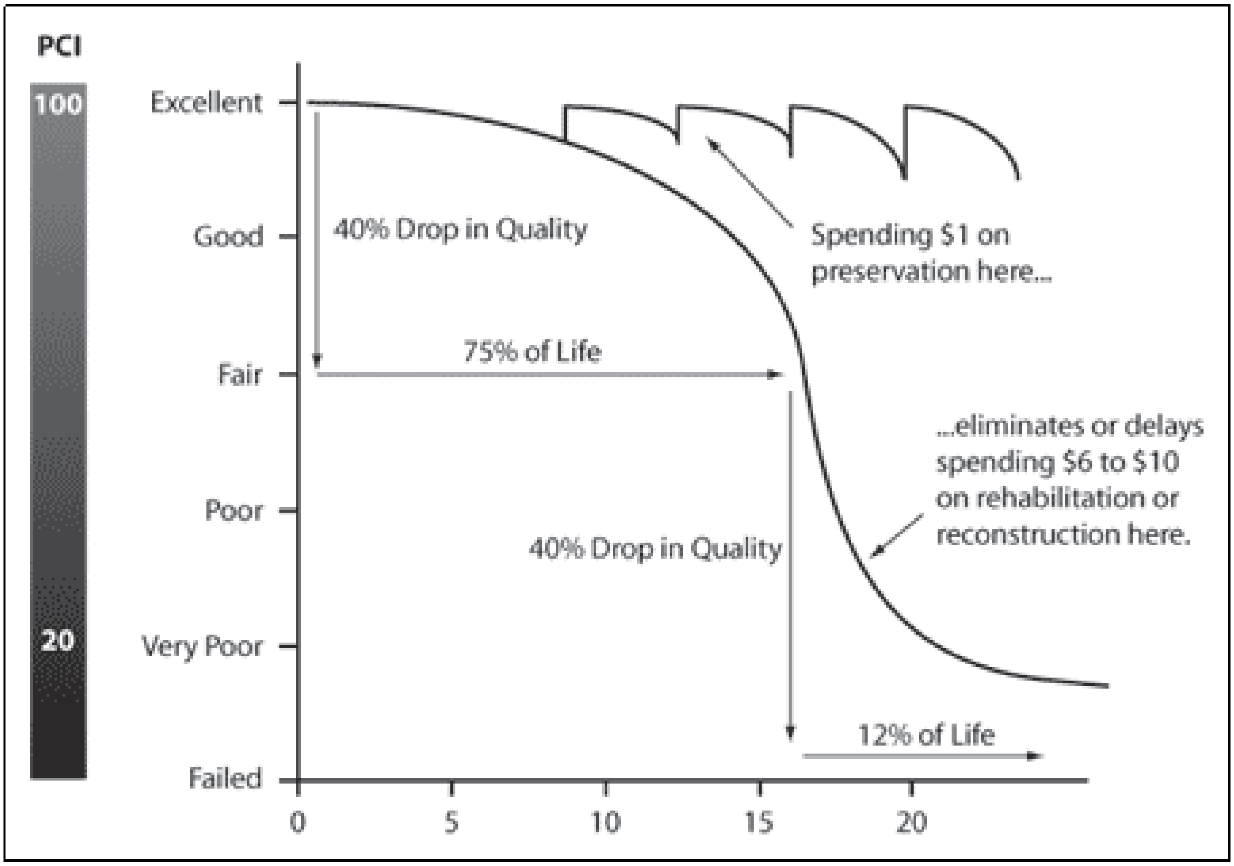


Figure 4.1 - Illustration of the Deterioration Hypothesis

Source: Federal Highway Administration, Publoc Domain, 'Asset Sustainability Index, http://www.fhwa.dot.gov/planning/processes/statewide/practices/asset_sustainability_index/page01.cfm. A decline in condition over time without preservation efforts.

While the deterioration hypothesis is used for infrastructure components, it is also relevant and used for a variety of other devices. For example, paper may deteriorate due to insects, mold, fire, water damage, chemical reactions caused by light, wear-and-tear in use and other factors. Mechanical equipment is similar expected to deteriorate over time. For example, Figure 4.2 shows a worn car. In many cases, worn equipment must be replaced by regulatory requirements or owner decisions.

Figure 4.2 - Example of Vehicle Deterioration Over Time and Use

Source: By FlyByFire (Own work) [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File:Beater_Nissan.jpg

The choice of materials and quality of construction can slow the process of infrastructure deterioration. Similarly, favorable weather conditions can make even inevitable deterioration quite slow. For example, water penetration with freeze-thaw cycles in colder climates can result in more rapid occurrence of pavement cracking. Figure 4.3 shows the probability of acceptable quality (shown as 'survival probability') for bridge decks without rehabilitation work with different material, traffic and environmental conditions. As can be seen, the spread of survival probabilities over the different conditions is quite large.

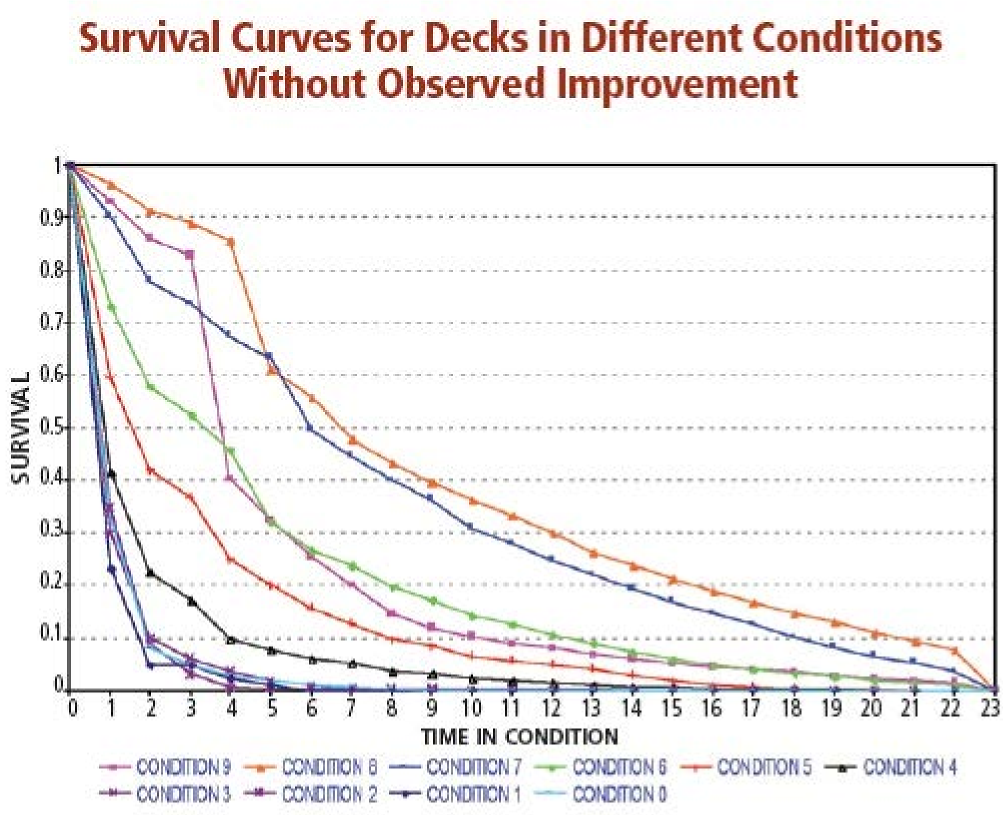


Figure 4.3 - Probability of Survival (Acceptable Condition) for Bridge Decks

Source: FHWA, 'History Lessons from the National Bridge Inventory, Public Domain, http://www.fhwa.dot.gov/publications/publicroads/08may/05.cfm. Illustrates different conditions of materials, traffic and weather.

As the condition of infrastructure declines, infrastructure managers must consider what steps (if any) should be taken to reverse the deterioration. Some decisions are relatively simple, such as intervening on structures in danger of collapse. More commonly, infrastructure managers make such decisions as part of the asset management process described earlier.

An important input into such decision making is the expectation of deterioration in the future if nothing is done to reverse the existing damage. Deterioration modeling is a process of taking condition assessment information (as described in Chapter 3) and forecasting expected future conditions.

Numerous approaches to deterioration modelling exist. In this chapter, we will briefly discuss the following approaches:

1. No deterioration modeling. Use existing condition for decision making.
2. Extrapolation/Moving Average of conditions over time.
3. Regression Models based on statistical analysis.

4. Markov Models of probabilistic deterioration.
5. Semi-Markov Models of probabilistic deterioration
6. Neural Networks using an artificial intelligence approach based on a learning set of deterioration examples.
7. Failure Distributions and Fault Tree Analysis to assess probability of failure.

In this discussion, our intent is to provide sufficient background for infrastructure managers to understand the different approaches, including their advantages and disadvantages. Where appropriate, references are provided for those wishing to delve more completely or deeper into particular approaches.

Finally, all of the deterioration modelling approaches noted above depend upon empirical data on component deterioration. Keeping such records is a critical asset management task!

4.2 Simple Decision Making and Forecasting from Condition Assessment

In many cases, asset management decisions are made without complicated deterioration models at all. The simplest approaches simply use the existing component condition, a linear projection of the component condition over time, or a projection based upon the past history of similar components (using a graph such as those illustrated in Figure 4.3). These approaches are discussed in this section.

Using the existing condition can be augmented with simple decision rules. For example, 'if condition is x or lower, then rehabilitation is desirable.' Components with only two condition states defined are particularly amenable to this approach. For example, an incandescent light either works or is burnt out. The maintenance rule might be to only replace lights when they burn out.

A subset of this simplified method incudes a "run to failure" approach. Unfortunately, this "fix it when it breaks approach" is a widely applied and expensive approach to infrastructure management. There are scenarios, like window air conditioners, when it simply doesn't make sense to replace before failure. As we will explore, it is nearly always more cost effective to replace before failure when considering major infrastructure systems.

Using existing conditions has the advantage of eliminating any costs associated with deterioration modelling. However, the amount of effort may fluctuate considerably as many components cross over the trigger condition for action and this may not be compatible with budget constraints. Also, if deterioration has significant costs, waiting until deterioration occurs may not be the best approach.

Simple linear extrapolation is another approach that is inexpensive to employ for deterioration models. In this approach, c where c_t is the condition at time t, and Δt is some desired time period in the future.

$$c_{t+\Delta t} = c_t + (c_t - c_{t-1}) * \Delta_t \qquad \text{Eq. 4.1}$$

As an example, suppose the component condition is now 3, last year the condition was 4, then the forecast for next year is 3 + (3-4)*1 = 3 – 1 = 2 and the forecast for the following year (two years from now) would be 3 + (3-4)*2 = 1. More complicated forms of extrapolation could also be used, but linear extrapolation is the most common for infrastructure deterioration.

A single year may be two short a period to effectively capture deterioration, so a moving average of multiple years might be used instead. In this case, c_t would be the average condition for the current period of years (which might be the past three years). This approach would be useful for very slowly deteriorating infrastructure components. Moving averages of this type are common for smoothing fluctuating time series histories such as stock prices.

Finally, forecasts of component deterioration might be based upon simple historical records. For example, Figure 4.3 shows the average deterioration trajectory of different bridge decks under specific conditions. An infrastructure manager might assume that a particular bridge deck with a particular condition would simply follow this trajectory in the future. Even without a formal database, infrastructure managers might have their mental model of expected deterioration and make subjective forecasts based upon their experience.

4.3 Regression Models

A more complicated approach to deterioration modelling than those in the previous section employs statistical approaches, most commonly regression analysis. These models are based upon observations of past history and conditions. The models can indicate the correlation between conditions and explanatory factors such as time and usage.

Statistical modelling is a topic of considerable interest and for which a large body of knowledge exists. In this section, we provide only the basic information that is useful for an infrastructure manager, not a researcher or expert modeler. Other works can be consulted, such as the variety of books recommended by the University of California, Berkeley, Statistics Department:

http://sgsa.berkeley.edu/current-students/recommended-books

There are also a variety of software programs that can be used for statistical modelling, including add-ins to spreadsheets such as Microsoft Excel, general modelling environments such as MATLAB, or programs focused on statistical modelling such as R, S, Minitab or Statistical Package for the Social Sciences (SPSS). Any of these software programs can be used for infrastructure deterioration modelling since the data usually available for deterioration modelling are well within the capabilities of any of these software programs. Also, these programs typically provide help files and tutorials that can be consulted.

For deterioration models, the dependent variable is typically condition expressed as a numerical index. Explanatory variables may be time (such as age in years since last rehabilitation), usage, weather zone and others. Different deterioration models may be estimated for different component designs, such as pavement characteristics, or these characteristics may be added. For example, a simple linear condition model might be:

$$c = \alpha + \beta * (age) + \epsilon \qquad \text{Eq. 4.2}$$

where c is a condition index (such as a scale of 1 to 10), α and β are coefficients to be estimated and ε is a model error term. A series of observations of c and age would be assembled as input data for estimation. Then, a software routine could be employed to estimate appropriate values of the coefficients α and β for the estimated model. In these routines, the coefficients α and β are calculated to minimize the sum of squared deviations between condition and the model forecast (represented by the ε values).

Equation 4.2 shows a linear deterioration model, meaning that the explanatory variable age is linearly related to the dependent variable condition index. Additional explanatory variables could be added to the model, each with a coefficient to be estimated. Also, non-linear model forms can be used, such as a quadratic model where age enters as both a linear and a squared explanatory variable:

$$c = \alpha + \beta_1 * (age) + \beta_2 * (age)^2 + \epsilon \qquad \text{Eq. 4.3}$$

Another common model form is an exponential model form:

$$c = \alpha * (age)^{\beta} \qquad \text{Eq. 4.4}$$

This exponential model is often linearized for estimation purposes by taking the logarithm of both sides of the equation to form a linear model with respect to the coefficients to be estimated:

$$\ln(c) = \alpha' + \beta * (age) + \epsilon \qquad \text{Eq. 4.5}$$

Where α' is the logarithm (ln function) of α in Equation 4.3. In this linear form, the input data for estimation would be ln(c) and age.

Which model form should be chosen for use in any particular case? Generally speaking, simply forms are preferable to more complicated forms. Also, model forms that correspond to reasonable deterioration causes are preferable. For example, desirable pavement deterioration model forms would include both deterioration over time and for different levels of vehicle usage.

As an example, Morous (2011) estimated a polynomial model of bridge deck deterioration in Nebraska based simply on bridge deck age. The estimated model was:

$$y = 10 - 0.25 * x + 0.0093 * x^2 - 0.0001 * x^3 \quad \text{Eq. 4.6}$$

where y is condition rating (c in Eq. 4.1-4.4) and x is age (or age in Eq. 4.1-4.4). As can be seen in Fig. 4.4, the polynomial model is close to the historical data on bridge deterioration. Morous (2011) also reports the R^2 value of the estimated regression equation (equal to .99 in Figure 4.4) which is a measure of 'goodness of fit' of the model to the data. In this case, 99% of the variation in the dependent variable is captured by the regression model.

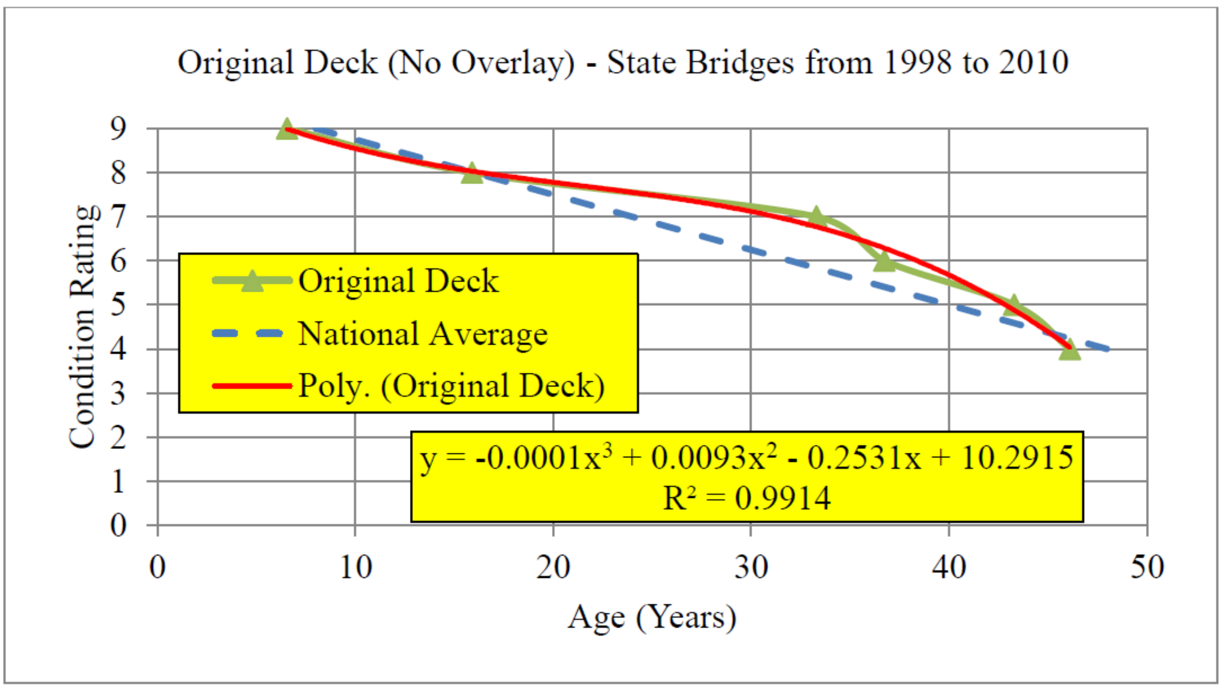


Figure 4.4 - Deterioration History and Model of Original Bridge Decks in Nebraska

Source: Morous, 2011, UNL Digital Commons. http://digitalcommons.unl.edu/. In the model, y is condition-rating index and x is age in years.

The usefulness of regression deterioration models really derives from situations in which multiple explanatory factors are of interest, such as age, pavement type and vehicle usage (generally measured in equivalent standard axle loads) for roadway pavements or bridge decks. For the model shown in Fig. 4.4, the use of historical data or the regression model has the same forecasting ability. But with more factors considered, two dimensional graphical representations such as Fig. 4.4 cannot be used directly.

Regression approaches typically make fairly heroic assumptions about the available data and appropriate model forms. In particular, the values of the error term ε in Equations 4.1 - 4.3 are generally assumed to be normally distributed with mean zero, independent of each other and with a constant variance. It is unlikely that any deterioration models fulfill these formal assumptions exactly. If nothing else, condition ratings typically are constrained to be positive, so highly negative values of ε are not allowed. Moreover, historical observations of components are unlikely to be completely independent. Fortunately, regression deterioration models are usually fairly robust, so deviation from the formal assumptions is not a practical problem to obtain reasonable coefficient estimates. However, factors such as correlated error terms make the use of formal statistical testing approaches problematic.

Regression models indicate correlations rather than causation. For example, deterioration with age (as in Figures 4.1, 4.3 and 4.4) may not be 'caused' by age itself, but by weather related effects. Weathering would be highly correlated with age for most pavement sections. However, a pavement or bridge deck section kept inside a building would likely not deteriorate over time in a manner that sections exposed to weather would deteriorate. Managers should always be cautious to ascribe causation in the case of correlations.

Forecasts from regression models are uncertain, as is the case for all deterioration models. Based on past histories and distribution assumptions, it is possible to estimate confidence intervals for forecast values. Figure 4.5 provides an example, with confidence intervals for Australian tax receipts shown, where a 90% confidence interval suggests that the forecast receipts will fall within the interval 90% of the time. The 90% confidence interval in this case for the following year is from 18 to 22.5 as a percent of Australian Gross Domestic Product (GDP). Developing formal confidence intervals would be unusual for infrastructure management, but the managers themselves should always be aware that the actual outcomes will likely differ from forecasts.

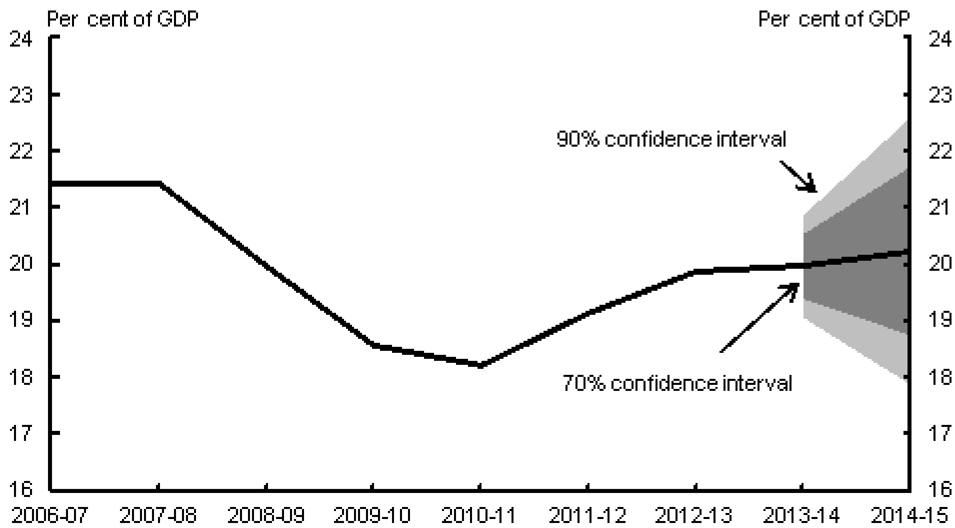


Figure 4.5 - Forecast for Australia Tax Revenues - Example of Probability Confidence Intervals

Source: By The Commonwealth of Australia. http://www.budget.gov.au/2013-14/content/myefo/html/05_attachment_b.htm. Creative Commons BY Attribution 3.0 Australia https://creativecommons.org/licenses/by/3.0/au/. Forecast is for Australia tax revenues.

4.4 Markov Deterioration Models

Markov deterioration models are used in numerous asset management software programs. Markov models can readily accommodate use of condition indexes with integer values and deterioration estimation for discrete time periods such as a year or a decade. As a result, Markov models can be combined with typical condition assessment techniques and budgeting processes.

Markov models are stochastic processes with forecast probabilities of transitions among different states (x, where x is a vector of multiple potential states) at particular times (t) or x(t). Markov models of this type are often called 'Markov chains' to emphasize the transitions among states. For infrastructure component models, the states are usually assumed to be different condition indexes. If a component is in some particular condition state (x_i) then it might stay in that condition or deteriorate in the next year. Figure 4.6 illustrates a process with just three defined condition states (1 – good, 2 – intermediate, 3 – bad condition). If the condition at the beginning of the year is state 2 (intermediate), then the Markov process shows a 0.8 probability or 80% chance of remaining in the same condition and a 0.2 probability or 20% chance of deteriorating to state 3. If the component begins in state 3 (bad or poor condition), then there is no chance of improvement (or a 100% chance of remaining in the same state). State 3 is an 'absorbing state' since there is no chance of a transition out of state 3.

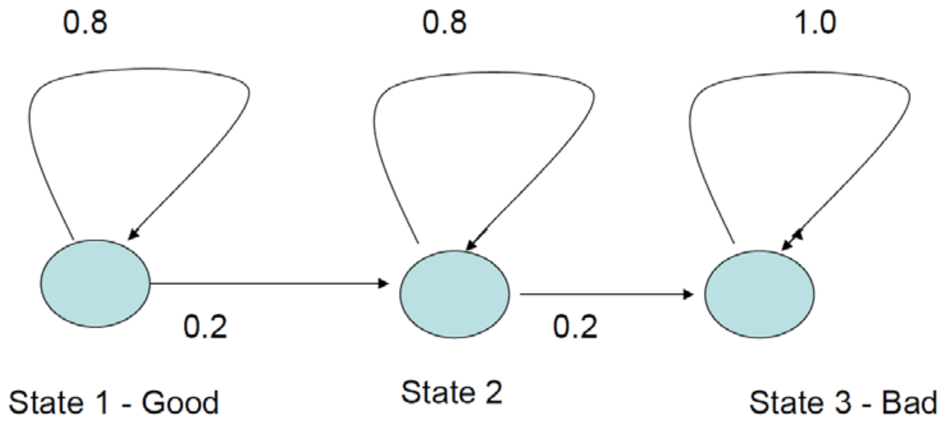


Figure 4.6 - Illustration of a Markov Process - 3 Condition States & No Intervention

Source: Authors. In each period, the condition may remain the same or deteriorate with the probabilities shown on the arrows.

The Markov process in Figure 4.6 illustrates the pure deterioration hypothesis, in that the component cannot improve condition over time. Beginning in state 1, the component could deteriorate to state 3 within two years and then remain permanently in state 3. More likely, the component would stay in state 1 or state 2 for a number of years, and the deterioration to state 3 would take multiple years. Note that the transition probabilities do not change over time, so the Markov model assumes that the time spent in any state does not increase the probability of deterioration (this is often called the 'memory-less property' of Markov models).

A Markov process may be shown in graphic form as in Figure 4.8 or as a table or matrix of transition probabilities. Formally, the state vector is x = (1, 2, 3) and the transition matrix P has three rows and three columns corresponding to the last three columns and bottom three rows in Table 4.1 (as shown in Figure 4.9). Note that the rows of the transition matrix must sum to 1.0 to properly represent probabilities.

Table 4.1 - Transition Probabilities for the Three State Process in Figure 4.8

State To: From:	**1**	**2**	**3**
1	0.8	0.2	0.0
2	0.0	0.8	0.2
3	0.0	0.0	1.0

Source: Authors

What happens if the infrastructure manager adopts the policy that components in state 3 will always be rehabilitated to state 1? In this case of intervention, there would be a transition from state 3 to state 1 with a 1.0 probability. The Forecasting conditions (or more precisely, forecasting the probability of particular states) with a Markov model involves application of linear matrix algebra. In particular, a one period forecast takes the existing state probabilities in period n, π_n, and multiplies the transition probability matrix:

$$\pi_{n+1} = \pi_n * P \qquad \text{Eq. 4.7}$$

The forecast calculation may be continued for as many periods as you like. A forecast from period n to period m would be:

$$\pi_{n+m} = \pi_n * P^{m-n} \qquad \text{Eq. 4.8}$$

Using Eq. 4.2, a forecast two periods from now would multiply π_n by P*P. Figure 4.7 illustrates the calculations for a two period forecast using the transition probabilities in Table 4.1 and assuming the initial condition is state 1 (good). While it is possible to transition from good condition to bad condition in two periods, the probability of deteriorating this quickly is only 0.04 or 4%. Most likely, the component would remain in good condition for two periods, with probability 0.64 or 64%. As a check on the calculations, note that the forecast probabilities sum to one: 0.64 + 0.32 + 0.04 = 1.0.

$$\pi_n = (1,0,0)$$

$$\pi_{n+1} = (1,0,0)\begin{vmatrix} .8 & .2 & 0 \\ 0 & .8 & .2 \\ 0 & 0 & 1 \end{vmatrix} = (0.8,0.2,0.0)$$

$$\pi_{n+2} = (0.8,0.2,0.0)\begin{vmatrix} .8 & .2 & 0 \\ 0 & .8 & .2 \\ 0 & 0 & 1 \end{vmatrix} = (0.64,0.32,0.04)$$

Figure 4.7 - A Two Period Forecast Using the Transition Probabilities of Table 4.1.

Source: Authors

The procedure shown in Figure 4.7 can be extended to find the median time until component failure. By continuing to forecast further into the future (by multiplying π by P repeatedly), the probability of entering the absorbing state 3 will increase. The median time until entering this state is identified when the probability reaches 0.5 or 50%. It is also possible to calculate the expected or mean time before component failure analytically. However, the median time is likely of more use in planning maintenance and rehabilitation activities for a large number of infrastructure components.

Numerous software programs can be used to perform the matrix algebra calculations illustrated in Figure 4.7. Two popular programs that have matrix algebra functions provided are the spreadsheet program EXCEL and the numerical analysis program MATLAB.

Where would an infrastructure manager obtain transition probability estimates such as those in Table 4.1? The most common approach is to create a historical record of conditions and year to year deterioration as described in Chapter 3: Condition Assessment or illustrated in Figure 4.3. Historical records could give the frequency of deterioration for a particular type of component and for a particular situation. Expert, subjective judgments might also be used, but these expert judgments are informed by analysis or observation of such deteriorations over time.

Finally, we have presented in this section the simplest form of Markov process modelling. We have done so because this simple form seems to be useful for infrastructure management, with many Markov process applications for components such as roadways or bridges. A variety of extensions or variations are possible:

- Rather than discrete annual steps being modelling, a Markov model may use continuous time. In this case, the transition probabilities are modelled as a negative exponential probability distribution.
- If the ‘memory less’ property of the simple Markov model seems unacceptable, you can adopt a semi-Markov assumption or even augment the state space to include both conditions and age in condition states. Unfortunately, the resulting models become more complicated and require more data for accurate estimation.

Readers wishing a broader and more mathematically rigorous presentation of Markov processes should consult a book such as Grimstead and Snell (2012) which is available for free download on the internet.

4.5 Artificial Neural Network Deterioration Models

Artificial Neural networks can serve as an alternative to regression or Markov deterioration models. They are based upon an analogy to how simple biological brains behave in transmitting signals among individual neural cells. They originated in work on artificial intelligence and machine learning.

Figure 4.8 illustrates a neural network. Inputs might be condition index values, age or weather effects. Outputs might be probabilities of transitioning to particular conditions over the course of a year. Figure 4.8 illustrates the signal processing that would be occurring within each of the artificial neurons (represented as circles in Figure 4.8). The input signals are weighted, combined and transformed into an output activation.

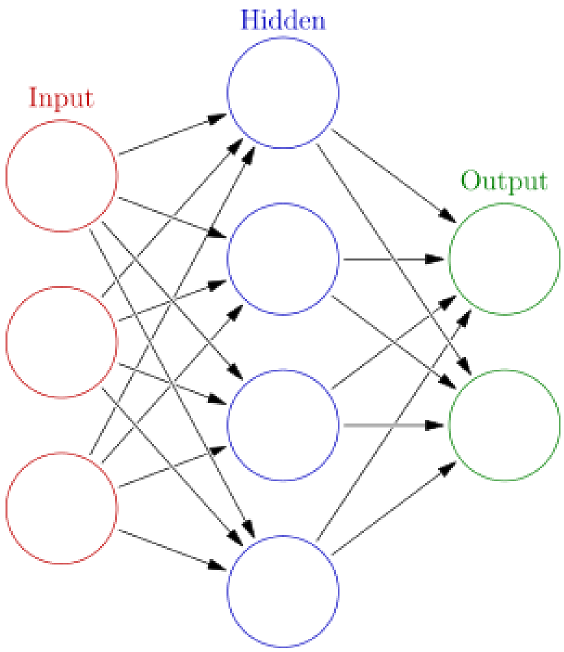


Figure 4.8 - Illustration of a Neural Network with Input, Hidden and Output Stages

Source: By Glosser.ca - Own work, Derivative of File: Artificial neural network.svg, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=24913461.

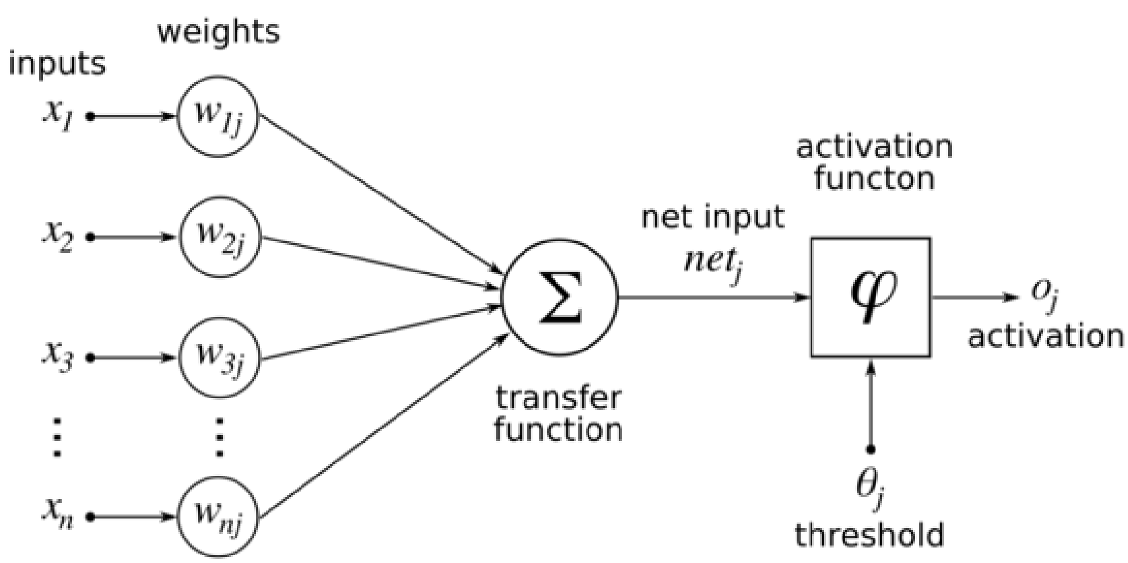


Figure 4.9 - Illustration of Artificial Neuron Processing

Source: By Chrislb - created by Chrislb, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=224555.

Artificial neural networks are typically 'trained' with a learning set. For a deterioration model, inputs might consist of conditions (and other relevant factors) in the base year and the training outputs would be the observed conditions in the following year. Training consists of altering parameters (such as the weights in Figure 4.9) to best reproduce the results observed in the training set.

Artificial neural networks are not frequently used for component deterioration modelling. One drawback to their use is the 'black box' nature of the results where the various weights and activation functions are difficult to interpret (or even obtain). Also, artificial neural networks typically have many more parameters than other types of models, requiring more data to be robust.

Infrastructure managers are more likely to encounter artificial neural networks in conjunction with sensor interpretation. For example, artificial neural networks can be used to identify vehicles or pavement distress from video inputs. Figure 4.10 illustrates a video based system for vehicle identification. A frame from the camera is divided into a two dimensional set of tiles within a pre-defined detection zone and the color and brightness of the pixels within each tile are input to an artificial neural network vehicle detector model. A training set of images with and without vehicles is used to adjust parameters in the detector model. In turn, traffic identification of this type can be used in a deterioration model for pavement condition.

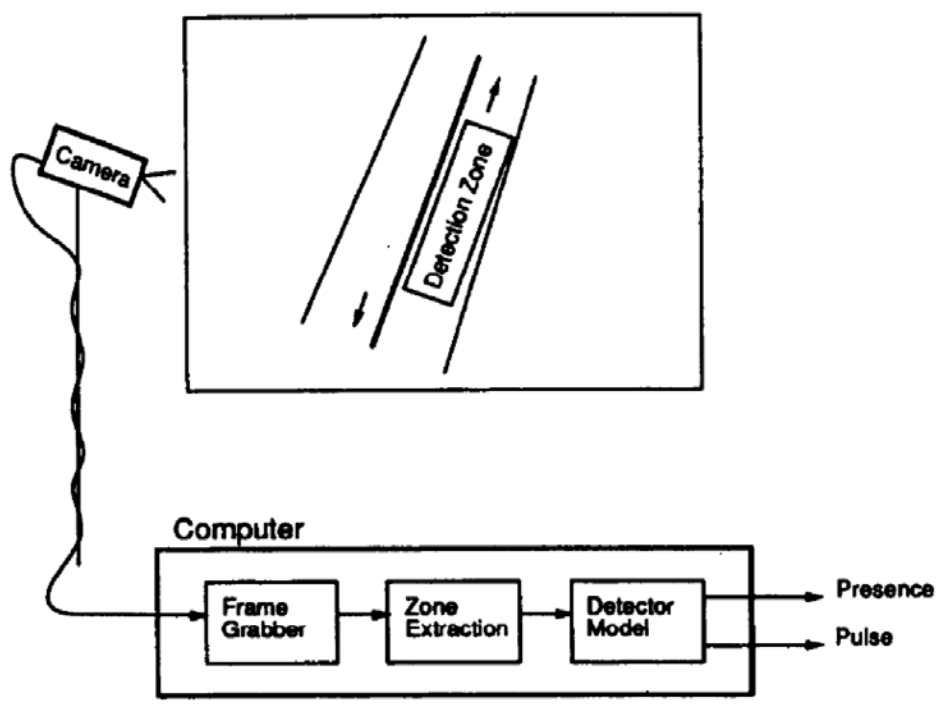


Figure 4.10 - Video Vehicle Identification System

Source: Bullock, Garrett and Hendrickson, 1995

A detection sequence for the video vehicle identification is illustrated in Figure 4.11. As the vehicle moves through the detection zone, counting output is activated for each part of the zone.

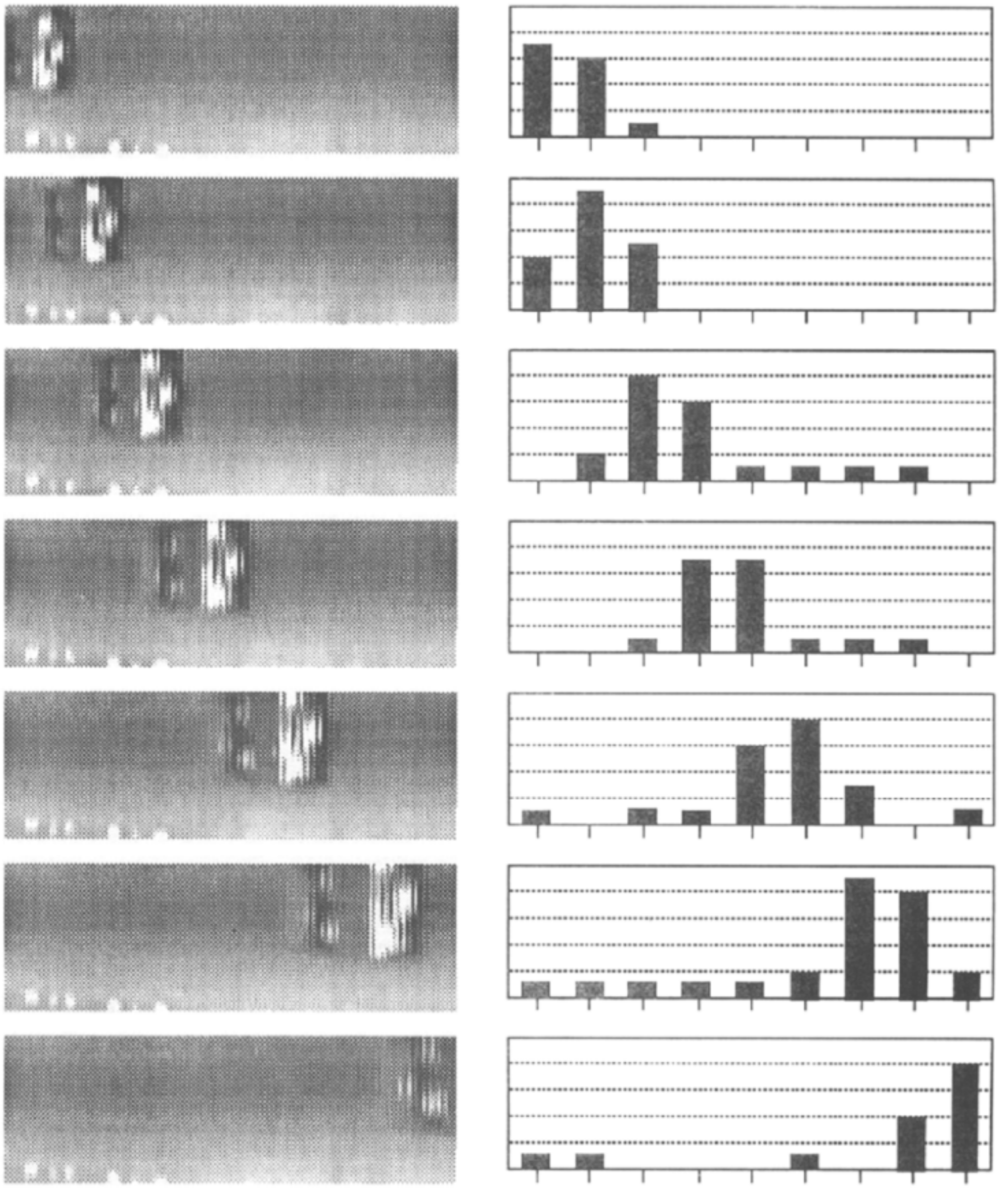


Figure 4.11 - Illustration of Output Activation for a Video Vehicle Identification System

Source: Bullock, Garrett and Hendrickson, 1995

4.6 Failure Rates and Survival Probabilities

In addition to deterioration models linked to component condition indexes, deterioration models may also be expressed as probabilities of failure (or survival as the inverse of failure) at different points of time. Of course, a difficulty in using this approach for infrastructure components is to define what constitutes 'failure.' For a mechanical device such as an elevator, failure might be simply regarded as ceasing to work. For a roadway pavement, the pavement might be considered to have failed when a desired level of service is not provided, even though the roadway may still be passable at low speed.

Failure rates are defined as the likelihood of failure in the next time interval assuming that the component has not failed up until the present time. The failure rate typically is larger than the failure density function since the component has survived for one or more periods. Since infrastructure managers are concerned with forecasting possibility of failure in the next period or two for decision making, the failure rate is generally of more interest rather than the direct probability of failure of a component at any given time in the future. We will use a numerical example to illustrate failure rates, survival probability and failure probabilities using the data shown in Table 4.2.

Table 4.2 - Numerical Illustration of Failure and Survival Probabilities and Failure Rates

Period (year)	Probability of Failure in Period f(t)	Cumulative Probability of Failure F(t)	Cumulative Probability of Survival R(t)	Failure Rate in Period λ(t)
1	0.1	0.1	0.9	0.100
2	0.02	0.12	0.88	0.022
3	0.02	0.14	0.86	0.023
4	0.02	0.16	0.84	0.023
5	0.02	0.18	0.82	0.024
6	0.02	0.20	0.80	0.024
7	0.1	0.3	0.70	0.125
8	0.2	0.5	0.50	0.286
9	0.2	0.7	0.30	0.400
10	0.3	1.0	0.00	1.000

Source: Authors.

Cumulative Probability of Failure F(t) is $F(t-1)+f(t)$. Cumulative Probability of Survival R is 1 – F(t). Failure rate $\lambda(t) is \frac{f(t)}{R(t)} or\ R(t)-\frac{R(t-1)}{R(t)}$.

Table 4.2 illustrates a component that is in good condition at the present but is expected to certainly fail after ten years of use. The probability of failure f(t) (Column 2) represents an estimate of failure in each period, with a 10% of failure immediately (during a break in period), a period of low probability of failure in years 2-6 (regular use) and then an increasing probability of failure in years 8 to 10 (wearing out). The cumulative probability of failure F(t) is the sum of failure probabilities for period t and previous periods. It begins at zero and increases steadily to 1.0 (certain failure) by year 10. Cumulative probability of survival R(t) is the inverse of the cumulative probability of failure, 1 – F(t). The failure rate λ(t) can be calculated as:

$$\lambda(t) = \frac{f(t)}{R(t)} = R(t) - \frac{R(t-1)}{R(t)} \quad \text{Eq. 4.11}$$

It has a value of 0.1 in period 1, reflecting the possibility of failure during the break in period. After this, the failure rate is relative low but increasing slowly. During the final wear our period, the failure rate increases substantially. Note that the sum of the failure rates during all periods is in excess of 1, so the failure rate is not a probability. However, for decision making, an infrastructure manager would find it helpful to know in year 5 that the risk of failure in the next period is small (0.024). However, in year 8, while the component still may be working, the risk of failure in the next period is substantial (0.400). The pattern of the failure probabilities and rates in Table 4.1 is common for infrastructure components and often called a 'bathtub shape' as illustrated in Figure 4.12 below.

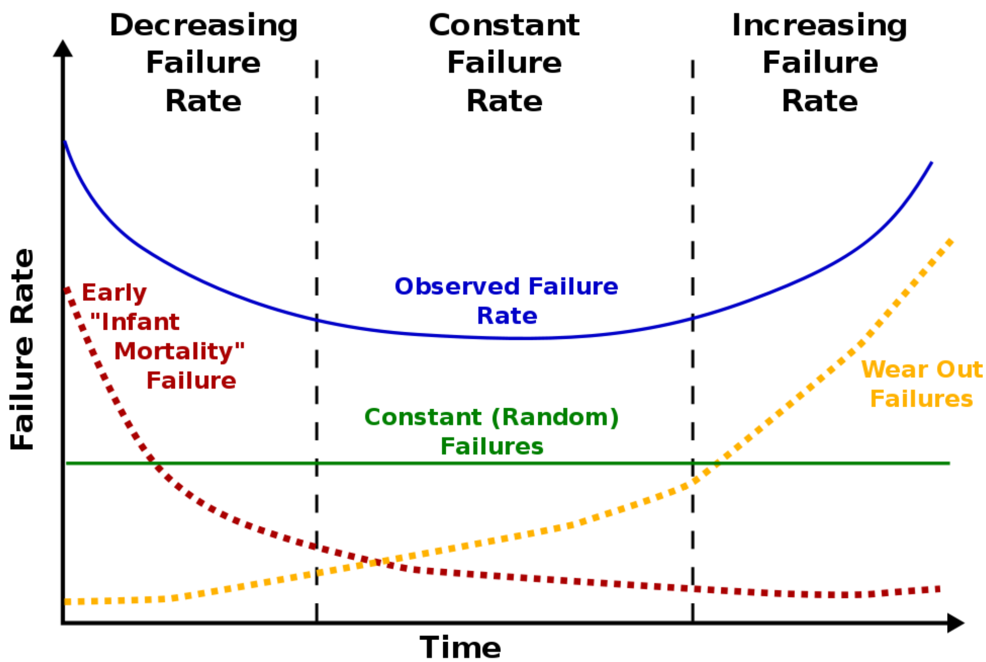


Figure 4.12 - Illustration of a Bathtub Curve

Source: By Bathtub_curve.jpg: Wyatts derivative work: McSush (Bathtub_curve.jpg) [Public domain], via Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Bathtub_curve.svg.

