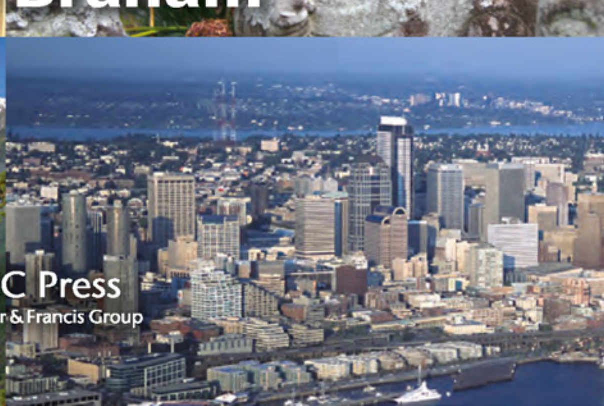
Fundamentals of Sustainability in Civil Engineering

Andrew Braham



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To Brenda

Cotents

Preface

The content of this textbook targets a senior-level undergraduate course in Civil Engineering. This textbook is intended to introduce students to the broad concept of sustainability while also preparing them for the Fundamentals of Engineering (FE) exam. Effort has been made to utilize concepts from the FE reference manual so that students become familiar with or reacquainted with terminology and nomenclature utilized in the FE reference manual.

All attempts were made to remove any errors from this book. However, there are no doubt lingering issues here and there, and for that I apologize. If you find an error within the text, whether grammatical or technical, please do not hesitate to email me at afbraham@uark.edu. Thank you.

Andrew Braham

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Author

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1 Introduction to Sustainability

> We hold the future in our hands, together, we must ensure that our grandchildren will not have to ask why we failed to do the right things, and let them suffer the consequences.
>
> **Ban Ki-moon**

The term "sustainability" is currently very popular. Industries and organizations realize the benefits of protecting the future while succeeding in the present. In the present, sustainability is most often defined as incorporating three pillars into design: economics, environmental, and social. However, the general concepts of sustainability have been in use for millennia. The design and construction of Roman aqueducts for drinking water distribution were so robust that they have lasted centuries, with dozens of aqueducts built as early as 300 BC still standing today and the "Roman Road" still being used for movement of traffic. The Iroquois Native American confederacy has been in place since approximately the twelfth century, and uses the concept of sustainability in their constitution. Finally, today, there is a significant push for many sustainability initiatives, including more fuel-efficient vehicles on the roadway. Fuel-efficient vehicles address all three pillars of sustainability, by reducing fuel consumption (economics), decreasing emissions (environmental), and allowing more diverse transportation options for consumers (social, or society). There are literally hundreds of existing books on sustainability discussing these and other concepts, but in order to demonstrate the development of sustainability overall, resources from the United Nations (UN) will be used to show how sustainability has been qualified and quantified over the past 40 years.

1.1 DEVELOPMENT OF SUSTAINABILITY THROUGH THE UNITED NATIONS

The UN, established in 1945 to avoid future conflicts on the scale of World War I and World War II, is an international organization made up of 193 member states as of 2016. Written in 1945, the UN's charter (from www.un.org) contains four aims:

1. To save succeeding generations from the scourge of war, which twice in our lifetime has brought untold sorrow to mankind
2. To reaffirm faith in fundamental human rights, in the dignity and worth of the human, in the equal rights of men and women and of nations large and small

3. To establish conditions under which justice and respect for the obligations arising from treaties and other sources of international law can be maintained
4. To promote social progress and better standards of life in larger freedom

In order to strive toward achieving these four aims, four guidelines (also from www.un.org) were also established:

1. To practice tolerance and live together in peace with one another as good neighbors
2. To unite our strength to maintain international peace and security
3. To ensure, by the acceptance of principles and the institution of methods, that armed force shall not be used, save in the common interest
4. To employ international machinery for the promotion of the economic and social advancement of all peoples

This basis of international cooperation provides a logical place to begin examining the development of the concepts of sustainability. At the end of the day, while each individual nation can work toward becoming more sustainable, pollutants that cause acid rain do not distinguish between borders, waste that accumulates in oceans does not follow international water law, and rivers that are dammed in one country may reduce flow in a second country downstream. These issues are complex. Therefore, taking a global perspective helps ensure that all countries are working toward similar common goals.

The first significant milestone for sustainability within the UN was the World Conservation Strategy, developed in 1980 (IUCN, 1980). In this document, sustainability was described through three goals:

1. Maintain essential ecological processes and life support systems
2. Preserve genetic diversity
3. Ensure the sustainable utilization of species and ecosystems

These three goals mainly revolve around the concept of protecting the environment, with terms such as ecological processes, life support systems, genetic diversity, species, and ecosystems. However, 7 years later, in 1987, the UN released the Brundtland Commission Report, which is probably the most recognizable milestone in the UN's sustainability development (Brundtland, 1987). Within the Brundtland Commission, a theme was developed to qualify sustainability. The theme reads that sustainability "meets the needs of the present without compromising the ability of future generations to meet their own needs." This theme is independent of protecting the environment, but the concept of the environment is still woven into the fabric of the theme. It is interesting that this concept is almost identical to the Constitution of the Iroquois Nations, which states (in part): "Look and listen for the welfare of the whole people and have always

SIDEBAR 1.1

To read more about the United Nations, visit their website at www.un.org.

in view not only the present but also the coming generations, even those whose faces are yet beneath the surface of the ground—the unborn of the future Nation."

In 2002, the UN hosted a World Summit on Sustainable Development, which for the first time defined what are called the three pillars of sustainability: economics, environmental, and social (UN, 2002). During this summit, a key theme was the commitment to "building a humane, equitable, and caring global society, cognizant of the need for human dignity for all" at local, national, regional, and global levels. With this new solid foundation of the three pillars, future conferences and summits began formulating objectives and themes around sustainability. For example, the 2012 UN Conference on Sustainable Development put forth three objectives (UN, 2012):

1. Poverty eradication
2. Changing unsustainable and promoting sustainable patterns of consumption and production
3. Protecting and managing the natural resource base of economic and social developments

Through these three objectives, the three pillars of sustainability are clear, with *economics* clearly a part of the second and third objective, the *environmental* also in the second and third objectives, and *social* spanning all three objectives.

Following the UN summits in 2002 and 2012, the UN developed a resolution in 2015 that went even further with quantifying the measures of achieving sustainability (UN, 2015). This resolution, titled "Transforming Our World: The 2030 Agenda for Sustainable Development," broadened the scope of sustainability significantly with 17 metrics. These metrics are summarized in Table 1.1.

In addition to these 17 metrics, a timeline was established in order to meet eight "Millennium Development Goals" (UN, 2007). The timeline goal is to achieve all eight by 2030. The eight Millennium Development Goals are

1. Eradicate extreme poverty
2. Achieve universal primary education
3. Promote gender equality and empower women
4. Reduce child mortality
5. Improve maternal health
6. Combat HIV/AIDS, malaria, and other diseases
7. Ensure environmental sustainability
8. Develop a global partnership

The UN has put sustainability metrics and Millennium Development Goals to practice through many channels, most noticeably through their Economic and Social Council and Secretariat. Through these "main bodies," the UN promotes and finances sustainable development, provides coordination and oversight, and builds partnerships.

While the UN has provided strong guidance on how to pursue sustainability, and has shown leadership in the implementation of their policies, it is important

TABLE 1.1
2015 United Nations Resolution on Sustainability Metrics

Metric		Brief Description
1	Poverty	End poverty in all its forms everywhere
2	Food	End hunger, achieve food security and improved nutrition, and promote sustainable agriculture
3	Health	Ensure healthy lives and promote well-being for all at all ages
4	Education	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
5	Women	Achieve gender equality and empower all women and girls
6	Water	Ensure availability and sustainable management of water and sanitation for all
7	Energy	Ensure access to affordable, reliable, sustainable, and modern energy for all
8	Economy	Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all
9	Infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation
10	Inequality	Reduce inequality within and among countries
11	Habitation	Make cities and human settlements inclusive, safe, resilient, and sustainable
12	Consumption	Ensure sustainable consumption and production patterns
13	Climate	Take urgent action to combat climate change and its impacts
14	Marine ecosystems	Conserve and sustainably use the oceans, seas, and marine resources for sustainable development
15	Ecosystems	Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
16	Institutions	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable, and inclusive institutions at all levels
17	Sustainability	Strengthen the means of implementation and revitalize the global partnership for sustainable development

to understand how we as civil engineers need to incorporate sustainability into our professional lives. Fortunately, the American Society of Civil Engineers (ASCE) has provided clear guidance on how to do this.

1.2 AMERICAN SOCIETY OF CIVIL ENGINEERS AND SUSTAINABILITY

The ASCE was founded in 1852 and is the oldest engineering society in the United States. More than 150,000 people are members across 177 countries, which includes more than 380 student chapters at universities in the United States alone. The ASCE has been active in promoting the importance of sustainability and has made sustainability a major focus area. The ASCE defines sustainability as: "A set of environmental, economic and social conditions in which all of society has the capacity and opportunity to maintain and improve its quality of life indefinitely without degrading the quantity, quality, or availability of natural, economic, and social resources." This definition clearly incorporates the three pillars of sustainability (economics, environmental, social) and draws on the latter UN work that also incorporates the concept of recognizing future generations. In addition to having a definition with several active initiatives, ASCE has also incorporated sustainability into their Code of Ethics.

In 1914, ASCE adopted a Code of Ethics, which is the "model for professional conduct" for ASCE members (ASCE, 2006). Within this Code, ASCE has four fundamental principles and seven fundamental canons. Sustainability is mentioned in the first principle: "using [engineer's] knowledge and skill for the enhancement of human welfare and the environment." This principle directly addresses two of the three pillars of sustainability, social and environmental. In addition to the first principle in ASCE's Code of Ethics, sustainability is mentioned in several of the seven canons. Canon 1 states that "engineers shall … strive to comply with the principles of sustainable development." Further discussion of Canon 1 indicates that if professional judgment is overruled, engineers should inform clients or employers of the possible consequences. In addition, engineers need to work for the advancement of safety, health, and well-being of their communities (social pillar) and the protection of the environment (environmental pillar). Canon 3 continues the sustainability theme by asking engineers to endeavor to extend public knowledge of engineering and suitable development. This dedication by ASCE of incorporating sustainable principles into their Code of Ethics enforces the commitment of the civil engineering community in understanding and incorporating sustainable practices into the field. The question becomes at this point: how is this done?

SIDEBAR 1.2 WRITING A HIGH-QUALITY ESSAY

A well-written essay contains three components: an introduction, a body, and a conclusion. The introduction should gently guide the reader into the topic, starting with a high-level discussion that sets up the reader to understand the purpose of the body content. The introduction should end with a topic sentence, which clearly states the main points of the body. This will allow the reader to be fully ready for the body of your essay, which usually contains 2–3 main points that you are trying to describe to the reader. These could be examples, arguments, or situations that form the skeleton of your essay. Within the body, you should support the points with ideas and facts that wrap the skeleton with muscle and create a clear picture of your discussion. After efficiently stating your main points, the conclusion is a recap of your introduction and body. No new information should be provided in the conclusion, and the reader should be able to obtain the gist of your essay from only reading the conclusion. This allows readers to gain a general idea of your essay, and if they are interested, they can read the entire document. Finally, engineering essays are generally written in third person. While they can be written in first person, take care as most readers are interested in the topic of the essay, and not the writer of the essay.

1.3 AS CIVIL ENGINEERS, HOW DO WE INCORPORATE SUSTAINABILITY?

After this introductory chapter, this book is divided into eight additional chapters, encompassing the three pillars of sustainability (Chapters 2 through 4), moving into applications of sustainability in the four primary areas of civil engineering (Chapters 5 through 8), and finishing with a glimpse into tomorrow's sustainability (Chapter 9).