Initial break in use of a component often reveals design or fabrication flaws that may cause failure. After this break in period, a (hopefully lengthy) period of regular use and low failure risk occurs. As the component wears out, the risk of failure increases. Figures 4.13 and 4.14 further illustrate these periods graphically for failure probability and cumulative probabilities.

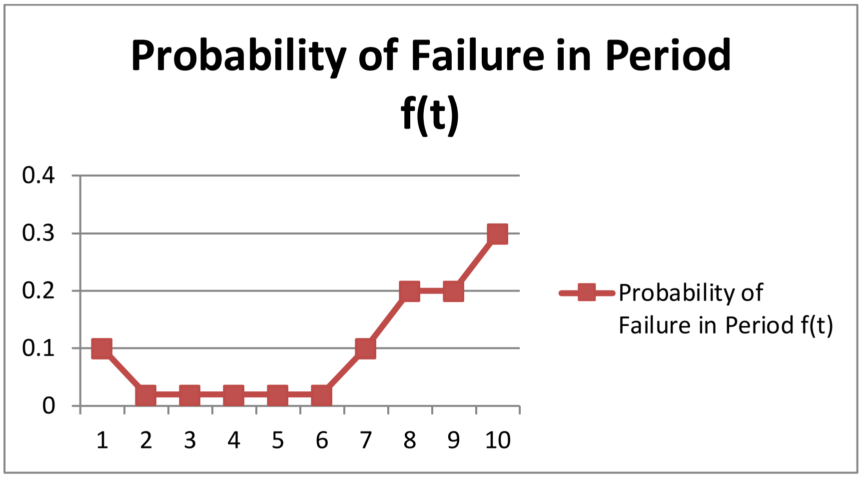


Figure 4.13 - Probability of Component Failure in Year t from Table 4.1 Data

Source: Authors

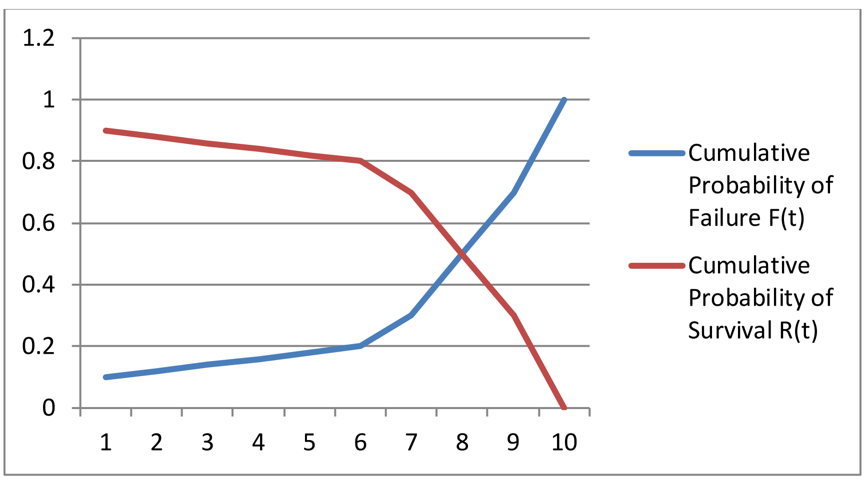


Figure 4.14 - Cumulative Probabilities of Failure and Survival from Table 4.1 Data

Source: Authors

The numerical example presented above did not assume any particular distributional form for the failure probabilities. However, many applications of failure models assume some particular distribution and use historical data to estimate the parameters of the distribution. We will discuss two distributions used in this fashion: the exponential and Weibull distributions.

The form of the exponential failure model for cumulative probability of failure is:

$$F(t) = \int_0^t \alpha * e^{-\alpha t}\, dt = 1 - e^{-\alpha t} \qquad \text{Eq. 4.11}$$

Which is the integral from 0 to time t of the parameter α times exponential of $-\alpha * t$ or, more simply, one minus the exponential of $-\alpha * t$. The probability density function of failure for the exponential distributions is $\alpha * e^{-\alpha t}$. The exponential function has only one parameter (α in this notation) and the average time to failure is the reciprocal of this parameter $(\frac{1}{\alpha})$. The failure rate is constant over time with a value of the parameter α (calculated from Eq. 4.11 as $* \frac{e^{-\alpha t}}{e^{-\alpha t}} = \alpha$). With the negative sign in the cumulative and density failure distributions, the exponential function is often referred to as a 'negative exponential distribution.'

Figures 4.15 and 4.16 illustrate the form of the exponential function for different parameter values. The cumulative failure probability increases relatively rapidly initially (except for low values of the parameter α) and continues to slowly increase for a long period of time.

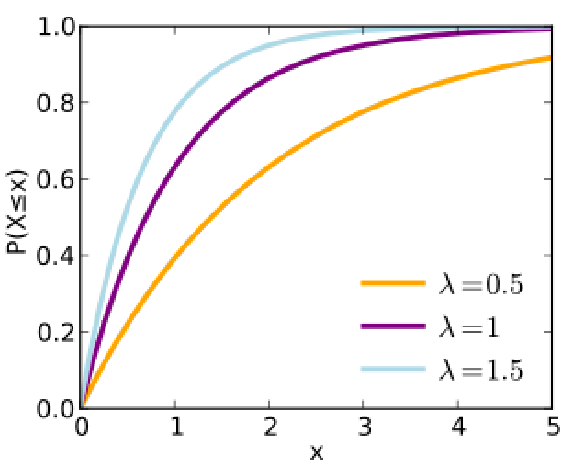


Figure 4.15 - Cumulative Failure Probabilities for Exponential Failure Models

Source: By Skbkekas - Own work, CC BY 3.0, https://commons.wikimedia.org/w/index.php?curid=9508326 via Wikipedia Commons, https://en.wikipedia.org/wiki/Exponential_distribution). This graphic uses λ for the distribution parameter rather than α, x for the time period rather than t and P(X≤x) for F(t).

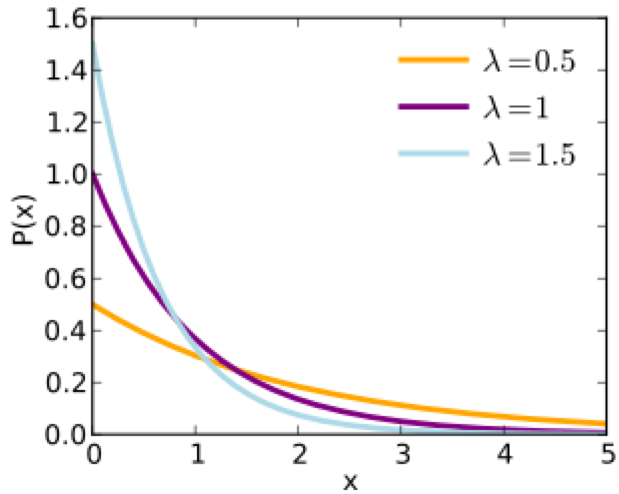


Figure 4.16 - Density Probabilities for Exponential Failure Models

Source: By Skbkekas - Own work, CC BY 3.0, https://commons.wikimedia.org/w/index.php?curid=9508311 via Wikipedia Commons. This graphic uses λ for the distribution parameter rather than α, x for the time period rather than t and P(x) for f(t).

Estimation of the parameter α is relatively simple in practice. Given a set of component failure observations, the parameter α is the inverse of the average time until failure observed in the sample.

A second distribution often assumed for failure models is the Weibull or 'extreme events' distribution. The term 'extreme events' reflects the use of the Weibull distribution for modelling events such as the probability of earthquakes or hurricane wind speeds. It also reflects the notion that the distribution returns the probability of most extreme value obtained from a series of random variable results. For infrastructure components involving a large number of pieces that might fail, this analogy is appropriate. The distribution is named for Wallodi Weibull, a Swedish engineer and mathematician who lived in the twentieth century.

The general form of the Weibull distribution includes three parameters. Using the notation of NIST (2016), the parameters are μ (called the location parameter), γ (called the shape parameter) and α (called the scale parameter). The failure probability density function is shown below, with x representing time:

$$f(x) = \frac{\lambda}{\alpha}\left(\frac{x-\mu}{\alpha}\right)^{(\lambda-1)} e^{\left(-\left(\frac{x-\mu}{\alpha}\right)^{\lambda}\right)} \text{ where } x \geq \mu; \lambda, \alpha > 0 \qquad \text{Eq. 4.11}$$

Simpler forms of the Weibull distribution function may be obtained by assuming values of the location parameter (such as μ = 0) and the scale parameter (such as α = 1). Thus, one, two or three parameter forms can be obtained.

With different values of the three parameters, a wide variety of distributional forms may be obtained. Figure 4.17 illustrates the effects of different values of just the shape parameter.

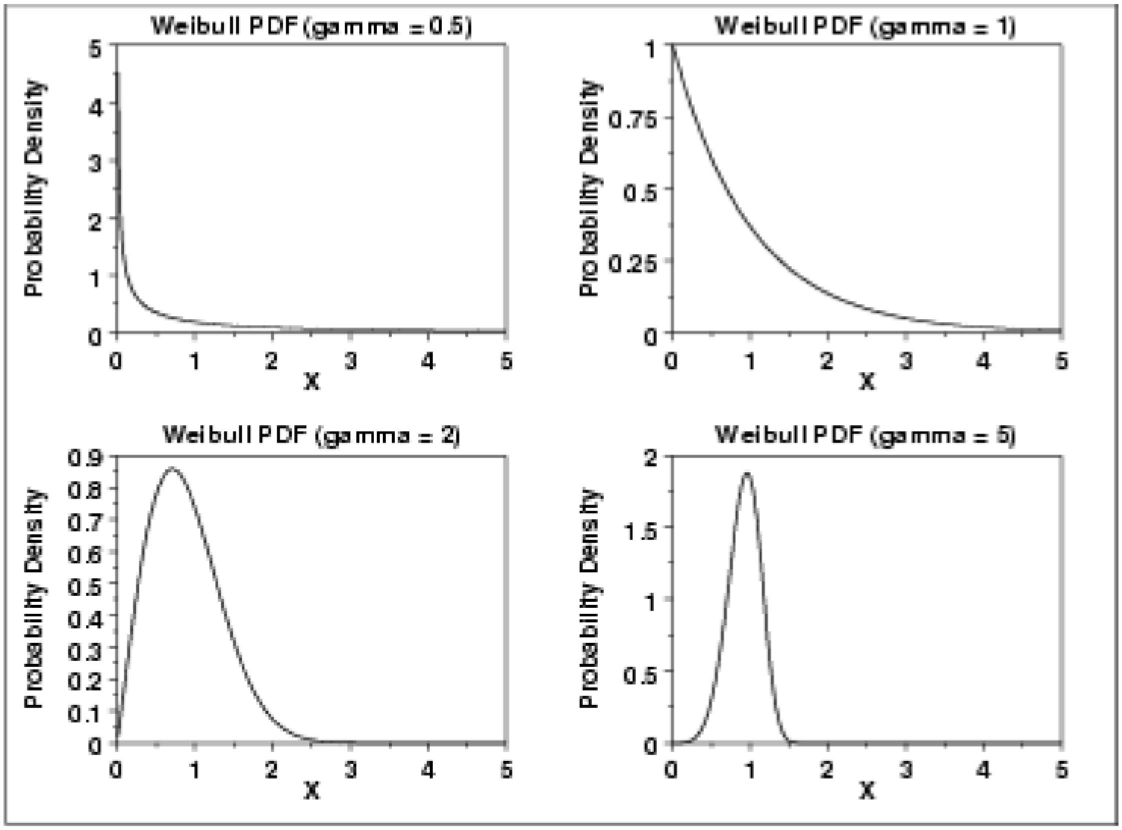


Figure 4.17 - Failure Probability Density Functions for the Weibull Distribution

Source: NIST 2016, Public Domain. Probability Density Functions for the Weibull Distribution with different values of the shape parameter (γ or gamma in the figure) and the location factor (μ) zero and the scale factor (α) one.

4.7 Fault Tree Analysis

The previous section described various models of component failure forecasting. Fault trees are used to forecast the failure probability of a system of components based upon the likelihood of component failures. Fault trees provide a means of identifying weaknesses in systems and allowing managers to make changes to reduce the risk of failure.

Fault trees begin with a top node representing the condition of the entire system. Causes for system failure are then developed as a series of events and subcomponents that may cause failures. Multiple layers of subcomponents may be included. Figure 4.18 illustrates a simple fault tree with three layers and eight different elements.

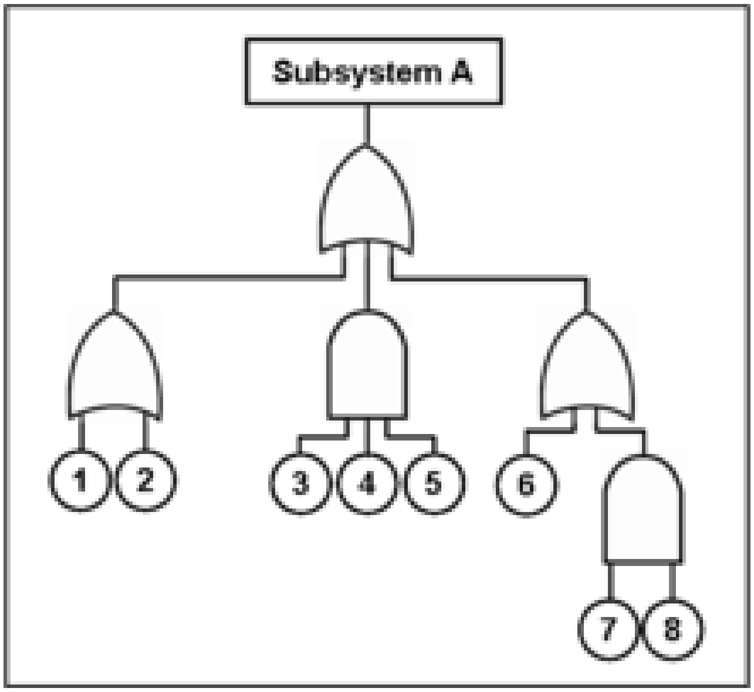


Figure 4.18 - Illustration of a Fault Tree with Eight Different Subcomponents or Events

Source: By Offnfopt, modeled after image create by U.S. Military - Own work created from scratch using File:Fault tree.png as a reference, Public Domain, https://commons.wikimedia.org/w/index.php?curid=52420454.

As an example, suppose an infrastructure manager is tasked with ensuring electricity is available in a building at all times. The manager invests in a back-up generator in case the grid electricity fails. In this case, the building might not have electricity if the grid fails and the back-up generator fails to start. In any given day, if there is a 1% chance (0.01 probability) that the power grid may fail and a 5% chance (0.05 probability) that the back-up generators fails, then there is a 0.0005 or 0.05% chance that electricity will fail. This is an example in which the redundancy of power sources reduces the chances of not having power for the building. A further step of analysis might be to examine reasons for failure of the back-up generator such as lack of fuel or damage to wiring. Also, a manager might set up a regular inspection regime for the back-up generator to attempt to reduce its 5% chance of failure.

This electric power provision is an example of redundancy with an 'and' node: both the power grid and the backup generator must fail for the system to fail. Unfortunately, system failures might also occur if any one of a number of events occurs. This is would be an 'or' node. For example, a ladder would fail if either of the two vertical supports failed. If the probability that a vertical support fails is 1% (0.01 probability) in normal use, then the probability of success is 0.99. There are four cases that might arise from use:

1. Both vertical supports work with probability 0.99*0.99 = 0.9801
2. Left support breaks and right support does not fail, but ladder as a system fails with probability 0.01*0.99 = 0.0099
3. Right support breaks and left support does not fail, but ladder as a system fails with probability 0.01*0.99 = 0.0099
4. Both vertical supports fail and the ladder system fails with probability 0.01*0.01 = 0.0001

With a 'or' node relationships (multiple potential causes of failure), the probability of failure can be calculated as:

$$\Pr\{failure\} = \sum_i \{1 - \Pr(subcomponent\ i\ failure)\} \qquad \text{Eq. 4.12}$$

Where the summation ∑ is taken over all the subcomponents included in the 'or' node level.

A common convention in drawing fault tree networks is to represent 'or' gate relationships with a curve at the bottom (as in the top gate in figure 4.17) and an 'and' gate relationship with a straight bottom (as in the bottom gate for events 7 and 8 in Figure 4.17). The failure probability of the system in Figure 4.17 would then be traced through the three 'or' gates and the two 'and' gates:

Pr{System Fig. 4.x failure} = [1 - (1-Pr{event 1 failure})*(1-Pr{event 2 failure}] +

Pr{event 3 failure}*Pr{event 4 failure}*Pr{event 5 failure} +

[1 – (1 - Pr{event 6 failure}*(1-Pr{event 7 failure}*Pr{event 8 failure}] Eq.

Eq. 4.13

More complicated relationship gates can be defined (such as exclusive 'or' gates), but they are not widely used for any infrastructure failure models. These more complicated relationships can find use in fault tree analysis of circuits or computer operating systems.

A complication in the calculation of failure probabilities shown above will occur when failures are correlated in some fashion. For example, flooding might cause both the power grid and the backup generator to fail in the electric power example above. In this case, the straightforward probability of the backup generator failing, Pr{failure backup generator} would be replaced with the probability of failure of the backup generator conditional on the power grid failure: Pr{failure backup generator │ failure power grid}. Of course, a prudent infrastructure manager might insure that the backup generator is protected from floods, so this chance of system failure due to flooding would disappear.

Another difficulty for fault tree analysis for infrastructure is that some systems may not fail completely but may degrade in performance. For example, a roof may start to leak rather than fail completely. For such cases, separate degradation states can be defined and fault trees developed for each level of degradation.

Fault tree analysis is fairly labor intensive and it is difficult to be comprehensive about potential failure modes. However, the conceptual process of identifying failure causes and events can be helpful in managing the reliability of infrastructure systems.

4.8 Exercises

P4.1 **(4 pts)** Many classrooms are equipped with video projectors that can be connected to portable, laptop computers for use during class meetings.

a. Based upon your experience with such systems, what is the probability of projection system failure over the course of a year of regular classes in such a room?
b. Develop a fault tree of potential causes for a classroom video projection system.

P4.2 **(8 pts)** Appearing below is a series of roof inspection condition summaries, where 1 is excellent and 5 is poor. Note that an inspection 1997.5 occurred in the second six months of 1997, whereas 1997 occurred in the first six months of 1997. The roof was replaced in 1985. Answer the questions below. You might use software aids, such as EXCEL or MATLAB, for this problem.

Date	Condition
1985	1
1985.5	1
1996.5	2
1997	2
1997.5	2
1998	2
1998.5	2
1999	3
1999.5	3
2000	4
2000.5	4
2001	4
2001.5	4
2002	4
2002.5	4
2003	5

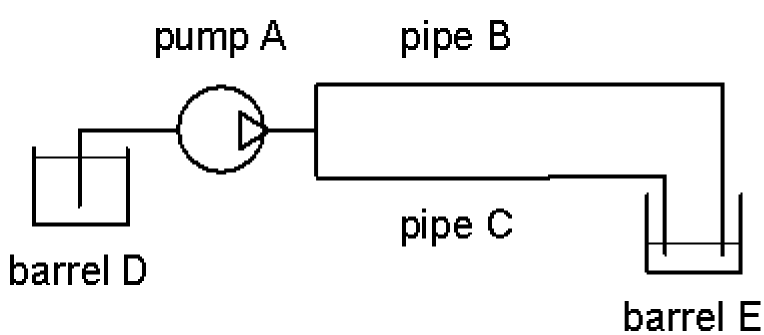
a. Estimate an ordinary least squares regression deterioration model of the form: Condition = a + b(age) where age is the age of the roof in years. Report your parameter estimates, standard errors, t-statistics and R^2 values. Note that there is a gap in the data from 1985 to 1996!
b. Suppose I have a comparable roof that is 12 years old. What would your regression model in (a) predict for its condition? What would it predict for age 18? At what age is condition expected to become 5?
c. Plot the data and your regression line.
d. Do you think a non-linear regression model would fit the data better? Try a quadratic model (Condition = a + b(age) + c(age^2) and an exponential model (Condition = a*age^b) and discuss your results. Which model has a better adjusted R^2? Which model would you use in practice for deterioration prediction?

P4.3 **(16 pts)** Formulate a simple Markov process model of roof condition. Assume that transitions occur every six months and can either be a return to current condition or a transition to the next worse condition (except for state 5 which is an absorbing state without exit in this deterioration model…)

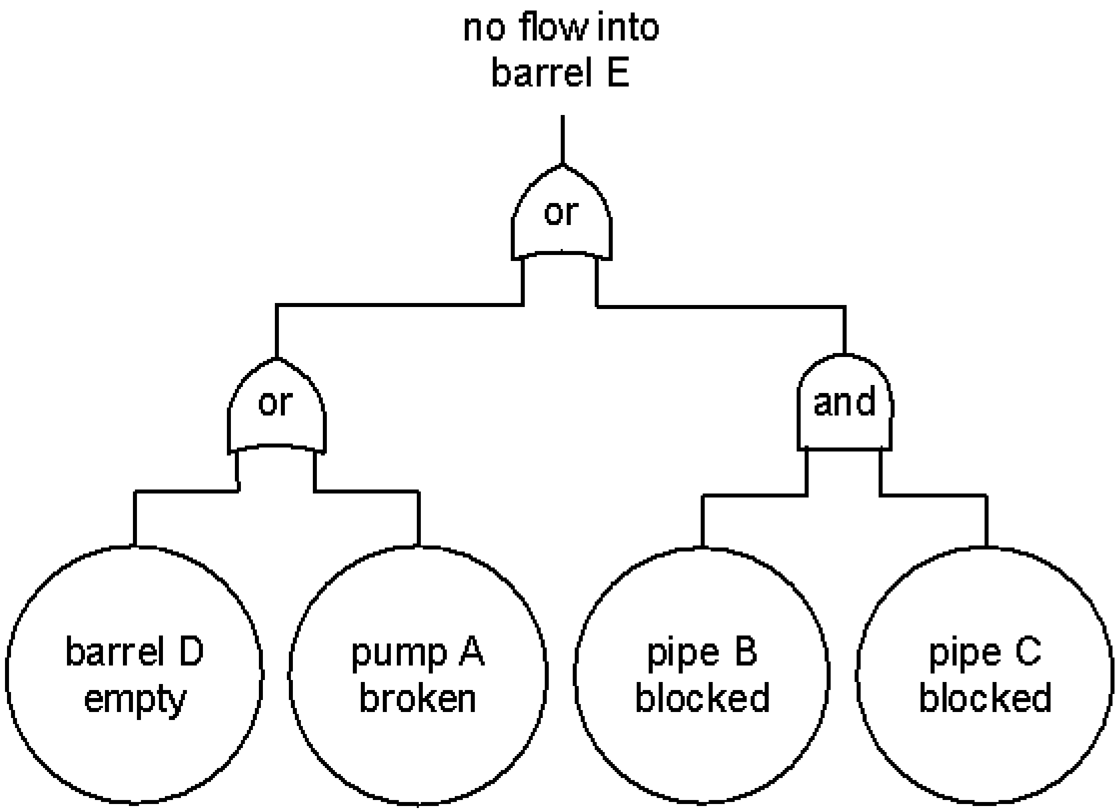
a. Draw your process model as a series of states (in circles) and transition possibilities (as arrows) for five states corresponding to roof condition 1 to 5.
b. Assume the probability of remaining in state 1 is 0.93 in any one transition. Estimate (from the data above) or calculate (when appropriate) the remaining transition probabilities and mark them on your process diagram.

c. Develop a Markov transition matrix for your process.
d. Suppose you start at time 0 in state 1. Calculate the probability of being in each state for the next twenty years (or 40 transitions) based on your model.
e. Suppose you believe that a roof must be replaced when the roof condition reaches state 5. Starting with a new roof (state 1 in time 0), plot the probability of being in state 5 as a function of time.
f. Calculate the expected service time of the roof based on your data in part e. You can assume that the expected service time is when the probability of entering state 5 reaches 50%.
g. If you ran your model to the limit (infinite time), what is the probability of being in each state?
h. How does your Markov process model compare with your linear regression model in Question 1? In particular, is the expected service time different? Is the Markov model non-linear? Why or why not? Which is preferable and why?

P4.4 **(6 pts)** Suppose I have the simple piping system shown below:



For this simple system, I develop a fault tree for failure analysis as:



Suppose further that the estimated failure probabilities of the four sub-events are independent and are as follows (left to right in figure):

Event	D empty	A broken	B blocked	C blocked
Event Probability	0.15	0.05	0.1	0.1

Calculate the probability of no flow into barrel E, showing your work.

P4.5 **(6 pts)** Appearing below is a roof condition Markovian state transition matrix model, where 7 is a new roof and 1 is a failed roof and the time step is one year.

a. Draw a state transition diagram corresponding to this matrix.
b. Suppose you start in State 7. What is the probability of being in state 7 after one year?
c. Suppose you start in State 7. What is the probability of being in state 5 after two years? What is the probability of being in state 4 after two years?

Deterioration Probability Matrix

Transition To State

Transition From State Condition State	7	6	5	4	3	2	1
7	0.000	1.000	0.000	0.000	0.000	0.000	0.000
6	0.000	0.415	0.585	0.000	0.000	0.000	0.000
5	0.000	0.000	0.528	0.472	0.000	0.000	0.000
4	0.000	0.000	0.000	0.766	0.234	0.000	0.000
3	0.000	0.000	0.000	0.000	0.907	0.093	0.000
2	0.000	0.000	0.000	0.000	0.000	0.765	0.235
1	0.000	0.000	0.000	0.000	0.000	0.000	1.000

P4.6 **(4 pts)** With the growth of internet service providers, a researcher decides to examine whether there is a correlation between cost of internet service per month (rounded to the nearest dollar) and degree of customer satisfaction (on a scale of 1 - 10 with a 1 being not at all satisfied and a 10 being extremely satisfied). The researcher only includes programs with comparable types of services. A sample of the data is provided below. (4 pts)

dollars	**satisfaction**
11	6
18	8
17	10
15	4
9	9
5	6
12	3
19	5
22	2
25	10

a. Plot the data. Do you think dollars and satisfaction are related (or correlated)?
b. Estimate a linear regression with Satisfaction = a + b*dollars. Discuss your results.

P4.7 (3 pts) Which of the following are transition matrices for Markov processes? Explain.

a. $$\begin{bmatrix} .4 & .3 & .3 \\ .2 & .4 & .4 \\ .6 & .1 & .3 \end{bmatrix}$$

b. $$\begin{bmatrix} .2 & .3 & .5 \\ .6 & .1 & .2 \\ .7 & .1 & .3 \end{bmatrix}$$

c. $$\begin{bmatrix} .25 & .15 & .3 & .4 \\ .5 & 0 & .15 & .3 \\ .15 & .35 & .4 & .2 \\ .1 & .5 & .2 & .2 \end{bmatrix}$$

4.9 References

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Chapter 5: Optimization and Decision Making

5.1 Introduction

Infrastructure managers must make decisions on a regular basis. They must make decisions about allocating time and other organizational resources. For infrastructure components, managers must make decisions about maintenance and rehabilitation in each planning period. In many cases, the decision about procedures to apply to a particular infrastructure component may be to 'do-nothing,' but it is prudent for a manager to make such a decision consciously rather than simply from lack of oversight. With continuing deterioration, some maintenance or rehabilitation will be needed to prevent failure of the component.

This chapter discusses the use of optimization approaches to aid infrastructure management decision making. No previous experience with formal optimization approaches is assumed. Our intent is not to cover all the different approaches to optimization, but to illustrate how optimization might be used for infrastructure management. We don't expect readers to become experts in optimization from reading this chapter. However, a manager may not ever develop their own optimization problem formulations. However, many asset management software programs include optimization sub-routines, and a manager using such programs should understand their approach. Also, optimization provides a useful conceptual approach to aid structuring decision making, even if formal optimization procedures are not used.

Optimization has been used in numerous applications that are not discussed in this chapter. In particular, optimization is used to aid production planning, vehicle routing, inventory controls, and engineering design. Optimization is also used for estimation of parameter values. Regression models, as discussed in Chapter 4 on Deterioration Models, is a form of optimization. Just as one example, the package delivery company UPS uses optimization to suggest vehicle routes for their deliveries. The route planning minimizes driving cost in terms of time and fuel use. With route planning technology introduced in 2004, UPS has saved a million gallons of fuel each year (UPS 2016).

All optimization problems have some common features. The user is interested in searching for maximum (or minimum) values for an objective function. For infrastructure management, the objective might be to maximize the average condition of components or to minimize money spent on maintenance and rehabilitation. There are a set of decision variables obtained in finding an optimization solution. For infrastructure management, the most common decision variables are actions performed on particular components, such as rehabilitation options for different roadway sections. There are a set of constraints imposed on the decision variables. For example, there may be an available budget for infrastructure management, a minimum allowable component condition, or a requirement that one and only one rehabilitation option is chosen for each component in a single year. Finally, there is some solution process (usually called a solution algorithm) to obtain optimal values of the decision variables. In practice, management problems are sufficiently large that software packages are used to obtain such solutions.

Engineers and scientists first encounter optimization as part of the study of calculus. In particular, maximum values of a function with a single variable can be obtained by setting the first derivative to zero and insuring that the second derivative of the function is positive:

$$\frac{df(x)}{dx} = 0, \frac{d^2f(x)}{dx^2} > 0 \qquad \text{Eq. 5.1}$$

There may be a single value of x that maximizes the equation, or there may be multiple values.

5.2 Linear Optimization for Infrastructure Management

Problems with continuous decision variables and linear constraints and objective functions are very common and have attracted considerable research attention. These problems are solved with linear programming algorithms such as the Simplex method. Typical software can accommodate thousands of decision variables and constraints.

Formally, a linear program is represented as:

Maximize $c * x$ subject to $Ax = y$ and $x \geq 0$ Eq. 5.2

Where c is a vector of parameters, x is a vector of continuous decision variables, A is a matrix of parameters and y is a vector of constraint parameters. This formulation can accommodate inequality constraints with the addition of decision variables representing slack in the constraints. For example, the constraint $x1 + x2 \leq 5$ (shown in Figure 5.1) would be re-written as $x1 + x2 + x3 = 5$ and a positive value of x3 in the optimal solution would indicate that the constraint is not binding. Similarly, decision variables can take on any value (both negative and positive) with the addition of decision variables. In practice, linear programming software can take as input inequalities and unconstrained decision variables and convert the problem into the standard form of Eq. 5.2

A linear program has three types of solution possibilities:

- No solution possible. An example would be: Maximize decision variable x subject to the constraints x < 1 and x > 5. No value of x will satisfy both constraints. For infrastructure management, an example would be if a budget is inadequate to achieve required functional conditions.
- A single optimal solution exists. For example, a roadway management problem might be to maximize average condition of roadway segments subject to a budget constraint. Typically, a set of maintenance actions (such as repaving or patching) for a subset of roadway segments will be identified that completely uses the budget. A more extensive example of this problem appears below.

Multiple optimal solutions exist. In Figure 5.1, the line segment between A and B includes an infinite number of optimal solutions which are combinations of the two decision variables x1 and x2 for the linear program Maximize $2 * x1 + x2\ subject\ to\ 2 * x1 + x2\ \leq 4\ and\ x1, x2\ both\ \geq 0$. The feasible region is the triangular area ABO.

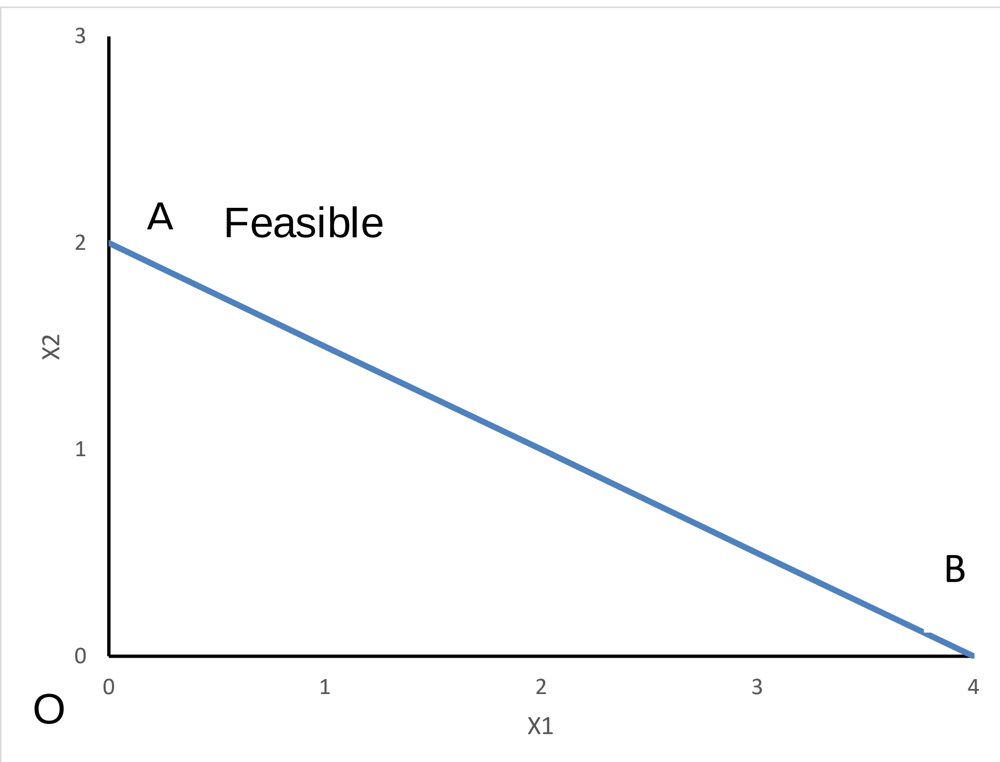

Figure 5.1 - Illustration of Multiple Optimal Solutions

Source: Authors, Problem is to

$\boldsymbol{Max\ 2 * x1 + x2\ subject\ to\ 2 * x1 + x2\ \leq 4\ and\ x1, x2 \geq 0}$

Linear programs possess the useful property that the set of feasible solutions form a convex region. ‘Feasible’ in this context means a combination of decision variables that satisfy the problem constraints. The shaded area in Figure 5.1 is the feasible region for x1 and x2. The shaded area is convex because the line segment between any two feasible combinations of x1 and x2 would still be in the feasible region. This convexity has two useful implications. First, any optimal solution will not be a local optimum but would be a global optimum. That is, if you find a combination of x1 and x2 for which no improvement is possible from small changes, then no other combination of x1 and x2 with be better. Second, optimum values of the decision variables for a linear program problem will lie on the boundary of the feasible region, such as the line segment in Figure 5.1. This property is used by the Simplex solution algorithm for linear programs.

The Simplex method is a common solution method for linear programming problems. It begins with a ‘basic feasible solution.’ With m constraints and n decision variables, a basic feasible solutions consists of n-m decision variables set to zero and the remaining m decision variables the solution to the m linear constraint equations. The simplex method checks to see if improvement is possible by exchanging one of the n-m decision variables set to zero with a decision variable in the basic feasible solution. If improvement is possible, the algorithm makes this switch, which is equivalent to ‘pivoting’ from one extreme point on the convex feasible region to another. Pivots continue until no such improvement is possible. An initial basic feasible solution can be obtained simply by adding ‘artificial decision variables’ equal to the value of constraint parameters and then pivoting away from these artificial variables.

Roadway maintenance and rehabilitation is a good example of linear programming applied to infrastructure management. In this application, a roadway network is divided into numerous short sections which might vary from a few kilometers down to individual blocks in an urban network (with index I ranging from 1 to n segments). Possible maintenance actions are defined for the roadway sections, such as filling potholes (j = 1), repaving (j = 2) or do-nothing (j = 3). Costs of each action for each pavement section are then estimated, usually based upon the area of the pavement section (p_{ij}). The condition of each pavement section is forecast assuming that one action is performed (filling potholes, repaving or doing nothing in this example) (c_{ij} where lower values of c_{ij} are more desirable). Then a budget constraint for actions and an objective function (such as maximizing average system condition) is defined. The result is a linear programming problem:

$$Minimize \sum i \sum j \ \frac{x_{ij} * c_{ij}}{n} \qquad \text{Equation 5.3}$$

$$subject\ to \sum j \ \ x_{ij} = 1\ for\ all\ i \qquad \text{Equation 5.4}$$

$\sum i \sum j \ \ x_{ij} * p_{ij} \leq B$ Equation 5.5

$x_{ij} \leq 0 \ for \ all \ i,j$ Equation 5.6

Where x_{ij} is action j on section I, c_{ij} is forecast condition with action j on section I, n is the number of roadway segments, p_{ij} is the cost of action j on segment I and B is the overall budget constraint.

In theory, the x_{ij} might take on non-integer values between 0 and 1 in this formulation, but in practice nearly all the optimal x_{ij} would be zero or one.

A variety of modifications could be made to the basic formulation of Eq. 5.3 to 5.6. For the objective function (Eq. 5.3), the condition of each segment might be weighted by amount of traffic and the segment area. These weights would lead the optimal solution to favor work on heavily traveled roadways and to minimize average roadway area condition rather than average segment condition as in Eq. 5.3. Additional roadway maintenance actions could be defined to extend the constraint Eq. 5.4. The problem could be altered by defining maximum allowable conditions as a constraint on each section and then minimizing the cost of achieving this constraint. Even without changing the objective function in this fashion, maximum allowable condition constraints can be added if desired.

This strategy of defining actions on infrastructure components is not restricted to roadway segments. For a manager of a military base or a campus, the problem formulation in Equations 5.3 - 5.6 might be used for roofs (with replacement or maintenance as actions), storm water components, building components or a range of other infrastructure systems.

In formulating linear programming problems, it is useful to address a series of questions:

- What are my possible decisions? How can they be represented as decision variables?
- What is my objective? Can it be represented as a linear function of my decision variables?
- What are the constraints on chosen values of my decision variables? Can they be represented as linear functions of the decision variables?

Problem formulation is challenging but is an essential step in any optimization. Indeed, formulation is more challenging than solution since there are many good software programs available for solution.

The following example illustrates the use of the formulation questions.

Problem: Suppose you wish to minimize the cost of delivering ethanol from a set of production facilities with a maximum production supply Si where i goes from 1 to n, to a set of metropolitan petroleum mixing facilities (as ethanol is mixed with gasoline) with required amounts P_j where j goes from 1 to m. Assume the cost of transportation from a production facility to a mixing facility is C_{ij}. Formulate a linear program problem to serve the required demand with least cost.

- What are my possible decisions? How can they be represented as decision variables? Amount of ethanol shipped from each supply facility to each metropolitan area would be my decision variables. Let us define x_{ij} as the amount of ethanol shipped from production facility.
- What is my objective? Can it be represented as a linear function of my decision variables? The problem statement gives the objective to minimize transportation costs. The objective function would be: $\sum i \ \sum j \ c_{ij} * x_{ij}$ which is total transportation cost and is linear with regard to decision variables.
- What are the constraints on chosen values of my decision variables? Can they be represented as linear functions of the decision variables? One set of constraints is to insure that ethanol shipped from each production facility does not exceed the available supply: $\sum i \ x_{ij} \leq S_i$ for each i. A second set of constraints is to insure demand is met at each metropolitan area: $\sum i \ x_{ij} \geq P_j$ for each j metropolitan area. Finally, the flows must all be positive: $x_{ij} \geq 0$.

There are a variety of software packages that can be used for linear programming. For example, the spreadsheet program EXCEL has a routine for optimization called Solver. Frontline Systems (2016) has a tutorial available for the use of Solver. Readers interested in more in-depth treatment of linear programming might consult a relevant textbook (Boyd and Vandenberghe, 2004).

5.3 Integer Optimization for Infrastructure Management

In many infrastructure management optimization problems, the decision variables may be restricted to integer values. For example, in the previous section, decision variables were defined as undertaking a particular maintenance or rehabilitation action j on a roadway segment i. While the decision variable could be a fraction, so that only part of the roadway segment undergoes a maintenance activity, it is more natural to manage the segment as a whole and wish to have binary decision variables that are zero or one.

Integer constraints impose several problems in obtaining optimal solutions. For linear programming, optimal values could be sought on the extreme corners of the feasible region. With integer value constraints, the optimal solution may be inside the feasible region. As illustrated in Figure 5.2, feasible integer values are shown as dots within a region satisfying the linear constraints. The only feasible solution on an extreme corner would be the solution x1 = 0 and x2 = 0. Point A marked on the figure would have fractional values of x1 and x2.

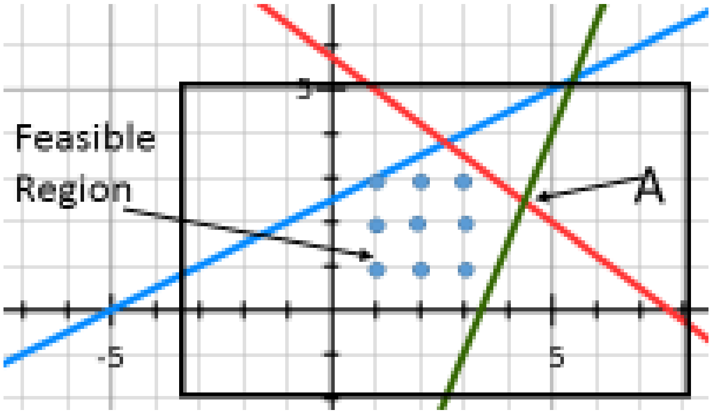

Figure 5.2 - Illustration of Integer Feasible Solutions to a Linear Optimization Problem

Source: Authors

One approach to integer programming is to ignore the integer constraints and solve the problem as a linear program. With binary restrictions and integer parameters and constrain values, this approach works frequently to give optimal, binary solutions. A fractional decision variable value might be rounded by a manager to obtain a very good but not necessarily strictly optimal solution in this approach. Given the uncertainty in costs and action effects, the rounding might not affect the overall infrastructure performance.

More formal methods of obtaining optimal integer solutions also exist. A popular approach is 'branch-and-bound.' In this process, an initial linear solution is obtained, and then constraints are added to force the solution to be integer. For example, in Figure 5.2, if point A was obtained as the optimal solution, and good additional constraint might be to require x1 to be 3 or less: $x1 \leq 3$. This would be a new 'branch' for the problem solution with a 'bound' that cuts out a portion of the region that does not contain integer values. Adding constraints in this fashion would continue until an integer valued optimal solution is obtained.

'Branch and bound' or other integer programming approaches are part of most popular optimization software, including the Solver program for the EXCEL spreadsheet. Integer constraints are specified when problems are input to the programs. However, solving integer programs requires more calculation time than comparably sized linear programs. While linear programs with thousands of decision variables can be easily solved, integer programs may be realistically limited to hundreds of decision variables. Still, this could well a useful range for many infrastructure management problems.

The ‘travelling salesman’ problem is a classic example of an integer programming problem. The problem is to develop a round-trip tour that visits each and every one of a set of cities exactly once with minimum travel distance. For infrastructure management, a tour of this type might be formulated by an inspector of different infrastructure components or a maintenance worker with a set of assigned jobs. In these problems, ‘cities’ would be inspection or job sites. The UPS routing software for delivery trucks mentioned in the introduction to this chapter solves this problem (UPS 2016). Variations of the problem can be found in manufacturing (where ‘cities’ may be spots on a chip) and DNA sequencing.

A decision variable for the travelling salesman problem might be x_{ij} which is 0 if the trip from i to j is not on the tour and 1 if the trip from i to j is on the tour. The objective function would be to sum the distance (or cost) of the trip from i to j multiplied by the x_{ij} values. Only those trips which are part of the tour would incur any distance and affect the value of the objective function. Constraints require that there is exactly one departure from each city (so the sum of the x_{ij} from I equals one) and exactly one arrival at each city. Additional constraints are needed to insure that the tour is complete (that is, the tour doesn’t have multiple disjoint circuits). Finally, the decision variables x_{ij} are restricted to zero or one.

Numerous specialized algorithms have been developed for the travelling salesman problem. In practice, heuristic approaches can obtain very good (but not necessarily optimal) solutions.

5.4 Non-Linear Optimization

As discussed earlier, most infrastructure management optimization problems are formulated as linear programming problems. However, in some cases, non-linear optimization may be needed. The general form of the non-linear optimization problem is:

$$\text{Minimize or Maximize } f(x) \text{ subject to } g_i(x) \leq 0 \text{ and } h_j(x) = 0 \qquad \text{Eq. 5.7}$$

Where x is a vector of decision variables, f(x) is a non-linear objective function, $g_i(x)$ and $h_j(x)$ are sets of constraints which may be linear or non-linear.

One source of non-linearities is that of scale economies in performing a maintenance or rehabilitation task. This might occur if there are fixed mobilization costs to undertake a task which are then spread over the amount of work. Components such as tanks also have scale economies since their volume grows faster than the (expensive) tank surface as the tank size increases. Figure 5.3 illustrates scale economies in two related graphs. In the upper graph, the cost per unit of work declining as the amount of work increases. In the lower graph, the total cost goes up slower than the increase in the amount of work.