Chapter 2 will cover the *economic* pillar of sustainability. Tools to quantify economic measures of sustainability will be introduced, along with case studies and examples studying civil engineering projects that have incorporated economic aspects of sustainability. Specific tools include life cycle cost analysis, present/future/annual worth, rate of return, and benefit/cost ratio. Chapter 3 will explore the *environmental* pillar of sustainability. In this chapter, life cycle analysis, ecological footprint, planet boundary, and environmental product declarations will be discussed. Similar to this chapter on the economic pillar, examples of environmental implementation of these metrics in civil engineering projects will be shown. The third pillar of sustainability, *social*, will be covered in Chapter 4. The social pillar has not been quantified to the same depth as the economic and environmental pillars, but there are several tools available that could provide insight on potential social impacts of civil engineering. These tools include previously published articles in civil engineering journals, the five documents produced by the UN, the Oxfam Doughnut, the Human Development Index, and the Social Impact Assessment. In addition, emerging areas of social metrics will be introduced. The concepts covered in the three sustainability pillars are summarized in Table 1.2.

While Chapters 2 through 4 provide foundational information as to quantitative and qualitative metrics to the three pillars of sustainability, Chapters 5 through 8 will delve deeply into specific applications of sustainability in the four primary areas of civil engineering. Chapter 5 is devoted to environmental applications of sustainability while Chapter 6 covers geotechnical applications of sustainability. Chapter 7 will explore structural applications of sustainability, and Chapter 8 will cover the fourth and final area of civil engineering—transportation applications. Chapters 5 through 8 will cover a wide range of topics, from drinking water treatment to geofoam fill, steel diagrids to recycled asphalt pavement. In addition, these four chapters of application will provide extensive practice problems that utilize concepts taken

TABLE 1.2
Key Concepts Covered in the Economic, Environmental, and Social Pillars of Sustainability

Economic	Environmental	Social
• Life cycle cost analysis • Present/future/annual worth • Rate of return • Benefit/cost ratio	• Life cycle analysis • Ecological footprint • Planet boundary • Environmental product declarations	• Existing civil engineering examples • United Nations • Oxfam Doughnut • Human Development Index • Social Impact Assessment

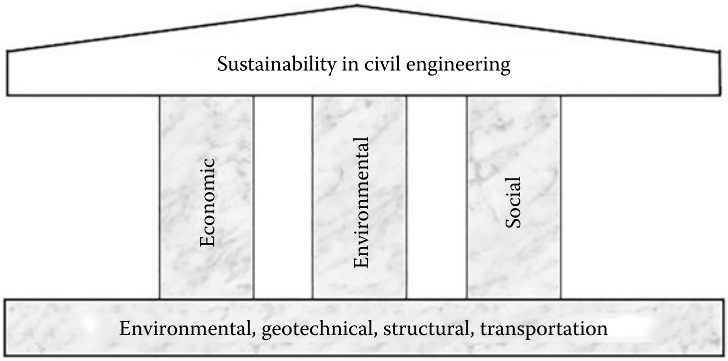

FIGURE 1.1 Components of civil engineering sustainability. (Credit: A. Braham.)

directly from the National Council of Examiners for Engineering and Surveying (NCEES) Fundamentals of Engineering (FE) reference handbook. This will not only allow for additional practice in preparation for the FE exam, but will also provide insight as to the broad scope of coverage on the FE exam. The content of Chapters 2 through 8 is graphically represented in Figure 1.1.

This book will finish with Chapter 9, which will give a survey of the future direction of sustainability in civil engineering, Sustainability is not a straightforward issue and the field itself is highly underdeveloped. In order to fully implement concepts from all three pillars, a paradigm shift will need to occur in industry and government. Engineers are typically strong in the STEM fields (science, technology, engineering, math), but are less robust in the "softer skills" such as policy making and human development. This should not be viewed, however, as an obstacle but as an opportunity to continue identifying, building, and nurturing relationships across multiple disciplines in order to not only improve our world today but also tomorrow.

HOMEWORK PROBLEMS

For all answers in this chapter, use the format provided under Sidebar 1.2 "Writing a High-Quality Essay."

1. The first paragraph of this chapter discussed how ancient civilizations were either actively participating or providing governance in sustainable practices. Find a third ancient civilization that also incorporated sustainable practices, and give three examples on how they did so.
2. The United Nations was established in 1945, but its aims have not changed since. Examine the four aims—do you think that all four are still important today? In your answer, provide three examples of why you think that they are still either important or not important.
3. Similar to question 2, the United Nations also have four guidelines that have not changed since 1945. Examine the four guidelines—do you think that all four are still important today? In your answer, provide three examples of why you think that they are still either important or not important.

4. Over the years, the United Nations hosted five conferences or summits (1980, 1987, 2002, 2012, and 2015) that directly revolved around sustainability. Of these five, which conference or summit do you think was most important in the development of sustainability on a global scale?
5. Of the 17 metrics developed during the 2015 UN Sustainable Development Summit, choose which metric you believe is most relevant and which metric you believe is least relevant. Provide two examples for each argument.
6. Two of the 17 metrics developed during the 2015 UN Sustainable Development Summit are directly related to civil engineering: water and infrastructure. Choose one of these two metrics and discuss three examples of sustainability in your chosen metric.
7. Eight goals were developed during the 2015 UN Sustainable Development Summit. Choose which goal you believe is most achievable by 2030 and which goal you believe is least achievable by 2030. Provide two examples for each argument.
8. After examining ASCE's definition of sustainability, do you feel it is complete? If so, justify with three discussion points. If not, provide three discussion points on how you think it could be improved.
9. There is no mention of cost or economics in the ASCE Code of Ethics. As one of the three pillars of sustainability, economics is an important component. Why do you think that economics was not mentioned in the Code, and do you think it should be included? Use three discussion points in your answer.

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2 Pillar
Economic Sustainability

We make a living by what we get, we make a life by what we give.

Winston Churchill

At the end of the day, private companies, public agencies, and all owners need to stay in business. This is often driven by financial considerations. If an organization is "in the red," it means that they are spending more money than they are making, and, in the long term, the organization will fail. However, many choices are only made by considering today's costs. So, if choice A costs less than choice B today, the organization will default to choice A. However, what if choice A costs less today, but will cost more over the 15-year design period versus cost B? Is it worth spending more money today to save money tomorrow? This is one of the key concepts of economics in sustainability, looking beyond today's cost and ensuring that, in the long term, the best economic decisions are being made. This concept is the cornerstone of the economic pillar of sustainability.

2.1 TRADITIONAL SUSTAINABLE ECONOMICS

Traditional economic considerations of sustainability revolve around three main points: local impact, material savings, and reuse. When considering economics and local impact, sustainable practices provide employment and stimulate local economy. By saving materials, that is, reusing existing materials, organizations can reduce upfront costs, reduce the transportation of materials, and reduce onsite waste. In addition, by utilizing fewer natural resources, future savings are gained in many areas, such as reducing the amount of material going to landfills. While these are all important concepts of reuse, they are limited in the fact that raw costs are not the only factor; what is more, maintenance and disposal costs may be quite different depending on the manufactured product or the engineering infrastructure. Finally, long-term performance is not taken into account, and in some applications, the longer-term performance may not even be known. These are certainly challenges while considering the economic perspectives of sustainability, but there are several concepts that can aid in more accurately capturing the full life span. These include life cycle cost analysis (traditional and probabilistic, Section 2.3), present/future/annual worth (Section 2.4), rate of return (Section 2.5), and benefit/cost ratio (Section 2.6).

2.2 LIFE CYCLE COST ANALYSIS

A life cycle cost analysis, or LCCA, is a very well-established method of quantifying long-term economic impacts. An LCCA takes into account both initial and discounted future costs in an attempt to identify the best value over the life of either a manufactured product or engineering infrastructure. A convenient feature of an LCCA, when comparing two different cost alternatives, is that common costs can cancel out and only costs that are different are considered. This highlights the importance of stating assumptions in the analysis, as different stakeholders in a project could make very different assumptions. Another key aspect of an LCCA is determining the analysis period. An analysis period can cover either a portion or the full life of a product or infrastructure, and can even extend through the salvage of material at the end of life. Regardless of the analysis period that is chosen, however, care must be taken when stating assumptions and defining the analysis period to reduce confusion.

When considering the life cycle stages, both manufactured products and engineering infrastructure can be broken down into six stages. For a manufactured

SIDEBAR 2.1 SALVAGE VALUE

Salvage value, in short, is the economic value of either a product or infrastructure at the end of the analysis period for the product or infrastructure. This can include the recycle, the remanufacture, or the reuse value of the product or infrastructure. If no specific data is available to calculate the salvage value, it is assumed to be zero. There are several methods for calculating or estimating the salvage value. For example, the Federal Highway Administration uses the following for pavements:

$$\text{Salvage value} = \left[1 - \left(\frac{\text{actual life of alternative}}{\text{expected life of alternative}}\right)\right] \times \text{cost of alternative}$$

This simplified approach is acceptable by many because of the high level of uncertainty associated with service lives and costs for different pavement layer components, and the relatively small impact that salvage value has on life cycle cost comparisons. However, more complicated measurements for salvage value have been developed for pavements, including the following:

$$\text{Salvage value} = \left[\text{CLR} \times \frac{\text{remaining life of last resurfacing}}{\text{service life of last resurfacing}}\right] + \text{CRI}$$

where CLR is the cost of the last resurfacing, and CRI is the cost of the lower asphalt layers remaining from the initial construction. This calculation of salvage value accounts for the in-place value of the pavement structure in addition to the remaining life of the last resurfacing.

The use of this simplified approach in estimating salvage value is justified by the fact that there are several uncertainties associated with the service lives and costs for the different pavement component layers, and the relatively small impact that salvage value actually has on life cycle comparisons.

product, such as aggregate in Portland cement concrete (PCC), the first stage is material extraction. After extraction, the material is processed (stage two) in order to reach the third stage, manufacturing. After manufacturing, the product is used (stage four), and finally, the product has an end of life (stage five). At this point, there is the possibility for the sixth stage, which is material reuse. For example, aggregates for pavements are either taken out of a quarry through a blasting operation (for manufactured aggregate), or can be dredged from a river bed (for natural aggregate). Generally, the aggregate needs to be processed by screening out nonaggregate material, or deleterious material, and washing excess clay or dust off the aggregate. Next, the aggregate is crushed in a jaw crusher, cone crusher, or impact crusher and then screened in order to achieve specific gradations for either a base course in a pavement structure or within the concrete layer. This stage is the manufacturing stage (stage three). Once the desired gradation is achieved, the aggregate is ready for use in the pavement structure. However, over time, PCC weathers and ages under traffic loads and environmental conditions, and the aggregate reaches the end of its life. The sixth and final stage of a manufactured product is the use of the material in another project, for example, crushing the weathered and aged PCC roadway for use in a new application.

A similar sequence of life cycle stages can be evaluated for engineering infrastructure. The first life cycle stage for engineering infrastructure is site development. The second is infrastructure manufacturing, which is followed by materials and product delivery (stage three). The fourth life cycle stage is infrastructure use, and the life cycle is complete at the end of the infrastructure's life and use in other applications. For example, during the construction of a bridge, the first stage is preparing the approaches and pylons for the support columns. The second stage would be the manufacture of the steel, concrete, and bridge deck material that will be utilized during construction. The third stage would be the actual delivery of the steel, concrete, and bridge deck material and assembly on site. Once the bridge construction is completed, the bridge is in use for the life span, which eventually leads to the end of life. If the opportunity presents itself, the components of the old bridge can be reused (stage 6). For example, it is not uncommon for bridge girders to be taken from high-volume roads, sorted for functionality, and then used on lower-volume roads; this is a lower cost and a more sustainable option for small agencies such as cities and counties that can work with larger agencies, such as state and national agencies, in order to maximize the life use of each piece of infrastructure. A summary of the life cycle stages for both manufactured product and engineered infrastructure can be found in Table 2.1.