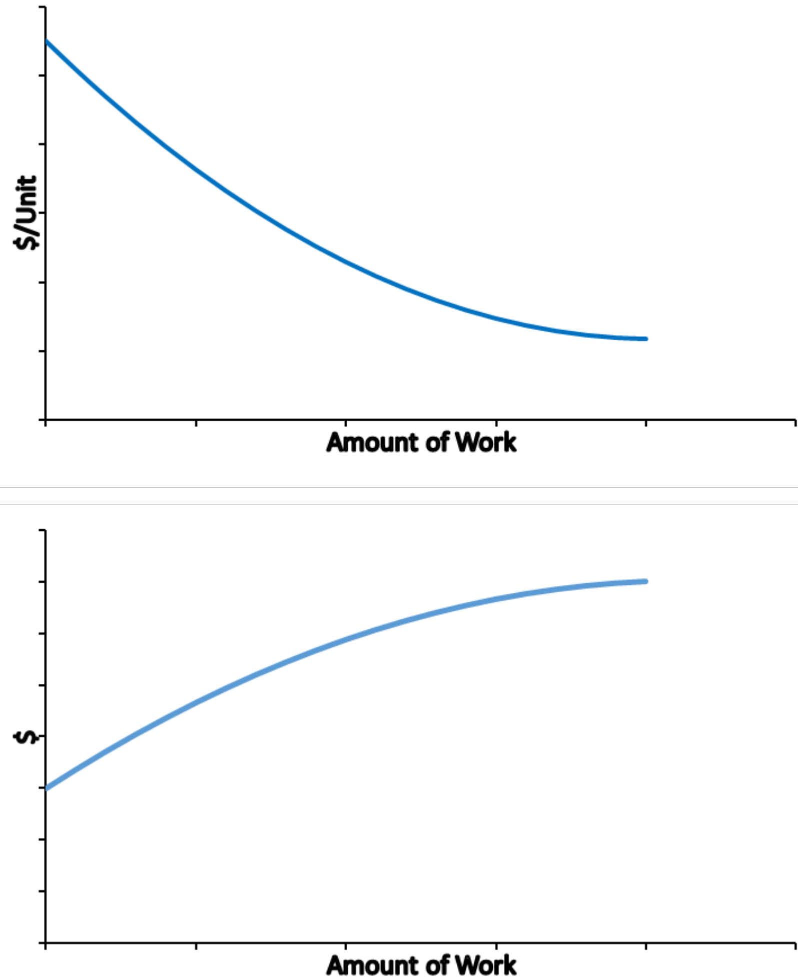

Figure 5.3 - Illustration of Scale Economies with respect to the Amount of Work

Source: Authors

Another source of non-linearity for infrastructure management comes from flow effects. For example, roadway traffic congestion is non-linear in that a small increase in traffic may result in large amounts of delay. With roadway maintenance blocking lanes of traffic, the capacity of the roadway network is reduced and congestion may increase considerably. Figure 5.4 illustrates the non-linear increase in average travel time.

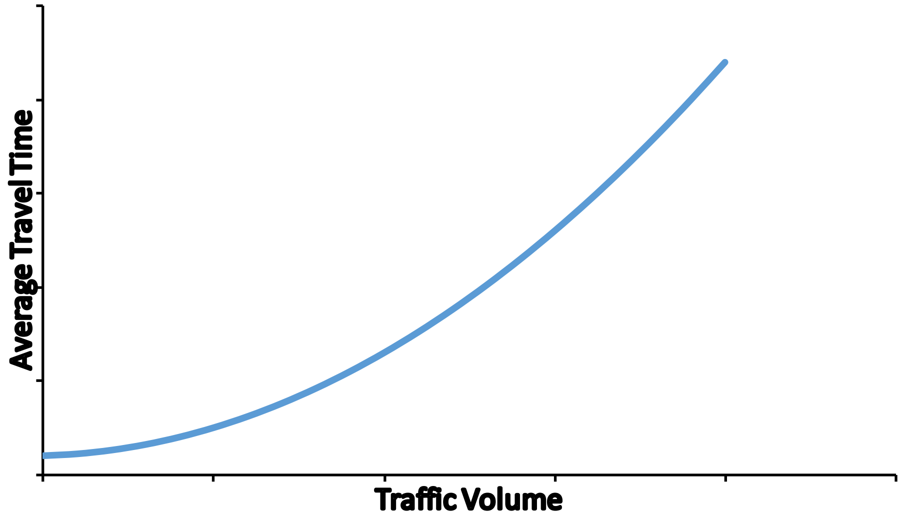

Figure 5.4 - Illustration of Non-Linear Travel Time Effects with respect to Vehicle Volumes

Source: Authors

Non-linear optimization has some pitfalls. First, solutions obtained may not be global optimum but only local maximum or minimum values of the objective function. Second, particular formulations may lead to physically impossible results. For example, in a case of scale economies, a non-linear optimization may wish to build the top few feet of a dam rather than the entire dam since the top two feet would hold more water back than average and would be cheaper to build!

Most non-linear optimization uses some form of a gradient approach in which a set of feasible decision variable values are chosen and then these are altered to improve the objective function and still remain feasible. Solver in the spreadsheet program EXCEL uses this type of technique. In many cases, it is useful to use multiple starting points to reduce the chance of ending up with a local optimum.

As an example of non-linear optimization useful for infrastructure management, we can suggest a flow problem which can be applied to traffic flow in road networks or water flow in pipe networks. The costs of maintenance or rehabilitation work can be estimated by comparing flow costs before and during network disruption. The same approach can be used for assessing new capacity or operating procedures. The problem appears in Hendrickson (1984).

We assume that a network exists with a set of nodes (intersections) N and arcs (pipe links or streets) A. There is a cost of flow on link ij f(y) which is assumed to be monotonically increasing as in Figure 5.4. This assumption is physically realistic and insures convexity for the problem solution space making a solution easier.

The general problem of equilibrium flow is:

$$P1\colon minimize \sum_{(i,j)\in A} \int_0^{x_{ij}} f_{ij}(y)\,dy$$

subject to:

$$\sum_{(i,k)\in A} x_{ik} - \sum_{(k,j)\in A} x_{kj} = q_k \; for\ all\ k \in N$$

$$x_{i,j} > 0 \; for\ all\ (i,j) \in A$$ Equations: 5.8 - 5.10

Where x_{ij} is flow on link ij and qk is the net inflow or outflow at node k. The objective is to minimize 'impedance' of flow on each link, and the constraints conserve flow through nodes and require all flows to be positive.

For pipeline hydraulics applications, the flow would be fluid flow measured in volume per unit time. The impedance function would be head loss (or gain) per unit of distance. The impedance function should include elevation differences of nodes as well as pipe friction loss (through a function such as the Hazen-Williams function $f(x) = k * x^m$.

For traffic networks, a slightly more complicated form of the problem must be used to keep track of flows between particular origins and destinations. The impedance is travel time and relates to total flow on link ij. Problem P2 below shows the traffic flow problem with the rs notation for traffic from node r to node s, a constraint to insure conservation of flow through intersection nodes, and a constraint to aggregate the individual origin-destination flows for each link.

$$P2\colon minimize \sum_{(i,j)\in A} \int_0^{x_{ij}} f_{ij}(y)\,dy$$

$$\sum_{s\in A} \left[\sum_{(i,k)\in A} x_{ik}^{rs} - \sum_{(k,j)\in A} x_{kj}^{rs} \right] = q_{rk} \; for\ all\ \ k\ \in N, r \in N$$

$$\sum_{s\in N}^{r\in N} x_{ij}^{rs} = x_{ij} \; for\ all\ (i,j) \in A$$

Equations 5.11 - 5.13

For the traffic flow application, the solution set of flows represents a 'user equilibrium solution' in which the travel time on each path used between origin r and destination s has the same overall travel time (if not, travelers would change path and reduce their travel time). Paths not used between origin r and destination s would have higher travel time and would be unattractive.

As noted earlier, the problem P2 could be solved to obtain travel times and flows on an existing network. After the network is altered due to construction, the equilibrium travel time after the alteration could then be modelled. Noted that in this simple application form, the origin-destination flow would not change. More elaborate analyses could relax this assumption to allow new destination or other travel choices.

Gradient solution algorithms exist for problem P1 and P2 that can easily accommodate thousands of nodes and links. Author, (Hendrickson, 1984) presents one solution algorithm as well as additional applications of the model form to project task scheduling and structural analysis. Numerous software programs exist for this type of model formulation.

5.5 Combining Linear Optimization with Markov Deterioration Models

The previous section illustrated the use of expected component conditions for use in optimization and decision making. It is also possible to include a distribution of possible conditions over a period of time. The most common means of making this synthesis is to combine optimization with Markov deterioration models. A number of bridge and pavement management systems are based on this synthesis; for an example, see AASHTO (2016) or Golabi (1997). It is unlikely that an infrastructure manager would formulate an optimization problem synthesis such as these, but managers regularly use the software programs embedding the synthesized optimization.

Table 5.1 presents an example of a Markov process transition matrix and possible actions for a concrete component. Five condition states are defined, with 1 representing good condition and 5 representing failure of the component. For components in state 1, recommended management action is to do-nothing. In each year in State 1, there is a 3% chance of deterioration to state 2. For components in states 2 and 3, do-nothing or patch are possible actions with the probability consequences as shown. There are substantial chances that the patching may not be effective, as the components might remain in their initial state or deteriorate further (although with a low probability of such deterioration). For components in state 4, do-nothing, rehabilitation or replacement are possible actions. With do-nothing action and initial state 4, there is a 13% chance of failure over the course of a year.

Table 5.1 - Illustrating a Markov Transition Probability Matrix with Different Management Actions

Initial State	Action	Pr{state 1}	Pr{state 2}	Pr{state 3}	Pr{state 4}	Pr{state 5}
1	Do Nothing	0.97	0.03	0.0	0.0	0.0
2	Do Nothing	0.0	0.97	0.03	0.0	0.0
2	Patch	0.62	0.34	0.04	0.0	0.0
3	Do Nothing	0.0	0.0	0.92	0.08	0.0
3	Patch	0.52	0.35	0.10	0.03	0.0
4	Do Nothing	0.0	0.0	0.0	0.87	0.13
4	Rehabilitate	0.68	0.27	0.05	0.0	0.0
4	Replace	0.99	0.01	0.0	0.0	0.0

Source: Authors

An initial analysis step with a table of transition probabilities such as this could be to minimize the long-term cost of maintaining the concrete component. Of course, doing nothing at each stage would minimize cost, except that eventually the component would fail. Presumably, a manager would attempt to minimize cost subject to avoiding transitioning to state 5. Decision variables would be a particular action given a state. The objective function would be to minimize expected condition (or perhaps the probability of failure). With a planning horizon and an initial state, the changes in probabilities over time can be traced as a linear function of the decision variables. A budge constraint might also be imposed (as in Eq. 5.5) added over all the bridge components being managed.

We will illustrate this optimization approach with a small problem. Suppose a set of identical components can have three possible condition states: 1 – good, 2 – average and 3 – poor. One maintenance activity can be undertaken, which will move the component from any state to state 1 at a cost of c_i. Table 5.2 shows the transition probabilities for the component with do-nothing and maintenance. Finally, there is a budget available for the year and a known state s_i for each component.

Table 5.2 - Illustrative Transition Probabilities and Actions for a Small Problem

Initial State	Action	Pr{State 1}	Pr{state 2}	Pr{state 3}
1	Do-nothing	0.8	0.2	0.0
1	Maintenance	1.0	0.0	0.0
2	Do-nothing	0.0	0.8	0.2
2	Maintenance	1.0	0.0	0.0
3	Do-nothing	0.0	0.0	1.0
3	Maintenance	1.0	0.0	0.0

Source: Authors

Following the formulation approach discussed in the previous section:

- Let us define our decision variable as xi = 0 if do-nothing and xi = 1 if maintenance is performed. (If there were more than two actions possible, then we could add a subscript as in Eq. 5.3 for each component and each possible action, and the decision variable xij would be 0 if the action j was not undertaken on component I and one if action j was taken on component i).
- Let us assume that the objective is to minimize the average component condition.
- The only constraint is the budget constraint for all the actions. (If more than one action is possible, however, we would have to add a constraint similar to Eq. 5.4 for each component however).

The resulting problem is:

$$Minimize\ Average\ Condition\ State = \sum_{s=1}(.8+2*.2)*(1-x_i)+\sum_{s=2}(2*0.8+3*0.2)*(1-x_i)+\sum_{s=3}3*(1-x_{is})+\sum_{i}x_i$$

$$Subject\ to\ \sum_i c_i*x_i \le B, x_i binary$$ Equation 5.14

Where the objective function has four terms: (1) resulting condition of components in state 1 with no action, (2) resulting condition of components starting in state 2 with no action, (3) resulting condition of components in state 3 with no action (they stay in state 3), and (4) components with maintenance moving to state 1. The constraints are the overall budget and the restriction of the x_i to zero or one. As noted above, variation would add additional potential actions (using notation x_{is}) and different resulting conditions.

5.6 Exercises

P5.1 **(8 pts)** Suppose I am managing a system of n cell phone sites. A site consists of 'antennas and electronic communications equipment placed on a radio mast or tower to create a cell in a cellular network.' I have records of the age of the electronic equipment (a_i where a is the current age of the site i) and a physical condition assessment rating (r_i where r is the condition rating index for a site i on a scale of 1 to 5 with 1 being excellent) of the physical systems each year. I also have a measure of the importance of each site, t_i where t is the amount of cellular traffic at a particular site i. In each year, routine maintenance is performed at each site. I can also choose to rehabilitate the physical site (antenna towers, etc.) (which would move the site to condition 2, replace the electronic components (which would also move the site to condition 2), or do both physical rehabilitation and electronic component replacement (which would move the site to condition 1). Each of these actions has an associated cost, denoted c_{ij} where i indicates a particular site i and j is one of the management strategies.

Formulate a linear programming decision model that would select the best management action for each site in the coming year. 'Formulate' means to write out the problem equations. Define appropriate decision and other variables. Your objective is to minimize the sum over all sites of site condition multiplied by importance of each site. Your constraints are an allowable budget and a requirement that the electronics must be replaced if the age is greater than 6 years old.

P5.2 **(4 pts)** Suppose you wish to minimize the cost of delivering ethanol from a set of production facilities with a maximum production supply S_i where i goes from 1 to n, to a set of metropolitan petroleum mixing facilities (as ethanol is mixed with gasoline) with required amounts P_j where j goes from 1 to m. Assume the cost of transportation from a production facility to a mixing facility is C_{ij}.

a. Formulate a linear program problem to serve the required demand with least cost.
b. What might cause your linear program to be infeasible for solution?

P5.3 **(8 pts)** Let us try an application of a roadway management system optimization model. Suppose I have a small roadway network with 10 links as shown below. In this example, we will just number links (rather than naming them by beginning and end points) and consider three action possibilities with forecast pavement conditions post-action as shown. Pavement condition varies from 1 to 7, with 7 excellent. This problem is sufficiently small that in can be solved with the add-in solver program in EXCEL.

Link	Length	Average Daily Traffic	PCI Do-Nothing	PCI with Main	Maintenance Cost	Rehabilitation Cost	PCI with Rehab.
1	5	10	4	5	5	16	7
2	4	13	3	4	4	15	7
3	3	12	3	4	3	10	7
4	6	11	2	3	6	20	7
5	7	25	5	6	7	22	7
6	5	50	4	5	5	20	7
7	4	40	3	4	4	15	7
8	3	20	3	4	3	10	7
9	8	15	2	3	8	28	7
10	2	10	1	2	2	6	7

a. Your objective function will have 30 terms, corresponding to the 10 links multiplied by three possible action decision variables: do-nothing, maintenance or rehabilitation. Each term is the product of length, average daily traffic, forecast pavement condition index (PCI) and a decision variable and divided by the sum of the product of length times average daily traffic. Write out your complete problem formulation, including definitions of variables, the various terms in your objective function, and your various constraints (including non-negativity and integral restrictions).

b. Find optimal solutions for budgets of 40 and 100. What do you conclude about the maintenance and rehabilitation strategies from your results?
c. Do either of your optimal solutions have a fractional decision variable value? What could you do about this in practice knowing that costs and pavement conditions are all uncertain?
d. Do you think this problem formulation and data are reasonable? Why or why not?

P5.4 **(4 pts)** Let us couple a linear programming problem with a Markov deterioration model. Suppose you have components with three possible States: 1 – good, 2 – ok, 3 – poor. You have one possible action: moves to state 1 with probability 1 at cost c_i for component i. State transition probabilities with no action are: p11 = .8, p12=.2, p22 = .8, p23 = .2, p33 = 1. others zero. You have a budget B for the year and current conditions are described by a vector s_i. Formulate problem to minimize average condition of all components at end of year.

P5.5 **(8 pts)** The facility manager of a plant is attempting to devise a shift pattern for his workforce. Each day of every working week is divided into three eight-hour shift periods (00:01-08:00, 08:01-16:00, 16:01-24:00) denoted by night, day and late respectively. The plant must be manned at all times and the minimum number of workers required for each of these shifts over any working week is as below:

- Mon Tues Wed Thur Fri Sat Sun
    - Night 5 3 2 4 3 2 2
    - Day 7 8 9 5 7 2 5
    - Late 9 10 10 7 11 2 2
- The union agreement governing acceptable shifts for workers is as follows:
    - Each worker is assigned to work either a night shift or a day shift or a late shift and once a worker has been assigned to a shift they must remain on the same shift every day that they work.
    - Each worker works four consecutive days during any seven day period.
    - In total there are currently 60 workers.
- Formulate an optimization problem to minimize the number of workers in the labor pool.

5.7 References

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Chapter 6: Performance, Usage, Budget and Cost Functions

6.1 Introduction

Some infrastructure managers adopt a narrow view of their work, focusing simply on maintenance and rehabilitation decision making. However, an appreciation and understanding of the overall performance, costs and finance of infrastructure is extremely useful in interacting with the users of infrastructure and organizational decision makers. For example, an extremely congested roadway may be in good physical condition, but users of the roadway are likely not to appreciate the good pavement condition while waiting in traffic queues. Figure 6.1 illustrates a roadway in good condition but with heavy traffic congestion. This chapter is intended to provide an understanding of the fundamentals of infrastructure costs and finance topics.

The amounts and components of infrastructure costs depend upon your viewpoint. For a building manager's viewpoint, costs might be limited to the initial construction (or the payments for borrowed money used for construction), building utilities and maintenance. However, the building occupants might incur costs if the roof leaks, power fails or water is unavailable. If the building has a boiler, then air emissions might impose costs on nearby residents. The air emissions costs are often called 'external' since they don't appear on any accounting sheet for the building. However, any public health effects due to such air emissions represent real social costs. Whenever considering costs, the appropriate viewpoint should be selected, whether social or private!

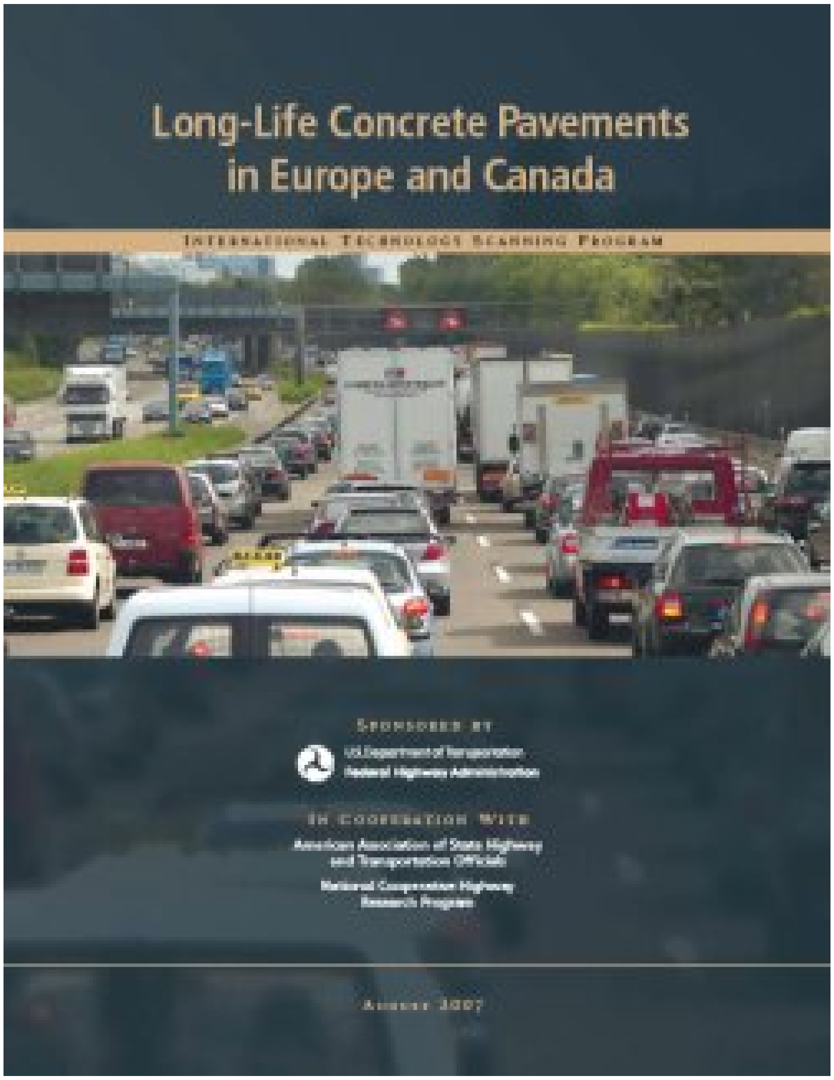

Figure 6.1 - Illustration of Good Roadway Pavement Condition but Heavy Traffic Congestion

Source: FHWA, Public Domain, https://international.fhwa.dot.gov/pubs/pl07027/.

6.2 Short Run Cost Functions for Infrastructure

Economists differentiate between short run and long run cost functions. In the short run, capital facilities are fixed. That is, an infrastructure manager must deal with the existing facilities. Any major capital project will take a year or more to be implemented to change facilities. In the long run, capital projects may be implemented, so additional capacity and facilities may be added.

Short and long run are useful distinctions for developing cost functions, but there are many cases in which intermediate run cost functions may be needed, when operational changes might be accomplished. For example, a transit manager may be limited to no changes in operations in the short run. However, schedule and route changes may be made without major capital expenditure. Vehicle fleets can be altered with new purchases in a somewhat longer time frame. Over the long run, capital facilities such as garages, rail lines and busways might be changed.

Costs can be divided into fixed costs of providing a facility and variable costs which depend upon usage. Fixed costs would be the cost of infrastructure services even without usage. Examples include:

- Roadways for transportation
- Generating plants, transmission lines and distribution lines for power
- Pumps, pipes and storage for water systems
- Buildings for office infrastructure.

In many infrastructure cases, these fixed costs may be substantial.

Variable costs are incurred to provide infrastructure use. These costs generally increase as the amount of usage increases. For example, more maintenance is needed as the travel volume on a roadway increases. As another example, more building occupants will result in more power use, bathroom use and elevator trips. In most infrastructure systems, there are capacity constraints in which the variable cost increase rapidly as capacity is approached. An example is the roadway congestion shown in Figure 6.1 in which the user cost of travel is quite high. Buildings often have a maximum allowable occupancy, but crowding may be uncomfortable even before this maximum is attained.

Figure 6.2 illustrates the important short fun cost functions of interest for infrastructure management. The top graph in Figure 6.2 shows a fixed cost (F) even with no usage. As usage increases, the short run total cost (SRTC(q)) increases, where q is a measure of usage such as traffic volume. If no capacity constraints or congestion effects exist, then the SRTC might increase as a straight line.

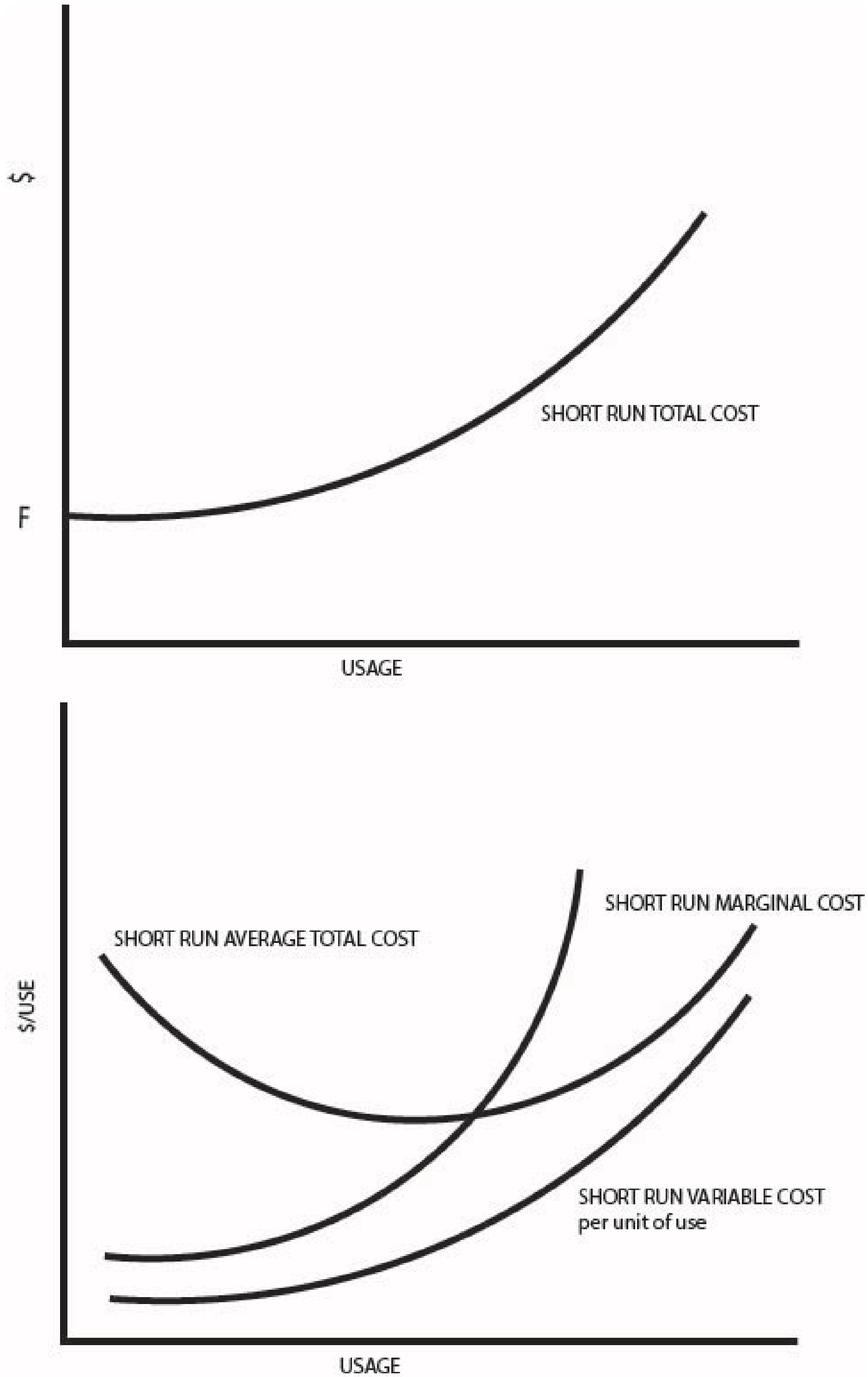

Figure 6.2 - Illustration of Short Run Cost Functions - Total, Avg. Total, Avg.Variable and Marginal

Source: Authors

The bottom graph in Figure 6.2 shows three different short run cost curves:

- Short Run Average Total Cost is the total cost divided by usage: $SRATC(q) = \frac{SRTC(q)}{q}$. This curve initially declines as fixed costs are spread over more usage. Eventually, capacity constraints and congestion result in higher costs and the SRATC begins to increase. A line drawn from the origin to the SRTC curve has a slope equal to the short run average total cost. The low point of the SRATC curve occurs where such a line has minimum slope and is tangent to the SRTC curve.
- Short Run Average Variable Cost is the total cost less fixed cost divided by usage:

$$SRAVC(q) = \frac{[SRTC(q) - F]}{q}$$

  This curve increases as capacity constraints and congestion result in higher costs. In the absence of such effects, the SRAVC(q) would be a flat, horizontal line.
- Short Run Marginal Cost is the derivative of the SRTC with respect to q (or approximately the change in total cost from an additional unit of usage: $SRMC(q) = \frac{\delta SRTC(q)}{\delta q} \approx \frac{[SRTC(q) - SRTC(q-1)]}{q}$. The SRMC begins at a low value and increases as capacity constraints and congestion effects. The SRMC crosses the SRATC curve at its lowest, inflection point. Beyond this point, the marginal cost of additional usage exceeds the average cost.

As noted in the introduction, these various cost curves will differ depending upon the analysis viewpoint adopted. The major changes occur if external and user costs are included or not included. For a roadway system, user costs would include vehicle operating costs, travel time opportunity cost and potential costs from crashes. Vehicle operating costs include taxes that support roadway maintenance and construction in many cases. Travel time opportunity cost will likely vary with the income (or wealth) of the traveler and the opportunities foregone. A passenger in an autonomous, self-driving vehicle might have low travel time opportunity cost since the passenger could be doing activities other than driving. External costs would include air emissions effects, congestion and crash costs. Many of these ‘external’ costs are external to any individual traveler but are borne by other travelers. For example, an additional vehicle may add congestion that is a travel time penalty for the other vehicles on the road.

For telecommunications infrastructure, these cost functions would differ by type of technology used. For broadcast, over-the-air radio and television stations, all costs are fixed and no congestion effects occur so the SRTC function would be a horizontal line.

As many users can listen or watch as are in the area being served. This is an unusual situation and represents a 'public' good in the parlance of economics in which users cannot be easily excluded and do not interfere with other users. In contrast, cellular service infrastructure has capacity limits in base units, so greater usage imposes user costs in the form of inferior service.

6.3 Demand Fluctuation with Low, Medium and High Usage Situations

As noted earlier, low usage is usually associated with declining average costs as fixed costs are spread over more users. For medium usage, the average costs are fairly flat and don't change dramatically. With high usage, capacity constraints and congestion come into play and the average costs begin to increase.

Usage of infrastructure systems tends to vary considerably over time and over geography. As a result, costs also tend to vary considerably. As an example, Figure 6.3 illustrates a typical variation in traffic volumes by time of day, with the peak travel occurring the morning and the late afternoon. Roadway congestion is heaviest in these peak hours of travel. As another example, Figure 6.4 illustrates typical electricity demand by time of day for two different months. In this case, there is variation in demand over the course of a day, but it is not as extreme a fluctuation as for roadway traffic. Figure 6.4 also shows that electricity demand varies over the course of a year, with higher demand in the summer likely due to air conditioning use.

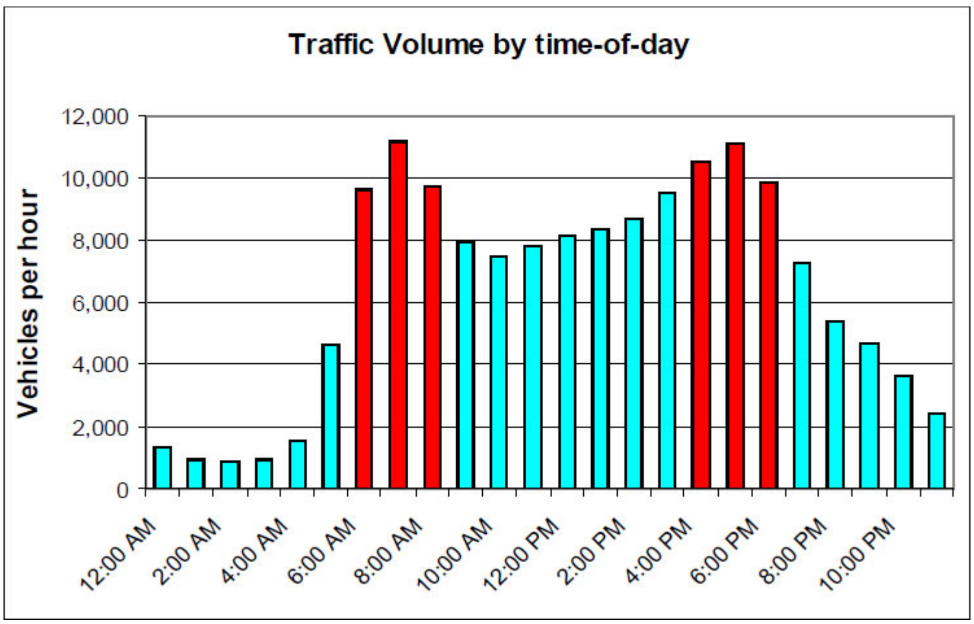

Figure 6.3 - Illustration of Typical Traffic Volume Variation by Time of Day

Source: FHWA, Public Domain, http://ops.fhwa.dot.gov/freewaymgmt/publications/documents/nrpc0610/workshop_materials/hov_to_hot/tabletop_poster.htm**. Commuting Rush Hours shown in Red**

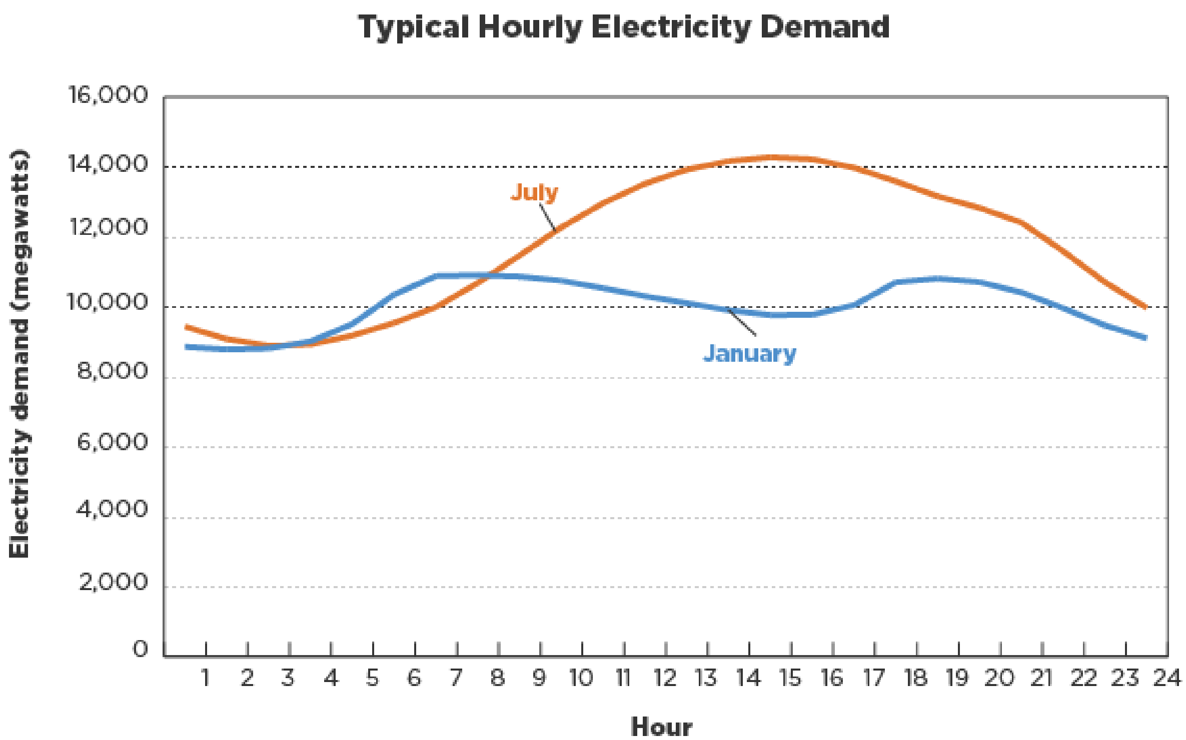

Figure 6.4 - Illustration of Typical Hourly Electricity Demand

Source: EPA, Public Domain. https://www.epa.gov/energy/electricity-delivery

Infrastructure managers often must respond to these fluctuating demands. In many cases, maintenance activities are scheduled for low usage periods to avoid imposing costs. For example, building floors may be cleaned at night. As another example, power grid managers must respond to not only varying demand (as shown in Figure 6.4), but also varying supply as solar and wind generators respond to environmental conditions.

Another important variation in demand for many infrastructure systems occurs over time, from year to year or over the course of decades. For example, demand for water will typically increase with an increase in population. Demand for electricity will also typically increase with population, but may also depend upon the numbers of households being served, incomes and new technologies. New technologies may reduce demand (with more energy efficient refrigerators for example) or increase demand (with battery electric vehicles or fancier entertainment systems).

To the extent that cost functions represent user costs, then the cost functions shown in Figure 6.2 can be coupled with demand functions to estimate equilibrium demand for service. Figure 6.5 illustrates a linear user cost and demand curve for a service. The equilibrium demand occurs at the intersection of the two curves with usage q_e and user cost p_e. Of course, demand is likely to be varying over time, so the equilibrium demand and user costs will similarly vary.

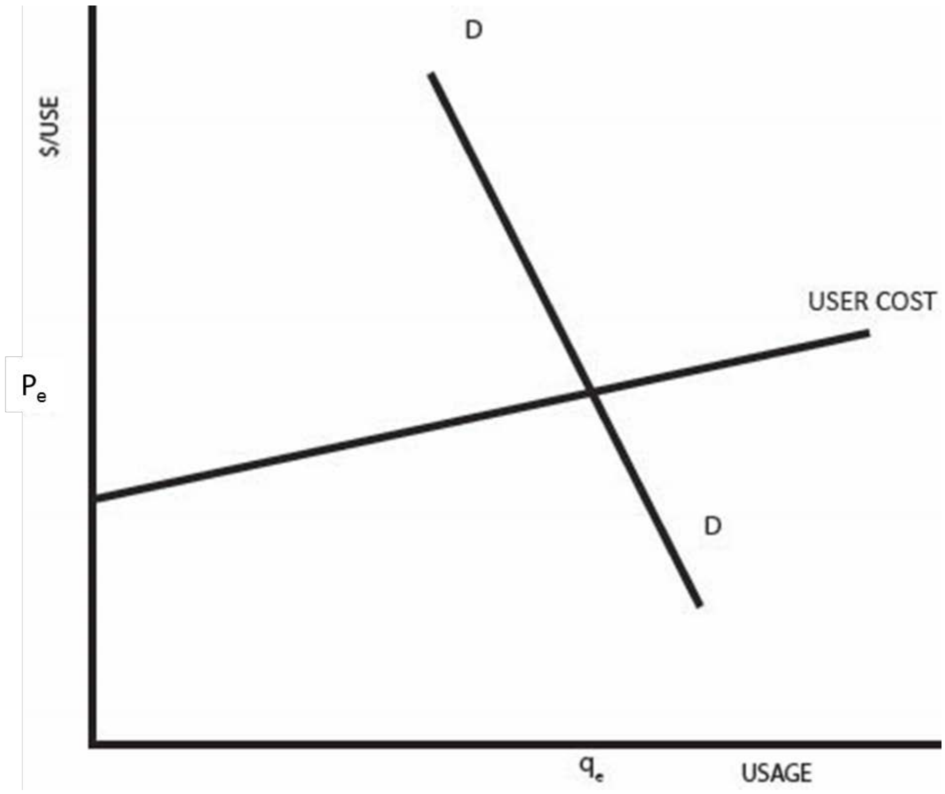

Figure 6.5 - Illustration of Cost Functions with Equilibrium Usage qe and User Cost pe

Source: Authors

6.4 Budgets and Revenues from Usage

In addition to the cost implications of different levels of infrastructure usage, there is often a revenue effect. Many infrastructure systems obtain revenues from user fees such as power sales or gasoline taxes. In turn, budgets for infrastructure maintenance and rehabilitation rely upon these revenues. The alternative to using user fees is to rely on general taxation of some sort, but this is only feasible for public infrastructure.

Generally, user fees can be set at any level. A few cases of user fee strategies are of interest:

- Set user fees equal to the short run average total cost of providing the infrastructure. In this case, the infrastructure provider is fully funded and compensated for the infrastructure service costs.
- Set user fees equal to an amount that maximizes total revenue. This strategy can be pursued with an optimization problem to maximize revenue (p*q where p

is user fee and q is equilibrium usage) subject to the demand function (q = f(p,x) where f(p,x) is a demand function with usage dependent upon the user fee and other factors x). Even with a maximizing revenue strategy, usage may not be sufficiently high to cover all agency costs. For example, the Pennsylvania turnpike has increased tolls every year from 2008 to 2016 and made transfer payments to the Commonwealth of Pennsylvania, but the managers feel that the revenues are insufficient in the long run to maintain the system effectively and make required transfer payments (Pittsburgh Post-Gazette, 2016).

- Set user fees in accord with user's willingness-to-pay. Demand curves reflect individual's willingness-to-pay for infrastructure services. If the user cost function shifted up in Figure 6.5, some usage would disappear but a remaining amount of usage demand would continue at higher user cost. With a single user cost, the revenue would be roughly $q_e * p_e$ in figure 6.5 (less any user costs incurred directly rather than as a service price). Perfect price discrimination would gain revenue equal to the complete area under the demand curve in Figure 6.5 (again less any user costs incurred directly). However, individuals don't usually reveal their willingness-to-pay for service and there are restrictions on discriminating among different types of users. Indirect methods can be adopted, however, such as lower airline fares for earlier purchases or for trips involving a Saturday night stay. Business travelers with a higher willingness-to-pay tend to make late purchases and not stay at destinations over a weekend.
- Set user fees equal to short run marginal cost. This is a common economics prescription because this strategy will minimize overall costs as long as the short run marginal cost function includes all relevant social costs (including externalities). Users would be paying exactly the cost associated with their service use. Unfortunately, it is difficult to impose short run marginal cost pricing exactly since demand fluctuates so much. An example of approximating this policy appears in Figure 6.6, where toll on a roadway in San Diego CA increase during peak periods of travel demand. By increasing tolls, some users would be diverted from the roadway and congestion costs avoided.

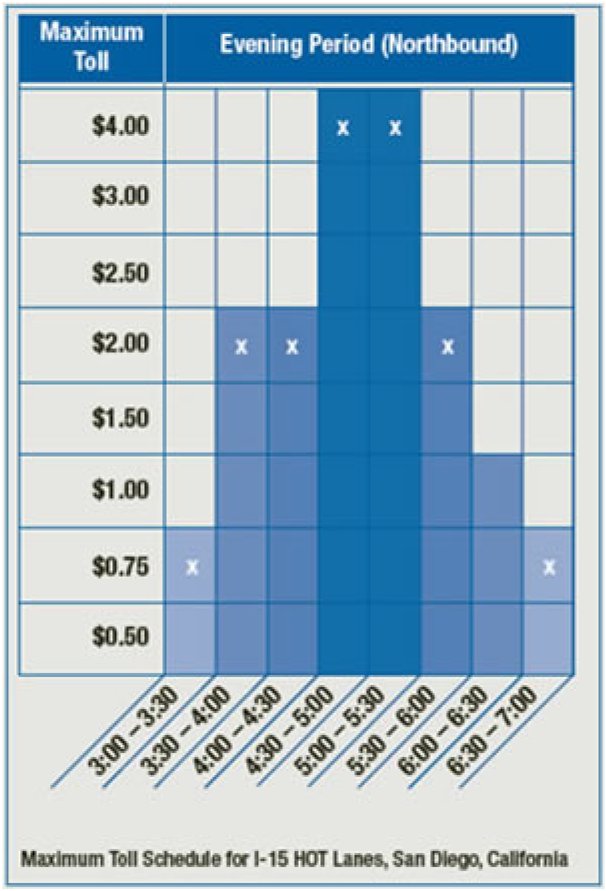

Figure 6.6 - Illustration of User Charges (Tolls) Increasing During Peak Usage Periods

Source: FHWA, Public Domain. http://ops.fhwa.dot.gov/publications/congestionpricing/sec2.htm

6.5 Life Cycle Costs, Taxes and Finance of Infrastructure

For long term rehabilitation investment planning, a life cycle viewpoint is normally used. 'Life cycle' in this context generally refers to a planning horizon for investments and not necessarily the obsolescence of some infrastructure. In performing life cycle analysis, you must select an appropriate planning horizon, a discount rate to account for the time value of money, and forecast benefits and costs of the infrastructure over the course of the planning horizon.

Selection of a planning horizon and a discount rate are often organizational choices, so most infrastructure managers need not be concerned with these two inputs. For the US, any project involving federal dollars must use the discount rate chosen by the US Office of Management and Budget (OMB, 2015). In the absence of organizational guidance, an infrastructure manager might use a discount rate reflecting marketplace long term borrowing rates and a planning horizon consistent with the expected useful lifetime of the infrastructure. For example, a planning horizon for a building might be fifty years, while a cellular hub might be ten years.

Even formulation of the short run cost functions discussed earlier can involve life cycle cost analysis to estimate the fixed costs of infrastructure in each period. Infrastructure typically requires an initial large capital expenditure for construction, and this fixed cost is usually annualized to uniform amounts to obtain the fixed costs allocated to any year of operation. The formula for anualization of an initial cost P to uniform amounts U over a planning period with n compounding periods at a discount rate I is (Au, 1992):

$$U = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \qquad \text{Equation 6.1}$$

Where U is uniform annualized amount, P is the present expenditure, i is a discount rate and n is the planning horizon (or technically the number of compounding periods). This process is equivalent to that of assuming a mortgage on the infrastructure component in which the entire construction cost is borrowed at an interest rate of i and a repayment period of n years.

Why isn't the uniform amount simply the value P divided by the number of payment periods, $\frac{P}{n}$? The use of a discount rate reflects the 'time value of money.' Lenders usually require a return on their lending, so they charge an interest rate. Individuals always prefer receiving money in the present rather than an equivalent amount in the future. The amount of extra required to make a future amount equivalent is a personal discount rate. Organizational discount rates are typically set with reference to the market equilibrium for long term borrowing.