An advantage to defining projects with these six life cycle stages is the ability to clearly define three concepts: recycling, remanufacturing, and reuse. Going from the fifth step (end of life) to the second step (processing for materials, manufacturing for infrastructure) is recycling. Recycling is very common in materials such as steel and asphalt pavements, which are the two largest recycled materials by weight in the world. Remanufacturing occurs when moving from the fifth stage (end of life) to the third stage (manufacturing for materials, delivery and construction for infrastructure). One example of remanufacturing is the utilization of existing facades in new buildings. When a historic building needs extensive renovation, a potential

TABLE 2.1
Life Cycle Stages

Stage	Manufactured Product	Engineering Infrastructure
First	Material extraction	Site development
Second	Process material	Manufacturing of infrastructure
Third	Manufacturing of material	Infrastructure delivery and construction
Fourth	Product use	Infrastructure use
Fifth	End of life	End of life
Sixth	Reuse of material	Reuse of infrastructure

solution is to keep the facade of the building but completely replace the interior of the building. During this process, the facade needs a complete overhaul, which is a form of remanufacturing. The third concept of sustainability is reuse, which moves from the fifth stage (end of life) to use (the fourth stage). The previous example of reusing bridge girders from state roadways in country roadways is a good example of reuse. Within the three concepts of recycling, remanufacturing, and reuse, reuse has the highest level of sustainability. It requires the least amount of material transportation and processing. Conversely, recycling has the lowest level of sustainability, as material generally needs to be collected in a central location for processing and then redistributed to the field. Table 2.2 summarizes the concepts of recycling, remanufacturing, and reuse.

The traditional LCCA has six steps:

1. Establish alternative design strategies for the analysis period
2. Determine performance periods and activity timing
3. Estimate agency and user costs
4. Develop expenditure stream diagrams
5. Compute net present value (NPV)
6. Analyze results and reevaluate design strategies

The first step to LCCA, establish alternative design strategies for the analysis period, allows the engineer to decide what different options are worthy of being

TABLE 2.2
Concepts of Sustainability, as Defined by the Six Life Cycle Stages, and Their Impact

From	To	Concept	Impact (Relative Sustainability)
Stage 5	Stage 2	Recycle	Lowest
Stage 5	Stage 3	Remanufacturing	Moderate
Stage 5	Stage 4	Reuse	Highest

explored. While skyscrapers will probably never be constructed from aluminum (for both cost and material properties), the debate of steel versus PCC is always of interest, as is traditional steel designs such as moment frames versus diagrids. Therefore, understanding the options, and then deciding the analysis period provide the foundation for the LCCA.

The second step to LCCA is determining the performance periods and activity timing. Typical performance periods include maintenance and rehabilitation schedules. Maintenance includes activities that have to be performed on a consistent schedule in order to allow the infrastructure to perform as designed, whereas rehabilitation occurs when more than maintenance is required but a full replacement is not necessary. A good example is a wood structure. If the wood is exposed, it needs to be sealed at least every 3–5 years in order to maintain integrity. The sealing is an example of maintenance. However, after several seals, often, individual pieces of wood must be replaced. It is anticipated that every 10–15 years, a portion of the structure will need to be replaced. However, the entire structure should not need to be replaced at 10–15 years if properly maintained.

The third step, and often the most difficult step for the LCCA, is estimating the agency and user costs. Here, the initial cost must not only be considered, but then maintenance cost, the rehabilitation costs, and then the salvage value all also need to be quantified. Pavements are an excellent example of breaking out agency and user costs. For state agencies, examples of agency costs include materials, production, and construction for the initial cost. A popular comparison of two different pavements is asphalt concrete versus PCC. These have very different initial costs, which are highly dependent on geographic region and traffic level. However, user costs must also be considered. Not only is pavement construction a temporal inconvenience for drivers, it also costs the user money in lost productivity. In fact, the 2015 Urban Mobility Scorecard estimated that traffic congestion cost users $160 billion nationwide in 2014 (Schrank et al., 2015). This number is a combination of both fuel costs and lost time costs. While this is a combination of both construction congestion and standard congestion, it still shows the extreme scale of the impact of user delays on our economy.

The fourth step of the traditional LCCA is to develop an expenditure stream diagram. Continuing on with the pavement example, an LCCA analysis was done on Arkansas State Highway 98 on the cost of a 2-in asphalt concrete overlay (Braham, 2016). The production, construction, and rehabilitation costs were estimated for a 50-year design period, with rehabilitation costs performed every 11 years. Note that there is no maintenance in this analysis, as it was assumed that maintenance costs were the same on all of the pavement types in the study. Figure 2.1 clearly shows the power of these expenditure stream diagrams; notice that it is very quickly obvious from the figure what the costs are and how they change over time.

The fifth step of the traditional LCCA is computing the NPV. The NPV takes all anticipated future costs and converts the costs to today's dollar value. When these converted future costs are added to the initial cost, a single number is created and multiple alternatives can be compared directly. Equation 2.1 is used to compute the NPV.

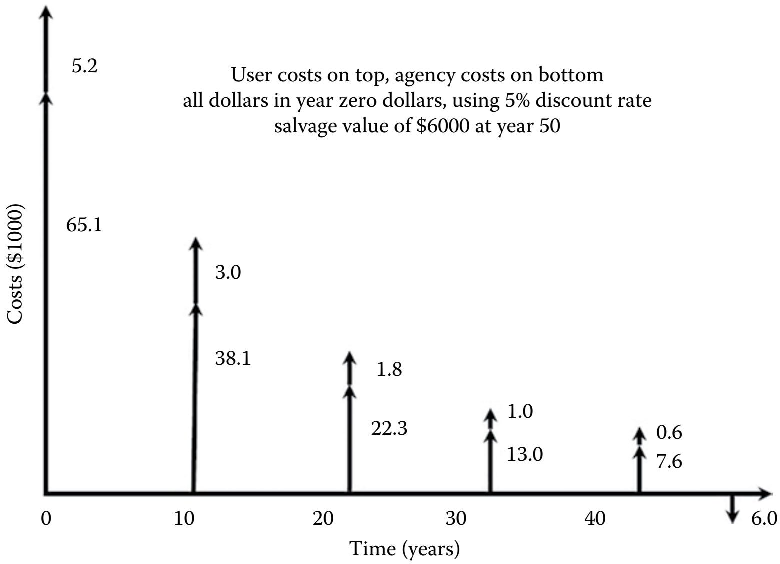

FIGURE 2.1 Expenditure stream diagram for a 2-in overlay on AR98 for a 50-year design. (Credit: A. Braham.)

$$\text{NPV} = \text{initial cost} + \sum_{0}^{t_n}\left(\frac{\text{maintenance cost}}{(1+r)^{t_n}}\right) + \sum_{0}^{t_n}\left(\frac{\text{rehabilitation cost}}{(1+r)^{t_n}}\right) - \left(\frac{\text{salvage cost}}{(1+r)^{t_n}}\right) \tag{2.1}$$

where
t = time period analyzed (years)
n = year of analysis
r = discount rate (%)

This analysis shows the importance of determining performance periods and activity timing, as well as the importance of having available dollar values for initial maintenance, rehabilitation, and salvage costs. The combination of all of these four costs will provide a sound platform for making the final design strategy. The sixth and final step to the traditional LCCA analysis is comparing the NPV of different design strategies, and reevaluate the strategies and assumptions to determine if any important details were overlooked.

At this point, it is important to note that the cost analysis done for the traditional LCCA has been deterministic. This simply means that single values were assumed for prices, both for initial costs and for future costs. However, this is an enormous assumption and not reflective of what actually happens in the real world, which has variability of the price of materials. A good example is the price of Portland cement.

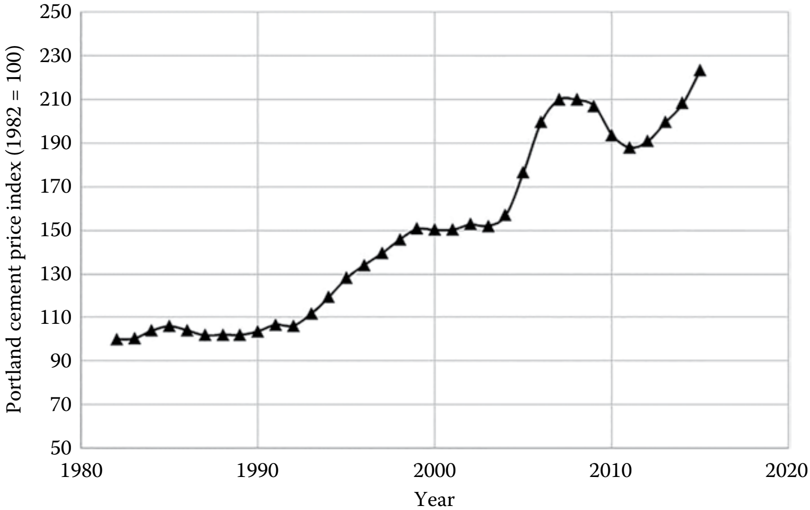

FIGURE 2.2 Unpredictable price of Portland cement. (Credit: A. Braham.)

According to the United States Bureau of Labor Statistics, the price of Portland cement (using the 1982 price as 100 for an index-based analysis) bounces from 100 in 1982, to 199.3 in 2006, 209.7 in 2008, 187.8 in 2011, and 223.4 in 2015. This trend is shown graphically in Figure 2.2.

As shown in Figure 2.2, it is difficult to predict the price of Portland cement, so an alternative to a deterministic LCCA evaluation can be used. A popular alternative to a deterministic LCCA evaluation is a probabilistic LCCA analysis. The basic principles are the same as the deterministic analysis. So, for example, the initial cost, the maintenance, the rehabilitation, and the salvage value would be determined. But instead of choosing a single number, a probabilistic analysis recognizes that there is a distribution of potential costs, especially when considering future costs. This analysis technique therefore includes uncertainty of future costs. This can be beneficial in three primary ways. First, the price of raw materials is rarely linear, and often single, unpredictable events (such as the 2008 housing crisis) can shift the global demand for material. Therefore, while prices do generally go up over time, there are small levels of unpredictableness when looking at short timescales. Second, determining the proper discount rate is also very difficult. The discount rate is loosely related to bank interest rates, which do have a high level of variability, often as a function of the health of the economy. It is preferable to show a range of discount rates, from 2% to 6%, but if one value has to be chosen, a value commonly chosen by engineers is 3%–5%. Finally, the third primary benefit of probabilistic analysis is that there are literally an infinite amount of variables not only in the production and construction of civil engineering infrastructure, but also in how it will perform over time due to external factors. Therefore, if a historical rehabilitation schedule is used with new materials and equipment, there is a chance that rehabilitation may need to occur either more or less frequently (ideally, less with an increase in technology).

Using a probabilistic analysis builds in these sources of uncertainty and variability, and allows for a more robust analysis.

EXAMPLE PROBLEM 2.1

In the state of Arkansas, a 2-mile stretch of an asphalt mixture four-lane road cost approximately $2,429,610 dollars to build in 2013. This cost includes the unbound aggregate base course, the asphalt mixture base course, the asphalt mixture binder course, and the asphalt mixture surface course. Assuming a 50-year design life, a 4.0% discount rate, and the following rehabilitation, maintenance, and salvage value cost, what is the NPV of the roadway section? State any assumptions you needed to make.

- Maintenance (years 1–19): $3300 per lane per mile
- Rehabilitation (year 20): $118,000 per lane per mile
- Maintenance (years 20–24): $1100 per lane per mile
- Rehabilitation (year 25): $351,000 per lane per mile
- Maintenance (years 25–44): $2900 per lane per mile
- Rehabilitation (year 45): $118,000 per lane per mile
- Maintenance (years 45–50): $1100 per lane per mile
- Salvage value (year 50): $341,877 total

Assumptions are that maintenance will be performed in years of rehabilitation, and in year 50 of the design life, but will not occur in year 0. Equation 2.1 is used to calculate the NPV.

$$\text{NPV} = \text{initial cost} + \sum_{0}^{t_n}\left(\frac{\text{maintenance cost}}{(1+r)^{t_n}}\right) + \sum_{0}^{t_n}\left(\frac{\text{rehabilitation cost}}{(1+r)^{t_n}}\right) - \left(\frac{\text{salvage cost}}{(1+r)^{t_n}}\right)$$

The initial cost is given = $2,429,610.

The maintenance calculation is split into four parts, and is a total of $62,068.45 per lane per mile:

$$\sum_{n=1}^{19}\left(\frac{3300}{(1+0.04)^n}\right) = \$43{,}342.00$$

$$\sum_{n=20}^{24}\left(\frac{1100}{(1+0.04)^n}\right) = \$2324.33$$

$$\sum_{n=25}^{44}\left(\frac{2900}{(1+0.04)^n}\right) = \$15{,}375.40$$

$$\sum_{n=45}^{50}\left(\frac{1100}{(1+0.04)^{n}}\right)=\$1026.68$$

The rehabilitation calculation is split into three parts, and is a total of $205,721.00 per lane per mile:

$$\text{Year 20}\rightarrow\left(\frac{118{,}000}{(1+0.04)^{20}}\right)=\$53{,}853.70$$

$$\text{Year 25}\rightarrow\left(\frac{351{,}000}{(1+0.04)^{25}}\right)=\$131{,}666.00$$

$$\text{Year 45}\rightarrow\left(\frac{118{,}000}{(1+0.04)^{45}}\right)=\$20{,}201.40$$

The salvage value calculation is given as $341,877.00. The maintenance costs and rehabilitation costs need to be multiplied by eight (as the prices above are per lane per mile, and it is a two-lane stretch of four-lane roadway). Therefore, the NPV is

$$\begin{aligned}\text{NPV} &= \$2{,}429{,}610+(\$62{,}068.45*8)+(\$205{,}721.07*8)-(\$341{,}877.00)\\ &= \$4{,}230{,}050\end{aligned}$$

2.3 PRESENT, FUTURE, AND ANNUAL WORTH

When analyzing economic alternatives, it is often convenient to present monetary amounts in different forms. For example, the LCCA discussion in Section 2.3 takes all future costs and brings them to one, single present cost. This has the benefit of essentially eliminating any concept of time from the equation and allowing for a direct comparison in today's dollars. However, in other situations, it may be more beneficial to know a single cost but at a future date. For example, if an agency is attempting to predict the funds available in 10 years for a highway rehabilitation, current funds may need to be converted into future dollars to, for example, account for inflation. Finally, a third common way of presenting money is in an annual form. When a company is attempting to compare the different energy costs associated with the heating and ventilation system in their building, for instance, it can be helpful to define costs on a yearly basis in order to better budget future costs. These concepts are summarized in Table 2.3.

While these three different forms of presenting monetary costs have their pros and cons, one very useful technique for engineers is the ability to convert between the three forms. Conversions are generally done in three ways: future worth (F) to present worth (P), present worth to future worth, or present/future worth to annual worth (A). These abbreviations will be used extensively in the upcoming paragraphs.

When converting future worth to present worth (F $\rightarrow$ P), all future costs and revenues are converted into present dollars. This makes it easy to determine any

TABLE 2.3
Three Forms of Representing Money

1. Single present cost	• Eliminates concept of time • Allows for direction comparison in today's dollars
2. Single future cost	• Current funds to future dollars • Predict funds available and accounts for inflation
3. Annual future cost	• Defines future costs on a yearly basis • Beneficial for future budgeting

potential economic advantage of one alternative over another. When presenting this concept, there are several common notations and equations. The official name is single-payment present worth, and the notation is (P/F, i, n), where P is the present value, F is the future value, i is the interest rate, and n is the number of years. Note that the interest rate in all of the present, future, and annual costs is in decimal form. The standard notation equation is P = F(P/F, i, n), and the equation with factor formula is shown in Equation 2.2.

$$P = F\left[\frac{1}{(1+i)^n}\right] \tag{2.2}$$

In a similar fashion, the second useful conversion is converting present worth to future worth (P → F), where all present costs and revenues are converted into future dollars. This conversion is often used if an asset (such as a building) might be sold or traded after construction but before expected end of life is reached. Using this technique, several alternatives' worth can be estimated at the time of either sale or disposal. The official name is single-payment compound amount, and the notation is (F/P, i, n). The standard notation equation is F = P(F/P, i, n), and the equation with factor formula is shown in Equation 2.3.

$$F = P \times (1+i)^n \tag{2.3}$$

Finally, the annual worth (A), which is the equivalent uniform annual worth of all estimated costs and benefits during the life cycle of the alternative, is a useful tool for estimating yearly budgets. The annual worth can be calculated from either the present worth or the future worth. When utilizing the present worth (P → A), the official name is capital recovery, and the notation is (A/P, i, n). The standard notation equation is A = P(A/P, i, n), and the equation with the factor formula is shown in Equation 2.4.

$$A = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \tag{2.4}$$

Similarly, when the annual worth is known, and the present worth is desired (A → P), the official name is uniform-series present worth, and the notation is (P/A, i, n). The standard notation equation is P = A(P/A, i, n), and the equation with the factor formula is shown in Equation 2.5.

$$P = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \tag{2.5}$$

When utilizing the future worth (F → A), the official name is sinking fund, and the notation is (A/F, i, n). The standard notation equation is A = F(A/F, i, n), and the equation with the factor formula is shown in Equation 2.6.

$$A = F\left[\frac{i}{(1+i)^n - 1}\right] \tag{2.6}$$

Similarly, when the annual worth is known, and the future worth is desired (A → F), the official name is uniform-series compounding amount, and the notation is (F/A, i, n). The standard notation equation is F = A(F/A, i, n), and the equation with the factor formula is shown in Equation 2.7.

$$F = A\left[\frac{(1+i)^n - 1}{i}\right] \tag{2.7}$$

Table 2.4 summarizes the discussed forms and equations of representing money.

TABLE 2.4
Classifying Worth Conversion in Engineering Economics

How Conversion Is Performed	Official Name	Standard Notation Equation	Equation with Factor Form
Future worth to present worth	Single-payment present worth	P = F(P/F, i, n)	$P = F\left[\frac{1}{(1+i)^n}\right]$
Present worth to future worth	Single-payment compound amount	F = P(F/P, i, n)	$F = P \times (1+i)^n$
Present worth to annual worth	Capital recovery	A = P(A/P, i, n)	$A = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right]$
Annual worth to present worth	Uniform-series present worth	P = A(P/A, i, n)	$P = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right]$
Future worth to annual worth	Sinking fund	A = F(A/F, i, n)	$A = F\left[\frac{i}{(1+i)^n - 1}\right]$
Annual worth to future worth	Uniform-series compounding amount	F = A(F/A, i, n)	$F = A\left[\frac{(1+i)^n - 1}{i}\right]$

EXAMPLE PROBLEM 2.2

The University of Arkansas has recently acquired a self-reacting frame that will hold an actuator to perform dynamic testing on structural elements in the laboratory. Although the frame was generously donated by a local steel manufacturer, the donation must be quantified for the development office. Assuming the present value of the frame is $32,000, what is the single-payment compound amount and the capital recovery? Use an analysis period of 10 years, and an interest rate of 3.5% for both calculations.

To calculate the single-payment compound amount, use the following equation:

$$F = P \times (1+i)^n = \$32{,}000 \times (1+0.035)^{10} = \underline{\$45{,}139}$$

To calculate the capital recovery, use the following equation:

$$A = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] = \$32{,}000\left[\frac{0.035(1+0.035)^{10}}{(1+0.035)^{10} - 1}\right] = \underline{\$3{,}847.72}$$

2.4 RATE OF RETURN

Care needs to be taken when calculating the rate of return, as the rate of return is based on the unrecovered balance, and not the initial balance. When an agency or firm borrows money, the interest rate is applied to the unpaid balance so that the total loan amount and the interest on the loan are completely paid with the last loan payment. The key is to determine the proper interest rate so that the final loan payment completely pays off both the total loan amount and the total interest amount. The rate of return is expressed as a percent per period (e.g., an interest rate per year).

To determine the rate of return, either present worth or annual worth forms can be used. If the present worth (or annual worth) of the costs is equated to the present worth of the incomes, the interest rate is called the root of the rate of return relation. If this root is equal to or larger than the minimum attractive rate of return, or MARR, then the alternative is economically feasible. If the root is less than the MARR, the alternative is not economically feasible.

The rate of return can be useful when issuing bonds, which is a common way to pay for large engineering infrastructure projects. Local and state agencies can often not afford to pay for mega projects, so they will issue bonds that investors can purchase. These bonds, over time, pay out with additional interest, which benefits both the agencies and investors. While these bonds may not have the highest rate of return, they are often more stable than other investment strategies and help round out an investor's portfolio.

EXAMPLE PROBLEM 2.3

The student union at the University of Arkansas has invested $225,000 to renovate the dining room. This is expected to save $9500 per year for 20 years in maintenance cost of the room, and will save $300,000 at the end of 20 years in rehabilitation of the room. Find the minimum attractive rate of return (MARR) in order to establish that this alternative is economically feasible.

Convert all costs to year zero. Use trial and error to determine the increment when the ROR results go from positive to negative:

Use –225,000 + 9500(P/A, i, 20) + 300,000(P/F, i, 20):

$$i = 4\% \rightarrow -225{,}000 + 9500\left[\frac{(1+0.04)^{20}-1}{0.04(1+0.04)^{20}}\right] + 300{,}000\left[\frac{1}{(1+0.04)^{20}}\right] = \$41{,}024$$

$$i = 5\% \rightarrow -225{,}000 + 9500\left[\frac{(1+0.05)^{20}-1}{0.05(1+0.05)^{20}}\right] + 300{,}000\left[\frac{1}{(1+0.05)^{20}}\right] = \$6458$$

$$i = 6\% \rightarrow -225{,}000 + 9500\left[\frac{(1+0.06)^{20}-1}{0.06(1+0.06)^{20}}\right] + 300{,}000\left[\frac{1}{(1+0.06)^{20}}\right] = \$-22{,}494$$

Use linear interpolation to get the MARR

$$i = 5.00 + \frac{6458}{6458.3-(-22{,}494)}(1.0) = 5.00 + 0.22 = \underline{5.22\%}$$

2.5 BENEFIT/COST RATIO

While the LCCA, present/future/annual worth, and rate of return are all useful tools in order to quantify alternatives economically, they are often used by corporations and businesses. Yet, a popular public service analysis technique is the benefit/cost ratio, or B/C. The B/C analysis technique was developed in response to the United States Congress Flood Control Act of 1936 and was designed to introduce a higher level of objectivity to public sector economics.

The first step is to convert all benefits and costs into a common equivalent monetary unit. Note that many assumptions and estimations go into this conversion, plus the analysis can change with different interest rates. The B/C can incorporate present worth (PW), annual worth (AW), and future worth (FW). The B/C is then calculated using one of the relationships shown in Equation 2.8.

$$B/C = \frac{\text{PW of benefits}}{\text{PW of costs}} = \frac{\text{AW of benefits}}{\text{AW of costs}} = \frac{\text{FW of benefits}}{\text{FW of costs}} \tag{2.8}$$

When performing the benefit/cost ratio analysis, if the B/C ≥ 1, the project is considered as economically acceptable. Conversely, if the B/C < 1, the project is not economically acceptable. Since the B/C is reported as a single number, clearly it produces an easy-to-understand result. As discussed in the previous sections of this chapter, there have been extensive tools provided to quantify economic alternative. However, if performed correctly, the B/C method will always select the same alternative as the present/future/annual worth and rate of return analysis techniques.

EXAMPLE PROBLEM 2.4

The Federal Aviation Administration (FAA) is awarding $12.5 million in grants to the Los Angeles World Airports in order to improve lighting of the runways and taxiways at Los Angeles International Airport (LAX). These grants will extend over a 10-year period and will create an estimated savings of $1.35 million per year in energy costs and bulb replacement. The FAA uses a rate of return of 5% per year on all grant awards. The grants program will share FAA funding with ongoing activities, so an estimated $175,000 per year will be removed from other program funding. To make this program successful, a $435,000 per year operating cost will be incurred from the regular maintenance and operation budget. Use the B/C method to determine if the grants program is economically justified.