In addition to the initial capital construction expenditure, infrastructure will often have major expenditures associated with rehabilitation. Figure 6.7 illustrates this type of rehabilitation. The pavement condition deteriorates during use and weathering until a rehabilitation occurs. The rehabilitations have lower cost than the initial construction and take place over the service lifetime of the pavement. For discussion of methods of estimating such costs, see Hendrickson (2008).

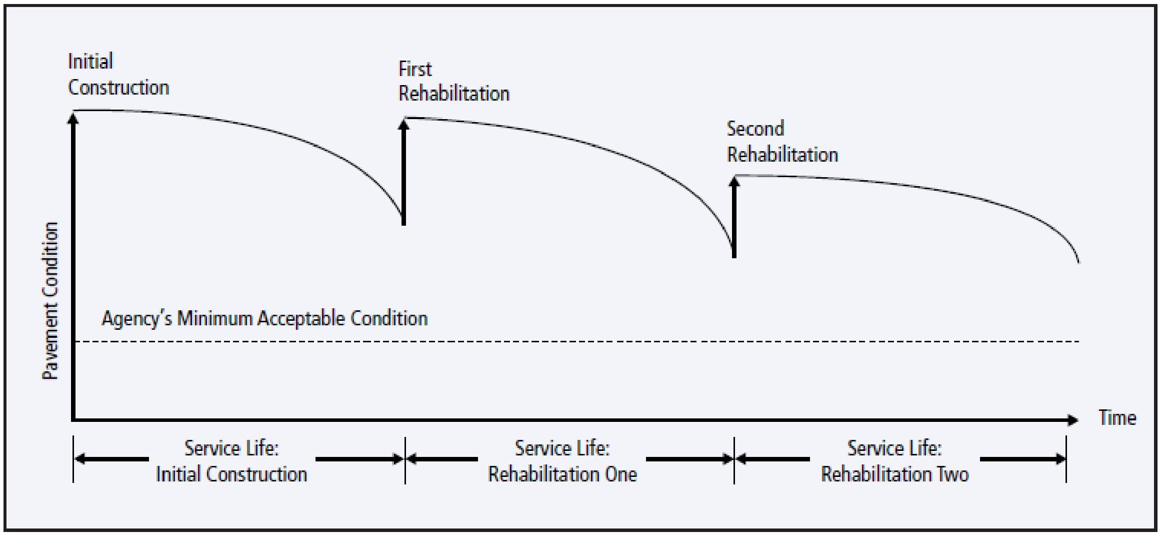

Figure 6.7 - Illustration of Life Cycle Costs for Pavement Construction and Rehabilitation

Source: FHWA 2002, Public Domain,

How can these rehabilitation expenses be converted into a uniform annual cost? The most direct means is to find the present value of such costs over the infrastructure lifetime by discounting future costs:

$$P = \sum_{(t=o)}^{n} F_t (1+i)^{-t}$$

Equation 6.2

Where P is present value, t is a time index, n is the planning horizon, F_t is the cost incurred in year t, and i is the discount rate. Uniform costs can then be obtained using Equation 6.1.

As a numerical example, suppose the costs illustrated in Figure 6.7 are estimated as shown in Table 6.1. With a 30 year planning horizon and a 1% discount rate, the life cycle costs (in $ million) would be:

P = Initial Construction Cost + Discounted First and Second Rehabilitation + Discounted Maintenance Cost

$$= 5 + \frac{2}{1.01^{10}} + \frac{1}{1.01^{20}} + \sum_{t=1}^{30} 0.1 * 1.01^{-t}$$

= 5 + 1.8 + 0.8 + 2.6 = 10.2

Equation 6.3

For a social cost analysis of the pavement, user costs of roadway delays for construction might be added.

Table 6.1 - Illustration of Costs for a Life Cycle Cost Analysis

Cost Component	Year of Occurrence	Cost Estimate (Base Year $)
Initial Construction	0	$ 5 million
First Rehabilitation	10	$ 2 million
Second Rehabilitation	20	$ 1 million
Annual Maintenance	Each year 1-30	$ 0.1 million

Inflation and deflation will affect life cycle cost analysis if current dollars are used for analysis. With inflation, the purchasing value of a unit of currency declines over time; deflation reflects an increase in the value of a currency. Current dollar amounts can be converted to 'real' or base year dollar amounts by applying an inflation index adjustment: $Index_{base\ year} / Index_t$ or by discounting using Eq. 6.2 and the expected rate of inflation. Different types of infrastructure have their own inflation indexes or a general index such as the gross domestic product index can be used. Life cycle cost estimates are generally made in base year 'real' dollars. Financial agreements for payments such as mortgages usually are based upon current dollars. With these mixed dollar amounts, you should apply an inflation calculator to convert to one type of dollar amounts.

Discount rates also can be for constant 'real' dollars or for current inflated dollars. The relationship is:

$$I' = I + j + ij \qquad \text{Equation 6.4}$$

Where I' is the annual discount rate including inflation (for current dollar discounting), I is the real discount rate, and j is the inflation rate. Readers unfamiliar with these engineering economics calculations can refer to Au (1992) or other textbooks.

For investment decisions, the life cycle costs can be compared to the life cycle benefits in a similar fashion by placing the costs and benefits into present values. In this case, you can examine the net present value of an investment: $NPV = P_{benefit} – P_{cost}$. With a series of mutually exclusive infrastructure design or rehabilitation options, you might select the one that maximizes this net present value.

Spreadsheet or numerical analysis software is readily available to perform the engineering economics calculations for analyzing life cycle costs. For a spreadsheet, a separate row (or if you prefer a separate column) is used for each period and the costs and benefits recorded. The discounting functions in Equations 6.1 and 6.2 are usually already available in the software.

6.6 Long Run Investment Decisions and Cost Functions

It is possible to also develop long run cost functions in which the infrastructure itself may be changed to maximize net present value. In particular, rather than incur the high costs of congestion in high usage situations (as in Figure 6.3), an infrastructure manager might add capacity as rehabilitation investments are made.

The long run total cost curve is the lower cost envelope of all possible short run total cost options. Figure 6.8 illustrates the situation in which two possible infrastructure capacity options exist (which might represent different size components, an additional floor on a parking garage or an additional lane of roadway capacity). There is a usage point (q_b) in Figure 6.8 at which it is desirable to shift from option 1 to the larger capacity option 2. The long run average total cost has a significant turn at this usage breakpoint, with scale economies beginning again! The long run marginal cost curve has a discontinuity at the breakpoint. With lower demand (demand curve D), the smaller option has lower costs, but with higher demand (demand curve D'), the larger option 2 is more desirable.

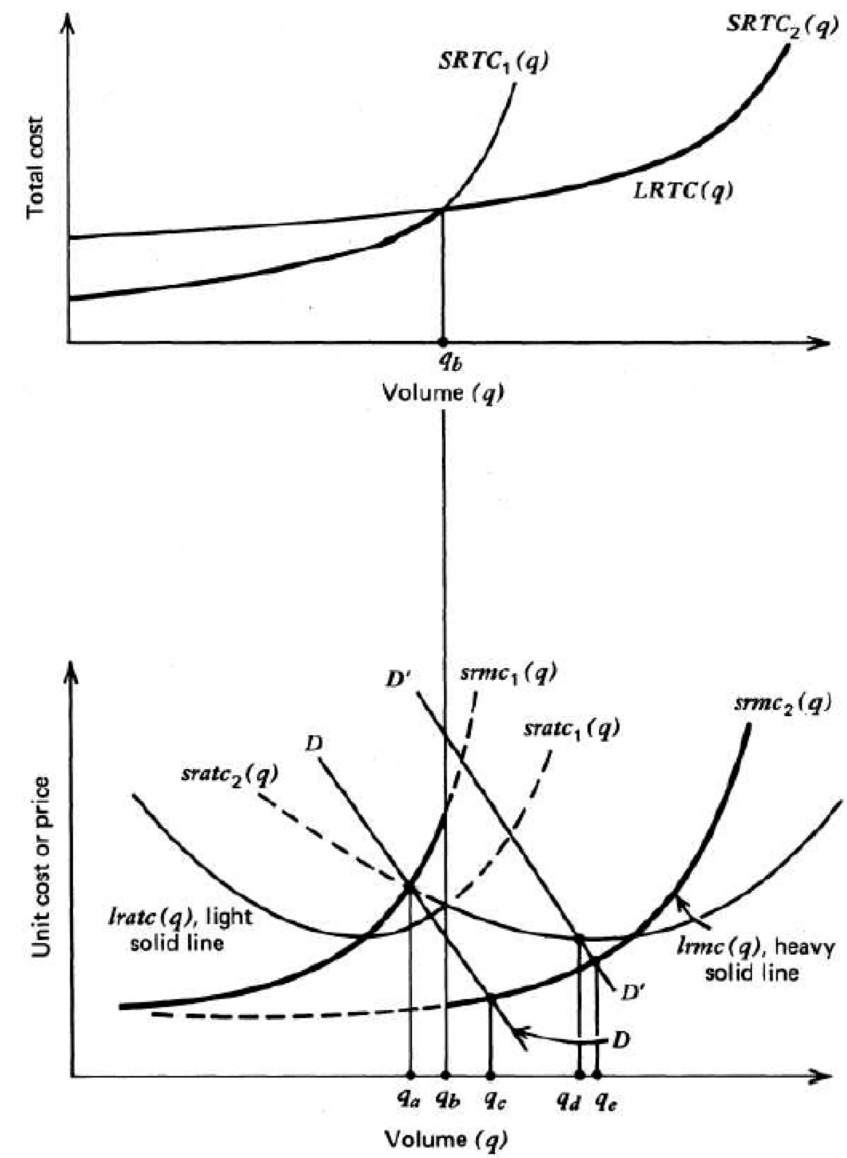

Figure 6.8 - Illustration of Long Run Cost Curves with Two Distinct Infrastructure Options

Source: Hendrickson and Matthews, 2011

6.7 Decision Analysis and Monte Carlo Simulation for Investment Decisions

The earlier discussion in this chapter noted the effects of demand fluctuations, but did not address uncertainty and contingencies. However, costs and demands are likely to be quite uncertain to forecast. Moreover, external events such as extreme events may also profoundly affect infrastructure costs, demand and usage.

A common approach to dealing with uncertainty is to employ some form of 'Monte Carlo' simulation, where the name 'Monte Carlo' refers to a casino in Monaco with gambling on chance events. Monte Carlo simulation requires not only cash flow estimates in each year, but also the probabilistic distributions of such cash flows as input information. As a result, there is considerably more work to prepare input (which is expensive and still uncertain) and to perform calculations (which fortunately is not very expensive with modern information technology).

The essential idea of Monte Carlo simulation is to obtain a sample from input parameter distributions and then assess the outcome from this sample. This process of sampling and assessment is repeated numerous times, resulting in a distribution of possible outcomes. So rather than a fixed, deterministic estimate of life cycle costs, Monte Carlo simulation results in a probability distribution of possible life cycle costs.

As an example, suppose you decided to do a Monte Carlo simulation of the life cycle roadway cost shown in Table 6.1 and Equation 6.3. The parameters in Table 6.1 might be used as input for a Monte Carlo roadway life cycle cost analysis with the following assumptions:

Table 6.2 - Illustrative Input Parameter Distributions for a Roadway Life Cycle Cost

Component	Year of Occurrence	Cost
Initial Construction	0	N(5,1)
First Rehabilitation	U[8,12]	N(2,2)
Second Rehabilitation	U[16,24]	N(1,1)
Maintenance	Each Year 1-30	U[0.05,0.15]

Source: Authors

Monte Carlo Simulation (Note: N(μ, σ) is normal distribution with mean μ and standard deviation σ, and U[i,u] is the uniform distribution with lower bound i and upper bound u).

The assumed parameter distributions are either normal or uniform with the mean equal to the values in Table 6.2. As a reminder, Figure 6.9 illustrates a normal distribution with different parameter values. To perform the Monte Carlo simulation, numerous samples (perhaps 500) would be drawn from the relevant distributions, each to form a single example case, and then Equation 6.3 applied to calculate life cycle costs for that case. The result would be numerous observations of possible life cycle costs.

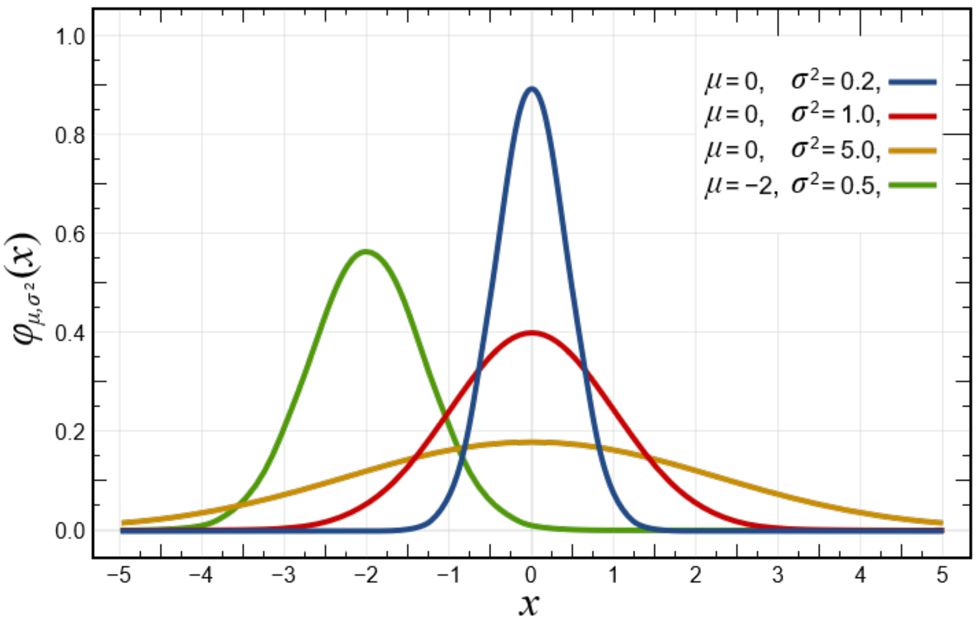

Figure 6.9 - Illustration of Normal Distributions with Different Parameters

Source: By Inductiveload - self-made, Mathematica, Inkscape, Public Domain, via Wikimedia Commons https://commons.wikimedia.org/w/index.php?curid=3817954

Many software programs easily accommodate Monte Carlo simulation, including the Excel spreadsheet and Matlab. These software programs have regular functions or subprograms to generate random samples from input distributions. Monte Carlo simulations find use in a variety of application domains beyond infrastructure management, including environmental life cycle assessment and production planning. While Monte Carlo simulation explicitly considers uncertainty with stochastic inputs, it is crucially dependent upon the correctness of these input assumptions and modelling the effects of inputs. Accurately knowing the distributions of infrastructure costs and usage is unlikely. Users of Monte Carlo simulation should be aware of the classic computer adage: 'garbage in, garbage out.' Just because the results come from a complicated computer program, inaccurate inputs will not result in accurate results.

Another approach to exploring the effects of uncertainty is to use scenario and decision analysis. For our roadway cost example, scenario analysis might pertain to major underlying usage influences or natural disasters. For example, new industrial development in the roadway vicinity may result in much larger usage and faster pavement deterioration. As another example, major rehabilitation may be required in the case of earthquakes. Each of these situations may be a different scenario with different life cycle costs as a consequence. The scenarios might each have a Monte Carlo simulation analysis with different assumptions about input distributions.

Decision analysis would go further and include probabilities associated with different scenarios. Each scenario might also have different assumptions about future actions, such as a decision to widen the roadway in connection with a rehabilitation action. For this decision analysis approach, common applications would include both cost and benefit assessments to evaluate net present value effects.

6.8 Exercises

P6.1 **(4 pts)** Suppose you have an electric powered building water heater.

a. Graph the Short Run Total Cost (SRTC) and the Long Run Total Cost (LRTC) of a water heater.
b. Suppose you have an electric water heater and your utility introduces variable pricing by time of day. How do you minimize cost of providing your hot water needs?

P6.2 **(16 pts)** Develop a life cycle cost estimate for the differences between compressed gas (CNG) and bio-diesel (B20) alternative buses. We can ignore drivers and other overhead expenses since they are the same for the two vehicles. Use the following data:

- Bus purchase: $ 342,366 for CNG, $ 319,709 for B20.
- Assume 12 year life, with 37,000 miles per year of operation.
- Assume average speed of 12.72 mph, 3.27 mpg for CNG (where 1 gal = 126 cu.ft. NG) and 3.80 mpg for B20.
- Assume CNG is $ 2.00 per gallon and B20 is $ 3.00 per gallon in current dollars.
- Assume maintenance cost of $ 9,000 per year for CNG bus and $ 7,000 for B20.
- Assume a discount rate of 4%.

a. What is the annual operating cost of the two buses (excluding drivers and other overhead items)?
b. What is the net present value of the two buses’ cost streams?
c. What is the annualized uniform cost of the two buses?
d. What is the annualized cost per mile of the two buses?
e. Assuming 40 seats per bus, what is the annualized cost per seat-mile of the two buses?
f. What would be the impact on net present value of the cost differences if CNG doubled in price? What if both CNG and bio-diesel doubled?
g. Capital costs for buses are usually 100% subsidized and do not appear in the agency operating costs. How much is the annualized cost per mile of the two buses excluding capital costs?
h. Suppose that a driver and other expenses added $ 50. per hour to operating costs. How many riders would be needed to cover the costs of the cheaper of these buses for the 28X route? (Assume a one hour, 20 mile trip and a fare per rider of $ 3.25).

6.9 References

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Chapter 7: Interdependence, Resiliency and Security

7.1 Introduction

Infrastructure managers may go long periods of time without significant failures, extreme events or security breaches occurring for their infrastructure. However, a manager must be prepared to deal with such events and should plan ahead to mitigate the potential costs of such events. This chapter discusses approaches to prepare for and to mitigate the damages of such events.

The list of potential adverse events is long indeed:

- Critical infrastructure failure, such as electricity, water supply, telecommunications, etc.,
- Extreme events, such as earthquakes, fires, floods, hurricanes, landslides, lightning strikes, tornadoes, etc., and
- Security problems, such as bombs, guns, computer hacking, riots, etc.

News media regularly report such events throughout the world on a daily basis. Even the resignation or retirement of an employee with critical management knowledge can reveal a lack of resiliency in management.

While the chance of occurrence for any of these events is quite low in any particular year, the probability is typically not zero. The exception might be physically impossible occurrences such as flooding to a facility at the top of a hill (but then the top of the hill may be more prone to have high wind!). Figure 7.1 illustrates the estimates of probabilities of significant (magnitude greater than 6.7) earthquakes in California. The figure outlines the boundaries of California in white and the various earthquake fault lines show up as higher probability linear segments. The probability scale ranges from 10^{-6} (0.0001% chance per year) in blue to 10^{-2} (1% chance per year) in purple. While these particular estimates are uncertain, California infrastructure managers should be prepared for an earthquake event!

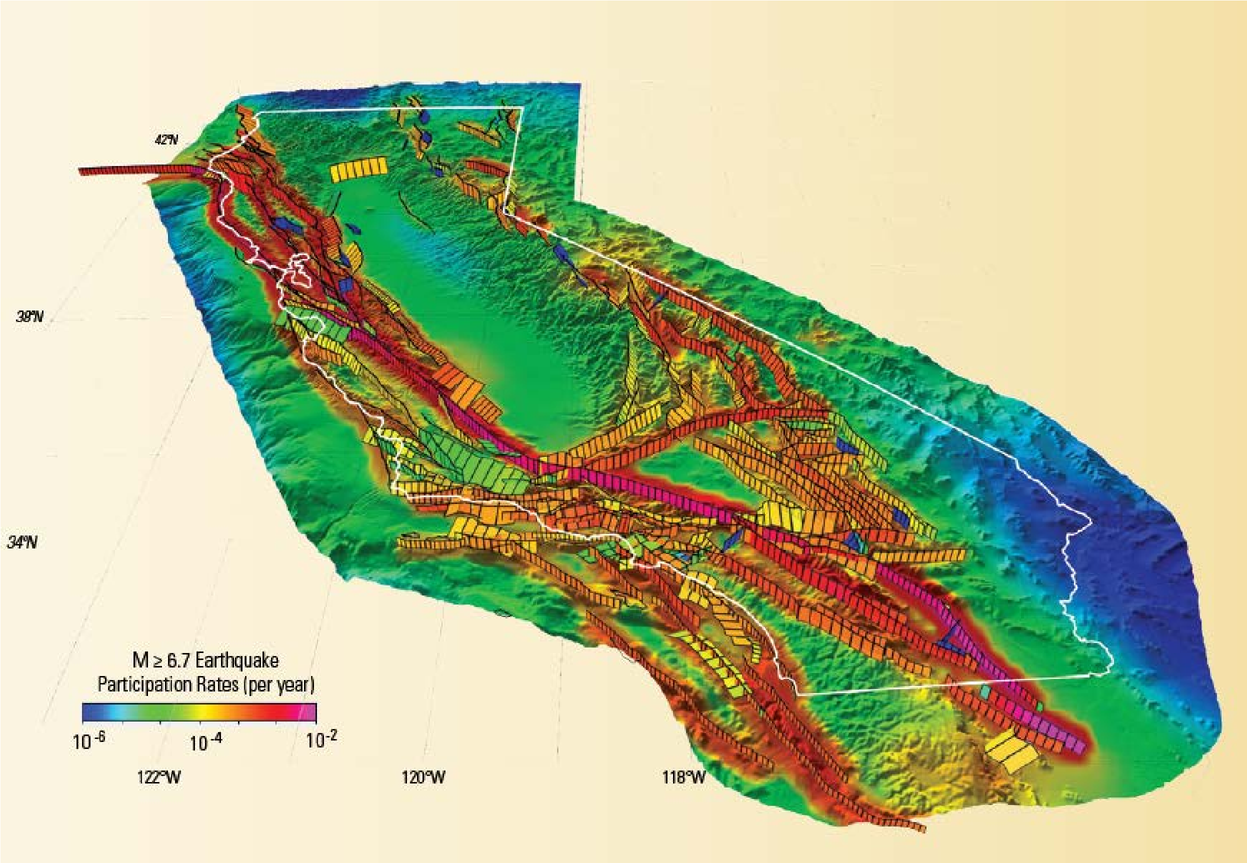

Figure 7.1 - Estimated Probability of Significant Earthquakes per Year in California

Source: Field, 2013, Public Domain, http://pubs.usgs.gov/of/2013/1165/

Even with a low probability of an event occurring, the number of repetitions of the underlying risk opportunity may result in a significant risk. For example, suppose your risk of falling from a scaffold is 0.1% in any particular day, which likely seems like a small risk to you. However, if you are on a scaffold 365 days a year, the probability of a fall over the course of a year would be (as discussed in Chapter 4):

$$P_r\{fall\} = 1 - P_r\{no\ fall\}^{365} = 1 - 0.69 = 0.31 \qquad \text{Equation 7.1}$$

So you would have a 31% chance of a fall over the course of a year spent on scaffolding. Over fifteen years, the probability of a fall would increase to 99.6%. Similarly, riding a bike to and from work might have a low probability of experiencing a crash, but over a long period of time the likelihood of a crash increases. Better risk management might make changes such as safety straps on scaffolding or dedicated bike lanes. The result would be to lower the daily probability of an event considerably.

In addition to the chance of occurrence, the other dimension of risk management is to consider the severity of consequences for an event. A small flood may have some costs, but an organization could likely recover its infrastructure services rather quickly. In contrast, a large flood or a terrorist attack could have major consequences, including subsequent legal procedures. Similarly, small earthquakes or wildfires may have limited impacts, but a large earthquake or fire could require major rehabilitation or rebuilding.

Infrastructure managers should prepare for events with high frequency and low impact such as heavy rainstorms. For example, a large company with multiple oil platforms in the Gulf of Mexico should be prepared to secure and evacuate the platforms regularly due to hurricanes. But managers also need to prepare for high impact, low probability events such as earthquakes. Fortunately, high impact and high probability risks are rare. Also, low impact and small probability events are less of a concern than these other categories. Figure 7.2 illustrates the disruption probability and consequences for several organizational threats.

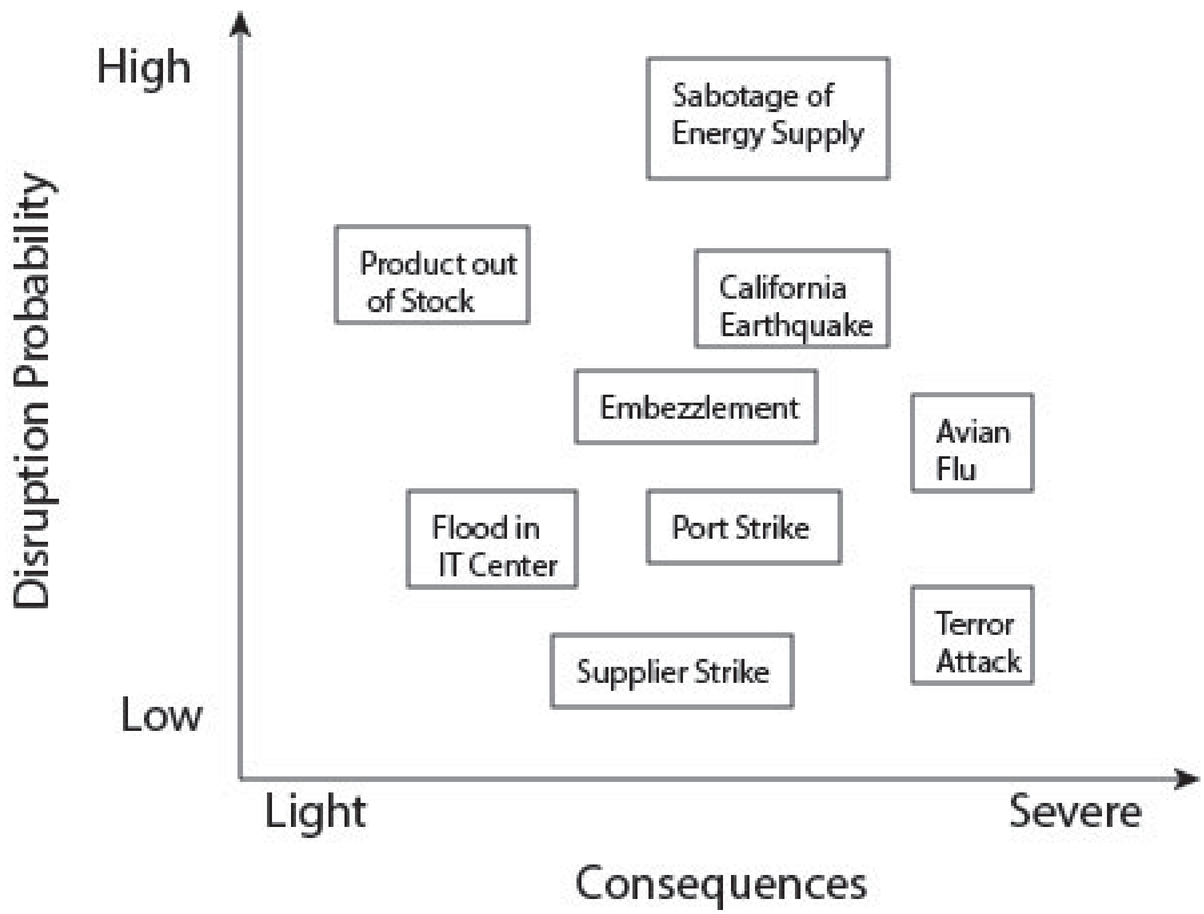

Figure 7.2 - Illustration of Organizational Risk Probabilities and Consequences

Source: Sheffi 2007. Redrawn and altered by Authors

As an example, Figure 7.3 shows identified risks for water and wastewater systems.

Most Significant Risks

- Natural disasters (such as impacts on water quality and quantity from floods, hurricanes, earthquakes, ice storms, pandemic flu and other geographic catastrophes)
- Economic implications of aging infrastructure
- Cyber events
- Capability in managing an area-wide loss of water
- Although the Water Sector has been defined as a lifeline sector, this is not commonly recognized among all relevant stakeholders, a situation that can escalate consequences during area-wide events

High Risks

- Economic costs of preparation and response: The Water Sector can create a large economic risk in a disaster, but there are insufficient funds to prepare for and address risks ahead of time
- Ignorance about the consequences of inaction and apathy from some stakeholders in utilities, the customer base, state/local government and Federal Government/Congress
- Inadequate coordination and information sharing during preparation, response and recovery
- Intentionally malicious acts
- Limited resource availability: Many utilities are faced with competing needs (e.g., regulatory, aging infrastructure, environmental and public health protection, and workforce succession requirements) that are immediate, concrete and can limit resource availability for implementing preparedness and resiliency improvements
- Unenforced and outdated requirements that do not address evolving threats

Medium Risks

- Lack of mutual aid agreements, effective education and outreach to emergency management, and lack of best practices for emergency response planning
- Technology interoperability issues that create information-sharing challenges during response
- Insufficient communication to water utility boards of the definition, management and prioritization of critical assets and needs

Source: Adapted from the *2013 Roadmap to a Secure and Resilient Water and Wastewater Sector*

Figure 7.3 - Risks for Water and Wastewater Systems

Source: DHS, Public Domain, https://www.dhs.gov/sites/default/files/publications/nipp-ssp-water-2015-508.pdf

Good infrastructure design and construction can significantly reduce the consequences of many risks. For example, earthquake resistant facility design has become required in earthquake prone areas. Similarly, adequate storm water systems (and good preventive maintenance) can reduce the risk of flooding.

7.2 Infrastructure Interdependencies

Infrastructure is interconnected, interdependent, and Complex. Infrastructure systems have complex connections and interdependencies that can lead to cascading failures. In many cases, infrastructure systems depend upon services provided by other infrastructure. For example, if electricity supply is disrupted, then water supplies may be affected since pumps and treatment plants require electricity. If gasoline stations and oil pipelines depend upon the power grid for electricity, then transportation services may be disruped. Second order effects can also occur. For example, if electricity supply failure occurs and affects water supplies, then agriculture will be affected and eventually banking and finance will have an effect. Figure 7.4 illustrates some of the interdependencies among six infrastructure services.

Geographic proximity can also result in infrastructure interdependencies. All the infrastructure on a flood plain may be vulnerable to a flood event. Similarly, an earthquake can disrupt multitude infrastructure systems, including bridges, buildings, pipelines, electricity transmission lines, fiber optic cables, ports and roadways.

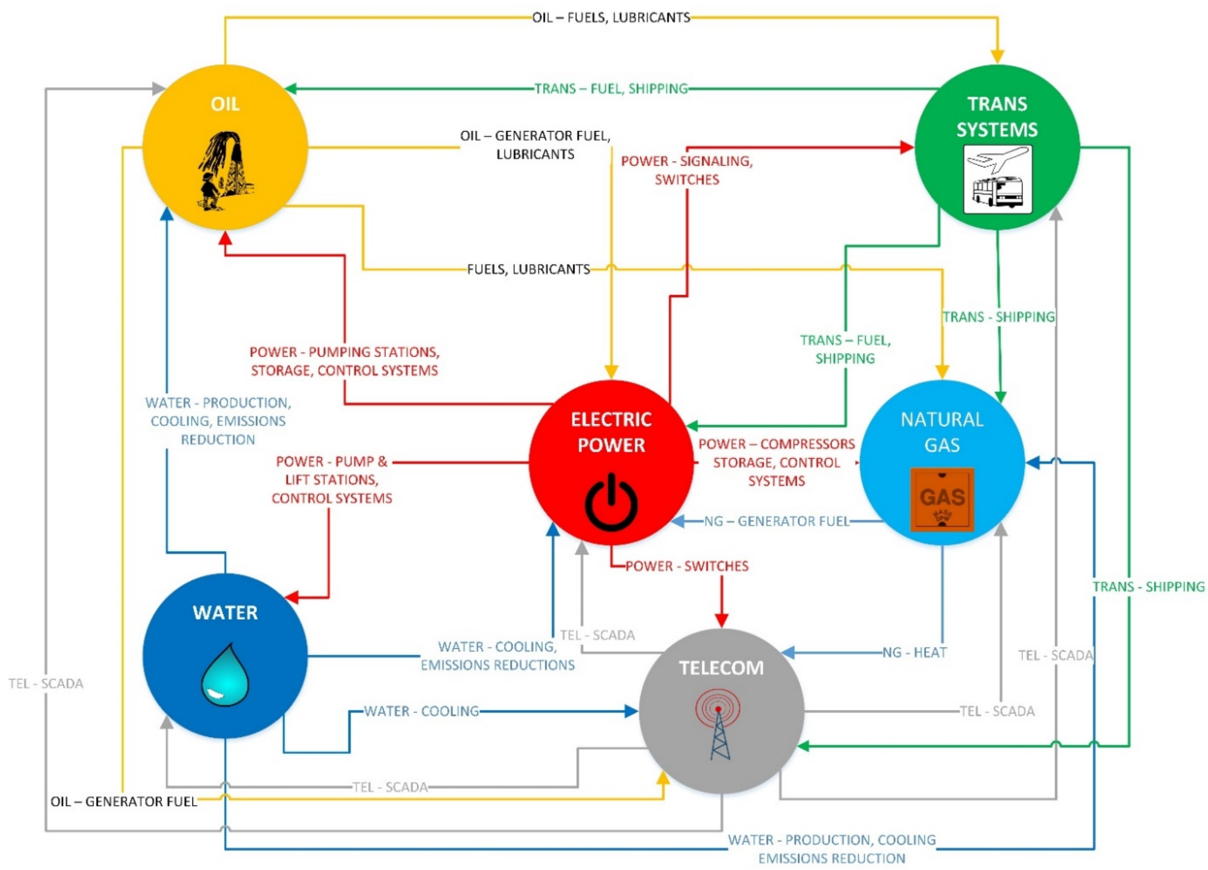

Figure 7.4 - Illustration of Infrastructure Interdependencies

Source: Rinaldi, 2001. Redrawn and altered by Authors. Note: SCADA is Supervisory Control and Data Acquisition.

Of course, infrastructure managers may be responsible for only one particular type of infrastructure. For example, a building manager usually relies upon the power grid for electricity, the local water supply utility for water, a telecommunications company for telephone and internet, and suppliers for a variety of resources. However, a building manager can estimate the likelihood and consequences of disruptions. Moreover, planning ahead can reduce the consequences of disruptions. Backup power systems for essential services (such as lighting) or back up communications capability can be installed in the building.

Modern communications and information technology has become pervasive in the provision of infrastructure services. Note that supervisory control and data acquisition (SCADA) and communications has the most occurrences among the interdependencies shown in Figure 7.3. Telecommunications companies need to be ready for rapid response to restore services in the event of disruptions to avoid cascading effects.

7.3 Improving Infrastructure Resiliency

Infrastructure resiliency is the capability to restore infrastructure to its original state after a disruption occurs. Improved resiliency can be achieved with planning for disruptions and having resources available to respond to disruptions. Figure 7.5 illustrates the various time periods. Prior to an incident or disaster, preparations can be made. At the time of an incident, the infrastructure performance degrades, especially as failures propagate through associated components. In extreme cases, the infrastructure performance may degrade to closure (so I would equal zero in Figure 7.5). A recovery period ensues until the infrastructure returns to normal performance.

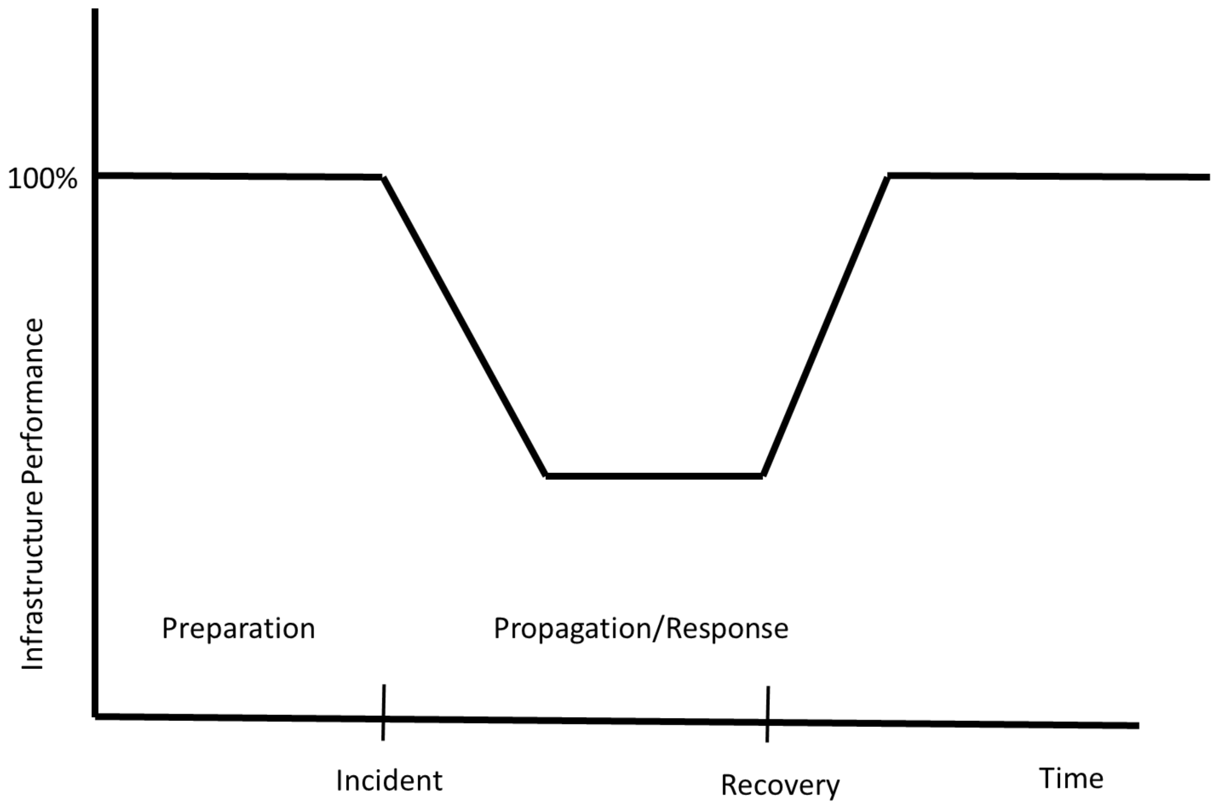

Figure 7.5 - Infrastructure Performance After an Incident

Source: Authors. More Resilient Infrastructure would have Lower Performance Reduction and Faster Recovery

Table 7.1 lists some strategies to improve resiliency along with technical, organizational, social and economic examples. The strategies are:

- Robustness may refer to facility design and construction but also includes good planning for emergencies and rehearsals.
- Redundancy includes strategies such as back-up power and lifeline resources such as food and water.
- Resourcefulness involves the resources that can be mobilized in response to an event.
- Rapidity is the speed at which restoration can occur.

Table 7.1 - Technical, Organization, Social and Economic Dimensions of Infrastructure Resiliency

Strategy	Technical	Organizational	Social	Economic
Robustness	Appropriate building codes and construction procedures.	Emergency operations planning and practice	Degree of community preparedness	Regional economic diversification for supply
Redundancy	Capacity for technical substitutions	Alternative sites for managing emergency operations	Availability of Housing options for disaster victims	Investment in backup systems
Resourcefulness	Availability of equipment and materials for response	Capacity to improvise and innovate	Capacity to address lifeline needs	Capacity to improvise
Rapidity	Restoration time	Reduced Reaction Time	Time to restore lifeline services	Time to regain capacity

Source: O'Rourke, 2007. Redrawn and altered by Authors

As an example of resiliency planning, consider an electricity utility. The utility can insure redundancy in transmission lines and power generation sources. Individual facilities can be design and built to withstand significant stresses. With major storms forecast, crews with equipment and supplies can be pre-positioned to respond to any outages rapidly. While the utility may still see disruptions, all of these activities will improve the resiliency of the utility.

Another example is planning for evacuation effectively. Figure 7.6 shows a 2005 evacuation of Houston due to forecast hurricane. During this evacuation, roadway lanes in to the city have been reversed to increase the available capacity. Unfortunately, the traffic volumes resulted in major traffic jams. Improved entry controls onto the highway could eliminate this type of jam.

Figure 7.6 - Hurricane Rita Evacuation Operations

Source: By Ashish from Houston, TX - I-45 & louetta... Rita Evacuation, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=2612379

Climate change and sea level rise are two factors that are increasing the importance of infrastructure resiliency. As average sea level increases, the likelihood of flooding increases. A variety of new strategies may be required, as with the response to Hurricane Sandy that flooded portions of the New York subway system.

Finally, the use of scenario analysis (as described in Chapter 6) may be useful for planning. A regular session to consider possible risks, preparedness, and documentation of procedures can be extremely useful.

7.4 Infrastructure Security

Security has become a major concern for infrastructure managers. Infrastructure systems have been targets of terrorist attacks, such as the attack on building facilities using airplanes by agents of Al-Qaeda on September 11, 2001. Numerous other examples exist, such as bombs place in subway systems and railcars. Theft is also a security concern for infrastructure systems.

Responses to improve security have been widespread. Physical barriers have been erected to prevent vehicles or unauthorized individuals to come onto vulnerable infrastructure. Surveillance for suspicious activity has been increased. Communication protocols with law enforcement agencies have been refined.

For an infrastructure manager, the key questions to ask are:

- What are the major risks facing my system?
- How can these risks be reduced?
- How much should be invested in security versus other resource needs?

The most frequent security threat is due to computer hacking. It is not uncommon to have numerous hacking attempts on a local network per day. Much of this activity is intended to reveal financial information, but some of it is malicious. As noted earlier, many infrastructure systems rely upon SCADA systems and communications software for operation, so the infrastructure services may be vulnerable to such attacks. Investment in good personnel and software protection is critical for such services.

7.5 Preparing for and Responding to Emergencies

Organizations should be prepared to respond to emergency situations. These situations may arise from a multitude of sources, including natural and man-made hazards. Large emergencies typically involve multiple infrastructure systems and large populations, so co-ordination with emergency services and managers is critical.

A few elements of preparation can be noted. First, a communications strategy should be in place. This strategy should include means of communicating with infrastructure users and response personnel. For example, a broadcast strategy of emergency communications via email and text messaging should be in place. The broadcast mechanism should be regularly tested.

A second component of emergency preparation is a decision making strategy. Who is empowered to make decisions in event of an emergency? Successors should also be identified in case the primary decision maker is not available.

In an emergency, knowledge of available resources may be critical. Where and what resources and emergencies supplies are positioned can be important information to aid effective decision making.

As noted earlier, pre-positioning personnel, equipment and supplies can be a very effective preparation strategy. Temporary bridges, transformers, power lines and the like can be all readied for rapid deployment.

Temporary facilities may also be needed for emergency operations. Shelters can be assembled for individuals made homeless by fires or other destruction. Dirt runways can be used for delivery of emergency supplies by air. Temporary cellular telephone and Wi-Fi stations can be moved in and installed rapidly.

Response to emergencies generally requires immediate attention from all the members of the infrastructure management team. Innovation, co-ordination and rapid decision making are necessary elements of a successful response!

7.6 Exercises

P7.1 **(10pts)** Using the latest EPA E-GRID 'Power Flows' spreadsheet available on the internet, you will find electricity export and import estimates for all of the states in the US.

a) What are top 5 importing and exporting states in terms of GWh? What about in terms of percent of state consumption? What are the reasons why states may import significant amounts of electricity?

b) Focus on the twelve Western United States. Does the western grid region come close to providing a 'zero balance' of imported and exported power? If not, what might be the cause of the net import or net export of this entire region?

c) Make a small optimization model to estimate the power flows in the 12 Western US states (i.e. try to match up the importing and exporting states and make the overall power flow balance). If necessary, use import/export data for a 'super' region located near Chicago to help your balance. Make a summary table, spreadsheet, etc. that shows where states get their imported power from (or export to). Assume that utilities try to minimize the transport cost of electricity, which is roughly proportional to distance between states; you can use a rough estimate of distance accurate to the nearest 500 miles. Report your results as a matrix in which entries represent the estimated flow between states and column and row totals represent exports and imports of power given from e-grid.

d) Let us simulate a storm along the west coast, with all transmission capability among WA, OR and CA knocked out (so these three inter-state distributions are set to zero. Other inter-state distributions are ok as well as in-state generation.). Re-estimate your flows for this case. What has changed, if anything?

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Chapter 8: Contract and Workflow Management

8.1 Introduction

Contract and workflow management are often major time commitments for infrastructure managers. Contract management is the process of ordering and monitoring outside organizations to do some work required for infrastructure management. Workflow management is the process of organizing and scheduling tasks related to infrastructure management. The extent to which tasks are contracted out will depend upon the internal resources available for infrastructure management.

As with many processes, information technology aids are available and useful for both contract and workflow management. As tasks are defined, they can be logged into a database, monitored and progress recorded. Contract documents and records are quite likely to be kept digitally by both the principal and the contractor. Either specialized or general purpose software can be used for these purposes.

Of course, contract and workflow management is not limited to the domain of infrastructure management. Large firms such as Amazon have very sophisticated financial, inventory and order tracking software. The transportation provider firm Uber has large numbers of contractor drivers as well as suppliers. Similarly, hospitals have systems in place for contracting and workflow management. We will focus on contracting and workflow management for infrastructure, although the processes are similar for other applications (Monczka et. al 2015; Van Der Aalst and Kees, 2004).