If B/C < 1.0, not economically justified
AW investment cost → $12,500,000 (A/P, 5%, 10) = $1,618,807 per year
AW of benefit → $1,350,000 per year
AW of disbenefit → $175,000 per year
AW of M&O cost → $435,000 per year
B/C = (AW of benefit – AW of disbenefit)/(AW of investment cost + AW of M&O cost) = ($1,350,000 − $175,000)/($1,618,807 + $435,000) = 0.57, not economically justified

2.6 SUMMARY OF ECONOMIC PILLAR

While there are many tools available to quantify the economic pillar of sustainability, the tool chosen is highly dependent on the information available, and the desired results of the analysis. The LCCA can compare multiple alternatives of either a manufactured product or engineering infrastructure, and determine from a monetary standpoint which alternative is more cost effective. It is also necessary to convert dollar amounts to different forms. Here, present, future, and annual worth conversions can assist with issues such as inflation and budget planning. Other techniques, such as rate of return, exist to understand the consequence of choosing the correct interest rate when evaluating loan or bonding options. Finally, the B/C is convenient as it provides a single number comparison, which high-level politicians and administrators can quickly and easily process and understand. All of these tools have pros and cons, and it is up to the engineer to choose the most appropriate method for each unique situation.

HOMEWORK PROBLEMS

1. Using the data found in Example Problem 2.1, recalculate the NPV assuming a discount rate of 2.5% and 5.5%. How much does the NPV change compared to a discount rate of 4.0%?
2. Using the data found in Example Problem 2.1, recalculate the NPV assuming an initial cost of the pavement in 2007 dollars, of $2,177,437. In addition, recalculate the NPV assuming an initial cost of the pavement in 2010 dollars, of $2,432,059. How much does the NPV change compared to the initial cost of the pavement in 2013 dollars?

3. Using the format provided under Sidebar 1.2 "Writing a High-Quality Essay," compare the difference in using different discount rates (2.5%, 4.0%, 5.5%) and initial cost (2007, 2010, 2013 dollars). Which change has a great influence on the NPV? Use two discussion points in your answer.
4. A rural township in central Arkansas has recently replaced several septic tanks that have an anticipated life span of 24 years. Today, these septic tanks cost $24,000. However, they received a grant from the Environmental Protection Agency that matched the cost of the tanks today in order for the tanks to be replaced after their end of life. Assuming an interest rate of seven and a half percent, how much will a complete replacement of the septic tanks cost in 20 years?
5. Washington County, in northwest Arkansas, has plans to purchase $1.2 million worth of bridge girders from a bridge reconstruction on I-40 near Russellville. The purchase will occur in 20 years. These bridge girders will be used on small, low-volume bridges, and are an excellent example of the concept of reuse. Washington County, however, knows that they will not have $1.2 million in 20 years. Therefore, they have two options. They can either set aside a lump sum today, and over the 20 years, the amount they set aside will grow to $1.2 million, or, they can set aside a certain amount each year for 20 years and at the end of the 20 years, they will have $1.2 million. Calculate the total amount they would have to set aside just this year, and the yearly amount they would have to put aside in order to have $1.2 million after 20 years. Assume an interest rate of 6.3%.
6. A geotechnical engineer constructing a new levee in Arkansas has requested that $450,000 be spent now during construction on innovative geotextiles to improve the stability of the slopes of the levee. This is expected to save $11,000 per year for 15 years in maintenance cost of the levee, and will save $625,000 at the end of 15 years in rehabilitation of the levee. Find the minimum rate of return in order to establish that this alternative is economically feasible.
7. The Arkansas State Highway and Transportation Department (AHTD) is investing $1,520,000 to be spent now for rehabilitation of I-30 near Arkadelphia, Arkansas. This is expected to save $66,000 per year for 30 years in maintenance cost of the roadway, and will save $868,000 at the end of 30 years in rehabilitation of the roadway. Find the minimum rate of return in order to establish that this alternative is economically feasible.
8. The Beaver Water district has been granted a $5.3 million grant from the Environmental Protection Agency (EPA) to upgrade the sedimentation basin of the water treatment plant. This grant will extend over a 20-year period and will create an estimated savings of $735,000 per year in equipment and chemical savings. The EPA uses a rate of return of 4% per year on all grant awards. The grants program will share EPA funding with ongoing activities, so an estimated $65,000 per year will be removed from other program funding. To make this program successful, a $225,000 per year operating cost will be incurred from the regular maintenance and operation budget. Use the B/C method to determine if the grants program is economically justified.

9. A local consulting firm has been granted a $25,000 grant from the Bill and Linda Gates Foundation to upgrade the installed solar power panels on a local school. This grant will extend over a 5-year period and will create an estimated savings of $6000 per year in energy costs. The Bill and Linda Gates Foundation uses a rate of return of 7% per year on all grant awards. The grants program will share Bill and Linda Gates funding with ongoing activities, so an estimated $2500 per year will be removed from other program funding. To make this program successful, a $3500 per year operating cost will be incurred from the regular maintenance and operation budget. Use the B/C method to determine if the grants program is economically justified.

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3 Pillar
Environmental Sustainability

Perplexity is the beginning of knowledge.

Khalil Gibran

While the majority of businesses focus on economic repercussions of business decisions, almost all civil engineering infrastructure projects have an impact on the environment as well. This book will not debate concepts such as global warming, but it does recognize that construction of infrastructure and control of the environment often does produce emissions and waste.

In Chapter 2, topics such as LCCA, present/future/annual worth, rate of return, and benefit/cost ratio were reviewed. All of these metrics only consider the financial aspect of projects. An important question to ask, as well, however, through the lens of sustainability is: What sort of environmental impacts are there to a project? The environment is impacted during production, construction, use, and termination of roadways, wastewater treatment plants, dams, and buildings. There is not only energy used during all of these stages, but there are also wastes generated. Emissions are anything from carbon dioxide to volatile organic compounds (VOCs), and waste is anything from demolished structures to scalped raw material. Similar to the economic sustainability pillar section, there are several potential tools available to quantify the environmental impact of projects. These tools will help associate actual numbers with emissions and waste, which will then allow for an understanding of how designs could be changed to reduce such emissions and wastes. The first topic covered will be life cycle analysis (LCA), followed by ecological footprint (EF), and then planet boundary. Finally, this chapter will end with a tool that can be used to help capture these topics called an Environmental Product Declaration (EPD).

3.1 LIFE CYCLE ANALYSIS

LCA utilizes a very similar methodology as the LCCA presented in Chapter 2, but instead of using dollars and cents, emissions are quantified. Emissions come either in the form of compounds, such as carbon dioxide (CO_2) or methane (CH_4), or as combinations of emissions, such as greenhouse gas (GHG) or smog. The latter metrics have been developed to better understand the impact of humans on the Earth. Table 3.1 summarizes the more common emissions and combinations of emissions used in an LCA.

The compounds listed in Table 3.1 are emitted during the production of materials (such as aggregate or Portland cement), the construction of civil engineering infrastructure, the use of infrastructure (vehicle emissions, water treatment), and end of life (milling pavement, building demolition). While the emissions are relatively

TABLE 3.1
Common Emissions Used in a Life Cycle Analysis

Compound	Common Name
CO	Carbon monoxide
CO_2	Carbon dioxide
SO_2	Sulfur dioxide
NO_x	Nitrogen oxide (NO, N_2O, and NO_2)
O_3	Ozone
CH_4	Methane
SF_4	Sulfur tetrafluoride
VOC	Volatile organic compound (paintings, coatings, formaldehyde, etc.)
PM10 (PM2.5)	Particles measuring 10 μm (2.5 μm) or less
GHG	Greenhouse gas
Smog	Smog
THC	Total hydrocarbons (including methane)

straightforward and easy to quantify, additional metrics have been developed to better understand the effect of the combination of compounds. The two most common metrics are GHG and smog.

GHG is a combination of gases that contribute to the absorption and emission of radiation in the atmosphere. Without these gases in the atmosphere, the Earth would not be able to sustain life, as the temperature at the Earth's surface would approach zero Fahrenheit. However, after the Industrial Revolution, the amount of GHG has increased significantly, with some estimates reaching 40% over pre-1750 levels. In a sense, this could potentially cause more of the Earth's heat to be trapped by the atmosphere, which is what is commonly referred to as global warming. The majority of the gases emitted that contribute to GHG are from the burning of fossil fuel and animal agriculture, and offsets have been reduced with deforestation.

The second metric, smog, was created as a by-product of the visual effect of pollution, commonly found over urban areas. Smog comes from two primary sources, emissions from coal power plants or from transportation sources. When coal burns, it releases many emissions, such as carbon monoxide, carbon dioxide, sulfur dioxide, nitrous oxides, and PM10. While significant efforts have been made to clean the air as it escapes from coal power plants in the United States, some undesirable emissions still make it to the atmosphere. This problem is significantly higher in developing countries versus developed countries, as the cost of emission control at point sources is significant. The second main source of smog, transportation, often emits carbon monoxide, nitrous oxides, VOC, and various hydrocarbons (such as methane). High volumes of vehicles, especially slow-moving vehicles (such as those in traffic flow approaching jam density), exasperate the emissions. What is more, once sources such as power plants or traffic emit emissions to create smog, a photochemical process can compound the smog generation. When sunlight strikes nitrous oxide or VOC, it reacts with these emissions and generates even more smog. A continuous cycle is formed, where emissions that cause smog react with the sunlight to create more smog.

In addition to these single emissions and emission metrics, several new quantifications have been developed in order to better understand how emissions influence nature's natural air and water cycles. Figure 3.1 shows the different layers of the Earth's atmosphere.

Four quantifications specifically will be explored here: ozone depletion, eutrophication, ocean acidification, and global warming potential (GWP).

The first quantification, ozone (O_3) depletion, attempts to capture the deterioration of ozone in the Earth's stratosphere. The general principle is that when atomic halogens (such as refrigerants, solvents, propellants, etc.) are released into the atmosphere, they release chlorine molecules, which react with and destroy ozone (O_3) molecules. The reaction takes place as follows:

$$Cl^- + O_3 \rightarrow ClO + O_2$$

$$ClO + O_3 \rightarrow Cl^- + 2O_2$$

The reaction process feeds on itself, as through the two reactions, more single chlorine atoms are created, which then react with more ozone. The single chlorine atoms react with ozone to create hypochlorite (ClO), which reacts with more ozone, creating more single chlorine atoms, and so on. The loss of ozone is most pronounced in the polar regions as the extreme cold promotes conditions that accelerate the two reactions above.

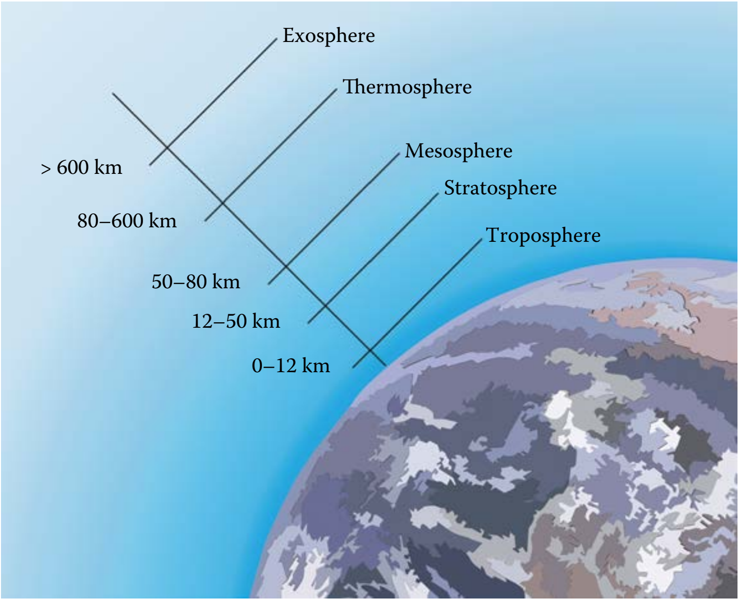

FIGURE 3.1 Layers of the Earth's atmosphere. (Credit: William Crochot.)

The second quantification, eutrophication, is the measurement of the addition of phosphates to the ecosystem. While eutrophication is a perfectly normal phenomenon in many cases, excessive phosphates can create highly toxic situations for native plants and fishes. Excessive phosphates can come from many sources, including detergents and fertilizers, and also from civil engineering sources such as wastewater. Point sources such as large-scale cattle or chicken farms, or sewage overflow devices can accelerate the detrimental process. The addition of these phosphates cause accelerated growth of plants and algae, especially in calm water sources such as ponds and lakes. These plants and algae consume oxygen, which can lead to hypoxia in the water. In general, aquatic life requires greater than 80% dissolved oxygen for a healthy environment. However, hypoxia occurs when dissolved oxygen is between 1% and 30%.

The third quantification, ocean acidification, quantifies a by-product of the natural ocean cycle where water attracts carbon dioxide. Like ozone depletion and eutrophication, ocean acidification occurs naturally, but human influence can accelerate the process, upsetting the natural equilibrium and causing significant changes in the ecosystem. In short, ocean acidification is the decrease in pH of the ocean from uptake of CO_2 in the atmosphere, and can be shown in the following reaction:

$$CO_2 + H_2O \rightarrow HCO_3^- + H^+ \leftrightarrow CO_3^{2-} + 2H^+$$

As can be seen, the carbon dioxide (CO_2) reacts with the water (H_2O) of the oceans, which then causes two potential reactions to create acid (H^+).

The fourth quantification, GWP, revolves around the concept of radiative force capacity. Radiative force capacity is the amount of energy (per unit area, per unit time) that is absorbed by GHG. A standard unit of radiative force capacity is W/m^2-kg/years. GWP is simply the ratio of the radiative force capacity of any substance over time of 1 kg by the radiative force capacity of carbon dioxide over time of one kilogram:

$$GWP = \frac{\text{radiative force capacity of any substance over time of 1 kg}}{\text{radiative force capacity of any } CO_2 \text{ over time of 1 kg}}$$

Based on this analysis, the GWP of carbon dioxide is one. Other common GWPs at different time periods are shown in Table 3.2.

This section has outlined many common emissions and compounds that can be used to quantify emissions from civil engineering applications, along with four quantifications that often occur naturally, but have also been accelerated with human influence, especially after the Industrial Revolution. All of these metrics can be calculated during the production, construction, use, and end of life. The combination of the metrics and steps in the production of materials or infrastructure forms the complete LCA. In addition to these tools, two additional concepts have been developed that can help quantify the environmental effect of civil engineering infrastructure: EF and planet boundary.

TABLE 3.2
Global Warming Potential of Several Common Emissions

Emissions		20 years	100 years
Methane	CH_4	86	34
Nitrogen oxide	N_2O	268	298
Sulfur tetrafluoride	SF_4	15,100	22,000

EXAMPLE PROBLEM 3.1

Google the document "Towards Sustainable Pavement Systems: A Reference Document" (Van Dam et al., 2015). One of the first links should be from the Federal Highway Administration (FHWA), and report FHWA-HIF-15-02. Many governmental reports are available online for free download. Find the section that defines life cycle assessment. Define the acronym ISO and state what ISO's LCA definition is.

ISO stands for International Organization for Standardization, which, as its name implies, is an organization that represents multiple national standards organizations. ISO defined LCA as a process that "addresses the environmental aspects and potential environmental impacts (e.g., use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition, through production, use, end-of-life treatment, recycling, and final disposal (i.e., cradle to grave)." This quote is found on pages 2–9 or page 49 of the .pdf file.

3.2 ECOLOGICAL FOOTPRINT

The concept of EF originated at the University of British Columbia in the early 1990s (Wackernagel, 1994). The concept is based on nature's capital, and the fact that certain needs are necessary for human life. These needs include healthy food, energy for mobility and heat, fresh air, clean water, fiber for paper, and clothing and shelter. The goal of the EF was to develop a scientifically sound calculation and that could relate to clear policy objectives. In addition, it needed a clear interpretation, to be understandable to nonscientists, and to cover the functioning of a system as a whole. Finally, the metrics had to be based on parameters that are stable over long periods of time so that minor or local fluctuations would not compromise quantifications.

EF is based on taking specific economy or activity's energy needs, and converting that energy and matter to land and water needs. In short, this leads to a five-step calculation. First, the consumption of a city, region, state, or country is calculated and split into food, housing, transportation, consumer goods, and services. Second, land area of the analysis zone is appropriated into cropland, grazing, forest, fishing ground, carbon footprint, or built-up land. Cropland is land available to produce food and fiber for human consumption, feed for livestock, oil crops, and rubber. Grazing is land that can raise livestock for meat, dairy, hide, and wool products. Forest provides the land for lumber, pulp, timber products, and wood for fuel, while fishing ground covers the primary production area required to support the fish and seafood caught. While forest is one category for providing wood products, the carbon footprint is the amount of forest land required to absorb CO_2 emissions. Finally, the last category is built-up land, which is the area of land covered by human infrastructure. Once the consumption and land use is identified, both resource and waste flow streams are calculated, which is the third step in the calculation. The fourth step is the construction of a consumption/land-use matrix. This matrix shows all categories of both consumption and land use, and it also indicates where there is not enough land for certain consumptions as well as which land is excess land. The deficiencies give numbers greater than one while the excess give numbers less than one. The fifth and final step sums all of the numbers and provides an estimate of EF for a region. These five steps are summarized in Table 3.3.

When considering EF from a country level, it is interesting to note that the highest EF countries are from the Middle East according to a 2010 report published by the Global Footprint Network (Ewing et al., 2010). This report states that the United Arab Emirates (UAE) and Qatar were producing EFs greater than 10.0 global hectares per person. This number states that if every person in the world was living the standard of living of the average UAE citizen living on UAE's resources, we would need over 10 Earths to sustain life. The next grouping down consists of Western, fully developed countries, which required approximately 5–8 Earths to maintain their standard of living. The list continues down through second-world, developing, and third-world countries. According to the report, it is interesting to note that the countries requiring less than one Earth is quite diverse both geographically and socioeconomically, from the Democratic Republic of the Congo (population 63 million) to Bangladesh (population 158 million) to Puerto Rico (population 4 million).

There are, of course, some drawbacks to the EF concepts. First, the physical consumption-land conversion factor weights do not necessarily correspond to social weights. The analysis focuses 100% on the metrics at hand, but do not consider the social choices people have to make. These concepts are often ignored; they will be covered more in Chapter 4. Second, the EF does not distinguish between sustainable and unsustainable use of land, only that land is being consumed. Therefore, forest could be clear-cut or sustainably harvested, two processes to extract wood from nature, but the EF would treat these practices as the same. A third criticism is that in the EF model, there are many options to compensate for CO_2 emission and

TABLE 3.3
Five-Step Calculation for Ecological Footprint (EF)

Step	Description of Each Step
1	Consumption of food, housing, transportation, consumer goods, and services determined
2	Land area appropriated into cropland, grazing, forest, fishing ground, carbon footprint, or built-up land
3	Resource and waste flow streams calculated
4	Construction of a consumption/land-use matrix
5	Sum all of the numbers, provide an estimate of EF for a region

CO_2 assimilation, such as by forest, chemosynthesis, and autotrophs. However, the EF model only compensates for CO_2 emission and assimilation by forest, neglecting the other options. A fourth criticism is that there is a significant correlation between population density and resource endowment. As populations move away from rural living to urban living, the EF will increase significantly, especially as the analysis zone shrinks. This artificially inflates the EF of urban areas while perhaps underestimates the true EF of rural areas. The fifth and final criticism discussed here is that EF is hard to use as a planning device. While it is noble to attempt to decrease the EF, there are few tangible concepts that agencies can focus on to begin the reduction, making it difficult to leverage. While no measure is truly perfect, these deficiencies have led to the development of other metrics, including the planet boundary.

EXAMPLE PROBLEM 3.2

Google the document "Ecological Footprint Analysis San Francisco-Oakland-Fremont, CA" (Moore, 2011). What is the largest EF category within the "Transport" area of consumption, and how does it compare to the largest consuming EF area of consumption?

The largest EF category with the transport area of consumption is carbon. Overall, the carbon consumption is much high for transport versus "Food and nonalcoholic beverages." This is reasonable, since the food area of consumption relies heavily on cropland, whereas the transport area of consumption has carbon emissions associated with the activities.

3.3 PLANET BOUNDARY

The concept of planet boundary was first proposed in 2009 and is defined as a "safe operating space" for humanity (Rockström et al., 2009a). According to this theory, if human activities stay within the safe space, the Earth is able to absorb the human activities with no long-term harm to the environment; however, if human activities move outside of the safe space, the planet boundary theory states that long-term harm may occur to the environment. These spaces are associated with the Earth's biophysical subsystems and processes.

A major premise of planet boundary theory is that the environment has been unusually stable for the past 10,000 years, commonly referred to as the Holocene period. During this time, the Earth's temperatures, freshwater availability, and biogeochemical flows have all stayed within a narrow, stable range according to some research (Rockström et al., 2009b). However, with the beginning of the Anthropocene period, which started after the Industrial Revolution in the 1800s, human influence may have begun to damage the system that keeps Earth within Holocene state according to planet boundary theory. This system was divided into nine subsystems, eight of which have been quantified. The nine subsystems have some overlap with both concepts learned in the LCA section and the EF section, but they also venture into new areas. The nine plant boundary subsystems are summarized and quantified in Table 3.4 for both 2009 and 2015 (Steffen et al., 2015), with a brief discussion following (Note: The nitrogen and phosphorus cycle are combined into one process called biogeochemical flows).

TABLE 3.4
Planet Boundary Summary

Earth System Process Subsystems	Proposed Boundary	2009 Status	2015 Status	Preindustrial Value
Climate change (ppm CO_2)	350	387	396.5	280
Rate of biodiversity loss (extinctions per million species-years)	10	>100	100–1000	0.1–1
Biogeochemical flows: nitrogen cycle (million tons/year)	62–82	121	150	0
Biogeochemical flows: phosphorus cycle (million tons/year)	6.2–11.2	8.5–9.5	14–22	−1
Stratospheric ozone depletion (Dobson unit, DU)	276	283	As low as 200	290
Ocean acidification (carbonate ion concentration)	>2.75	2.90	2.89	3.44
Global freshwater use (km^3/year)	4000	2600	2,600	415
Change in land use (percentage)	75	11.7	62	Low
Atmospheric aerosol loading (aerosol optical depth)	0.25–0.50	Not determined	0.30	Not determined
Chemical pollution		To be determined		

In Table 3.3, climate change is quantified by measuring the atmospheric carbon dioxide concentration, with units of parts per million by volume. Another quantification discussed for climate change was the change in radiative forcing. This radiative forcing is the same concept discussed earlier in Chapter 3 with the GWP, and was listed at 1.5 in 2009 and is set at 1.0 for the boundary. Additionally, the rate of biodiversity loss was measured by the extinction rate, and is the number of species per million species per year lost. The nitrogen cycle is the amount of N_2 removed from the atmosphere for human use in millions of tons per year, while the phosphorus cycle is the quantity of P flowing into the oceans per year, in millions of tons. The stratospheric ozone depletion is the concentration of ozone, using the Dobson unit, while the global freshwater use is the consumption of freshwater by humans per year, in kilometers cubed. The change in land use is simply the percentage of global land cover converted to cropland from the natural state of the land. The atmospheric aerosol loading is the particulate concentration in the atmosphere on a regional basis, and the chemical pollution, which include emissions of everything from organic pollutants, to plastics, to heavily metals, and nuclear waste, has not yet been quantified. Figure 3.2 shows a visual image of the processes.

Like the EF, planet boundary theory has some pros and cons, but it is another tool that can be potentially used to quantify the influence of civil engineering infrastructure on the environment. Below, the last point discussed in this chapter, is a procedure that has been developed in order in an attempt to help create understanding on the influence of a project on the environment, and this procedure is called an EPD.