8.2 Contract Management

Contracting with outside organizations to perform infrastructure management tasks is both common and useful. Contracting has several advantages relative to performing all tasks within the infrastructure owner organization:

- Can provide more resources for peak work period demands. For example, major rehabilitation projects require significant resources of equipment and manpower which are typically beyond the regular resources in an ongoing infrastructure management organization. As a result, rehabilitation work is usually contracted out.
- Can provide access to specialized knowledge and equipment. Outside organizations can specialize in a particular area such as elevator or roof inspection, for which expertise is not needed year-round for the infrastructure

management organization. Similarly, road repaving is generally contracted out rather than maintaining specialized paving equipment in a municipality.

At the same time, contracting incurs costs for contact management and payments of profits to contractors.

Contracts come in a bewildering variety of forms. They can have many different payment terms and risk allocation provisions (Hendrickson, 2007). They typically vary between countries, organizations and type of work. They are also subject to complex legal forms and reviews. By and large, actual contract documents are prepared by a legal department or a professional organization and contract provisions are re-used extensively, so individual infrastructure managers do not need to draft new contract documents.

The important stages in contracting are shown in Figure 8.1 and discussed briefly below.   Not all of these stages will occur in every contracting process. For example, contract modifications may not be required in many cases.

1. Requirements definition is a process to specify the work desired from the contractor.   For a major rehabilitation project, this definition may require a significant component design process.
2. Contracting strategy formulation is series of decisions about the contracting process, such as pricing and time frame requirements.
3. Pre-Qualification is a process of selecting a group of potential contractors. Pre-qualification may be a subjective judgment by a manager or may be a formal process of application and qualification reviews. In many cases, infrastructure managers may have long term relationships with contractors and build up confidence and trust in their capabilities.
4. Request for a quote or proposal from potential contractors. The request will usually include pricing parameters and desired time frame for the work. Pricing options include fixed price, cost plus profit, guaranteed maximum price, and unit cost. Unit cost pricing is useful for ongoing contracts with numerous tasks. For example, a unit cost pricing for roadway repaving might have a price per lane-mile of repaving.
5. Negotiation and selection of a contractor can take many forms. A classic, competitive fixed bid approach receives monetary bids from pre-qualified contractors and awards the work on the basis of lowest costs. The infrastructure manager may also negotiate terms with multiple potential contractors and eventually award the contract to the most desirable terms.
6. Inspection and Quality Assurance is a post-award task to insure that the work is done to the desired requirements.

7. Contract modification is a common process. During the course of work, the desired requirements may change or unforeseen circumstances dictate different approaches. Contractors will typically be willing to negotiate contract modifications in response.
8. Payments and reporting are processes that make periodic and final payments to contractors as well as documenting the entire process.

Figure 8.1 - Important Stages in Contract Management

Source: Authors

Allocation of risks between contractors, owners and other interest parties is an important issue in contracting. Risk allocation becomes important whenever unexpected events occur. For example, the required work may be more extensive than originally expected and then the question arises: who will pay for the extra work? A partial list of responsibilities with concomitant risk that can be assigned to different parties would include (Hendrickson, 2007):

- Force majeure (i.e., this provision absolves an owner or a contractor for payment for costs due to "Acts of God" and other external events such as war or labor strikes).
- Indemnification (i.e., this provision absolves the indemnified party from any payment for losses and damages incurred by a third party such as adjacent property owners.).
- Liens (i.e., assurances that third party claims are settled such as "mechanics liens" for worker wages).
- Labor laws (i.e., payments for any violation of labor laws and regulations on the job site).
- Differing site conditions (i.e., responsibility for extra costs due to unexpected site conditions).
- Delays and extensions of time.
- Liquidated damages (i.e., payments for any facility defects with payment amounts agreed to in advance).
- Consequential damages (i.e., payments for actual damage costs assessed upon impact of facility defects).
- Occupational safety and health of workers, including insurance provisions and payments in the event of safety damages.
- Permits, licenses, laws, and regulations. It is often difficult to know exactly what permits may be required.
- Equal employment opportunity regulations.
- Termination for default by contractor.
- Suspension of work.
- Warranties and guarantees.

8.3 Workflow Management

Infrastructure management involves long term cycles of asset management planning and implementation, often for periods of a year or even longer. But another aspect of infrastructure management is dealing with the day to day desired work tasks. For example, on a military base, a campus or a large building, there will be requests for repair and re-stocking tasks as well as scheduled activities such as inspection and maintenance. Workflow management is the process of identifying these tasks, assigning tasks to workers (or contractors), setting priorities among tasks, and documenting the resulting work. Analysis of workflow tasks is also a useful activity, as problems can be identified (e.g. which elevator is breaking down most often?) and worker productivity monitored.

Work tasks may have a variety of forms and involve distinct skills. For example, author Don Coffelt's facility management group provides the following services to campus departments:

- Heating and air conditioning
- Carpentry

- Custodial services
- Roof and gutter repair
- Electrical repairs
- Window washing
- Elevator maintenance
- Gardening
- Pest Control
- Plumbing
- Meeting setup
- Trash and recycling
- Painting
- Locksmith

In addition to service requests from departments, there are a large number of tasks generated from the facilities management group itself, such as ice and snow clearance and preventive maintenance. Figure 8.2 illustrates a typical preventive maintenance task, in this case clearing debris from a stormwater sewer sump. Departmental payments may also be required for work flow tasks, such as changing locks in the events of lost or misplaced keys.

Figure 8.2 - Example of a Contracted Preventive Maintenance Task

Source: Authors. Vacuuming out debris in a storm water sewer sump avoids clogging and reduced flow volumes.

Setting priorities among tasks is an important component of workflow management strategy. If tasks are simply handled in a first come, first served basis, then critical tasks such as safety hazards may be neglected. At the same time, a general buildup of unfulfilled tasks may require special efforts to catch up, such as contracting out more tasks or hiring more staff.

As with many aspects of infrastructure management, software and communication aids are available for workflow management. Service requests can be made directly and digitally, rather than using paper or telephone requests. Task completion can be documented by workers using mobile devices. Databases can track the status of tasks. Geographic information and computer aided design software can help route planning or identifying problem areas.

8.4 Exercises

P8.1 **(4 pts)** Find a contract that you participate in (such as a telephone or a utility service contract). Read the contract and prepare a summary of the parties responsibilities and options in your own words.

P8.2 **(4 pts)** Regulatory compliance is an increasingly important component of infrastructure contracting. Research and report on one progressive contracting element. Examples include “job order”, “performance fee”, “design build” and “term service” contract models.

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Chapter 9: Commissioning New Facilities

9.1 Introduction

Commissioning is a process of transforming a completed construction project into a functioning and useful infrastructure system. The construction project might be a complete new facility, a major new piece of equipment, a facility addition or a major rehabilitation. The tendency of construction project managers is to focus on simply completing the construction process itself. Commissioning is intended to insure that the new construction operates as planned and that the new facility can continue to operate with regular infrastructure management. So commissioning is an important although likely infrequent activity for infrastructure managers.

New facilities can be quite complex, with a variety of systems needed to be commissioned. Electronics, mechanical equipment, software controls, and even components such as windows need to be tested and operation plans for asset management developed. An example of a complicated machine room is shown in Figure 9.1.

Figure 9.1 - Example of a Complex Machine Room

Source: Authors. A major pumping station

For larger projects, a specialized manager for the commissioning process may be retained. This manager would be responsible for insuring that all the major commissioning tasks are completed adequately. A challenging aspect of the commissioning agent's job is that the construction organization(s), the infrastructure manager, the facility users and the facility owner must all be satisfied and involved.

Major steps in the commissioning process include:

1. Preparation and planning involves identifying tasks, individual responsibilities and required documentation.
2. Completion and integrity testing involves comparison of as-built and as designed plans, often using computer aided design or facility information models.
3. Operational testing involves preliminary testing of equipment and software as built in the facility. This initial testing may rely upon construction or equipment supplier professionals, but should also involve the future operators of the equipment.
4. Start-up and Initial Operation involves actual use of the facility with monitoring to insure that the new facility is operating as planned.

5. Performance testing occurs during use to assess the overall performance of systems such as heating, ventilating and air conditioning systems in new buildings.
6. Post commissioning occurs when the regular infrastructure management procedures are in place and operating smoothly.

Of course, commissioning may not always go smoothly, and additional construction or adjustment tasks might be required in addition to the steps outlined above.

9.2 Testing New Facilities

Adequately testing the systems in new facilities can be difficult. While turning a system on will reveal basic operating information, it does not provide a test of operation under the various conditions that the facility will encounter during years of service. Moreover, some systems are intended for operation under extreme conditions of heavy rain, high wind or fire. Testing under these conditions would be costly and hazardous! For most commissioning procedures, testing of all operational modes is normal but usually not under all field conditions. For example, heating, ventilating and air conditioning in a new building would all be tested, even if only heating was required at the time of testing.

Some special tests that would not be part of normal operations may also be useful. For example, a fan pressurization test may be performed on a new building. With a higher pressure in the building provided by a fan, the extent of air leakage can be measured as the flow required to maintain the pressure differential. Figure 9.2 shows some possible features that could have air leakage and might be addressed as part of the final construction and commissioning activities. As another example, emergency vehicles might test new tunnels for any problems (either virtually in three dimensional models or in reality).

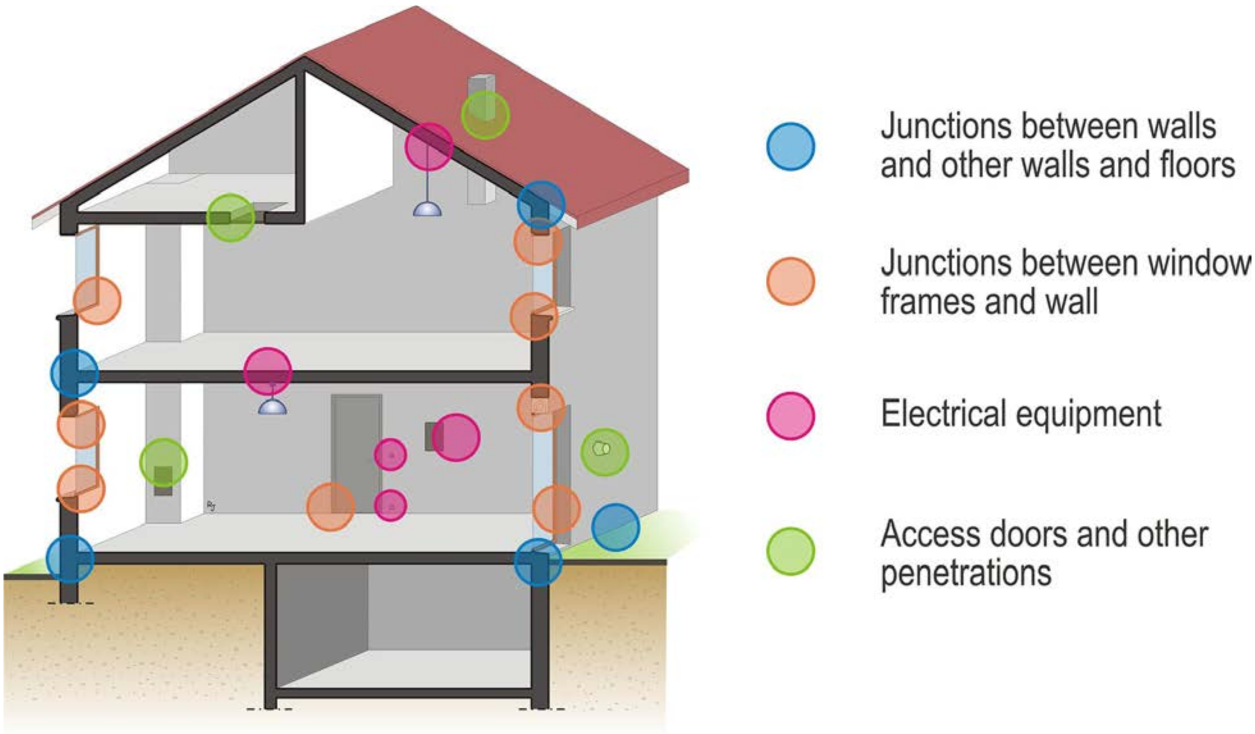

Figure 9.2 - Some Sources of Air Leaks in a Typical Building

Source: By CEREMA – Pôle QERA - http://tightvent.eu/faqs/what-are-the-most-common-air-leakageinfiltration-paths, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=31442687

9.3 Documenting New Facilities

Documentation of the new facility is an important part of commissioning. The manufacturer and construction personnel will be passing system control over to the infrastructure management organization, and they may not be familiar with the intricacies of the new facility.

Three dimensional computer aided design or facility information models are usually prepared prior to new facility construction. However, there are often modifications to the original design during the course of construction. As a result, as-built three dimensional models are often required for commissioning and are useful subsequently for infrastructure management. As built models may require field measurements and specialized companies or groups to prepare.

Equipment documentation for operation, maintenance and parts is also assembled as part of the commissioning process. While this documentation was on paper in the past, more and more documentation is available digitally. This has the advantage of providing immediate access to documentation in the field.

9.4 Integrating New Facilities into Infrastructure Management

A final commissioning task is to integrate new facilities into the regular practice of infrastructure management. Fortunately, most new facilities are provided in excellent condition, so the regular cycle of condition assessment, deterioration modelling and maintenance/rehabilitation may not be immediately needed.

One aspect of integration is to insure that the actual occupants or users of the new facilities are familiar with the various idiosyncrasies of the facility. Where are exits and elevators? Where are emergency supplies and first aid kits? Are offices and rooms set up in the most effective fashion?

Figure 9.3 shows the recommended transition steps for the commissioning of the Boston Central Artery/Tunnel (also known as the 'Big Dig') (Committee, 2003). This very large project replaced an elevated roadway with tunnels and added several new bridges and routes in Boston, Massachusetts. This new facility would be owned and operated by the Massachusetts Turnpike Authority (MTA), but the construction itself was largely contracted out, including a large project management team. As noted in Figure 9.3, an external review panel urged the MTA to adopt strategic thinking about the commissioning process needed during the transition to operations. This transition would also require a public education program to familiarize the traveling public with the new system.

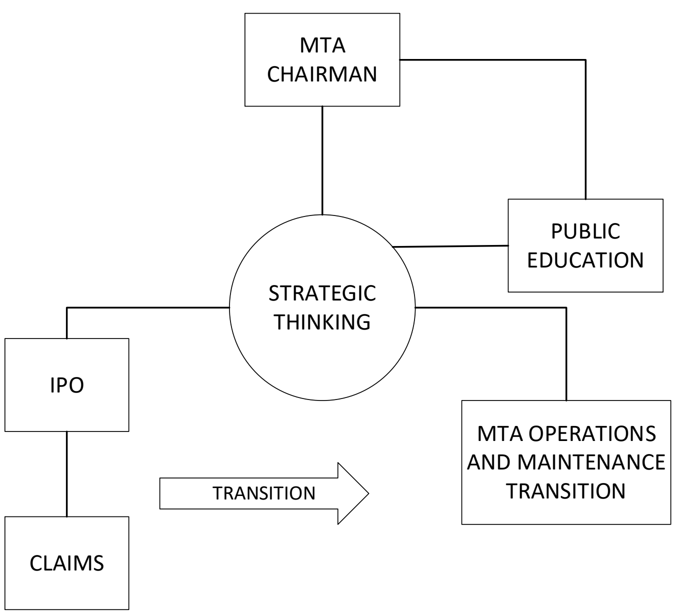

Figure 9.3 - Transition to Operations of the Boston Central Artery/Tunnel 'Big Dig' Project

Source: Committee, 2003. Redrawn and altered by Authors.

Commissioning is an ongoing and continuous activity that forms an important component of the asset management process as described in chapter 2. Properly implemented, commissioning improves building performance, energy efficiency and sustainability over the life of the asset. The "commissioning", "retro-commissioning", "continuous commissioning" processes include multiple, overlapping activities as illustrated in Figures 9.4 and 9.5 below.

New Building Commissioning Process Overview

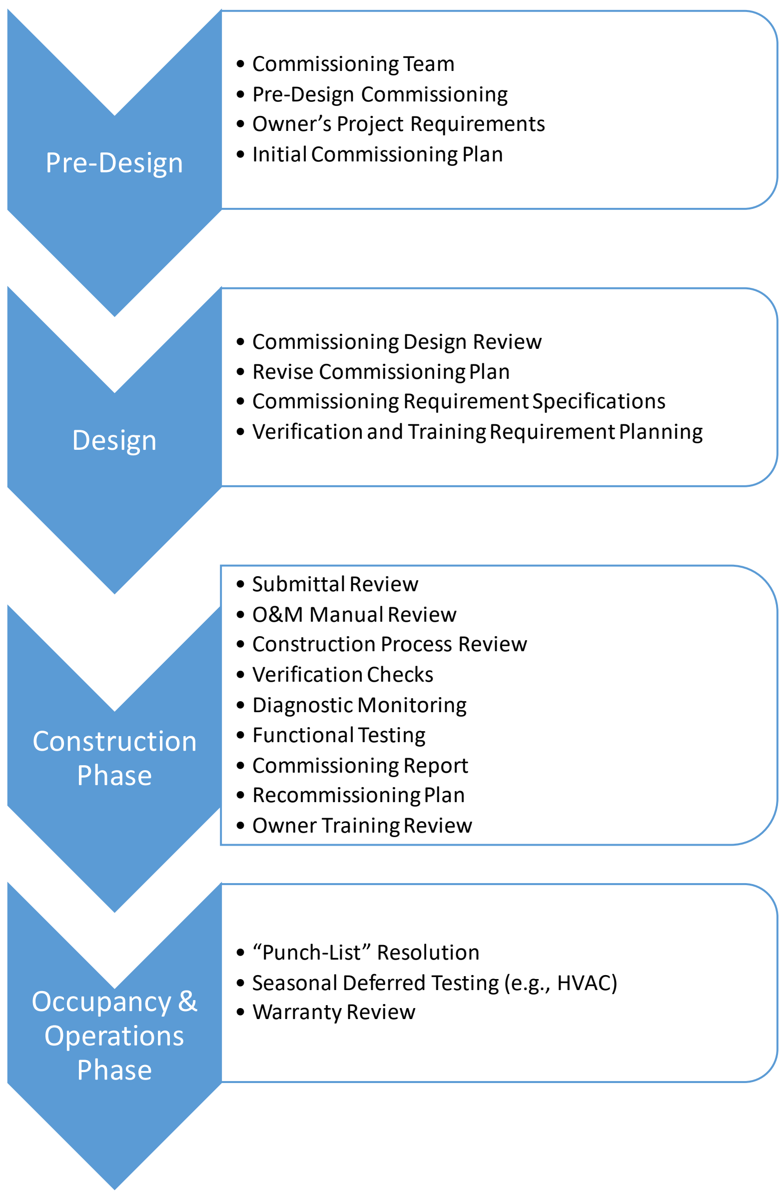

Figure 9.4 – New Building Commissioning Process Overview

Source: Figure By Donald Coffelt. Information from LBNL (2006), and Parrish (2013)

Existing Building Commissioning Process Overview

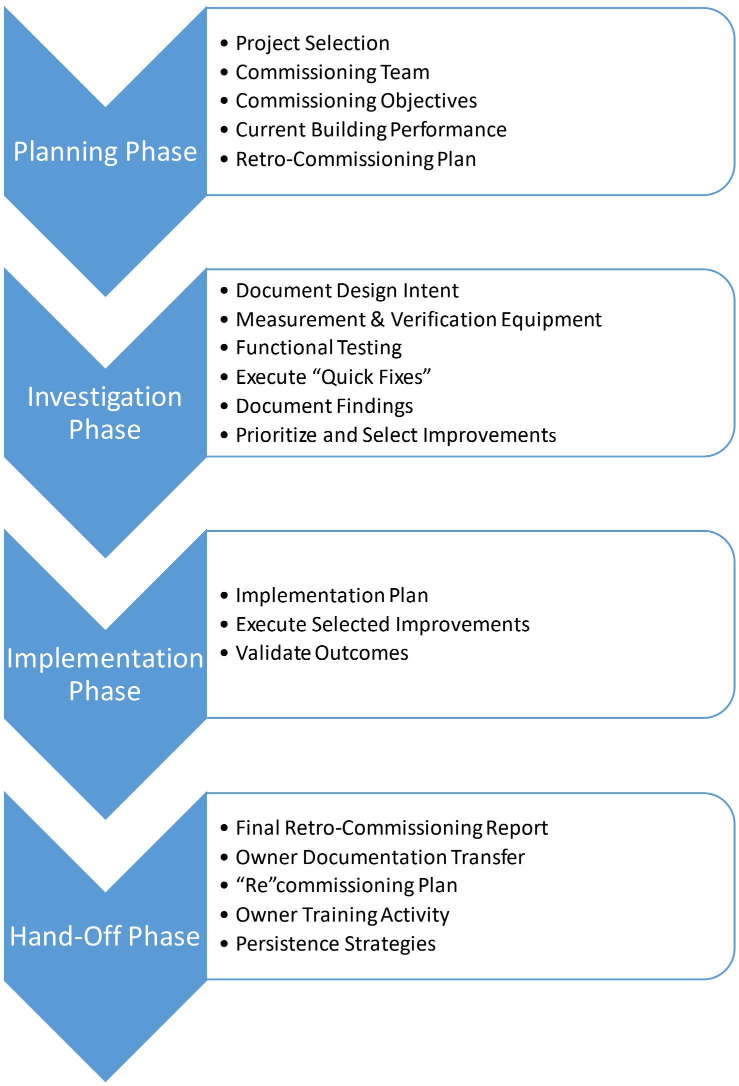

Figure 9.5 - Existing Building Commissioning Process

Source: Figure By Donald Coffelt. Information from LBNL (2006), and Parrish (2013)

9.5 Exercises

P9.1 **(10 pts)** Define "Commissioning" in terms of Building Commissioning, Retrocommissioning and Recommissioning. How might they differ in terms of process and objectives?

P.9.2 **(5 pts)** Describe a technology solution to new/existing facility documentation?

P.9.3 **(5 pts)** Summarize commissioning's effects on reduce energy costs and greenhouse gas emissions.

9.6 References

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Chapter 10: Benchmarking and Best Practices

10.1 Introduction

As previously noted, the opening chapters of this book were focused on the common methods and processes generally applicable for use in managing any infrastructure type. This chapter brings that portion of the text to a close and begins to shift our focus from a “generic” infrastructure application to consider specific infrastructure types. Before proceeding, it is useful to recall our purpose as well as the processes already introduced.

Despite the magnitude of the challenge, the purpose of the various infrastructure management processes the authors have introduced can be synthesized into a combination of three objectives Risk Management, Resource Allocation and Mission Performance. In pursuit, of these objectives, we have suggested the following processes as a means for developing and executing an effective infrastructure management program: Condition Assessment, Fault Tree Analysis, Deterioration Modeling, Optimization, and Life Cycle Cost Analysis. Remembering that we are using the asset management framework (FHWA 99) introduced in Chapter 2 and illustrated below, we can see that these process, or tools, provide methods for addressing each element of the system. While not inherently limited, our final process, Benchmarking, is focused on the performance monitoring and feedback component of the generic asset management system.

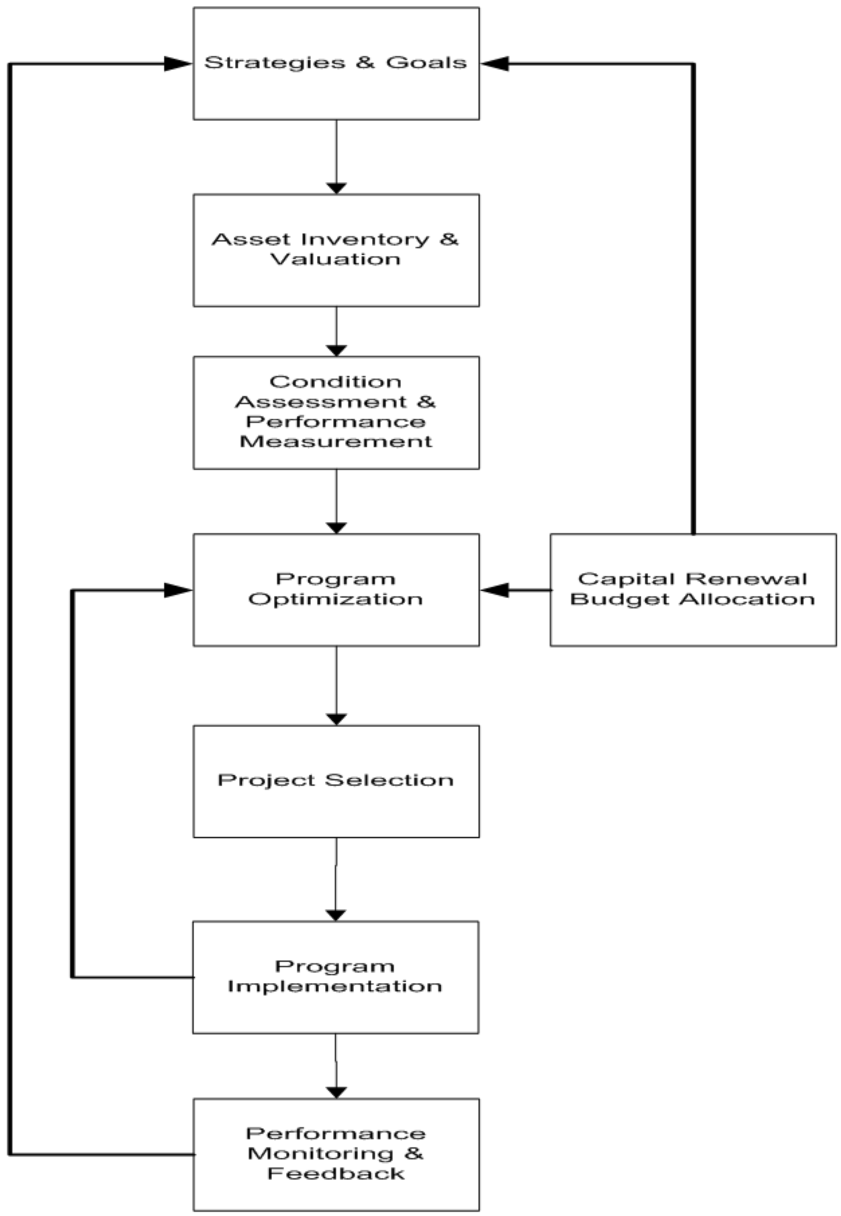

Figure 10.1 - Generic Asset Management System

Source: FHWA, 1999. Redrawn and altered by Authors.

Benchmarking is a means of comparing your infrastructure with others. It is useful for justifying resources, for checking on best practices, and for directing attention to particular problems. Benchmarking is generally not a topic of infrastructure research, but can be an important component of infrastructure management.

Benchmarking is distinct from the process of 'grading' infrastructure conditions. The American Society of Civil Engineers (2013) regularly issues a widely read 'report card' on US infrastructure, grading a variety of infrastructure types:

- Water and environment: Dams, Drinking Water, Hazardous Waste, Levees, Solid Waste, Wastewater.
- Transportation: Aviation, Bridges, Inland Waterways, Ports, Rail, Road, Transit.
- Public Facilities: Parks and Recreation, Schools.
- Energy.

The 2013 average ‘grade’ was D+. As noted in Chapter 3, these grades are subjective (reflecting the opinions of a committee) and based on a variety of factors, including condition, capacity and resiliency. These grades are intended to inform general infrastructure investment decision-making. In contrast, benchmarking for infrastructure management is focused upon improving management practices for specific pieces of infrastructure.

10.2 Benchmarking Methodology

Virtually any facet of infrastructure management processes can be benchmarked. Some important categories of benchmarking include:

- Costs for specific maintenance activities, specific rehabilitations, or general expenditure.
- Energy consumption.
- Conditions of assets and amounts of deferred maintenance.
- Staff resources and training.
- Standards adopted (as discussed further below).
- Processes used and documentation developed for management activities.
- Safety, environmental practices and emergency procedures.

The goal of such comparisons is to inform decision making and to identify the best practices available.

Figure 10.2 illustrates a typical benchmarking exercise, in this case for roadway fatalities by region. Bar chart comparisons within benchmarking groups of figures of interest such as this are very useful. Refinements of the basic chart in Figure 10.2 might include bars for multiple year histories in each region or a normalizing, unit comparison such as fatalities per million vehicle miles travelled per year or per thousand lane-miles of roadway.

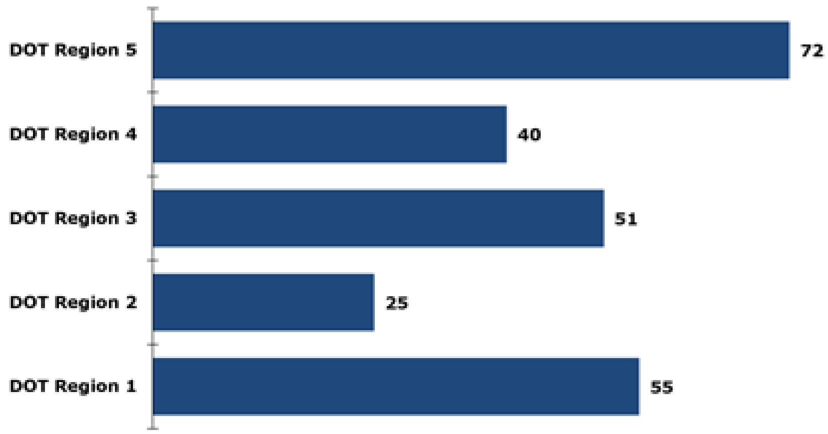

Figure 10.2 – Benchmarking Example: Roadway Fatalities by DOT Region

Source: FHWA, Public Domain, http://safety.fhwa.dot.gov/tsp/fhwasa15089/chap5.cfm.

In developing comparative benchmarks, normalized unit comparisons are generally more useful than totals. For example, building comparisons might be made on the basis of square meters of useful space and roadway comparisons on a lane-mile (or land-kilometer) of roadways.

10.3 Choosing a Benchmarking Cohort

A benchmarking cohort is the group of organizations or infrastructure systems chosen for comparison. In many cases, the possible members of a comparison group are limited by the availability and willingness of organizations to provide detailed data. So data limitations are a primary consideration in choosing a benchmarking comparison.

Another objective that is often used in choosing a benchmarking group is to choose organizations with similar circumstances. For example, if you are managing the facilities of a university (like author Don), you may wish to compare with other universities of similar age, size and research portfolios. Universities with a newer building stock or without research facilities might have very different infrastructure parameters than a school such as Carnegie Mellon University.

A very common stratification factor for an infrastructure benchmarking cohort is to have common climate zones. Infrastructure features such as energy use for heating and cooling or pavement stress from freeze-thaw cycles are affected by climate, so it is useful to have benchmark comparisons in similar climate zones. Figure 10.3 illustrates climate zones in North America, with the zones defined by general characteristics, precipitation, and temperature. There are a variety of climate zone definition classifications, as well as a variety of geographic aggregations (from local climates to large aggregations) available for climate zones.

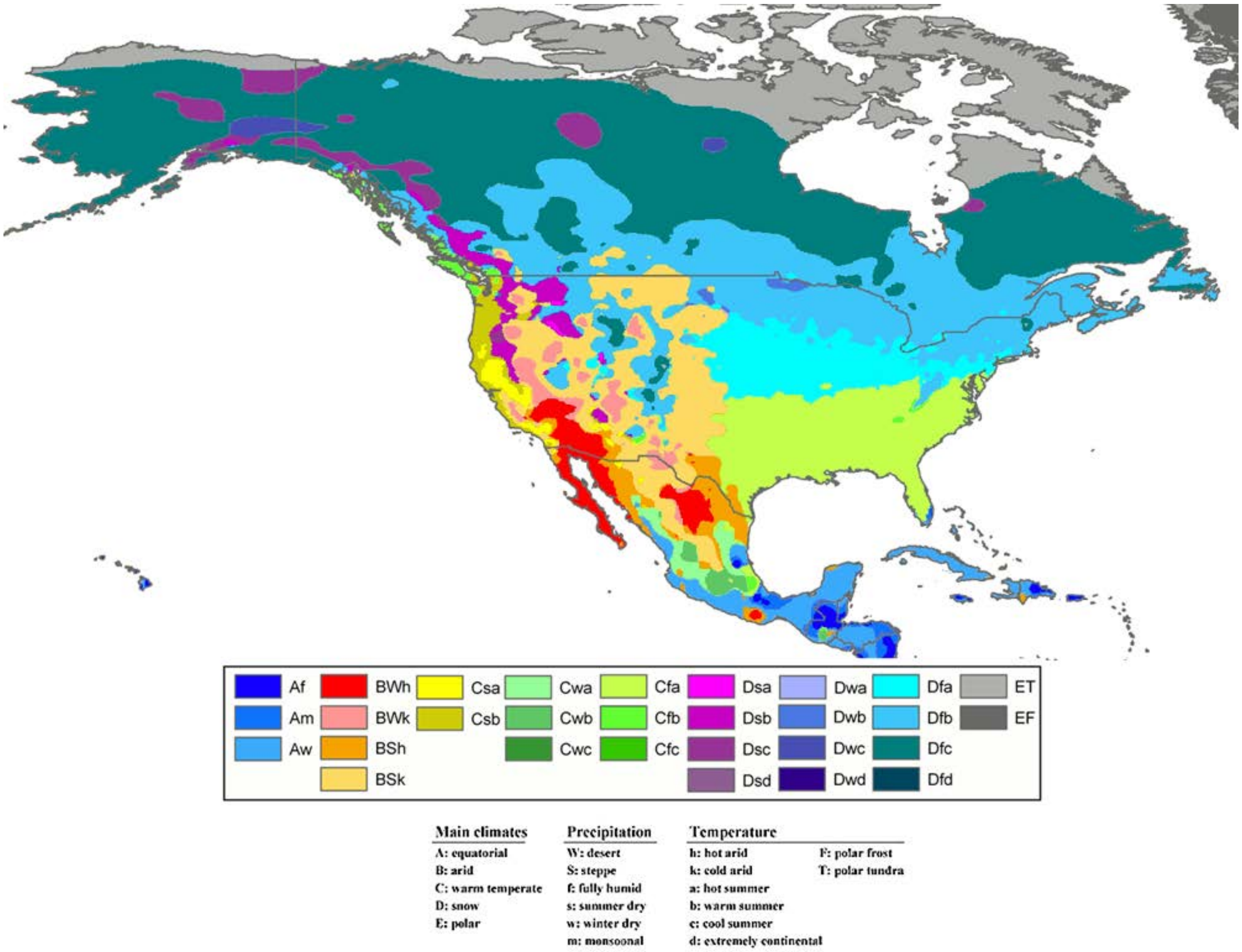

Figure 10.3 - Map of North American Climate Zones

Source: NASA, Public Domain, http://scijinks.jpl.nasa.gov/weather-v-climate/

Figure 10.4 illustrates the effects of different climates on operating costs for residential homes. Hotter climates in the South Atlantic, East South Central and West South Central region have a higher average use of electricity for air conditioning. With greater electricity demand, electricity expenses increase.

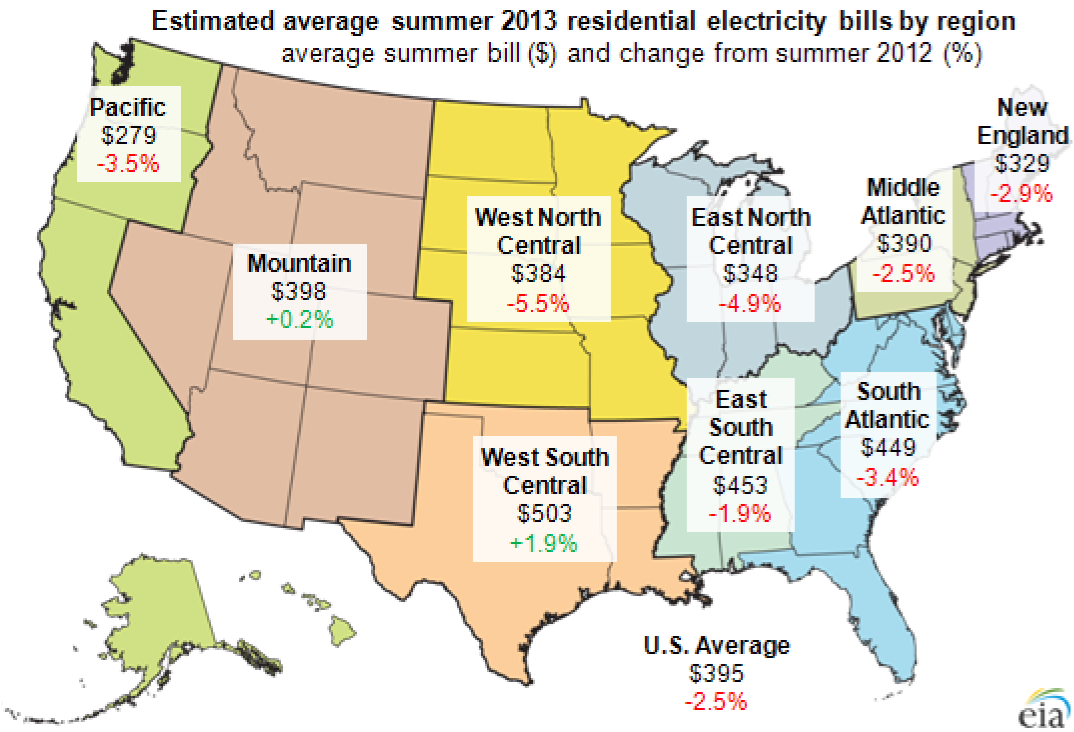

Figure 10.4 - Average Summer Residential Electricity Bills by US Region

Source: EIA, Public Domain, http://www.eia.gov/todayinenergy/detail.cfm?id=11831

Another approach for benchmarking is to not seek out comparable benchmark infrastructure, but to choose benchmarks from organizations thought to have the best practices and best infrastructure. This benchmarking approach is aspirational, where an organization is consciously trying to improve.

Finally, benchmarking can be usefully done within the different components of a large enterprise. For example, a large bank might compare the performance of its various bank branch buildings with regard to maintenance or energy costs. Figure 10.5 illustrates a benchmark comparison of the frequency of vehicle crashes along roadway segments. The high crash locations might receive management attention to suggest alternatives for greater safety as these locations.

Figure 10.5 - Example of Benchmarking Vehicle Crash Locations

Source: FHWA, Public Domain, http://safety.fhwa.dot.gov/tsp/fhwasa15089/chap5.cfm

Infrastructure benchmarking information may be available from public sources (such as the Bureau of Transportation Statistics), from private companies (generally for a fee) and from professional organizations (described below).

10.5 Networking and Standards for Best Practices

Professional organizations and societies play important roles in aiding benchmarking and in developing and spreading best practices and appropriate standards. As noted in Chapter 1, it is generally beneficial for infrastructure managers to be actively engaged in one or more relevant professional organizations. These organizations also provide a means of spreading relevant information, such as job availability. However, these organizations often are limited to particular types of infrastructure or specific regions or countries. A partial list of related professional organizations associated with the practice of infrastructure management in the United States is listed below:

- APPA (www.appa.org) Association of Physical Plant Professionals
- ASCE (www.asce.org) American Society of Civil Engineers
- ASME (www.asme.org) American Society of Mechanical Engineers

- SAME (www.same.org) Society of American Military Engineers
- BOMA (www.boma.org) Building Owners & Managers Association
- IFMA (www.ifma.org) International Facilities Management Association
- AFE (www.afe.org) Association of Facility Engineers

Codes and standards are developed by agencies and organizations to identify recommended practices and processes. Numerous codes and standards relevant to infrastructure management exist, from standards for inspection protocols to requirements for building insulation. Most standards are adopted voluntarily by an organization, but codes may be required by regulation, as with municipal building codes.

An example of a voluntary standard is the popular ‘green building standard’ Leadership in Energy and Environmental Design (LEED), developed by the US Green Building Council (2016). LEED standards exist for new building construction, building rehabilitation and remodeling and neighborhood development. The standard defines points that can be earned by projects for items such as high-energy efficiency, excellent indoor air quality or effective commissioning practices (See Chapter 9). Sufficient points will lead to different levels of recognition (e.g. gold and platinum awards). Other green building standards also exist, such as the UK Building Research Establishment's Environmental Assessment Method (BREEAM). Single attribute building standards also exist such as the US DOE/EPA Energy Star certification for energy efficient appliances.

In addition to the professional organizations listed above, there are a number of organizations that are focused on the development of standards. The International Organization for Standards (ISO, http://www.iso.org/iso/home.html) has developed over 21,000 international standards and has over a hundred national standard setting bodies as members. The ISO standards range widely, with popular standards for quality control, environmental, risk and emergency management. The American National Standards Institute (ANSI, https://www.ansi.org/) is the US member of ISO and also is active in developing a variety of standards.

Finally, there are also commercial entities that entered the benchmarking field. Sightlines, LLC (www.sightlines.com) is one such example whose focus is on higher education.

10.6 Exercises

P10.1 **(5 pts)** Consider that you are the Chief Facilities Officer for a major research university. List 5 criteria you would use to establish a benchmarking cohort.

P10.2 **(5 pts)** Considering the criteria identified above, list 5 possible members of your cohort.

P10.3 **(5 pts)** How would your criteria change if you were the chief facilities officer in a different industry (e.g., military base, chemical refinery)?

P10.4 **(5 pts)** List 5 infrastructure related factor that might form a part of a benchmarking methodology.

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Author’s Note: In the course of the next five chapters, we focus on background and issues for five different infrastructure systems. These chapters are intended to provide some familiarity with these infrastructure systems. While we do not discuss all infrastructure systems, we do cover the major systems. Since the authors teach in and are from the United States, we focus primarily on US infrastructure. Point being that infrastructure should be defined broadly and globally! Those in other countries and other disciplines can develop their own overviews.

Chapter 11: Roadway Infrastructure

11.1. Introduction

A road is an identifiable route or path between locations. Nearly all roads are constructed in some way, typically by smoothing the natural landscape and often by paving. Roads serve as transportation routes, accommodating bicyclists, horses, vehicles, and pedestrians. Roads also provide access to property and provide right-of-way to other infrastructure systems such as pipelines or telecommunications cables. Reflecting the ubiquity and importance of roads, there are many words denoting roadways, including: avenue, boulevard, court, drive, freeway, highway, parkway, street, etc.

Roadway construction dates back over 6,000 years. Early roads were paved with timber, brick and stone. The Roman Empire was noted for an extensive network of paved roadways, covering roughly 78,000 km in Europe and North Africa 2,000 years ago. Figure 11.1 shows a modern picture of former Roman road paved with stone and still in use in Syria.

Figure 11.1 - Example of a Roman Roadway Still Maintained

Source: By Bernard Gagnon (Own work) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons, https://commons.wikimedia.org/wiki/File:Ancient_Roman_road_of_Tall_Aqibrin.jpg

Roads can be one-way, but most are divided in the center and accommodate two-way traffic. About a third of worldwide roadway traffic follows the convention of vehicles traveling on the left side of roadways, while two-thirds follow a right-side convention, including the United States (Figure 11.2).

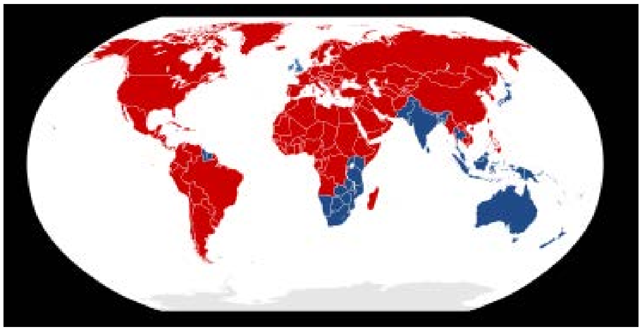


Figure 11.2 - Countries by handedness of traffic, c. 2017

Source: By Benjamin D. Esham (bdesham) - Created by bdesham in Inkscape from BlankMap-World6.svg, using information from Sens de circulation.png.This vector image was created with Inkscape. https://commons.wikimedia.org/w/index.php?curid=2653447. Countries driving on the left shown in blue.

Modern pavements are complex systems themselves, with multiple layers and drainage systems. Figure 11.3 illustrates a flexible (asphalt) pavement used for rural interstates in Idaho. The pavement has a surface layer of asphalt (six inches of plant mix bituminous pavement), a layer of asphalt treated permeable leveling course (two inches of ATPLC), gravel, a rock cap, a granular subbase, and a subgrade geotextile. The pavement is slanted to facilitate rain run-off.

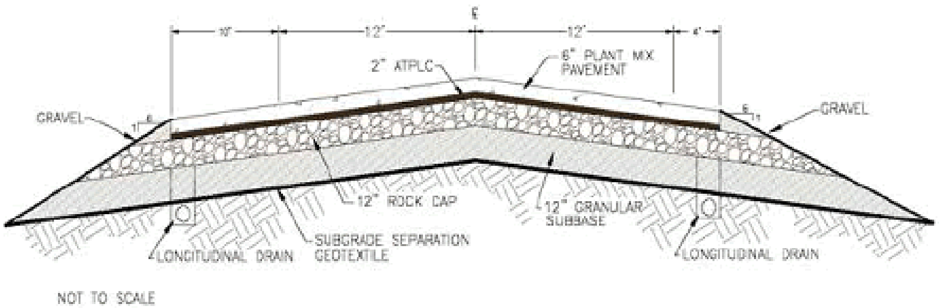


Figure 11.3 - Flexible pavement rural interstate, typical section for Idaho

Source: FHWA, Public Domain,
https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/ltpp/06121/appende.cfm

Roadways are used for numerous purposes and by multiple types of vehicles. Table 11.1 shows vehicle miles travelled (in millions) for different types of vehicles and types of roadways. Limited access interstate roadways have significant amounts of traffic, but most traffic is carried on other types of roadways. Motorcycles, buses and truck traffic are significantly smaller than light duty vehicle traffic.