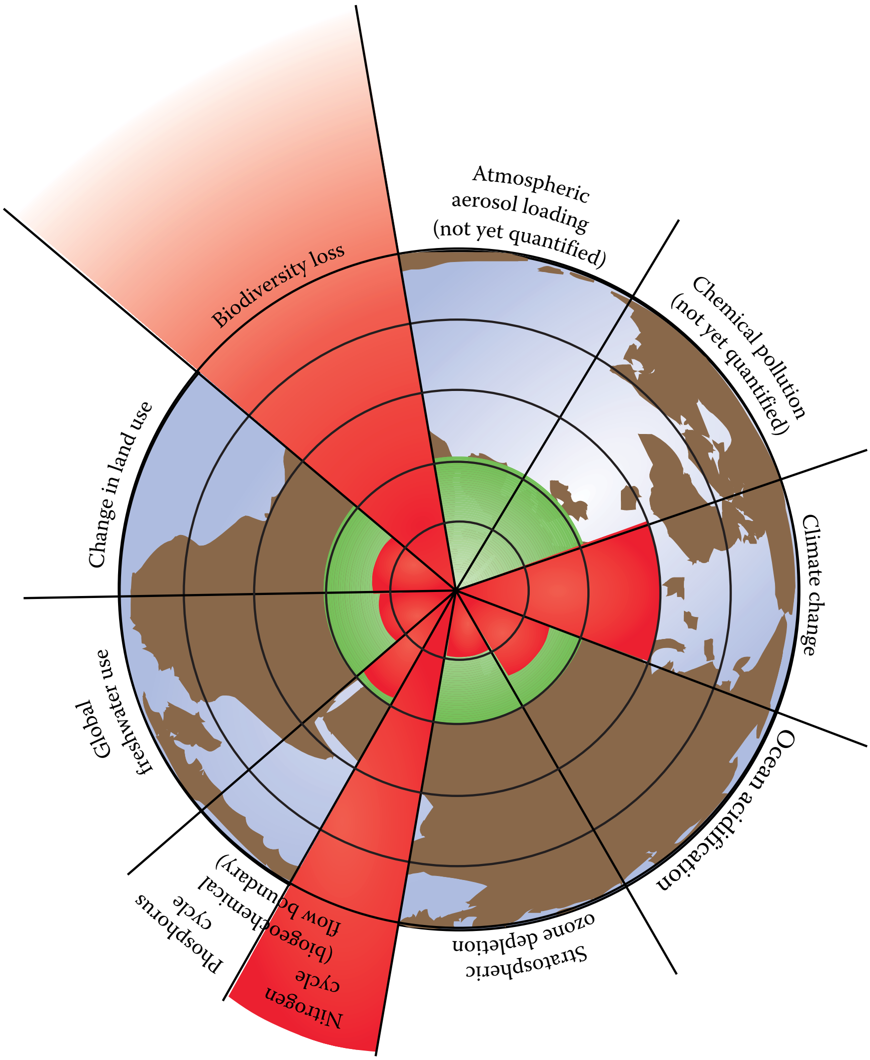

FIGURE 3.2 Planet boundary. (Credit: Azote Images/Stockholm Resilience Centre.)

EXAMPLE PROBLEM 3.3

On June 16, 2012, *The Economist* (a business magazine) published an article discussing planet boundaries (titled "boundary conditions"). The magazine article referenced a report by the Breakthrough Institute and highlights two points. What were the two points?

The two points highlighted by the Breakthrough Institute were (1) there is not a distinction between the global perspective and local/regional perspectives (i.e., policies in one country to better the environment might actually hurt other countries if applied in the same way) and (2) the planet boundaries limits were established considering conditions during the Holocene (and it is difficult to prove that the Holocene period is the "optimal" period in Earth's history).

3.4 ENVIRONMENTAL PRODUCT DECLARATION

An EPD is a document that is intended to communicate information about the life cycle environmental impact of a product. The document is intended to be transparent and comparable across multiple similar products, based on ISO 14025 (ISO stands for International Organization for Standardization) and EN 15804 (EN stands for European standards maintained by the European Committee for Standardization). EPDs are for disclosure of information only, and do not certify that any environmental performance standards are being met. According to ISO 14025, there are four objectives to an EPD:

1. To provide LCA-based information and additional information on the environmental aspects of products.
2. To assist purchasers and users to make informed comparisons between products.
3. To encourage improvement of environmental performance.
4. To provide information for assessing the environmental impacts of products over their life cycle.

For this discussion, a polyethylene (PE) pipe produced by Ilex Pipelines will be reviewed as an example for critical sections (iPlex, 2016).

In general, EPDs begin with a description about the company that produces the product and then proceeds into engineering properties of the product. For PE pipes, various material properties are required, including strength, stress, modulus, density, Poisson's ratio, thermal expansion coefficient, and thermal conductivity. After engineering properties, the model number is listed, followed by contact information for the company, the date of publication, and the period of validity. Next, in an EPD, there is a content declaration. For the PE pipe, the material breakdown is 96%–98% PE, 2%–3% carbon black, and <1% nonhazardous additives. After the content declaration, a discussion of the product life cycle is given. The four general stages to a life cycle are production, construction, use, and end of life. Specifically, the PE EPD states that during the production stage, the raw materials' supply, transport, and manufacturing are included, and the transportation and installation are included for the construction stage. The use stage of the PE EPD includes maintenance, repair, replacement, refurbishment, operational energy, and operational water. The end-of-life stage of the PE EPD includes deconstruction/demolition, transport, waste processing, and disposal.

Within the PE EPD's product life cycle section, there are several important details that help the reader understand details within each stage. For example, during the manufacturing process of the PE pipe, the location of source materials and general manufacturing guidelines are provided. In addition, a brief overview of how the pipes are distributed and installed is given. During these two sections, several assumptions are made, such as average transportation distance of the PE pipe and amount of backfill material needed to cover the pipe after installation. Finally, while developing the product life cycle section for any EPD, it is important to state if any stages are not being considered in the EPD being written. This will ensure that there were no oversights within EPD, as information simply left out could be interpreted as either not important or overlooked. The final section of an EPD before the assessment itself is the "declared unit." The declared unit is similar to the functional unit of an LCA, and ensures that the reader understands the quantity of product that is evaluated. For PE pipe, the declared unit is 1 kg of installed pipe.

After this preliminary information is provided, the LCA itself is provided. For the PE EPD, the assessment was broken into seven environmental indicators: GWP, ozone depletion potential, acidification potential, eutrophication potential, photochemical ozone creation potential, abiotic depletion potential (elements), and abiotic depletion potential (fossil fuels). Tables 3.5 through 3.7 summarize the findings. Again, for the PE pipe, the use stage and end-of-life stage were not included in the analysis, only the product stage and construction stage were reviewed. While some general trends can be observed, such as the relatively high level of carbon dioxide versus other environmental indicators, the relatively high level of energy use in product stage versus construction stage, and the highest waste in the installation portion of the construction stage, the most important takeaway from Tables 3.5 through 3.7

TABLE 3.5
Potential Environmental Impacts

	Product Stage (Raw Materials Supply, Transport, Manufacturing)	Construction Stage (Transport)	Construction Stage (Installation)
Global warming potential (kg CO_2 eq[a])	2.95	4.62×10^{-2}	1.08
Ozone depletion potential (kg CFC-11 eq)	7.00×10^{-8}	1.17×10^{-9}	5.45×10^{-8}
Acidification potential (kg SO_2 eq)	0.0107	1.12×10^{-4}	3.43×10^{-3}
Eutrophication potential (kg PO_4^{3-} eq)	1.07×10^{-3}	2.72×10^{-5}	8.35×10^{-4}
Photochemical ozone creation potential (kg C_2H_2 eq)	5.14×10^{-4}	7.22×10^{-6}	1.77×10^{-4}
Abiotic resource depletion potential—elements (kg antimony eq)	9.78×10^{-3}	1.12×10^{-4}	3.43×10^{-3}
Abiotic resource depletion potential—fossil fuel (MJ)	1.07×10^{-3}	2.72×10^{-5}	8.35×10^{-4}

[a] eq = equivalent.

TABLE 3.6
Use of Resources[a]

	Product Stage (Raw Materials Supply, Transport, Manufacturing)	Construction Stage (Transport)	Construction Stage (Installation)
Total use of renewable primary energy resources (MJ)	1.48	3.18×10^{-3}	0.356
Total use of nonrenewable primary energy resources (MJ)	90.2	7.21×10^{-1}	14.5
Use of net freshwater (m^3)	0.137	1.03×10^{-2}	0.863

[a] The following indicators were not assessed: use of renewable primary energy resources used as raw materials, use of nonrenewable primary energy resources used as raw materials, use of secondary material, use of renewable secondary fuels, and use of nonrenewable secondary fuels.

is the concepts and general ranges of numbers, which provide insight into the ranges of values obtained in such an analysis.

The next section of the EPD is an interpretation of the LCA result. For the PE EPD, the analysis concludes that the majority of the impact lies with the raw material supplied, followed by the energy used for excavation during pipe installation. Finally, the last sections of an EPD provide guidance for recycling the product and a full summary of the environmental impact of products. For the PE EPD, a discussion of the high recyclability either mechanically or chemically is provided, followed by LCA results for specific pipe products.

The previous paragraphs discussed a sampling of the information contained in an EPD and can be summarized as follows:

- Description of company
- Engineering properties of the product
- Model number

TABLE 3.7
Generation of Waste

	Product Stage (Raw Materials Supply, Transport)	Construction Stage (Transport)	Construction Stage (Installation)
Hazardous waste disposed (kg)	6.59×10^{-6}	3.83×10^{-7}	1.44×10^{-5}
Nonhazardous waste disposed (kg)	0.147	3.68×10^{-3}	0.254
Nonhazardous waste disposed (kg)	2.38×10^{-5}	9.32×10^{-9}	4.50×10^{-7}

- Contact information of company
- Content declaration
- Product life cycle
- LCA
- Interpretation of LCA
- Guidance for recycling
- Full environmental impact summary for all company products

EXAMPLE PROBLEM 3.4

Vulcan Materials recently released an EPD for their 12 concrete aggregate products (by Googling "Vulcan Materials Environmental Product Declaration," the .pdf can be quickly found) (Vulcan, 2016). Vulcan decided to only analyze the "cradle-to-gate" life cycle of the aggregate, focusing only on the raw material supply, the transport, and the manufacturing. In this document, compare the impact results for the manufactured sand (MFG Sand) to the top sand (WCS).

When looking at Table 4 in the document, it is obvious that the manufactured sand has a higher impact than the top sand (or natural sand). This is an interesting comparison because these are both very similar products as sands, but the manufactured sand requires more processing (extraction, crushing, and screening) versus the natural sand (extraction and screening). Essentially, the GWP, the acidification potential, the eutrophication potential, the ozone depletion potential, the use of net freshwater, the hazardous waste disposal, and the radioactive waste disposed is double for the manufactured sand versus the natural sand. In addition, the photochemical ozone creation potential, the use of renewable and nonrenewable primary energy, and the nonhazardous waste disposal are greater for the manufactured sand versus the natural sand. Therefore, it is apparent that the crushing of aggregate is a significant portion of the emissions associated with aggregate production.

3.5 SUMMARY OF ENVIRONMENTAL PILLAR

Unlike the variety of established tools available for the economic pillar of sustainability, there is only one well-established tool to quantify the environmental aspects of sustainability, the LCA. While other concepts are available, such as EF and planet boundary, these have not been implemented across a wide range of civil engineering applications. However, there is promise in these developing fields, and they may become more salient in the future. Along with these three concepts, tools are being developed and implemented by industry, such as an EPD, that outline the full environmental impact of products. Overall, the importance of the environmental impact of products and processes is becoming more pronounced, but there is still significant work to be done.

HOMEWORK PROBLEMS

1. Within the document "Towards Sustainable Pavement Systems: A Reference Document," Chapter 3 discusses considerations to improve pavement sustainability. List the strategies for improving sustainability for aggregate materials. Using the format provided under Sidebar 1.2 "Writing a High-Quality

Essay," discuss which approach you think is best for improving sustainability for aggregate materials. Use two discussion points.