Table 11.1 – U.S. Vehicle Miles Traveled by Type of Vehicle and Type of Roadway 2014

Roadway Type	Light Duty Vehicle (million miles)	Motorcycles (million miles)	Buses (million miles)	Trucks (million miles)	All Vehicles (million miles)
Rural Interstate	173,000	1,000	2,000	56,000	231,000
Other Rural	505,000	6,000	4,000	76,000	690,000
Urban Interstate	458,000	2,000	2,000	57,000	520,000
Other Urban	1,476,000	11,000	8,000	90,000	1,585,000
Total	2,711,000	20,000	10,000	279,000	3,026,000

Source: FHWA, Public Domain, Highway Statistics,
https://www.fhwa.dot.gov/policyinformation/statistics/2014/vm1.cfm

11.2. Duration and Extent of Roadway Infrastructure

Roadways are widespread throughout the world. As an example, Figure 11.4 shows the mileage of rural and urban highways in the United States from 1950 to 1997. Rural roadways are much more extensive than urban roadways, even though the bulk of population resides in urban areas. Unpaved roadways have declined, while the total mileage of roadways has shown modest increase over the past fifty years. In 1997, US population was roughly 270 million, representing 68 people for every mile of roadway. Not included in these highway totals would be a variety of trails, temporary roads for uses such as logging, or 'natural' roadways such as truck pathways on frozen lakes and rivers.

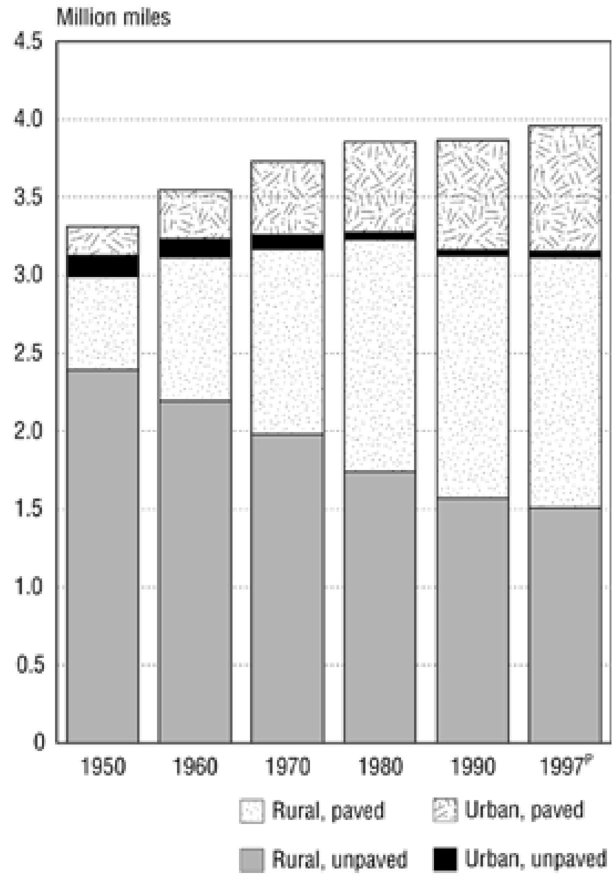


Figure 11.4 - US Roadway by Area and Paving, 1950-1997

Source: Public Domain, U.S. Department of Transportation, Federal Highway Administration, Highway Statistics (Washington, DC: Annual editions), table HM.

More recent trends in US public road mileage, lane miles and overall vehicles miles of travel are shown in Figure 11.5 for 1980 to 2014. Overall mileage has changed very little in this period, while lane-miles have increased slightly suggesting that lanes have been added to existing roadways. In contrast, vehicle miles of travel have increased significantly in this period, suggesting congestion has also been increasing. Note that the left vertical axis for road mileage and lane-miles starts at three million miles rather than zero.

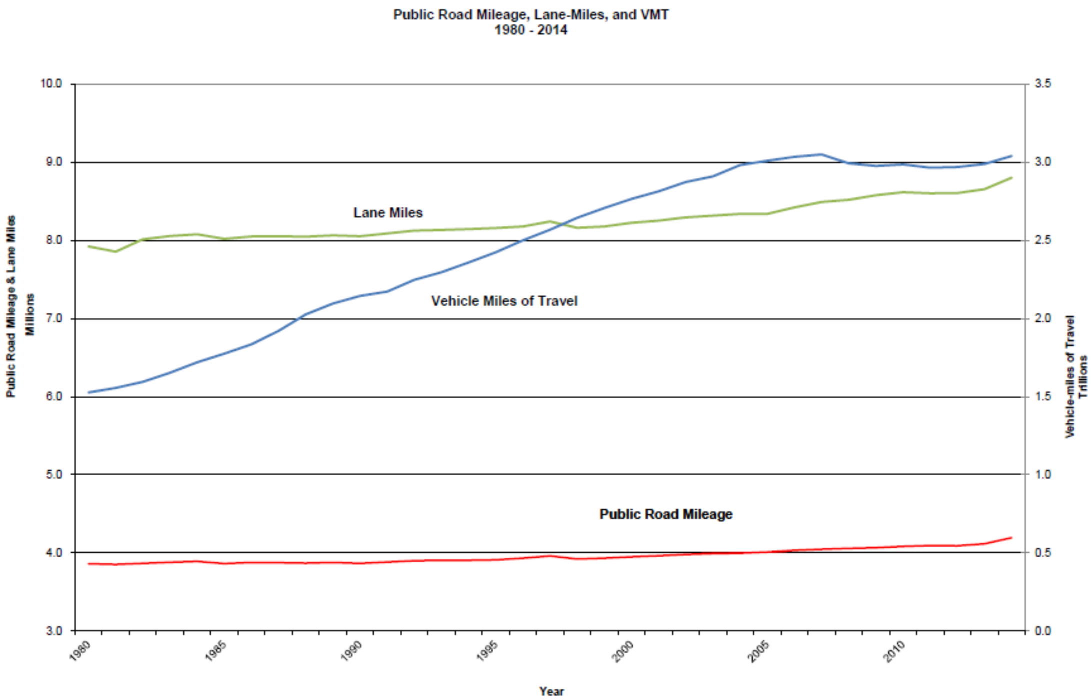


Figure 11.5 - Public Road Mileage, Lane Miles and Vehicle Miles of Travel, 1980-2014

Source: FHWA, Public Domain, Highway Statistics,
https://www.fhwa.dot.gov/policyinformation/statistics/2014/pdf/vmt422c.pdf

The durability of roadways and roadway components can vary considerably. Rights of way can exist for hundreds of years, especially if a roadway is in regular use. Pavements and other roadway components are not so longed lived, as discussed in Chapters 2-4.

Roadway surfaces deteriorate with use and weathering. Deterioration from use is correlated to the weight of vehicles or, more precisely, the weight of vehicle axles. The effect of additional tire weight is non-linear, with damage increasing by roughly a power of four. Roadway traffic is often measured in 'equivalent single axle loads' (ESAL) where the standard single axle load is 18,000 lb (8,200 kg). Figure 11.6 shows approximate ESAL values for typical vehicles. Buses tend to have higher loads because they have fewer axles than most trucks.

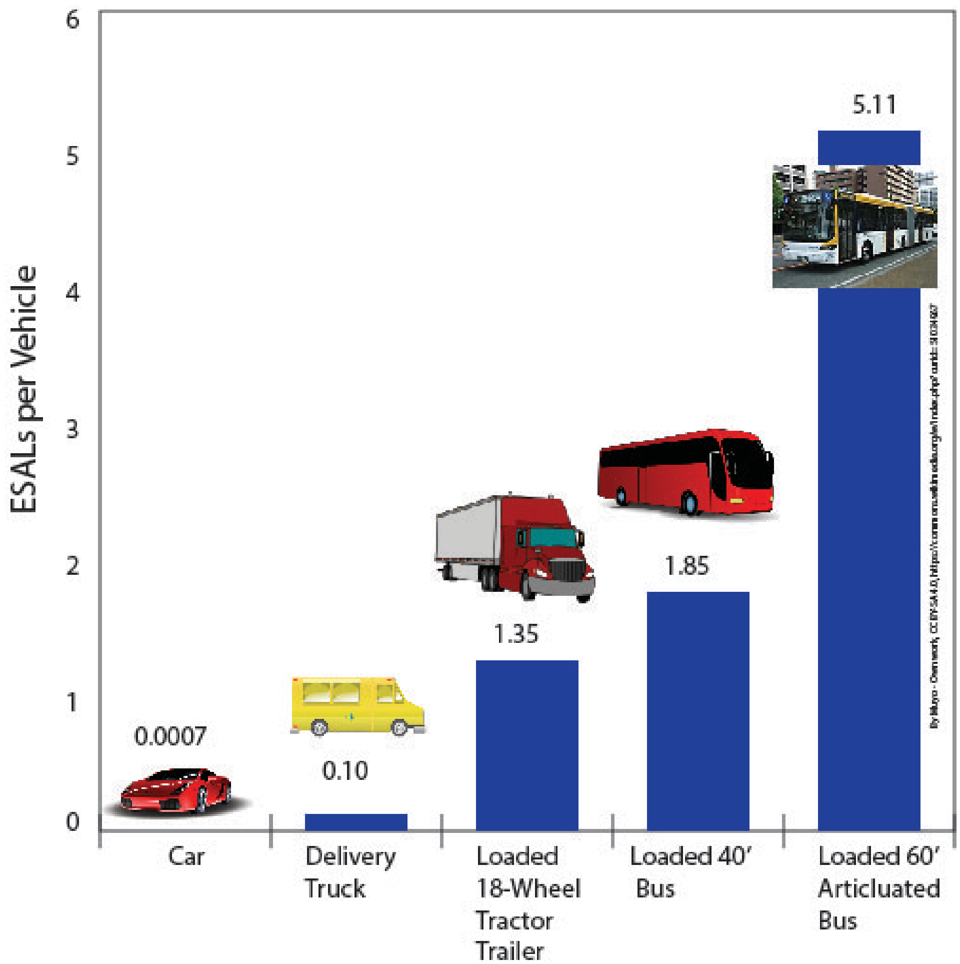


Figure 11.6 - Relative Use Impacts of Different Vehicles

Source: Washington Asphalt Pavement Guide, http://www.asphaltwa.com/design-factors-loads/. Redrawn and altered by Authors. Measured in equivalent standard axle loads, ESAL.

Pavement design, construction and maintenance are also critical elements affecting the durability of roadways. Stronger and thicker paving material with a good foundation is generally expected to last longer than weaker pavements. However, the initial costs of highly durable pavements may be difficult to justify for low volume roadways. Effective pavement lifetimes are roughly 10 to 50 years. Typical paving materials include hot mix asphalt, concrete, and bituminous surface treatment.

11.3. Institutional Arrangements for Roadway Infrastructure Management

Roadways are owned and managed by local governments, national governments, and private entities. These different groups often have complicated partnership arrangements in which multiple parties may contribute financing, standards, or other resources. The different groups may have very different objectives. For example, a national government may wish to promote inter-state transportation, whereas a local government may be primarily oriented towards providing roadway services for local businesses and residents.

Users provide the bulk of funding for roadways, with some revenues coming from general government revenues. Common means of securing revenues include:

- Tolls directly on roadway use, usually varying by distance traveled and type of vehicle. Electronic toll collection using RFID tags is becoming more common.
- Vehicle registration fees, usually imposed on an annual basis. These fees may be applied to roadway construction, management processes (including police) or be diverted to general government revenues.
- Fuel taxes, applied on volumes of fuel purchases. Figure 4 shows the combined local, state and federal taxes in different states in the United States in 2008. European fuel taxes tend to be higher than those in North America, whereas fuel taxes are low or non-existent in some countries.
- Vehicle sales taxes, although these taxes may flow to general government revenues rather than be dedicated to roadways.
- Property taxes may be used by local governments to provide local roadways.
- Fines such as parking violation fees may be used by local governments.

Figure 11.7 summarizes the sources of revenue for highways in 2010. Note that bond revenue must be eventually repaid as the bonds mature. Expenditures by type are shown in Figure 11.8. The capital outlay shown in Figure 11.8 represents rehabilitation and some lane expansion for existing roadway infrastructure rather than new construction (as discussed above).

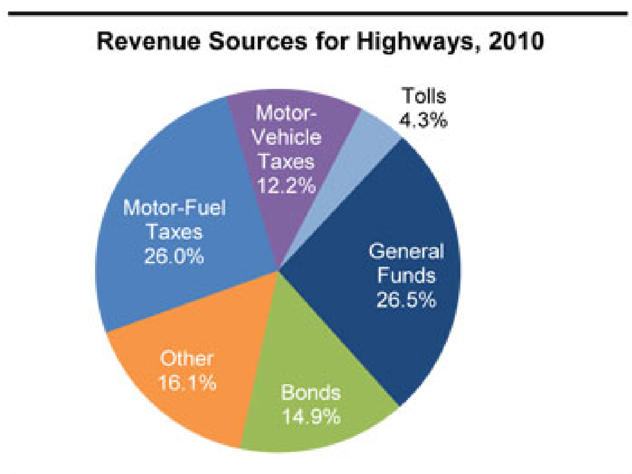


Figure 11.7 - US Revenue Sources for Highways, 2010

Source: FHWA, Public Domain, Conditions and Performance, 2013, https://www.fhwa.dot.gov/policy/2013cpr/overviews.cfm

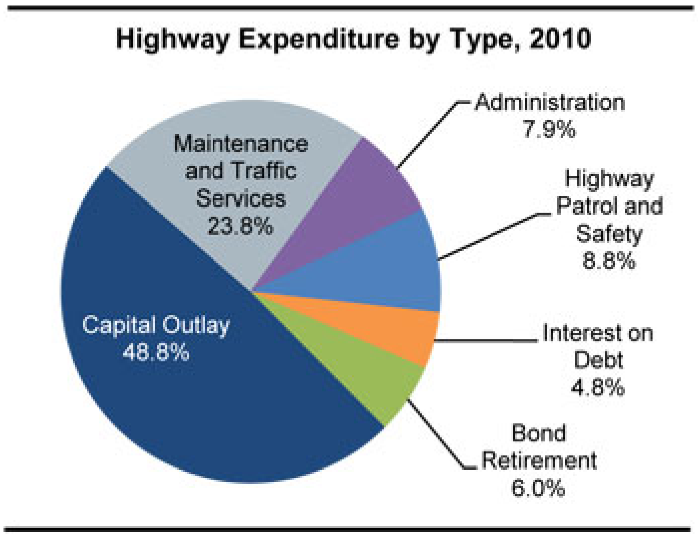


Figure 11.8 - US Highway Expenditure by Type

Source: FHWA, Public Domain, Conditions and Performance, 2013, https://www.fhwa.dot.gov/policy/2013cpr/overviews.cfm

11.4. Some Infrastructure Management Issues for Roadways

Roadways provided an application domain for the early development of asset and infrastructure management methods and systems. Since roadways are so widespread and long-lasting, adopting a life cycle viewpoint for design and maintenance decisions has been widespread but not universal. Bridge and road management systems are among the best developed software systems to aid infrastructure management. Examples include the Pontis bridge management system from AASHTO (1997), PAVER from the USACOE (Shahin, 2016), and HDM from the World Bank (Watanatada, 1987). Each of these tools involve comprehensive inspection and inventory data gathering as well as aids for decision making. The tools evolve with changing needs, conditions, more experience and more research.

Roadway congestion is a continuing cost and difficulty with roadway management throughout the world. As shown in Figure 11.9, even inter-urban roadways are showing the effects of congestion.

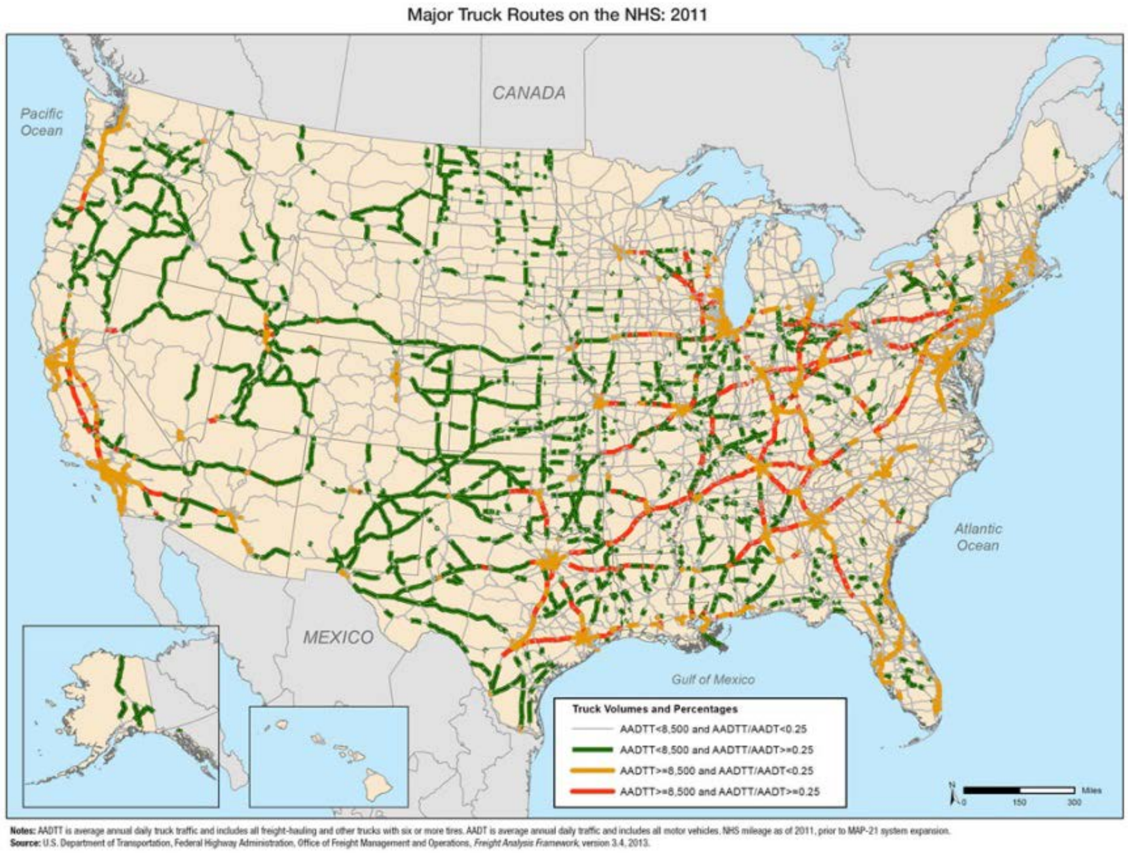


Figure 11.9 - Congestion on Major Truck Routes in the United State 2011

Source: FHWA, Public Domain,
http://www.ops.fhwa.dot.gov/freight/freight_analysis/nat_freight_stats/images/lo_res_jpg/nhsmajortrkrts2011.jpg

Figure 11.10 shows the different sources of roadway congestion in the US. The largest category is bottleneck roadway sections, followed by traffic incidents (such as vehicle breakdowns or crashes), and bad weather (such as snow or flooding). Work zones for roadway management activities are also a major source of congestion.

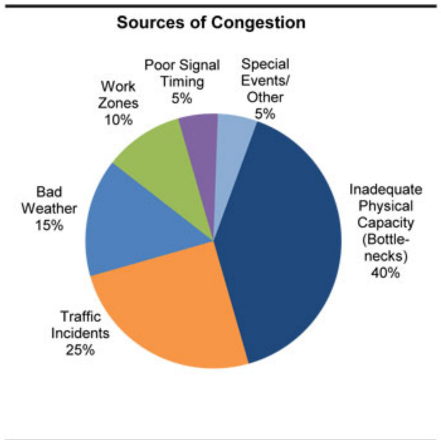


Figure 11.10 - Sources of US Roadway Congestion

Source: FHWA, Public Domain, Conditions and Performance, 2013,
https://www.fhwa.dot.gov/policy/2013cpr/overviews.cfm

Roadway renovation is a continuing problem in many countries. Projects are expensive and disrupt normal travel patterns. Novel contracting schemes to speed projects have been introduced, such as charging for closure of roadways per day. New materials can also reduce the costs of renovation.

Environmental concerns for roadways are becoming more common. The costs associated with urban sprawl and climate change reflect the dependence on motor vehicles and petroleum fuels. While there has been considerable success in reducing conventional air emissions from motor vehicles (Figure 11.11), greenhouse gas emissions are a major concern. This concern has resulted in new greenhouse gas emissions standards as well as promotion of alternative fuels such as battery electric vehicles powered by renewable power generation.

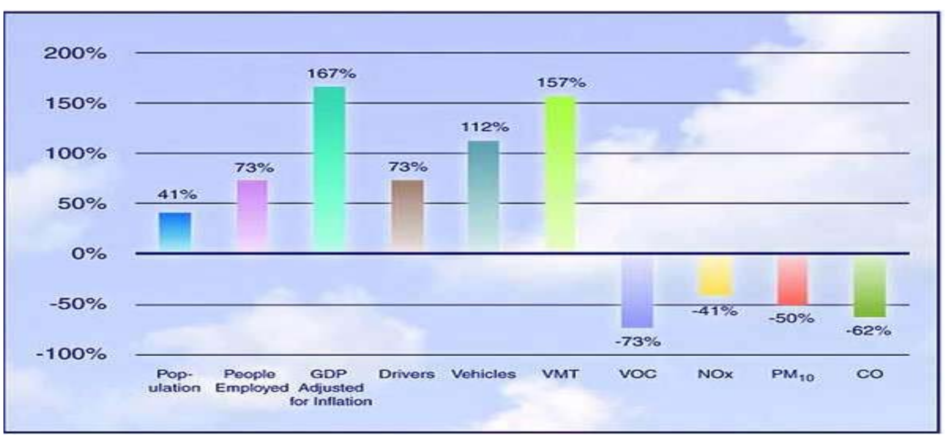


Figure 11.11 - Changes in Demographic Factors and Conventional Air Emissions, 1970-2002

Source: Federal Highway Administration, Public Domain,
www.fhwa.dot.gov/environment/aqfactbk/page05.htm

Safety also remains a significant issue for roadway infrastructure. Figure 11.12 shows fatality rates per capita in different countries of the world. Countries clearly differ in the risk of vehicle crashes. For roadway management purposes, normalization by vehicle miles of travel is likely more useful than fatalities per capita as in Figure 11.12. However, many countries do not report total vehicle miles of travel.

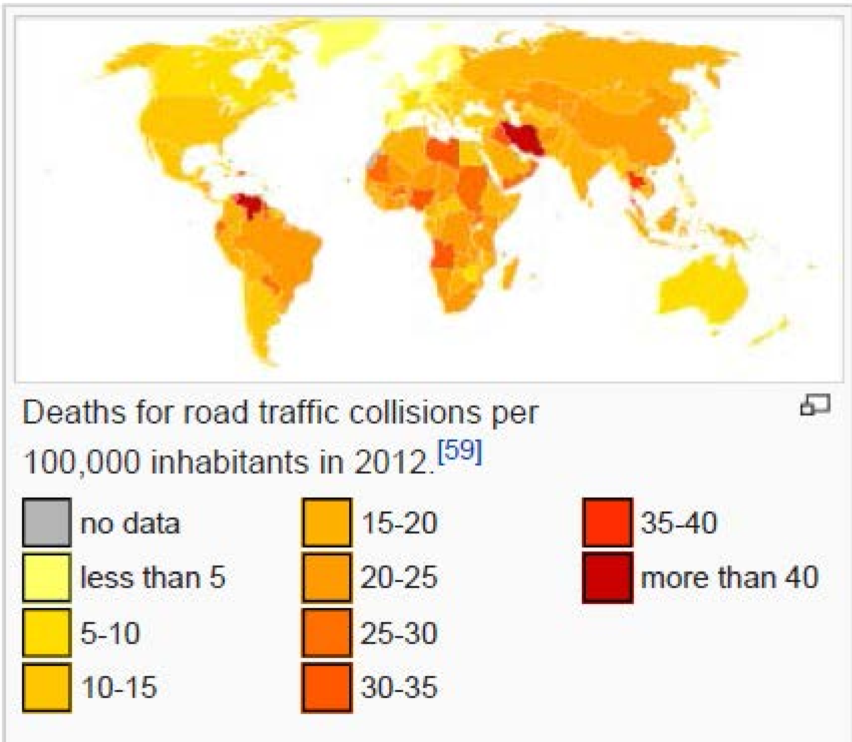


Figure 11.12: Roadway Fatalities per 100,000 Inhabitants in 2012 (

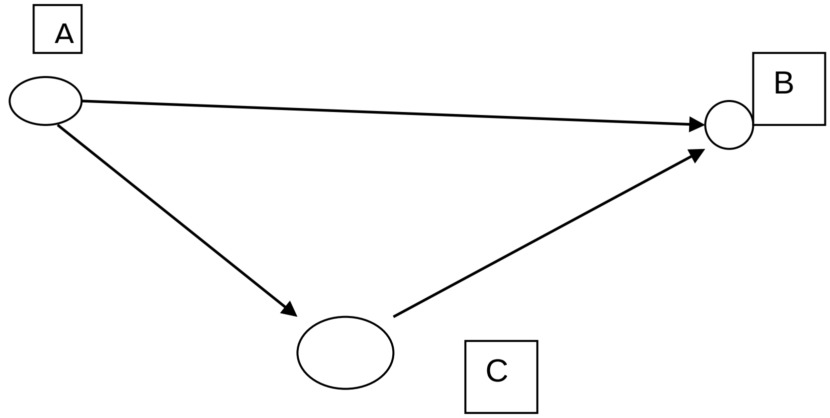
Source: By Chris55 - Vector map from BlankMap-World6, compact.svg by Canuckguy et al. adapted by Lokal_ProfilData from World Health Organization Estimated Deaths 2012, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=50161215,Wikipedia 'Traffic collision'.

11.5. Exercises

P11.1 **(6 pts)** How would you design vehicle fees for different types of vehicles to account for different impacts on pavements? How does your suggested design compare to existing fees?

P 11.2 **(6 pts)** The federal government collects diesel and gasoline taxes and puts them in the Highway Trust Fund. (a) How would you recommend that these funds be allocated among the different states? (b) Would you allocate any of the funds for public transit? (c) How might you tax (or should you tax) battery powered vehicles?

2. P 11.3 (**14 pts)** Suppose I have a simple network as shown below. I have 300 vehicles going from A to B, and they can either take route A-B or route A-C-B. The travel time per vehicle on route A-B is 10 + 0.5 qAB min where qAB is the travel volume on route AB. The travel time per vehicle on route A-C-B is 15 + 0.2 qACB min.



a. Suppose vehicles chose routes such that any route that was used from A to B had equal travel times. This is called a 'user equilibrium' since no single user has an incentive to change routes as there is no opportunity to save time by doing so. What are the travel volumes on the two routes for a user equilibrium?

b. Suppose vehicles are assigned to particular routes to minimize the total travel time on the network. The resulting pattern is called a 'system equilibrium' since changing a route can only increase overall system travel times. What are the travel volumes on the two routes for a system equilibrium?
c. Why do the system and user equilibrium flow volumes differ?
d. Suppose travelers have a value of time of $ 1/6 per minute per vehicle. For example, if a toll p was imposed on route A-B, the effective travel time would be 10 + 0.5*qAB + 6*p. Is there a toll we could impose somewhere on the network that would be a user equilibrium but have the system equilibrium route volumes? What is it? What is the resulting revenue?
e. Using the value of time in part d, what is the dollar value of the difference between user equilibrium and system equilibrium?
f. Suppose we have to do roadway maintenance and shut down link A-B in the network, diverting all traffic to route A-C-B. What would be the travel time on this route? Comparing this to the base user equilibrium (in part a), what is the increase in travel time? Using the value of time in part d, what is the increase in user cost?

g. Roadway renovation contracts often use a system called ‘A+B’ in which contractors bid’s include a ‘rental fee’ for closing roadways (that is the +B, whereas A would be the estimated renovation costs themselves). In the case of our small network, this +B amount might be represented by your answer to part f. In practice, the +B amount would be calculated from a typical value of time, volume on a roadway, and an estimate of the travel time increase from using alternative routes. What might be the advantage of the A+B contract system versus a conventional system (call it A) for infrastructure management? Do you think renovation costs overall would go up or down with the A+B system? (Hint: the table below is an example from WSDOT, with C being the winning, low bidder).

Contractor	A	B	C
A Bid Amount	$ 4,300 K	$ 4,900 K	$ 4,450 K
No. Days Bid	130	110	115
Road user cost	$ 12 K	$ 12 K	$ 12 K
Combined A+B Bid	$ 5,860 K	$ 6,220 K	$ 5,830 K**

11.6 References

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Chapter 12: Building Infrastructure

12.1. Introduction

Buildings are constructed to support and protect activity and artifacts. Buildings may incorporate natural structures, such as the document storage and server farms housed in rooms within a large, underground limestone mine owned by Iron Mountain in Pennsylvania. While human buildings are quite prominent, many animals engage in building activities for nests, hives, etc.

While buildings may be relatively simple structures, most include other systems providing quite extensive functionality, including:

- Electricity distribution and lighting, typically using alternating current of 110 to 220 volts.
- Water distribution and heating for human use.
- Waste disposal systems for solid or liquid wastes.
- Heating, ventilation and air conditioning (HVAC) systems.
- Internal transportation systems, including elevators, escalators, and stairways.
- Kitchens for food preparation and storage.
- Security systems to identify and discourage intruders.
- Telecommunications systems for data transfer.
- Garages for parking vehicles.
- Charging stations for battery electric and plug-in vehicles.

Buildings also have systems for emergencies and security. Fire alarms are often required by regulation. Signage for evacuation and emergency lighting is common. First aid supplies are common. Video cameras for security purposes are often installed.

12.2. Duration and Extent of Building Infrastructure

Building statistics often differentiate between commercial, residential and other types of buildings. Table 12.1 shows the 2003 distribution of commercial buildings in the United States with regard to size, use, and energy sources. The total inventory includes 4.6 million buildings. Not surprisingly, the numbers of buildings in each size category declines as size increases. Nearly all commercial vehicles have electricity, and most have other energy sources.

Table 12.1 - Characteristics of Commercial Buildings in the United States 2003

Characteristic	All Buildings (1,000)	Floor Space (million ft^2)	Mean FT^2 Per Building (1,000)	Mean FT^2 Per Worker (number)
All buildings	**4,645**	**64,783**	**13.9**	**890**
Building floor space (square feet):				
1,001 to 5,000	2,552	6,789	2.7	683
5,001 to 10,000	889	6,585	7.4	877
10,001 to 25,000	738	11,535	15.6	1,069
25,001 to 50,000	241	8,668	35.9	976
50,001 to 100,000	129	9,057	70.4	1,074
100,001 to 200,000	65	9,064	138.8	779
200,001 to 500,000	25	7,176	289.0	1,043
Over 500,000	7	5,908	896.1	676
Principal activity within building:				
Education	386	9,874	25.6	791
Food sales	226	1,255	5.6	877
Food service	297	1,654	5.6	528
Health care	129	3,163	24.6	501
Inpatient	8	1,905	241.4	513
Outpatient	121	1,258	10.4	484
Lodging	142	5,096	35.8	2,074
Retail (other than mall)	443	4,317	9.7	1,246
Office	824	12,208	14.8	434
Public assembly	277	3,939	14.2	1,645
Public order and safety	71	1,090	15.5	809

Characteristic	All Buildings (1,000)	Floor Space (million ft^2)	Mean FT^2 Per Building (1,000)	Mean FT^2 Per Worker (number)
Religious worship	370	3,754	10.1	2,200
Service	622	4,050	6.5	1,105
Warehouse and storage	597	10,078	16.9	2,306
Other	79	1,738	21.9	956
Vacant	182	2,567	14.1	(NA)
Energy sources:				
Electricity	4,404	63,307	14.4	871
Natural gas	2,391	43,468	18.2	837
Fuel oil	451	15,157	33.6	772
District heat	67	5,443	81.4	534
District chilled water	33	2,853	86.7	397
Propane	502	7,076	14.1	1,208
Wood	62	289	4.6	1,105

Source: Statistical Abstract of the United States, 2008, Public Domain, 'Commercial Buildings Summary,' Table 968.
https://www.census.gov/library/publications/2007/compendia/statab/127ed/construction-housing.html

The numbers of housing units in the United States is shown in Table12.2. The numbers of residential buildings would be smaller than the number of housing units since there are multi-unit buildings. Of the 124 million housing units in 2005, 76 million (or 61%) are single unit houses (Census, 2008). The numbers of housing units has been increasing over time, reflecting growth in population and a decline in the average size per household. The fraction of homes owned by residents has been increasing over time to 60% in 2005.

Table 12.2 - United States Housing Units 1980-2005

Item	1980	1990	2000	2005
	(1,000)	(1,000)	(1,000)	(1,000)
All housing units	**87,739**	**106,283**	**119,628**	**123,925**
Vacant	8,101	12,059	13,908	15,694
Total occupied	79,638	94,224	105,720	108,231
Owner	52,223	60,248	71,250	74,553
Renter	27,415	33,976	34,470	33,678
PERCENT DISTRIBUTION				
All housing units	100.0	100.0	100.0	100.0
Vacant	9.2	11.3	11.6	12.7
Total occupied	90.8	88.7	88.4	87.3
Owner	59.5	56.7	59.6	60.2
Renter	31.2	32.0	28.8	27.2

Source: Statistical Abstract of the United States, 2008, Public Domain, 'Total Housing Inventory for the United States,' Table 947.
https://www.census.gov/library/publications/2007/compendia/statab/127ed/construction-housing.html

Buildings tend to relatively long-lived types of infrastructure, with averages of 50 to 100 years not uncommon. Many buildings are demolished not due to deterioration, but due to functional obsolescence: building needs may change and replacing a building may become advantageous. The US Internal Revenue Service prescribes a depreciation lifetime of 20 years for farm buildings, 27.5 years for residential rental property and 39 years for nonresidential real estate (Treasury - https://www.irs.gov/pub/irs-pdf/p946.pdf). Figure 12.1 shows the reported age of US commercial buildings in 2012, with a median building age of 32 years. Within any building, components may be replaced more frequently, such as HVAC or roof replacements.

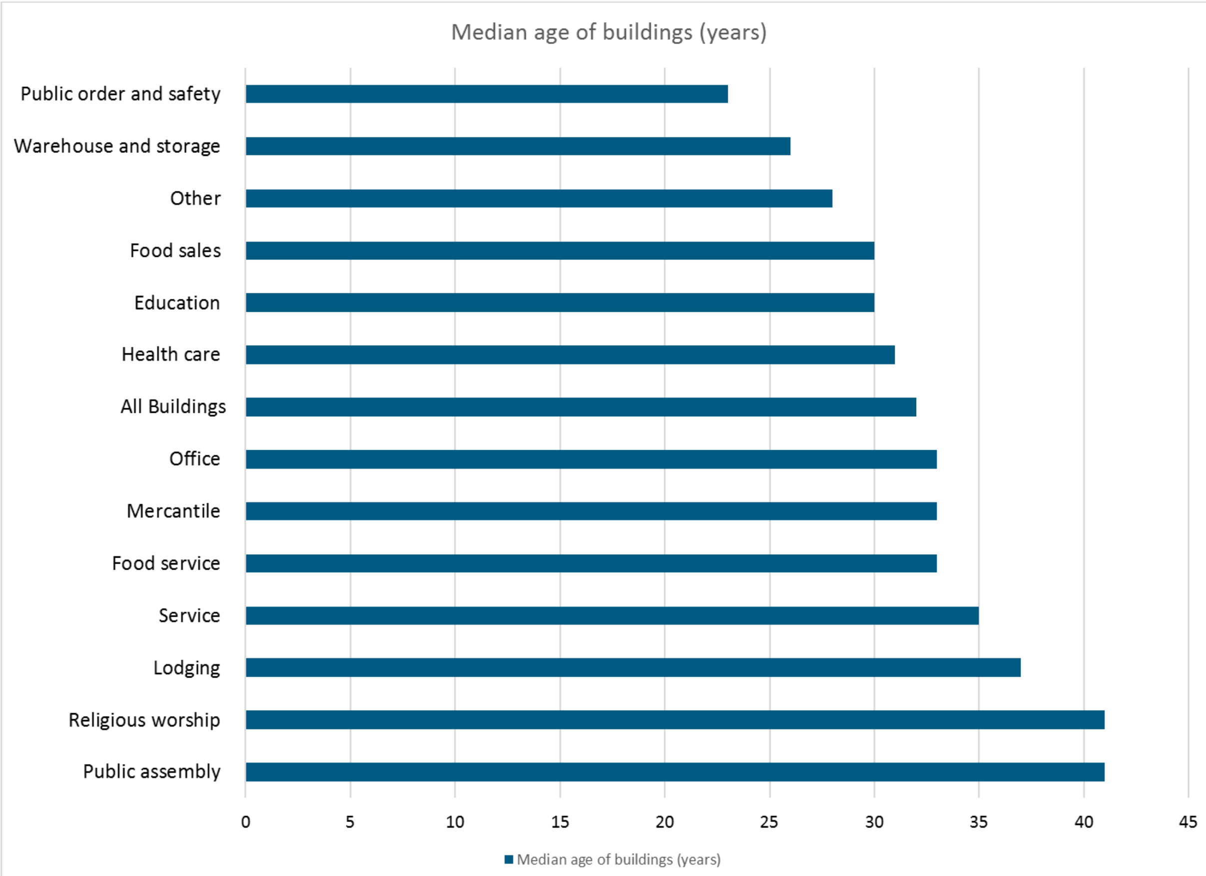

Figure 12.1 - Median Age of US Commercial Buildings by Type, 2012

Figure By Donald Coffelt. Data Source: U.S. Energy Information Administration, Office of Energy Consumption and Efficiency Statistics, Form EIA-871A of the 2012 Commercial Buildings Energy Consumption Survey, Public Domain, https://www.eia.gov/consumption/commercial/data/2012/#b11-b14.

12.3. Institutional Arrangements for Building Infrastructure

Buildings may be owned by occupants (or residents) or investors of various kinds. As shown in Table 12.2, nearly 30% of US housing units are owned by investors and rented to occupants.

Ownership of buildings commonly changes over the building lifetime. Initially, buildings may be constructed with the intent of re-sale upon completion of construction, as with residential developers. Active real estate markets aid in the transfer of ownership during the lifetime of buildings. Opportunities to gain tax advantages through rapid depreciation of buildings can motivate relatively frequent building sales. With or without ownership changes, buildings typically undergo renovations and changes in function during their lifetime.

Lending institutions often make loans using real estate as collateral. In the event of default on the loans, the lending institution can foreclose and gain possession of the property. During construction of buildings, the value of buildings is problematic, so lending institutions typically charge more for construction loans than for mortgage loans secured by a complete building's collateral.

Building management can be undertaken by a variety of parties, including owners, occupants or contractors. Automated aids for building management are typically less sophisticated than aids for other infrastructure systems, reflecting in part the diverse ownership of the building infrastructure.

12.4. Some Infrastructure Management Issues for Buildings

Buildings are large consumers of resources and producers of environmental impacts throughout the world. As a result of these impacts, buildings are receiving increasing attention to improve function, reduce costs and reduce environmental impact. At the same time, architectural interests are flourishing to promote 'aesthetic' designs. In addition, there is continuing concern to make buildings better at supporting the occupants through improved ventilation, noise control and temperature control.

As noted in Chapter 10, 'Green buildings' standards are becoming much more prevalent, with many entities committed to such buildings, including the US General Services Administration (GSA) (https://www.gsa.gov/portal/content/123747). The most common standard in the US is the Green Building Alliance's (a private non-profit group) 'Leadership in Energy and Environmental Design' (LEED) (USGBC, 2016). It is based on a point award system for a checklist of possible design and construction activities. Prerequisites and credits are included in the categories of:

- Sustainable site characteristics
- Water efficiency
- Energy and atmosphere
- Materials and resources
- Indoor environmental quality
- Innovation in design

Buildings are certified to different levels of standards based on submitted documentation and the published point system. Achieving savings in energy inputs during the building operational phase is of particular interest in the design stages.

Building construction and management improvement are continuing targets for research and innovation. Active areas include computer aids (such as Building Information Modeling), lean construction practices, new materials, pre-manufactured components, building resiliency, and life cycle costing for management.

12.5. Exercises and Questions

P12.1 **(5 pts)** What are the differences between commercial and housing buildings that influence management practices and decision making?

P12.2 **(10 pts)** Select a category of LEED credits and estimate their life cycle effect and cost for a typical building.

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Chapter 13: Water Infrastructure

13.1 Introduction

Water infrastructure is intended to provide water for a variety of uses, to remove and treat wastewater, to provide flood risk mitigation, to aid water navigation, to provide recreational opportunities and to generate electricity or power. Water is essential for human life, with humans comprised of roughly 50-70% water and drinking (or ingesting) roughly 2 liters of water per day. Droughts and agricultural salt incursion due to inadequate water management are often cited as significant causes for the failure of historic civilizations.

Anthropogenic water withdrawals in the United States are shown in Figure 13.1 in billions of gallons per day. Irrigation for agriculture and thermoelectric power are the two largest uses, and both of these uses have corresponding large wastewater runoffs. With public water supply at 50 billion gallons per day and a population of 300 million, per capita water use is roughly 50,000/300 = 170 gal/day (640 liters/day) which would include commercial uses, drinking water, fire fighting, washing, watering, etc. Note that Figure 13.1 does not include withdrawals for eco-system uses other than agricultural irrigation.

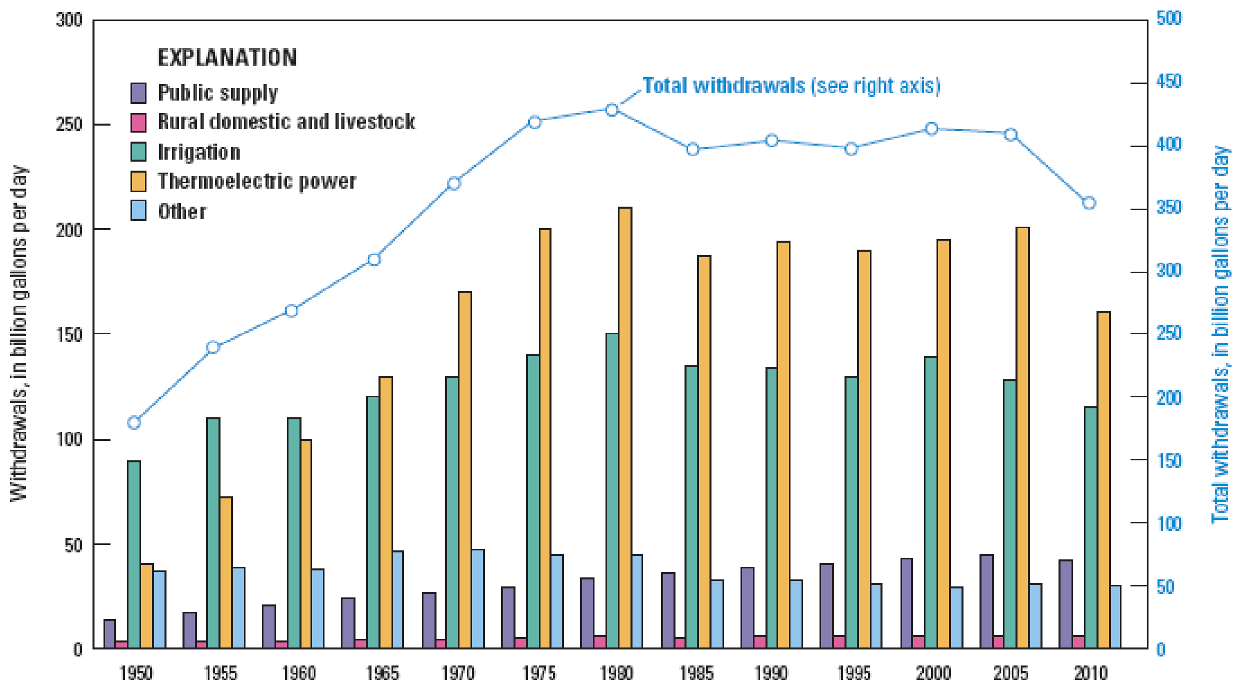

Figure 14. Trends in total water withdrawals by water-use category, 1950–2010.

Figure 13.1 - Water Withdrawals in the United States over Time

Source: USGS, Public Domain, http://water.usgs.gov/edu/wateruse-trends.html

Water withdrawals are different from water consumption or use. Withdrawals for uses such as thermoelectric power are often returned directly to their source, although at a higher temperature. Similarly, public water supplies may be used, treated as wastewater, and returned to a river. Thus, water may be re-used and withdrawn numerous times.

Access to safe and sustainable drinking water and sanitary resources are major problems in many areas. The United Nations estimates one billion people lack access to safe drinking water and 3.5 billion people lacking access to sanitary facilities (WWAP, 2016). A Millennium Goal is to reduce the number of people without access to safe water in half by 2015.

Water transportation is a significant mode for freight traffic. Figure 13.2 shows inland waterway freight flows in the United States. The importance of the Mississippi water system and the Great Lakes are evident.

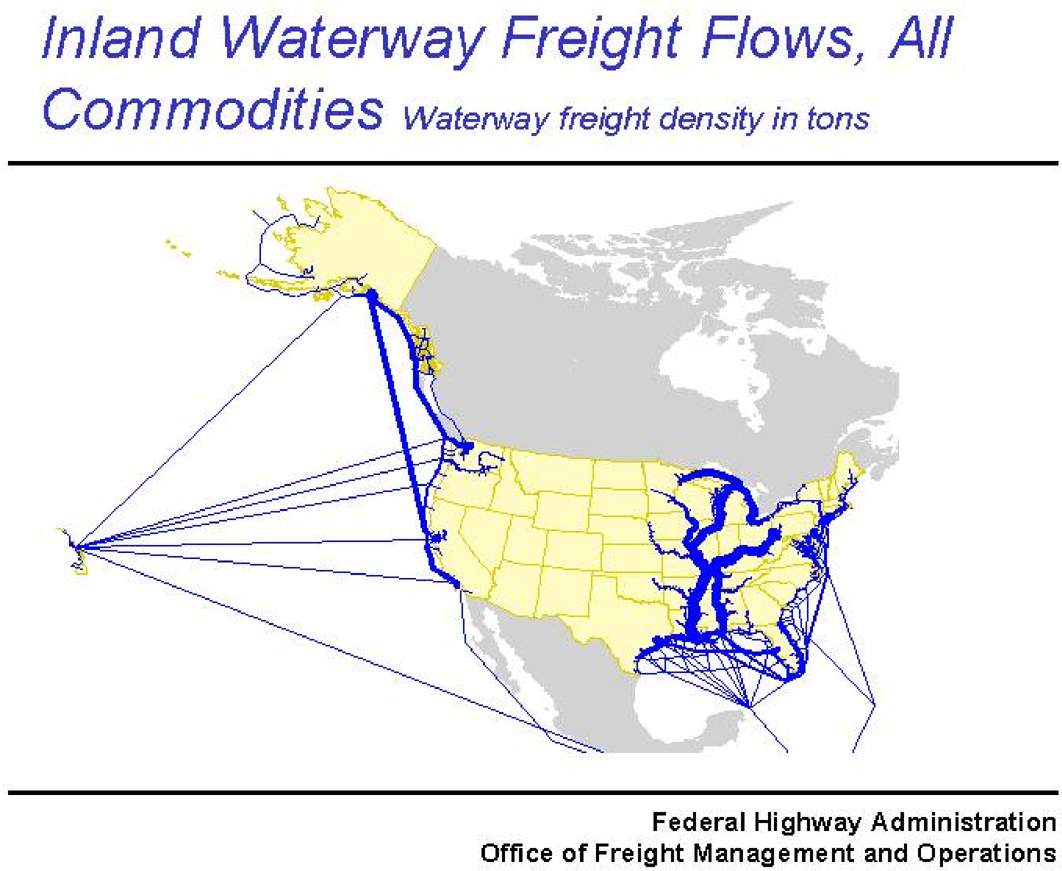

Figure 13.2 - Inland Waterway Freight Flows

Source: FHWA, Public Domain, https://ops.fhwa.dot.gov/freight/Memphis/appendix_materials/lambert.htm

13.2 Duration and Extent of Water Infrastructure

Statistics and studies of water infrastructure typically make major distinctions among water supply, wastewater treatment and other water infrastructure. We have combined all three in this module because particular infrastructure components may serve multiple purposes. For example, a particular dam may contribute water storage, hydroelectric power generation, flood control and recreational opportunities. Moreover, different water infrastructure elements all belong within the common general water cycle. For example, the output of a wastewater treatment plant will often be the input for a water supply system downstream. As recycling and reuse become more critical management strategies, an integrated strategy for water supply, wastewater treatment and other uses becomes more important.

Unfortunately, summary statistics on the physical extent of the water infrastructure system are difficult to obtain. After all, the infrastructure has numerous owners and purposes. Some indication of magnitude is indicated in Table 13.1, showing the revenues and numbers of establishments for water supply, irrigation and sewage treatment in 2002 obtained from the US Economic Census. Figure 13.3 shows state and local spending alone on water and wastewater operations to be roughly $ 20B each in 2001 dollars.

Table 13.1 - Summary Statistics for the Water, Sewage and Other Systems Sector from the 2002

2002 NAICS code	Kind of business	Establishments (number)	Revenue ($1,000)
2213	Water, sewage, and other systems	5 780	7 593 747
22131	Water supply and irrigation systems	4 830	5 860 181
221310	Water supply and irrigation systems	4 830	5 860 181
22132	Sewage treatment facilities	866	1 051 028
221320	Sewage treatment facilities	866	1 051 028
22133	Steam and air-conditioning supply	84	682 538
221330	Steam and air-conditioning supply	84	682 538

Source: US Census, 2004, '2002 Economic Census', Public Domain, http://www.census.gov/prod/ec02/ec0222i02.pdf

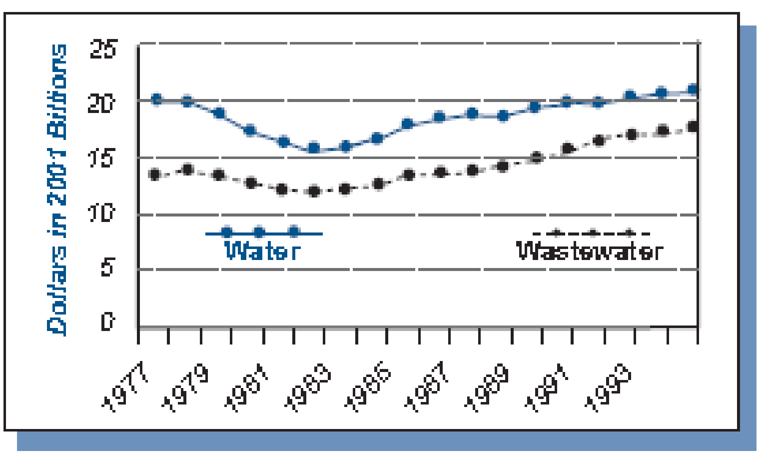

Figure 13.3 - State and Local Spending on Water and Wastewater Operations

Source: US EPA, 2002, 'Clean Water and Drinking Water Infrastructure Gap Analysis, 901R0200, Public Domain, https://nepis.epa.gov

A typical water supply plant involves several process operations to filter and disinfect 'raw' water (Figure 13.4). Wastewater treatment has more variations, depending upon the design level of treatment (Figure 13.5).

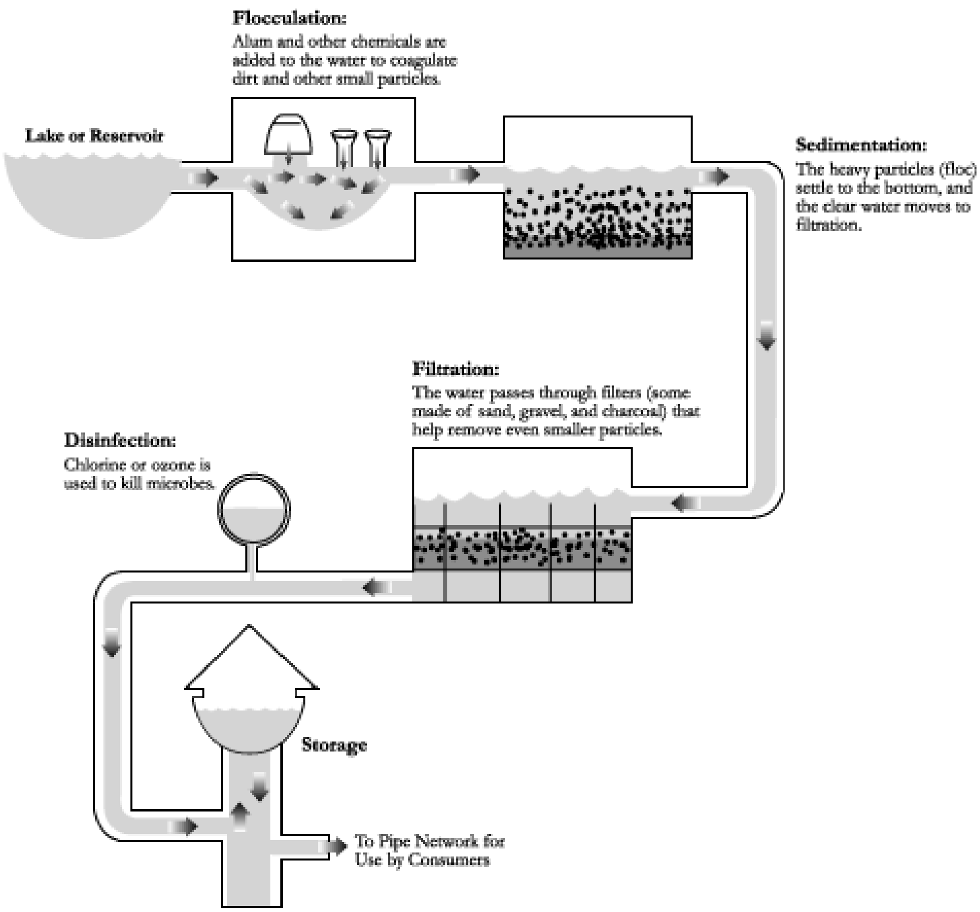

Figure 13.4 - Typical Processes in a Drinking Water Plant

Source: Congressional Budget Office, 2002, Public Domain, http://www.cbo.gov/doc.cfm?index=3983&type=0&sequence=2

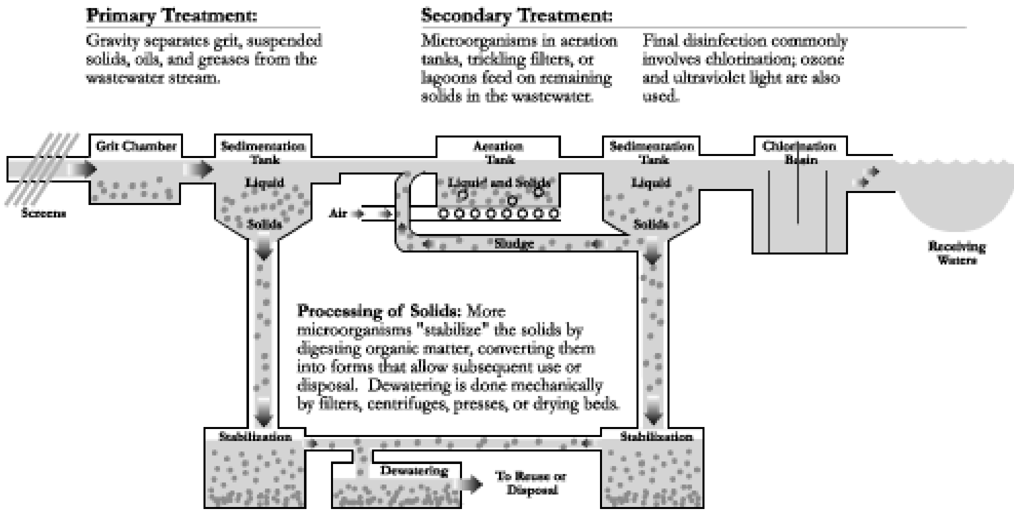

Figure 13.5 - Typical Processes in a Waste Water Treatment Plant

Source: Congressional Budget Office, 2002, Public Domain, http://www.cbo.gov/doc.cfm?index=3983&type=0&sequence=2, Based on Water Environment Federation, *Clean Water for Today: What Is Wastewater Treatment?* (Alexandria, Va.: WEF, November 1999).

Water infrastructure can be very long lived, especially buried pipes, earthen structures and canals. Table 13.2 shows some estimated lives of water infrastructure components.

Table 13.2 - Estimated Useful Lives of Water Infrastructure Components

Years	Component
	Clean Water
80 - 100	Collections
50	Treatment Plants - Concrete Structures
15 - 25	Treatment Plants - Mechanical & Electrical
25	Force Mains
50	Pumping Stations - Concrete Structures
15	Pumping Stations - Mechanical & Electrical
90 - 100	Interceptors
	Drinking Water
50 - 80	Reservoirs & Dams
60 - 70	Treatment Plants - Concrete Structures
15 -25	Treatment Plants - Mechanical & Electrical
65 - 95	Trunk Mains
60 - 70	Pumping Stations - Concrete Structures
25	Pumping Stations - Mechanical & Electrical
65 - 95	Distribution

Source: US EPA, 2002, "Clean Water and Drinking Water Infrastructure Gap Analysis", Public Domain, 901R0200, https://nepis.epa.gov

13.3 Institutional Arrangements for Water Infrastructure

Water infrastructure has a variety of government and private owners in nearly all geographic regions. In the US, city or regional public providers tend to be the most common arrangement. However, individual metropolitan areas may have multiple private and public water supply organizations. Municipal wastewater may be managed by a single entity, but industrial and residential wastewater treatment processes may also exist. For example, septic tanks may be used in outlying areas. Similarly, the US Army Corps of Engineers often has primary responsibility for flood damage mitigation, but numerous other entities may be involved. Navigation aids may be under the control of the US Coast Guard, but other agencies and private entities may also be involved.

Water quality standards play an important role in influencing infrastructure management. Most water standards are set at the national level, although standards exist for the European Union. Different standards may exist for drinking water quality, recreational water quality, and wastewater treatment outflows.

13.4 Some Infrastructure Management Issues for Water

Four overarching issues should be highlighted for water infrastructure management:

1. Achieving the United Nations' Millennium goal (described above) of significantly increasing the availability of clean water throughout the world is a major challenge. Significant new investments and technology will be needed.

2. Dealing with water shortages in areas where demand exceeds sustainable supplies. Prioritizing water uses, seeking new sources and expanding re-use are possible strategies in these areas.

3. Pollution prevention and treatment continue to be major concerns. New pollutants such as hormones or bio-terrorism provide new challenges.

4. Replacing and improving existing water infrastructure is an issue in many parts of the world. In the ASCE, the water infrastructure receives a grade of barely passing (D) (ASCE, 2005) and components are continuing to age.

Financing investments for dealing with these challenges is proving to be difficult.

The US EPA believes that 'better management practices, efficient water use, full-cost pricing of water and a watershed approach to protection can all help utilities to operate more sustainably now and in the long-term (EPA).

- Better Management of water and wastewater utilities can encompass practices like asset management and environmental management systems. Consolidation and public/private partnerships could also offer utilities significant savings.

- Rates that reflect the Full Cost Pricing of service and rate restructuring can help utilities capture the actual costs of operating water systems, raise revenues, and also help to conserve water.
- Efficient Water Use is critical, particularly in those parts of the country that are undergoing water shortages. We need to create market incentives to encourage more efficient use of water and to protect our sources of water.
- Watershed Approaches looks more broadly at water resources in a coordinated way, which is challenging because we have not traditionally thought of infrastructure management within the context of water quality protection.

13.5 Some In-Class Exercises and Questions

13.1 **(5 pts)** Where does your local drinking water come from? How might you identify its quality relative to clean water standards?

13.2 **(10 pts)** How much does drinking water cost (in $/liter) is your locality from (a) the regular tap or (b) the nearest source of retail bottled water.

13.3 **(10 pts)** Based on the typical local rainfall and water use in your area (e.g. city or metropolitan area), how much land is required as a watershed?

13.6 References

ASCE 'Report Card for America's Infrastructure.' (2005). https://www.infrastructurereportcard.org/wp-content/uploads/2016/10/2005-ASCE-Report-Card-for-Americas-Infrastructure.pdf

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Chapter 14: Telecommunications Infrastructure

14.1. Introduction

Telecommunications assist information exchange over a distance by means of transmitters, a transmission medium and receivers. A variety of transmission media have been used over time, such as the electric connection used in telegraphy or fiber optic cables for the Internet. Digital messages are becoming the norm for telecommunications, with analog signals such as speech translated to digital signals for transmission. A variety of protocols exists for interpreting messages on different media.

Figure 14.1 shows the growth over a fifteen-year period in various aspects of telecommunications, focusing on telecom and internet service. The rapid growth in Internet users and in mobile cellular subscribers is particularly notable.

Indicators	1991	1996	2001	2006
Telecom market total revenue (billion dollars)	523	885	1,232	(NA)
Services	403	672	968	1,492
Equipment	120	213	264	(NA)
Telecom telephone services total revenue (billion dollars)	331	444	479	(NA)
Other Services (billion dollars):				
International	37	53	56	(NA)
Mobile	19	114	317	627
Other	53	114	180	(NA)
Telecom services capital expenditures (billion dollars):				
Total	124	174	201	215
Other Statistics:				
Main telephone lines (millions)	546	738	1,053	1,270
Mobile cellular subscribers (million)	16	145	955	2,685
International telephone traffic minutes (billions)	38	71	127	183
Personal computers (millions)	130	275	555	885
Internet users (millions)	4	74	502	1,131

Source: International Telecommunication Union, Geneva Switzerland, 2007.
Reprinted: US Census, Statistical Abstract of the United States, Table 1344

Figure 14.1 - Global Telecoms Statistics (1991-2006)

Source: Statistical Abstract of the United States, Public Domain.

Figure 14.2 shows the growth over time of a segment of telecommunications, namely international calls from or to the United States. The amount of traffic has increased substantially, while the price per minute has declined by an order of magnitude from 2000 to 2014.

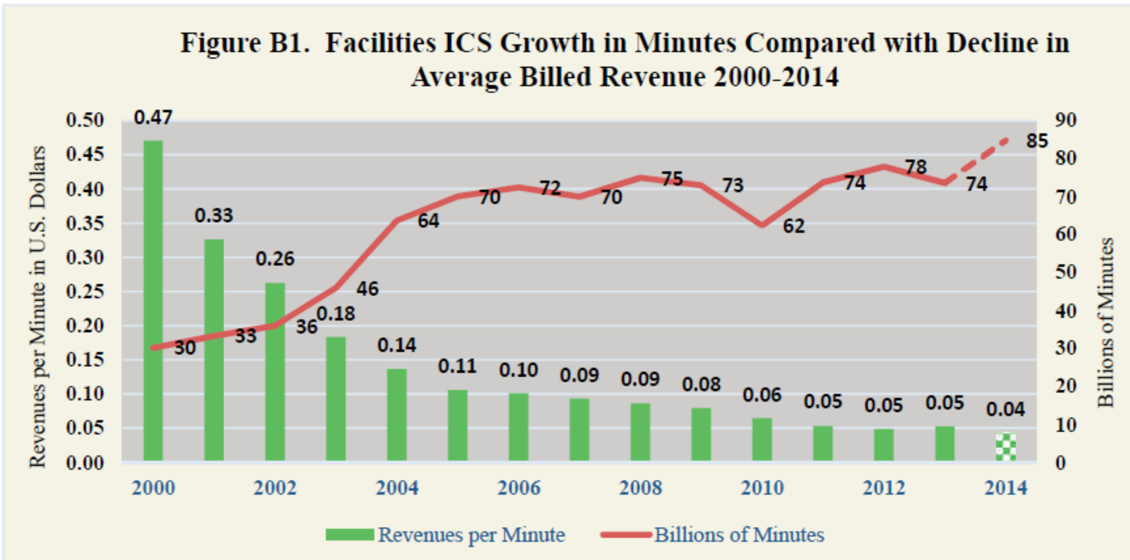

Figure 14.2 - International Telecommunication Minutes and Prices for the US, 2000-2014

Source: FCC, Public Domain,
http://transition.fcc.gov/Daily_Releases/Daily_Business/2016/db0701/DOC-340121A1.pdf

Telecommunications are dominated in the United States by private corporations (FCC 1996). Overseas, examples of both private and public providers exist. The ownership structure for telecommunications infrastructure is complex, with building owners responsible for their own internal telecommunications and companies often sharing facilities such as cell towers or neighborhood telephone poles.

14.2. Duration and Extent of Tele-communications Infrastructure

Figure 14.1 showed the rapid growth in the numbers of users of telecommunications services. In addition, new applications require large amounts of information to be available rapidly. Figure 14.3 shows some of the demands for applications such as videoconferencing and entertainment (such as movies on demand).

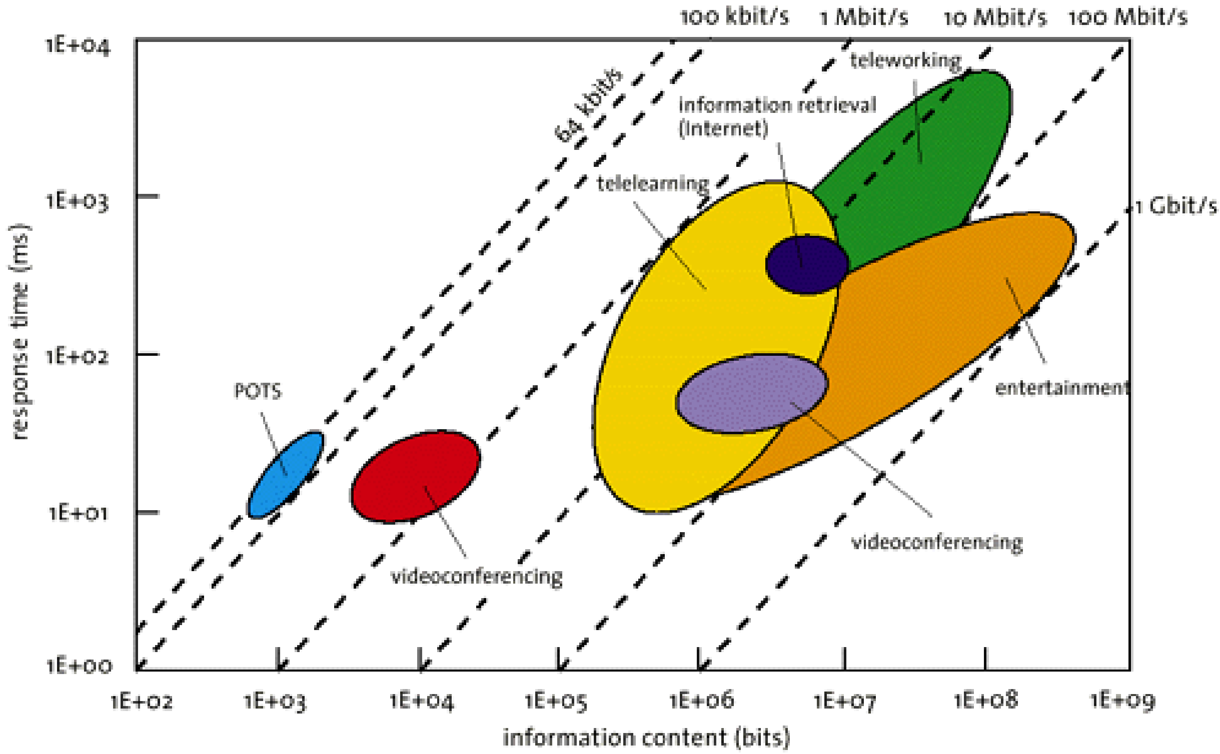

Figure 14.3 - New Applications Generate More Demand for Telecommunications

Source: Courtesy of Henrich Hertz Institute, Berlin. Reproduced in: http://cordis.europa.eu/infowin/acts/rus/impacts/photon.htm

A variety of media are used for telecommunications, including copper wires, fiber optic cables and wireless transmission. Even power wires can be used for communication. As an indication of the extent of this infrastructure, Figure 14.4 shows a map of submarine communications cable as of 2015. In addition to these undersea cables, roughly 1,000 communications satellites are in orbit around the earth. Internet services also make use of high speed, high capacity connections such as fiber optic cables and satellite communications.

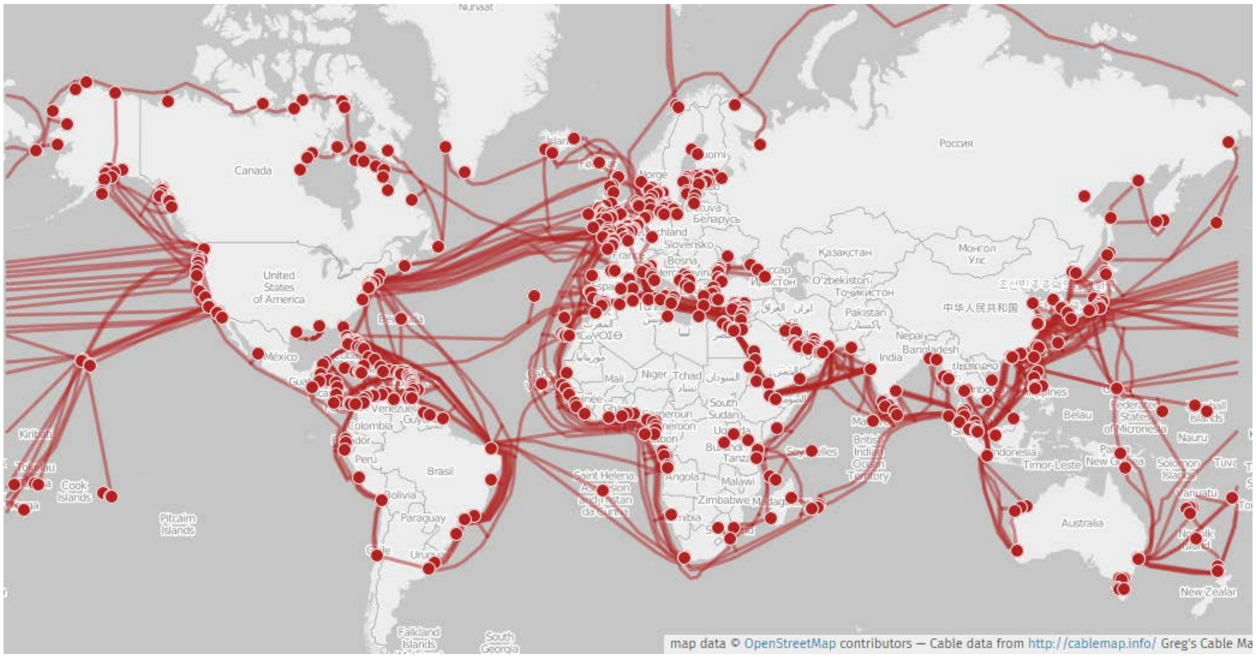

Figure 14.4 - World Map of Submarine Communications Cables

Source: Cable data by Greg Mahlknecht , map by Openstreetmap contributors - http://www.cablemap.info (cable data by Greg Mahlknecht released under GPLv3) http://umap.openstreetmap.fr/de, CC BY-SA 2.0, https://commons.wikimedia.org/w/index.php?curid=42437752

The duration and extent of telecommunications infrastructure depends in large part on how the infrastructure is defined. For example, radio and television transmission towers are often classified as entertainment rather than telecommunications (and are omitted from the statistics shown in Figure 14.1). Nevertheless, radio and television now may be broadcast or provided over the Internet.

Wireless communications, particularly with mobile telephones and personal digital assistants (pda's) have also seen notable growth Clarke, 2014). These services typically connect through cell sites to the regular telecommunications network; with some 300,000 such cell sites existing in the US in 2012 (See Figure 14.5).

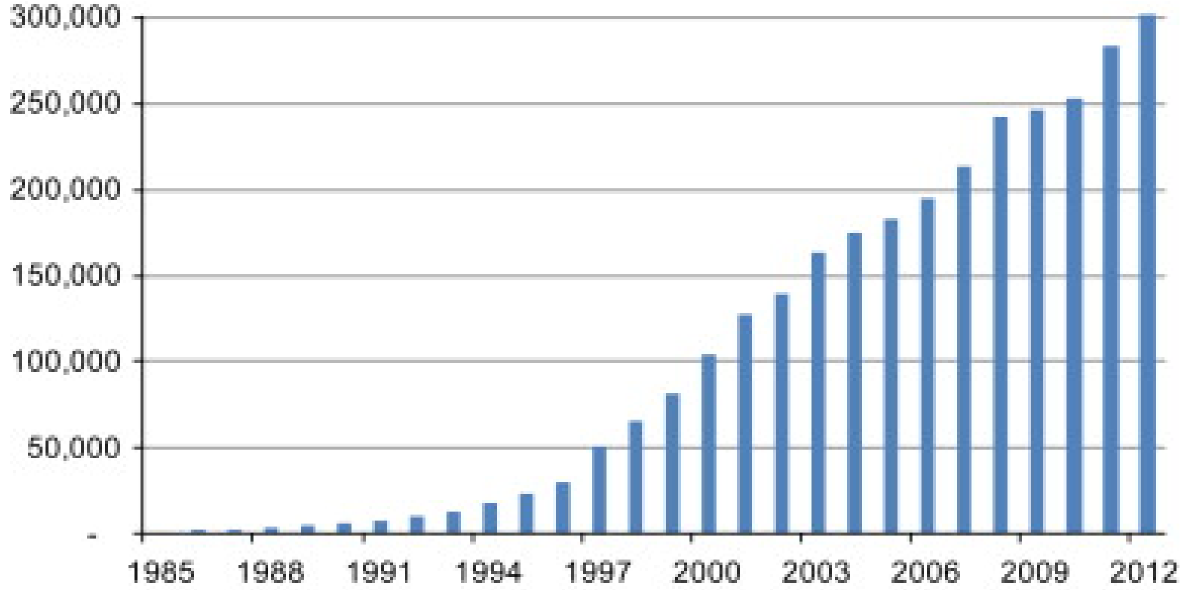

Figure 14.5 - Numbers of US Cell Sites

Source: Clarke, Richard N. "Expanding mobile wireless capacity: The challenges presented by technology and economics." ***Telecommunications Policy*** **38.8 (2014): 693-708. https://doi.org/10.1016/j.telpol.2013.11.006) https://creativecommons.org/licenses/by/3.0/**

With rapid expansion of use and growing speed and capacity, many parts of the telecommunications infrastructure have relative short lifetimes. Smart phones and computers may become functionally obsolete within five years. In contrast, some parts of the infrastructure may have relatively long lifetimes. Fiber optics

Interdependence between telecommunications and other infrastructure systems is apparent. For example, telecommunications is needed to manage the electric power grid, while electricity is needed for telecommunications. Back-up power by means such as batteries is provided to insure continuing telephone service in case of power interruptions.

The growth of the internet has increased the complexity of the telecommunications network and the extent of infrastructure interdependencies. As an illustration, Figure 14.6 shows a partial map of the internet, where nodes are internet protocol (IP) addresses and the length of links shows the typical delay between two IP addresses.

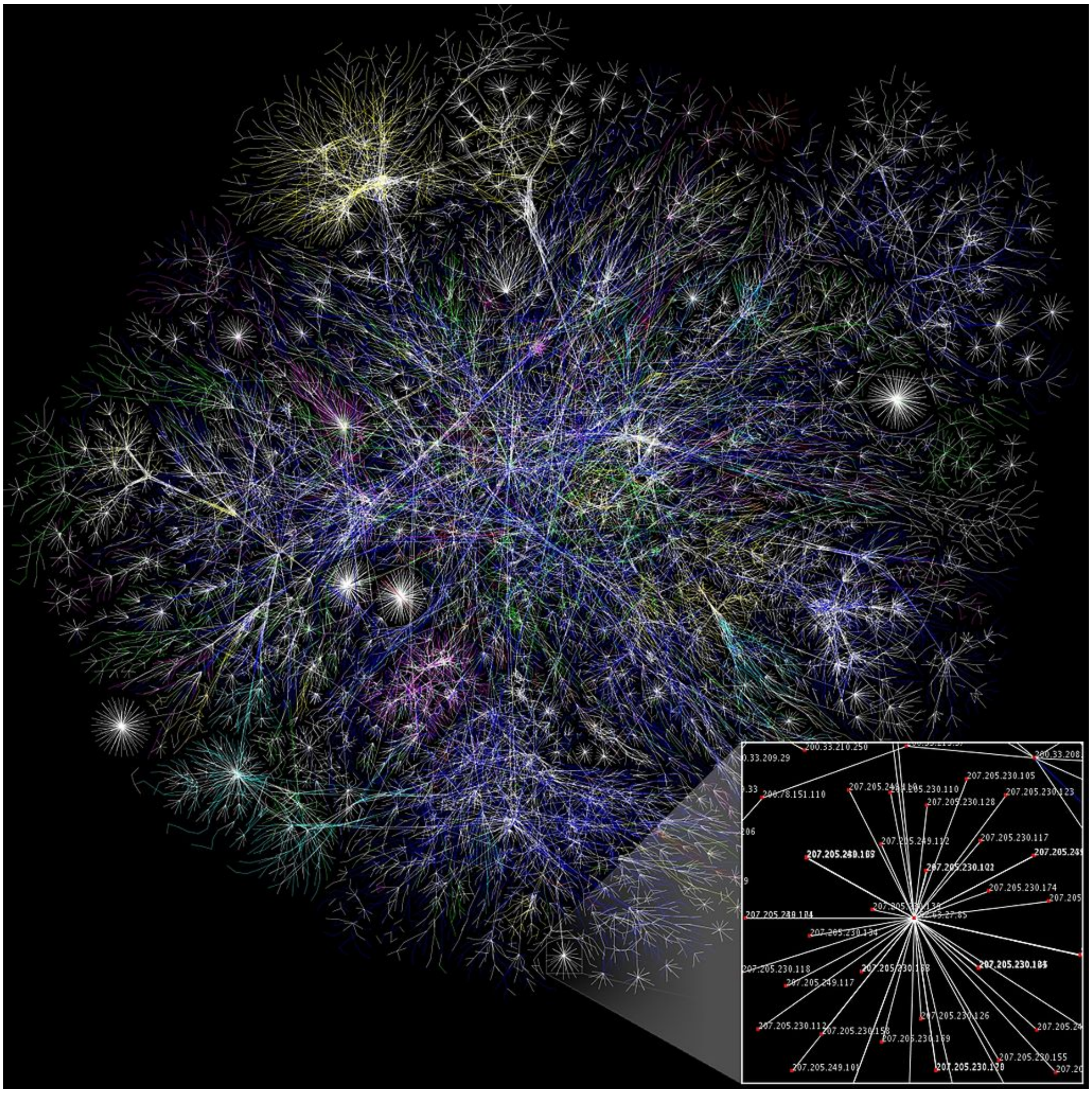

Figure 14.6 - Partial Map of Internet Connections

Source: By The Opte Project [CC BY 2.5 (http://creativecommons.org/licenses/by/2.5)], via Wikimedia Commons By The Opte Project – Originally from the English Wikipedia; https://commons.wikimedia.org/w/index.php?curid=1538544

14.3. Organization of Telecommunications

The bulk of telecommunications is in private ownership, although there are notable examples of public, non-profit owners and government owners of such infrastructure.

As an example, the Internet has multiple companies providing services. Individual companies or individuals may maintain local area networks which are connected to Internet Service Providers (ISPs). In turn, the ISPs connect to backbone service providers. In effect, the Internet is a network of networks with routers handling packets of information. Protocols and management guidance is provided by organizations such as the Internet Society.

Regulation of telecommunications is also distributed. In the US, the Federal Communications Commission (FCC) was established by the Communications Act of 1934 and is charged with regulating interstate and international communications by radio, television, wire, satellite and cable.

Allocation of the electro-magnetic radio spectrum is a major activity in telecommunications regulation. In essence, users do not want interference in using allocated parts of the spectrum. Broadcast radio stations were among the first to have allocated frequencies which were managed to prevent signal interference. As illustrated by the 2016 United States frequency allocation chart in Figure 14.7, a very large number of spectrum users must now be accommodated.

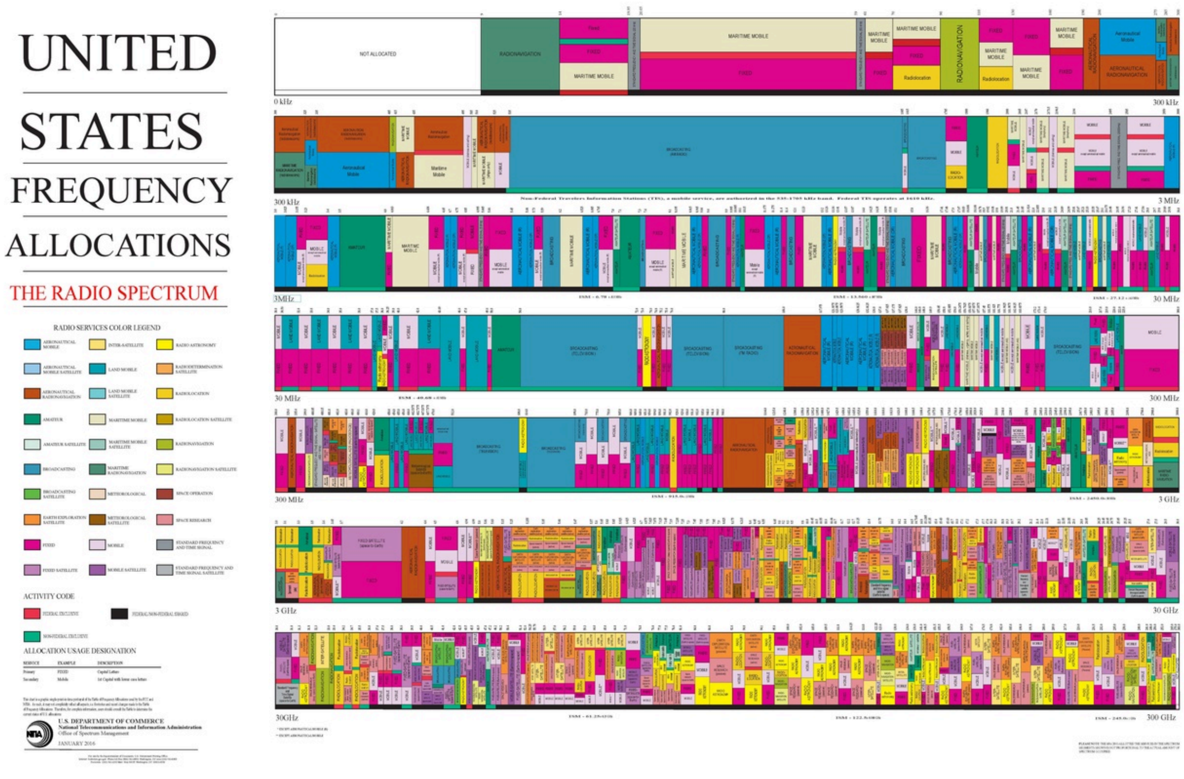

Figure 14.7 - US Radio Spectrum Allocation Illustration (2016)

Source: United States Department of Commerce, Public Domain, https://www.ntia.doc.gov/files/ntia/publications/january_2016_spectrum_wall_chart.pdf, https://commons.wikimedia.org/wiki/File:United_States_Frequency_Allocations_Chart_2016_-_The_Radio_Spectrum.pdf

14.4. Some Infrastructure Management Issues for Tele-communications

Tele-communications has similar management problems as other infrastructure systems, such as power generation or roadways. Numerous structural elements such as cables, satellites, towers and relay stations must be inspected, maintained and replaced over time. Communications traffic must be managed, including dealing with congestion.

Pricing of services and financing necessary infrastructure is a complex issue for tele-communications, particularly as multiple companies may be involved in handling communications. With the merging of Internet, telephone and entertainment, additional complications in pricing services (and illegal copying) arise.

14.5. Exercises

P14.1 **(5 pts)** How are the prices charged for mobile telephone service related to the cost of providing services?

P14.2 **(5 pts)** How many cell sites can you identify within 1 km of your residence?

14.6 References

Clarke, Richard N. "Expanding mobile wireless capacity: The challenges presented by technology and economics." *Telecommunications Policy* 38.8 (2014): 693-708.

Federal Communications Commission. "Telecommunications Act of 1996." Public law 104.104 (1996): 1-5.

Chapter 15: Electricity Power Generation, Transmission and Distribution Infrastructure

15.1. Introduction

'Electrification' was selected by the US National Academy of Engineering as the greatest engineering achievement of the twentieth century (NAE 2008). Electricity is a primary power source throughout the developed world and many other infrastructure systems depend upon electricity such as buildings and tele-communications.

Figure 15.1 shows the historical sources of energy consumption in the United States. Until the twentieth century, wood was a predominant source of energy, with the early twentieth century seeing the growth in coal use. By 1920, petroleum and national gas became large sources of energy. Nuclear power began in 1950 with the development of the atomic industry.

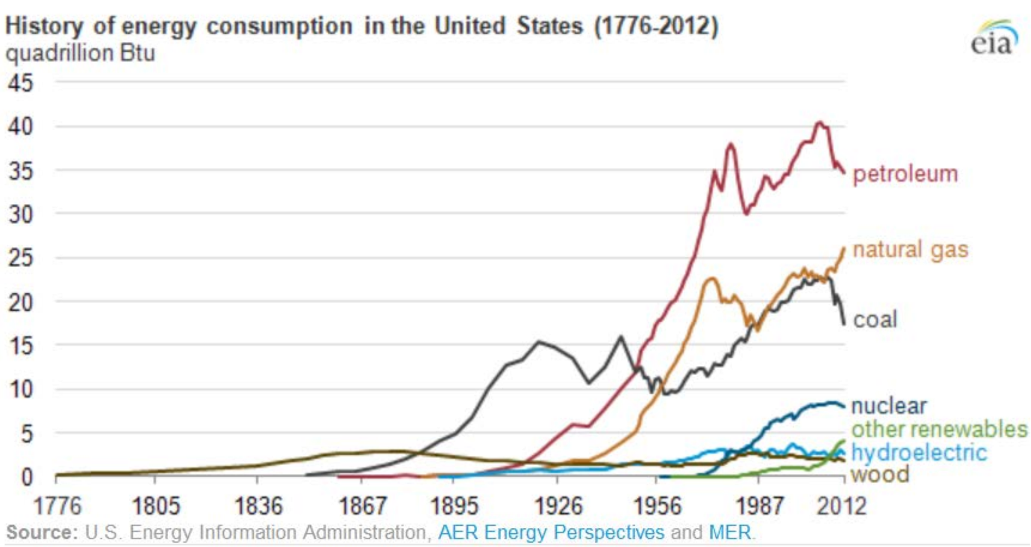

Figure 15.1 - Energy Consumption by Source, 1776-2012, Quadrillion BTU

Source: By U.S. DOE Energy Information Administration (Energy Perspectives 1949–2010[1]) [Public domain], via Wikimedia Commons, https://commons.wikimedia.org/w/index.php?curid=20977658

The electricity system was created in the late nineteenth century in the United States for the primary purpose of lighting. Thomas Edison built and promoted a direct current network, while George Westinghouse proposed an alternating current network. In 1881, electricity rates were $ 0.24/kWhr (equivalent to roughly $ 5/kWhr in current dollars), while modern electricity rates are around $ 0.10/kWhr. Alternating current power grids have become the norm for reasons of efficiency throughout the world, although local direct current wiring can be used for light emitting diode (LED) lighting and electronics.

US electricity energy flows for 2007 are shown in Figure 15.2. Coal, natural gas and nuclear power are the predominant primary energy sources, with renewable energy – including hydroelectric and wind power- fourth in magnitude. Other sources are relatively minor. Conversion losses of primary energy sources to electricity are substantial; moreover, this graphic does not include energy costs of mining, refining and transporting the primary energy sources to power generation sites. Predominant electricity uses are classified by EIA as residential, commercial or industrial.

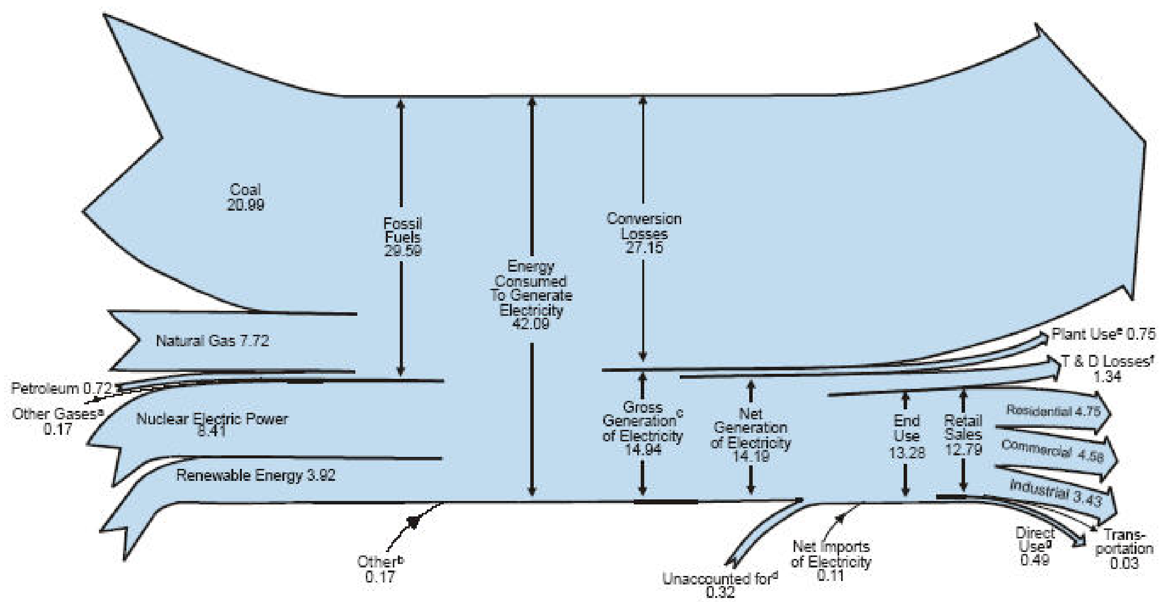

Figure 15.2 - US Electricity Flows, 2007, Quadrillion BTU

Source: Energy Information Agency, 'Annual Energy Review', Public Domain, http://www.eia.doe.gov/emeu/aer/diagram5.html.

World primary energy sources for electricity are similar to the US, with coal, natural gas, renewable sources and nuclear energy the primary sources (Figure 15.3), although hydroelectric is larger for the world than for the US itself. However, this distribution can vary substantially from region to region. Some countries have developed extensive and inexpensive geo-electric and hydro-electric power generation (such as Iceland), while others emphasize nuclear power generation (such as France.) Qatar is an example of a country dependent upon natural gas and oil sources.

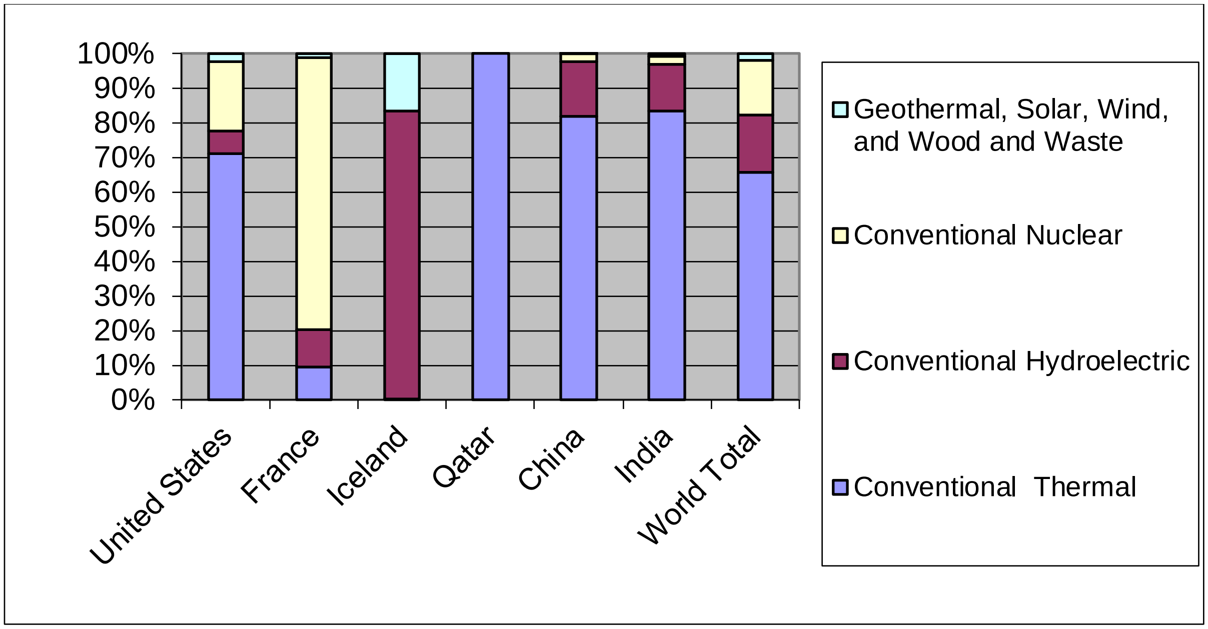

Figure 15.3 - 2005 Primary Sources of Electricity in Selected Countries and the World

Source: Authors Constructed from EIA, Electricity Data, http://www.eia.doe.gov/fuelelectric.html

Electricity is an intermediate carrier of energy, with a variety of underlying sources. Figure 15.4 illustrates overall US energy use and sources, with petroleum used primarily for transportation and heating.

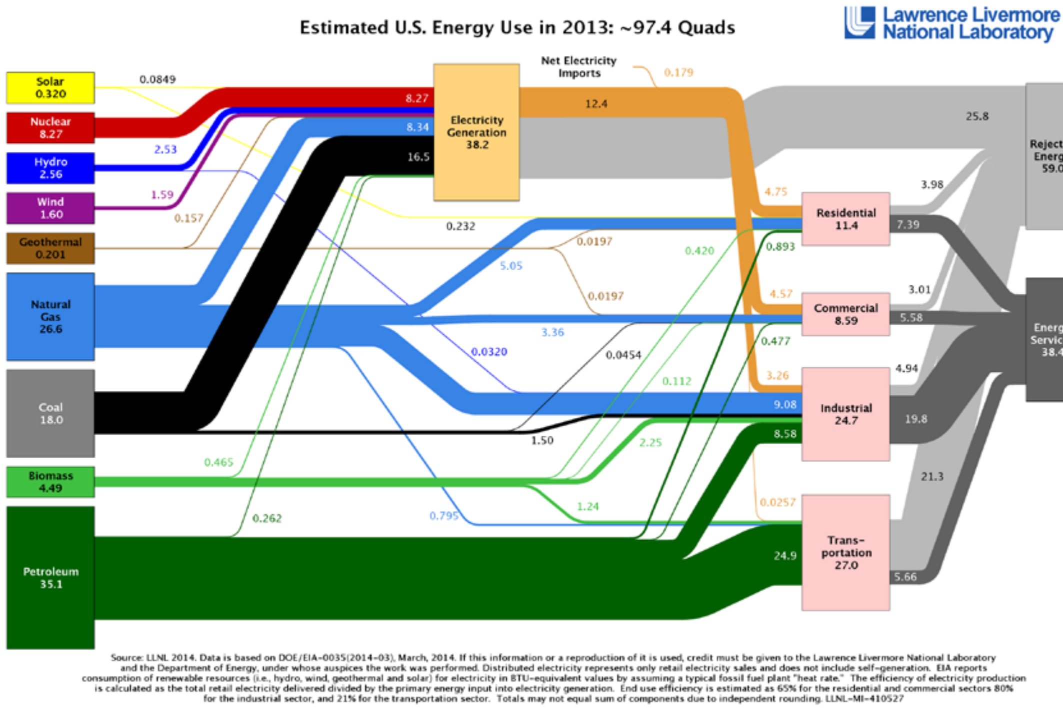

Figure 15.4 - US Energy Sources and Use 2013, including Electricity and Other

Source: U.S. Department of Energy and Lawrence Livermore National Laboratory, 2014. Fair Use. Data based on DOE/EIA-0035(2014-03), March, 2014.
https://flowcharts.llnl.gov/content/energy/energy_archive/energy_flow_2013/2013USEnergy.png)

15.2. Duration and Extent of Electricity Infrastructure

The electricity infrastructure includes generators (power plants), transmission lines, substations, distribution lines, transformers, control devices and users (Figure 15.5). There is also supply chain infrastructure required for electricity supply, such as the mining and transportation of coal to power plants for combustion.

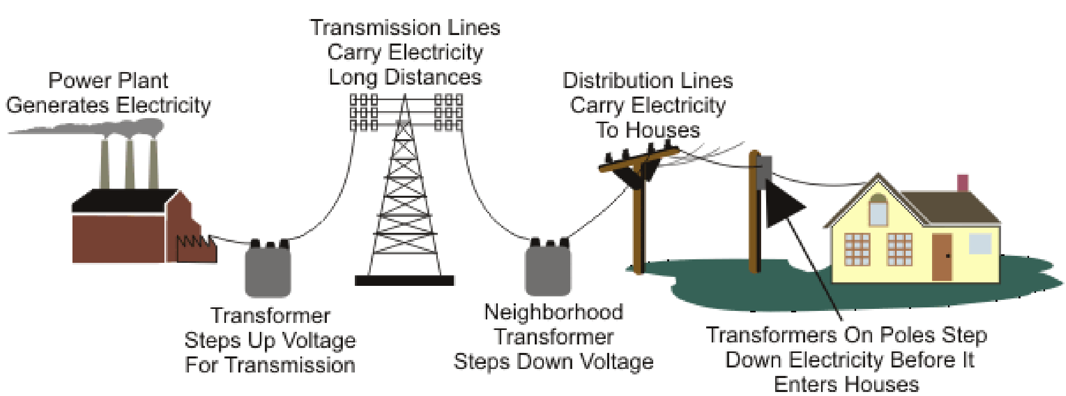

Figure 15.5 - Major elements of Electricity Infrastructure

Source: EIA, Public Domain, 'Electricity Basics,'
http://www.eia.doe.gov/basics/electricity_basics.html

Table 15.1 indicates the 2015 numbers and capacity of electricity generators in the US. The average generator has a rated capacity of 1,167,365MW/20,068 generators = 58 MW. Generation plants themselves can have long lives, with dams and power plant structures lasting for many decades. Operating equipment such as turbines have much shorter useful lives and must be replaced regularly in power plants. There is a trend for increasing reliance on natural gas and other renewable sources of energy and less reliance on coal due to environmental concerns and the relative prices of different sources.

Table 15.1 - Summary of Power Generation Statistics

Fuel Source	Generators	Nameplate Capacity (MW)	Summer Capacity (MW)	Winter Capacity (MW)
Coal	968.00	304,789.80	279,719.90	281,105.80
Hydroelectric	4,176.00	100,529.60	102,239.30	101,535.20
Natural Gas	5,717.00	503,822.70	439,320.80	472,388.40
Nuclear	99.00	103,860.40	98,672.00	101,001.40
Other	407.00	8,557.50	6,585.30	6,859.70
Other Gas	1,778.00	5,154.70	4,681.90	4,710.20
Other Renewable	623.00	11,177.70	9,768.30	9,877.40
Petroleum	3,550.00	42,321.30	36,830.30	40,372.60
Solar	1,652.00	13,758.30	13,663.30	13,427.00
Wind	1,098.00	73,393.20	72,573.40	72,675.80
Grand Total	**20,068.00**	**1,167,365.20**	**1,064,054.50**	**1,103,953.50**

Source: US Energy Information Administration, Form EIA-860, 2016. Public Domain.
https://www.eia.gov/electricity/data/eia860/

Generated power from turbines is normally transmitted as 3-phase alternating current. As a result, transmission lines usually provide three separate wires, one for each phase. Transmission lines are quite extensive throughout the United States, although congestion in some portions of the network is increasing. The US is divided into three major power grids (Figure 15.6), plus separate grids for Alaska, Hawaii and other territories. As of 2015, the US bulk electric distribution system consists of more than 360,000 miles of transmission lines including 180,000 miles of high-voltage AC transmission (Energy, 2015).

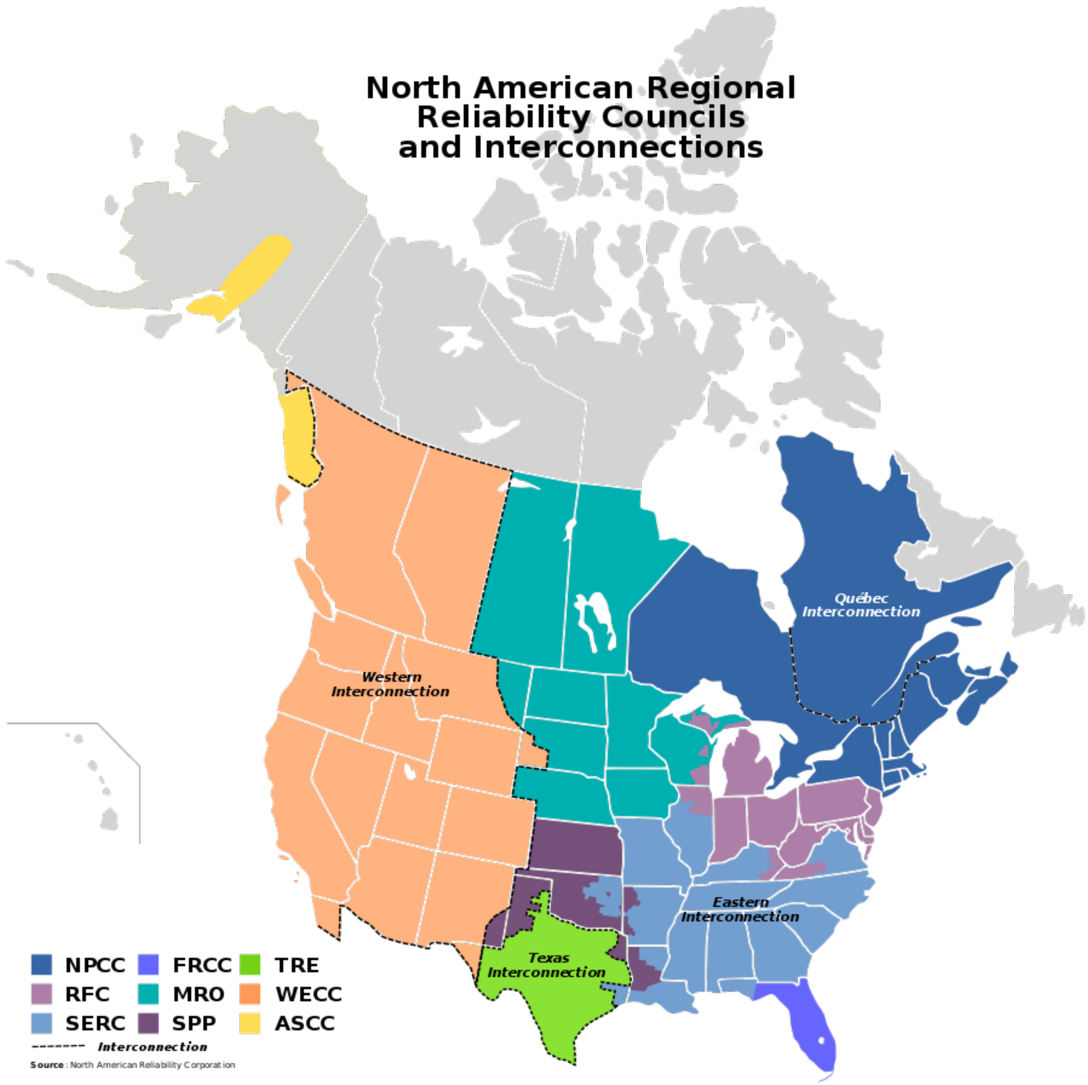

Figure 15.6 - North American Regional Reliability Councils and Interconnections

Source: Bouchecl, Own work, CC BY-SA 3.0,
https://commons.wikimedia.org/w/index.php?curid=6750405

Electric power distribution across the contiguous United States occurs through the operations of some 500 individual companies. Figure 15.7 below illustrates pre-2008 transmission grid voltage and density.

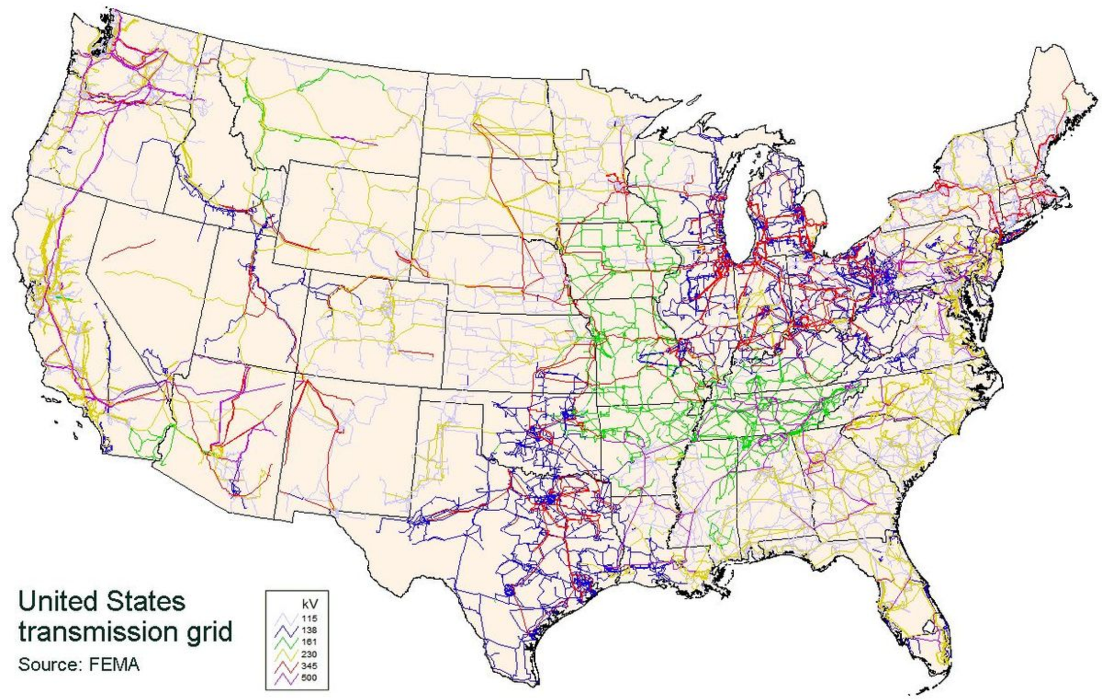

Figure 15.7 - Electric Power Transmission Grid of the Contiguous United States

Source: Rolypolyman. Data source: FEMA via NREL. http://www.nrel.gov/gis/data_analysis.html, Public Domain, https://commons.wikimedia.org/w/index.php?curid=5496554

From the transmission lines, substations typically step-down the voltage for distribution to end users (Figure 15.8). Large users such as industries or military bases might have their own substations.

Figure 15.8 -Components of a Typical Substation

Source: OSHA, https://www.osha.gov/SLTC/etools/electric_power/illustrated_glossary/distribution_system.html

Distribution to customers involves transformations to reduce voltage (to a common level of 240 or 120 V) and to provide single phase alternating current. Tele-communications and electricity service generally share the same telephone poles or underground pipes. For safety reasons, electricity service occupies the highest portion of the common telephone pole (Figure 15.9). Local transformers reduce voltage to residential service levels.

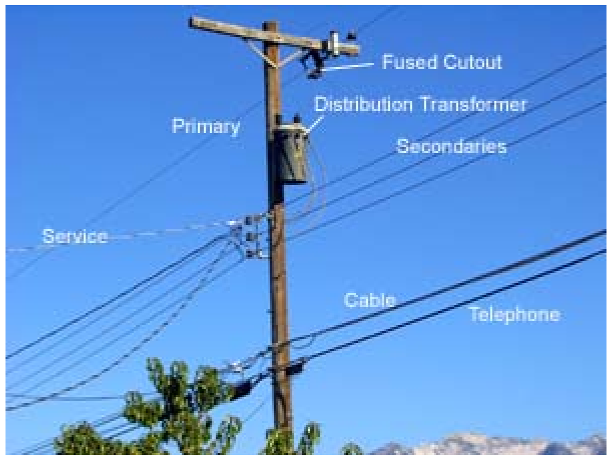

Figure 15.9 - Typical Residential Electricity Distribution Infrastructure

Source: OSHA,
https://www.osha.gov/SLTC/etools/electric_power/illustrated_glossary/distribution_system.html

15.3. Institutional Arrangements for Electricity Infrastructure

In the early years of electricity use in the US, electric utilities were private, small and vertically integrated. Over time, all of these characteristics have changed. Public operating companies emerged, such as the various rural co-operatives and the federal Tennessee Valley Authority. Economies of scale led to much larger companies, with Pacific Gas & Electric having over 5 million customers. Finally, organizations can now specialize in one system aspect, such as power generation, transmission or distribution.

Grid management is provided by regional transmission organization (RTO), such as PJM in the Pittsburgh region. These organizations provide a market for wholesale energy purchases, matching demands for power and supply from power generators. Electricity demand varies over the course of a day (with low points in the middle of the night) and over the course of a year (with heavy air conditioning electricity demands in the summer). Electricity supply can also vary as plants come on and off line or as wind turbines and solar panels respond to weather conditions. As a result, balancing demand and supply is sometimes difficult, especially since storage of generated power is expensive. In practice, the RTO must keep extra, rapid response generating capacity available for demand or supply fluctuations. Moreover, the marginal cost of providing electricity varies over time, including relatively short units of time.

The US regulatory regime for electricity is complicated and changing over time. At the federal level, the Federal Energy Regulatory Agency (FERC) is a key player, with authority to regulate inter-state electricity sales, wholesale electricity rates and hydroelectric power. FERC has issued reliability standards for electricity provision. At the state level, Public Utility Commissions provide varying levels of regulation.

15.4. Some Infrastructure Management Issues for Electricity

The relative costs of different generating modes vary considerably from year-to-year, day-to-day and even minute-to-minute. Solar and wind power are intermittent and subject to rapid stoppages. The prices of coal, natural gas and petroleum can vary considerably. The cost of nuclear power plant construction and uranium fuel also have great uncertainty. Tax credit provisions for renewable energy also exist, at both the federal and state levels, and these often change over time. As a result, risk management and cost minimization are continuing challenges.

A few power interruptions per year are fairly common but can have substantial costs for users (Figure 15.10). Worker productivity declines and refrigerated items may end up spoiling. Establishments with urgent needs for continuous power such as hospitals may invest in back-up generator systems.

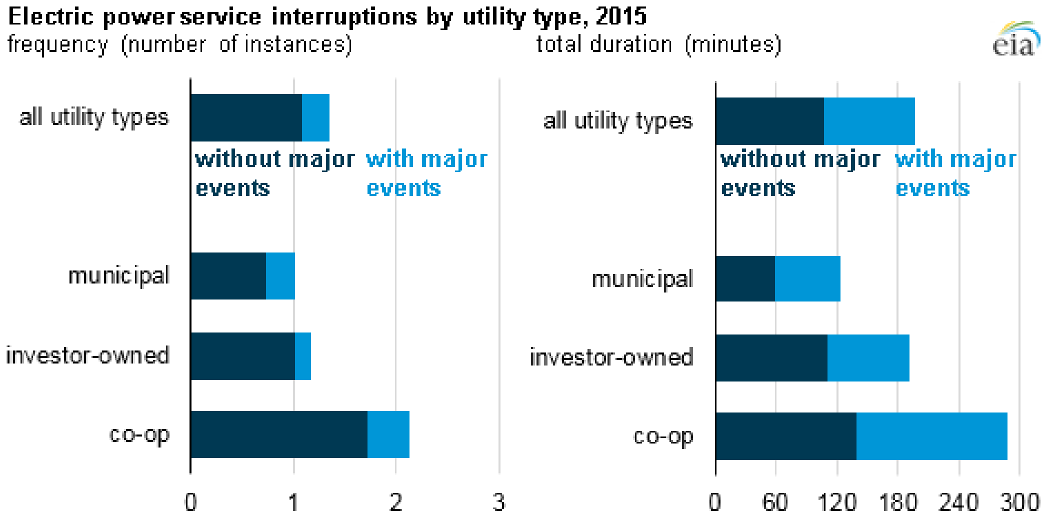

Figure 15.10 - US Electric Power Service Interruptions, 2015

Source: EIA, Public Domain, http://www.eia.gov/todayinenergy/detail.cfm?id=27892&src=email

Electricity generation is responsible for the largest sector share of greenhouse gas emissions in the US inventory (See Better Management EPA inventory reports at:

http://www.epa.gov/climatechange/emissions/usinventoryreport.html) As a result, there are continuing proposals for regulation or tax on power generation emissions. Conventional air emissions are already regulated, such as the cap-and-trade regulation on Sulphur dioxide emissions.

Renewable energy goals and standards are becoming common in the US, motivated by environmental concerns, energy independence and hopes that investment in new forms of energy will spur innovation and scale economies that reduce costs. For example, the renewable portfolio standard enacted by Governor Edward Rendell in 2004 as the Alternative Energy Portfolio Standards Actn213 in Pennsylvania has provisions requiring that qualified power sources provide 18.5 percent of Pennsylvania's electricity by 2020. There are two tiers of qualified sources that meet the standard. Tier 1 sources must make up 8 percent of the portfolio, and include wind, solar, coalmine methane, small hydropower, geothermal, and biomass. Solar sources must provide 0.5 percent of generation by 2020. Tier 2 sources make up the remaining 10 percent of the portfolio, and include waste coal, demand side management, large hydropower, municipal solid waste, and coal integrated gasification combined cycle (PA213, 2004).

With greater reliance on renewable energy sources, management of the grid becomes more difficult, with the need for robust back-up power or real time demand management. Interruptible power contracts already exist, and there is considerable interest in improved demand side management and real-time pricing. Moreover, the location of generating sources changes, with concomitant need for new investment in transmission infrastructure.

A variety of risks also exist for power generation infrastructure. As identified by the Department of Homeland Security (2015), the major risks to the US infrastructure are:

- Cyber and physical security threats;
- Natural disasters and extreme weather conditions;
- Workforce capability ("aging workforce") and human errors;
- Equipment failure and aging infrastructure;
- Evolving environmental, economic, and reliability regulatory requirements; and
- Changes in the technical and operational environment, including changes in fuel supply.

Cyber security and natural disasters have received considerable attention from power generation infrastructure managers, but much more effort is needed to insure resilient and secure infrastructure.

15.5 Exercises

P15.1 **(5 pts)** How could residences take advantage of real-time electricity pricing?

P15.2 **(5pts)** Small scale co-generation of heat and power for buildings is available from fuel cells. What are the grid implications for this effect?

P15.3 **(5pts)** Several automobile companies are planning plug-in hybrid vehicles. What are the implications for electricity provision? What are the management issues to be addressed?

15.6 References

Department of Homeland Security (2015) Energy Sector Specific Plan, https://www.dhs.gov/sites/default/files/publications/nipp-ssp-energy-2015-508.pdf.

EIA, Annual Energy Outlook, https://www.eia.gov/outlooks/aeo/

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http://www.legis.state.pa.us/cfdocs/legis/li/uconsCheck.cfm?yr=2004&sessInd=0&act=213

Chapter 16: Bases, Campuses, Parks and Port Infrastructure

16.1 Introduction

In the past few chapters, specific types of infrastructure systems have been discussed. Infrastructure such as roadways and power generation is widespread and of great social importance. Organizations exist for the management of this infrastructure. While managers must consider inter-action and inter-dependency among different types of infrastructure, the institutional control over different infrastructure systems are typically independent.

Military bases, campuses, parks and ports are different with regard to institutional arrangements for infrastructure. Typically, a single organization is responsible for managing all of the infrastructure for these entities. Moreover, these integrated entities are generally sufficiently large to warrant employment of a professional staff of infrastructure managers. As a result, many professional infrastructure managers work in these integrated entities.

These facilities are also unusual in the types of infrastructure that may be included. Military bases have specialized infrastructure for their specific missions, such as ordnance storage facilities. Industrial and university campuses often have specialized laboratory equipment and facilities. Parks have historic buildings and priceless natural features. Ports have specialized equipment for handling freight and passengers. Even golf courses (considered here a form of parks) have special requirements for landscaping.

Figure 16.1 illustrates a former military base (Fort Jefferson) now located in a national park (Dry Tortugas) on an island remote from the mainland. This is a complicated facility, with historic structures for the fort and modern infrastructure to generate power, water supplies, wastewater and telecommunications. A small port is also on the island for both boats and seaplanes. As a national park, preservation of the natural eco-systems is a priority. Managing the infrastructure on this island is a complicated job for the National Park Service!

Figure 16.1 - Fort Jefferson in Dry Tortugas National Park, Florida

Source: By U.S. National Park Service; English Wikipedia, original upload 2 March 2005 by Brian0918, Public Domain, https://commons.wikimedia.org/w/index.php?curid=326325, Example of a Former Military Base and Park

Figure 16.2 illustrates a university campus, which is another example of a single institution with multiple infrastructure systems. A university campus can rely on external infrastructure such as power generation and transportation services. But a multitude of services are provided on campus, including internal transportation circulation and parking, water and power distribution, and buildings.

Figure 16.2 - Illustration of a Campus: Dartmouth College

Source: By Kane5187 - Own work, Public Domain,
https://commons.wikimedia.org/w/index.php?curid=2949909

Ports are another example of single institution entities with significant amount of infrastructure and specialized facilities. Airports, seaports, and inland waterways (as illustrated in Figure 16.3) are all examples of such entities.

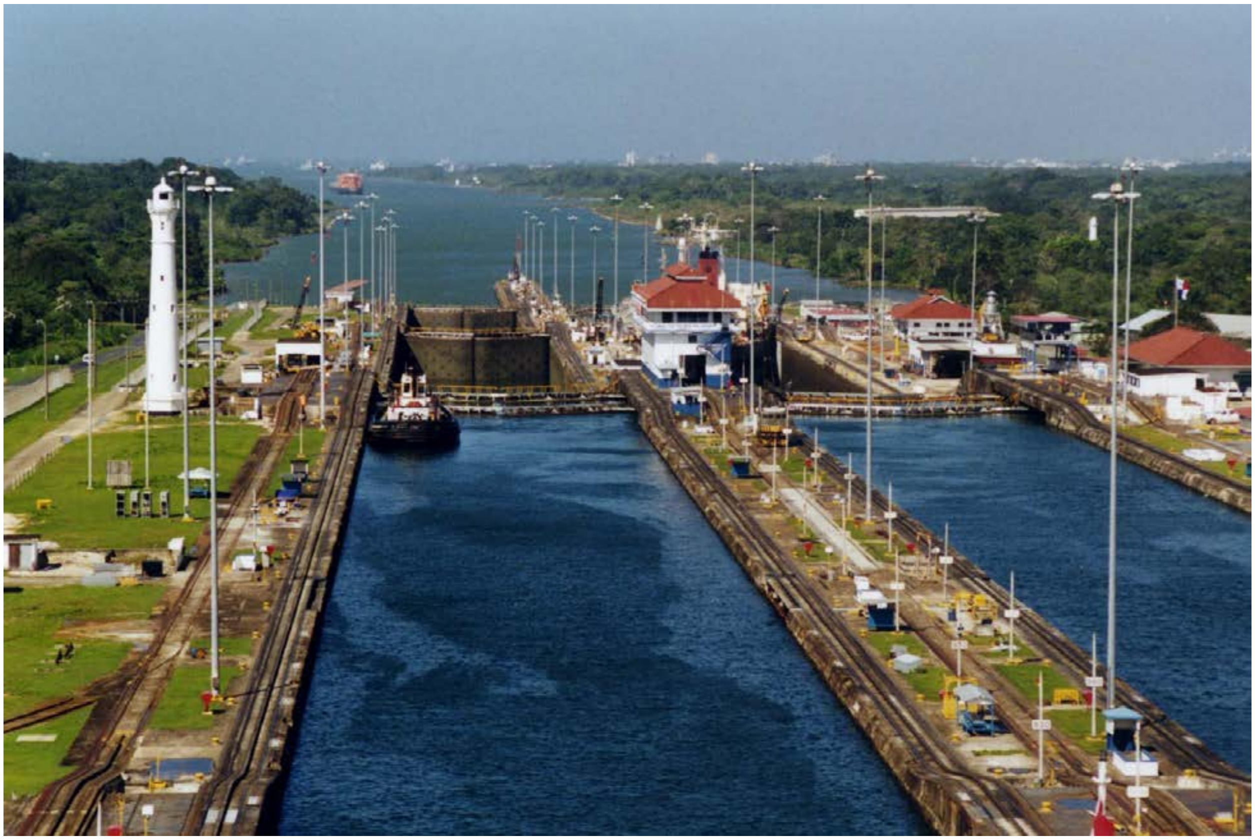

Figure 16.3 - Illustration of a Complex Infrastructure: Panama Canal Gatun Locks

Source: By Stan Shebs, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=51276

16.2 Extent and Duration of Base, Campus, Park and Port Infrastructure

Bases, campuses, parks and ports are widespread. Figure 16.4 illustrates the numbers of global airports; the numbers of military bases, campuses, parks and seaports would be just as large. Figure 16.5 shows the freight tonnage of imports, exports and domestic cargo at large US seaports in 2006. As can be seen, inland waterway ports (such as Huntington or Pittsburgh) handle significant amounts of freight. All countries have bases, campuses, parks and ports, and expansions such as designating new parks are common.

The duration of these entities is also quite lengthy, with university campuses, parks and ports lasting longer than institutions such as corporations. Military bases can be long lasting, although new technology can make some bases obsolete (such as Fort Jefferson in Figure 16.1). Similarly, seaport facilities must be periodically altered due to new technology such as freight containerization or larger vessels.

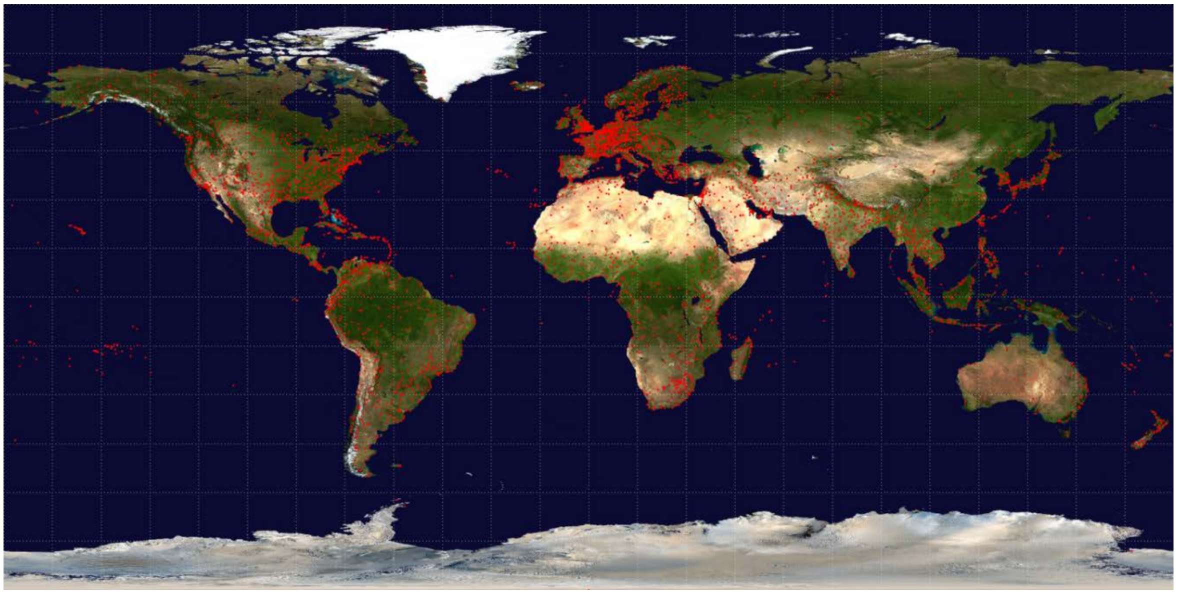

Figure 16.4 - Illustration of Global Airport Locations

Source: By Jpatokal - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=5862743

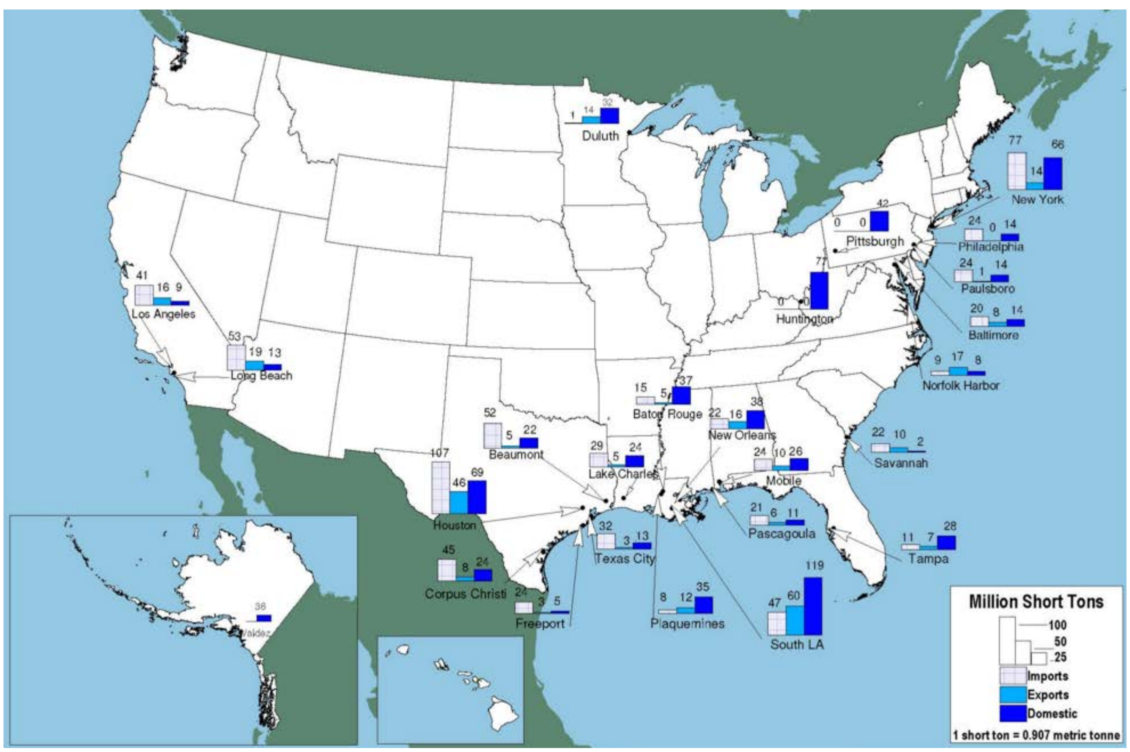

Figure 16.5 - Imports, Exports and Domestic Freight of Large US Seaports

Source: USDOT, Public Domain, http://www.ops.fhwa.dot.gov/freight/freight_analysis/nat_freight_stats/images/hi_res_jpg/top25wptonnage2006.jpg

Because these integrated entities are long lasting, infrastructure managers can often adopt a long planning horizon in making investment decisions. For example, buildings on university campuses can be rehabilitated regularly but the basic structures and layouts can last for decades (if not centuries). However, technological developments often suggest regular change in infrastructure for functions such as computing or communications.

All types of infrastructure can be found at these integrated entities, including roadways, buildings, power generation, telecommunication and power generation. In addition specialized infrastructure such as airport runways and docking facilities exist.

Another feature of these integrated entities is the concept of ‘deferred maintenance.’ Since integrated entities are long lived, recommended maintenance or rehabilitation can be deferred, resulting in lower infrastructure quality and functionality but corresponding with budget limitations. Deferred maintenance can and often does increase from year to year.

16.3 Institutional Arrangements for Bases, Campuses, Parks and Ports

The institutional managers of bases, campuses, parks and ports vary considerably among different entities and nations. Some typical arrangements are:

- Military bases are usually controlled by particular branches of the military service, such as Army, Air Force, Coast Guard, Marines or Navy.
- Campuses may be controlled by government agencies (as with Department of Energy Laboratories), corporations, or non-profit entities (such as Dartmouth College shown in Figure 16.2).
- Parks may be controlled by national, state or local government agencies. Privately owned parks also exist, such as the Disney Corporation resorts.
- Ports may be controlled by corporations, government agencies or other non-profit entities.

The concepts associated with infrastructure management outlined in the first ten chapters of this book, and illustrated in Figure 16.6 below, apply both to independently controlled and integrated entities. Campus infrastructure managers regularly perform asset management, inventory, benchmarking, etc.

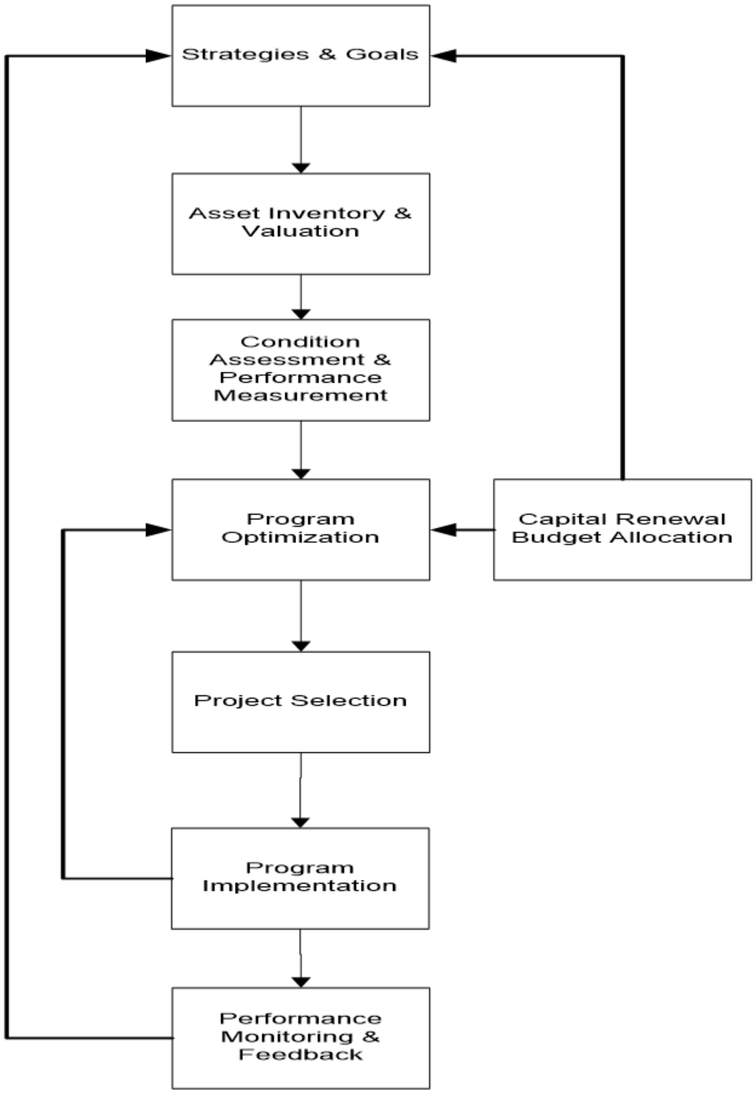

Figure 16.6 - Generic Asset Management System

Source: *Asset Management Primer*. U.S. Dept. of Transportation, Federal Highway Administration, Office of Asset Management, Public Domain, 1999.

However, some regulatory differences exist for integrated entities. For example, campuses, parks and ports typically have master planning processes in place for long-term infrastructure changes. These plans may include elements such as locations and rough shapes for future buildings and designations of permanent open space. New infrastructure is explicitly tied to the entities overall mission (e.g., education and research for universities), and all new buildings or other investments would then be designed to conform to the master plan. Cities and states have similar master planning processes, but these typically recognize the dispersed decision making associated with dispersed ownership of infrastructure.

Transitions in institutional arrangements for these integrated entities can also occur, although usually over a lengthy period of time. For example, Figure 16.1 showed Fort Jefferson which was transferred from military control to the National Park Service. Private community and resort developers may control the entire property initially, but then control is transferred to individual property buyers and eventually a community governing organization.

16.4 Issues in Infrastructure Management for Bases, Campuses, Parks and Ports

Integrated entities have some opportunities for synergies among infrastructure systems that may be difficult to achieve in more dispersed organizational settings. Adopting a long term management view can also provide advantages.

One example of such synergies is the use of 'utilidors,' or underground tunnels with multiple utilities for water, power, telecommunications and transport. Figure 16.7 illustrates a large utilidor used at a Disney resort. Figure 16.8 shows a smaller utilidor used for underground utilities at a university campus. Utilidors simplify maintenance of underground utilities, avoid overhead utility connections and permits easier upgrades for systems such as telecommunications. They require an initial capital investment for construction, but then lower costs over time.

Figure 16.7 - Illustration of a 'Utilidor

Source: (WP:NFCC#4), Fair Use, https://en.wikipedia.org/w/index.php?curid=47779101, Underground tunnel with utilities at a Disney resort

Figure 16.8 - Illustration of a Small Utilidor on a University Campus

Source: Authors

Another example of potential synergies is the adoption of combined heat and power (CHP) systems. These systems generate electricity but also use the waste heat productively. An isolated power plant may not have the opportunity to use the waste heat effectively and often must use significant amounts of water for cooling.

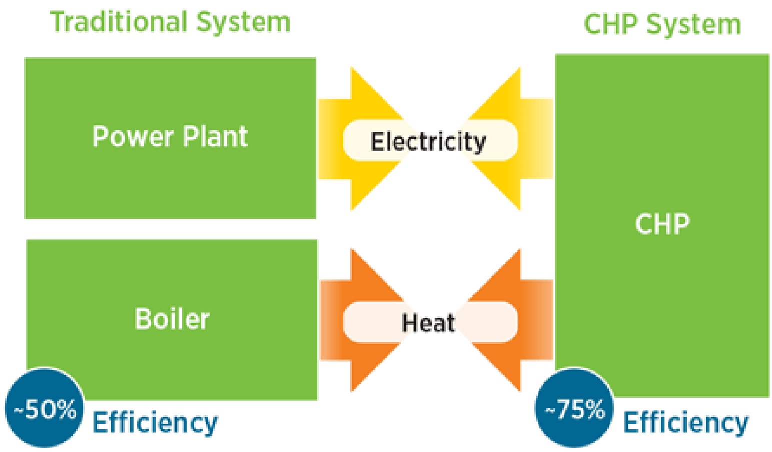

Figure 16.9 - Efficiency of Combined Heat and Power Systems

Source: U.S. Department of Energy, Public Domain, http://energy.gov/eere/amo/combined-heat-and-power-basics

Another source of potential advantages for integrated entities is the effect of scale economies on costs. For example, purchasing large amounts of supplies can result in cost savings. Similarly, integrated entities may be able to better control demands and scale infrastructure to the best sizes possible.

Not all integrated entities are compact, however. Parks may have multiple facilities spread over a large area. In these cases, managers may have to make special efforts to provide essentials such as power, water and wastewater treatment to isolated campgrounds or buildings. Figure 16.10 shows a typical isolated service structure of this type.

Figure 16.10 - Isolated Park Structure Requiring Water Supply

Source: National Park Service, Pubic Domain, https://parkplanning.nps.gov/projectHome.cfm?projectID=20710

Because of the scale of integrated entities, they can have significant environmental and social impacts. As a result, their infrastructure managers should endeavor to minimize their impacts. For example, integrated entities have been leaders in adopting green design standards (Committee, 2013).

16.5 Exercises

P16.1 **(5 pts)** Considering figure 16.6, describe how these generic asset management processes might differ between an integrated entity (university, military base, etc.) and a municipality.

16.6 References

Committee to Evaluate Energy-Efficiency and Sustainability Standards Used by the Department of Defense for Military Construction and Repair (2013), 'Energy Efficiency Standards and Green building Certification Systems Used by the Department of Defense for Military Construction and Major Renovations,' National Academies Press.