2. Find a report online that examines the life cycle assessment of a civil engineering application. Using the format provided under Sidebar 1.2 "Writing a High-Quality Essay," outline the application and provide a succinct of the findings. Ensure to take into account any potential affiliation of the authors when discussing your thoughts.
3. Within the document "Ecological Footprint Analysis San Francisco-Oakland-Fremont, CA," the transport area of consumption is broken down into subcategories. List the top three subcategories of the transport area. Were you expecting these three subcategories to be in the top three? Did you expect any of the other subcategories to be higher? Use the format provided under Sidebar 1.2 "Writing a High-Quality Essay" to discuss your answer.
4. Within the document "Ecological Footprint Analysis San Francisco-Oakland-Fremont, CA," Figure 1 shows a sampling of country's EF. Why do you believe Qatar and UAE have such high EF? Also, looking at the income level of the countries in Figure 1, can you develop a general relationship between income level and EF? Use the format provided under Sidebar 1.2 "Writing a High-Quality Essay" to discuss your answer.
5. Google "The Planetary Boundaries Hypothesis, A Review of the Evidence," and the .pdf article written by Nordhaus et al. (2012) should be one of the first links. Which of the nine Earth system process does the Breakthrough Institute believe can be successfully used on a global-scale threshold? Do you agree or disagree with their assessment? Use the format provided under Sidebar 1.2 "Writing a High-Quality Essay" to discuss your answer and include two primary discussion points.
6. Pick one of the nine Earth system process within the Breakthrough Institute document and carefully review the institute's full analysis of the process. Identify one concept you agree with in their analysis and one concept you disagree with. Use the format provided under Sidebar 1.2 "Writing a High-Quality Essay" to formulate your answer.
7. Compare the EPD for Vulcan Material's concrete aggregate products to the description of the PE pipe in the text. Using the format provided under Sidebar 1.2 "Writing a High-Quality Essay," discuss the two largest differences and the two largest similarities between the concrete aggregate and PE EPD.
8. Examine Table 4 in the EPD for Vulcan Material's concrete aggregate products. There are several impact categories that are listed as zero cradle-to-gate impact results. Why do you think that these values are zero, and how could Vulcan utilize some of these impact categories? Use the format provided under Sidebar 1.2 "Writing a High-Quality Essay" to formulate your answer.

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4 Pillar
Social Sustainability

Education is the most powerful weapon which you can use to change the world.

Nelson Mandela

The third pillar of sustainability, social, is the least quantified pillar compared to economic and environmental. Ongoing research in other disciplines, especially in the arts and sciences, has developed measurements for aspects of communities that have more success in addressing and solving problems. One such well-known community attribute is social capital. People are connected by social networks, and the exchange of trust and resources within those networks comprises measures of social capital. Community attachment is also recognized as another characteristic of engaged communities. The difficulty in measuring these well-known aspects of communities, however, lies partly in the differences between data sources, coverage, and availability. Much research has been performed with secondary data, often based on census data. This is because those publicly available datasets are available, affordable, generally have widespread geographic coverage, and large sample sizes. While many research projects collect primary data, primary data is more often limited to a relatively small population and/or geographic area as it is generally based on interviews or surveys. Primary data is expensive to collect and is also more difficult to use for generalizing because of limits in coverage, sample size, and/or comparability.

Metrics, to be effective indicators of a system, have four characteristics: relevancy, understandability, reliability, and accessibility. Relevance is key because the metric must provide information about the system one needs to know. Understandability is important so that even nonexperts can grasp the meaning of the metric. The metric must be trustable or reliable or the metric is of no use, and the data or information for the metric must be obtainable in a time frame suitable for decision-making. The quandary for measuring societal sustainability and application to civil engineering, comes in establishing effective metrics to answer three critical questions:

1. What level are we targeting for sustainability?
2. Who are we sustaining for?
3. Who gets to decide the answers to the first two questions?

In addition to these three questions and the difficulties with data mentioned earlier, other considerations are important as well. For example, if one area of society has a well-developed metric, does that influence other areas that do not have well-developed metrics? How do these metrics scale from a local or regional level upwards to state, national, and international levels? Social metrics exhibit spatial heterogeneity, or unequal geographic distribution, which can further complicate scalar relationships. In general, many of the existing social metrics fall under four emerging areas: human well-being, access to resources, self-government, and civil society. These four emerging areas have provided much of the foundation of agencies and frameworks discussed in this chapter, including the UN, the Oxfam Doughnut, Human Development Index (HDI), and Social Impact Assessments (SIA).

Finally, most existing social metrics have a short time horizon, and many are only available as cross-sectional data. Even those datasets that are longitudinal cover time periods of a few decades, not 50 or 100 years. How will these metrics change over time frames appropriate for sustainability planning—in 10, 20, or even 50 years? While this chapter does not comprehensively answer all these questions, it does expose the reader to multiple tools and resources that can help identify potential paths forward.

4.1 EXISTING CIVIL ENGINEERING CONCEPTS

As discussed in this textbook's introduction, the American Society of Civil Engineers (ASCE) incorporate social aspects of sustainability into many portions of their Code of Ethics. In the fundamental principles, engineers are called to "use their knowledge and skill for the enhancement of human welfare" and to be "honest and impartial and serving with fidelity the public." This theme continues in ASCE's canons, where engineers "shall hold paramount the safety, health and welfare of the public." The difficulty with following these charges in part comes with understanding the concepts behind specific terms. For example, what exactly is human welfare? What are the dimensions, attributes, and qualities of human welfare, and can these dimensions, attributes, and qualities be quantified?

There has been limited research performed specifically in the area of society and civil engineering. Yet, several groups within the civil engineering community have examined the issue. In 2007, for instance, Cheng et al. identified the need to measure sustainable accessibility in regional transport and land use systems (Cheng et al., 2007). They developed a model that utilized the average trip length and accessibility to jobs in an area, and created a four-dimensional analysis that studied whether both parameters (trip length, access to jobs) were positive, negative, or a mix of the two. Accessibility was enhanced by either increasing the travel speed or bringing urban activities closer. Only car commuting was considered in this study. If a mix of trip length or access to jobs occurred, a better transportation system could be implemented or more jobs could be moved into an area. Similar to the gravity model, Cheng et al. also established that friction factors could be developed to represent other barriers associated with commuting from home to work. While the authors acknowledged that the study was limited, they were confident it could provide a platform for further work. Another group that has exampled the issue of society and civil engineering is Lucas et al., performing work in a similar area of regional transport and land use (Lucas et al., 2007). Lucas et al. focused on five areas of social sustainability, and they associated various engineering metrics with each one. The first area, poverty, was quantified examining total household expenditure on travel. The second area, accessibility, focused on weighted journey times to employment, education, health care, and food shops. The third area, safety, analyzed the number of child pedestrian casualties per 1000 children in population. The fourth area, quality of life, captured the percentage of residents living within a 1 km or 15 minute "safe walk" to key destinations, including education, health care, leisure and cultural facilities, food shops, and the post office. The fifth and final area, housing, studied the lowest 10% value of house prices within the average local journey times to employment from the town center or other key centers of employment. Again, by Lucas et al.'s focusing on transportation issues and relative ease of access to important destinations, progress was made toward better understanding social aspects of sustainability in civil engineering.

Several studies considered transportation materials and design by Alkins et al. (2008) and Anderson and Muench (2013). Alkins et al. examined the social benefits of *in situ* pavement recycling by exploring cold in-place recycling (CIR). This study examined the Ministry of Transportation Ontario's (MTO) promotion of using technology that reduces, recycles, and reuses, qualities deemed important for a society. CIR, which mills existing pavement in-place, stabilizes with a binding agent, and then places the material back onto the same roadway for an enhanced structural layer, fulfills all three of these goals (reduces, recycles, reuses). They also discuss other social benefits of CIR, including improving safety. They found that safety is improved with the use of CIR by reducing traffic disruption and user inconvenience, reducing unsafe exposed edges and drop-offs (the milled pavement has a similar grade as the existing pavement after compaction), and expanding the worker's ability to work through certain types of incremental weather since the material is placed at ambient temperatures. In addition, Alkins et al. point out that with all of the CIR work being performed in place, there is reduction noise and disruption from traditional asphalt mixture production, transportation, and construction. Anderson and Muench, on the other hand, utilized a different approach to studying transportation materials and design by evaluating the Greenroads Rating System to measure sustainability trends. Greenroads, founded as a company in summer 2010 by Jeralee Anderson and Steve Muench, has 11 categories of project requirements and 37 voluntary requirements. Project requirements that revolve around societal concepts include a noise mitigation plan and educational outreach, while voluntary requirements include light pollution, safety audit, pedestrian access, scenic views, cultural outreach, and environmental training. Anderson and Muench compared 65 "typical projects," indicating projects that took no action toward sustainable components, and 40 "sustainable projects" that utilized the Greenroads standard or were specifically classified as sustainable by secondary sources. For the project requirements, it was found that typical projects were 12% less likely to have a noise mitigation plan versus a sustainable project (26% versus 38%), while typical projects were 22% less likely to have educational outreach (28% versus 50%). Similar trends were seen with the voluntary requirements, with typical projects 7%–15% less likely to achieve the requirements versus the sustainable projects in all categories except environmental training, where typical projects were actually 12% more likely to have such training versus sustainable projects. However, the majority of projects that specifically strived to incorporate sustainable practices showed an increase in success overall for social metrics.

Another group of researchers has taken a unique approach to incorporate social sustainability into civil engineering education (Valdes-Vasquez and Klotz, 2011).

In this work, both the traditional instructor to student teaching approach and the more innovative student to student teaching approach were utilized to convey social sustainability concepts. In both approaches, four dimensions of social sustainability were explored: community involvement, corporate social responsibility, safety through design, and social design. In addition to providing mapping and resources for both approaches, preliminary results were encouraging as initial feedback from students was positive for both approaches. The authors concluded by recommending that other civil engineering programs also strive to incorporate social sustainability concepts into the curriculum.

While this brief review has found that there have been several forays into concepts of social sustainability, there is not clear consensus on what social sustainability is, nor how it can be firmly measured in regard to civil engineering. In order to better develop tools, work done with the United Nations, Oxfam, the UN's HDI, and SIA is reviewed in order to gain a stronger foundation as to how other stakeholders are defining and exploring social impacts. In addition, a brief review of emerging areas will also be covered in order to provide stimulative thought moving forward in the field.

EXAMPLE PROBLEM 4.1

List the potential social metrics that have been developed within existing civil engineering concepts.

The potential social metrics that have been developed within existing civil engineering concepts include time, accessibility, poverty, safety, housing location, and quality of life.

4.2 UNITED NATIONS (2002, 2007, 2012, 2015)

As discussed in Chapter 1, the 2002 World Summit on Sustainable Development hosted by the UN was the first time the UN adopted the three pillars of sustainability: economic, environmental, and social. Broad topics that fell under the social pillar included poverty eradication, changing consumption and production patterns, human development, and the uneven distribution of the benefits and costs of globalization. These themes were continued and expanded on in 2007, when the UN released the third edition of indicators of sustainable development (UN, 2007). In this effort, the Commission on Sustainable Development (CSD) proposed 14 indicator themes and 44 subthemes, developed to emphasize the complexity of sustainable development and integration of the three pillars. Table 4.1 highlights the themes and subthemes that could potentially fall under the umbrella of the social pillar.

The themes in Table 4.1 were developed to be national in scope and rely on governments to develop metrics for local conditions. However, civil engineers can also begin incorporating these themes into their work in order to address the call from ASCE to incorporate sustainability and human welfare into our designs.

In 2012, the UN continued exploring the definition of social sustainability, reaffirming the need to eradicate poverty, change consumption and production patterns, and enforcing that people are at the center of sustainable development. While several issues were discussed at length, specific actions toward societal advancement

TABLE 4.1
Themes and Subthemes from the UN Commission on Sustainable Development

Theme	Subtheme
Poverty	Income poverty, income inequality, living conditions
Governance	Corruption, crime
Health	Mortality, health care diversity, nutritional status, health status and risks
Education	Education level, literacy
Demographics	Population, tourism
Natural hazards	Vulnerability to natural hazard, disaster preparedness and response
Atmosphere	Climate change, ozone layer depletion, air quality
Land	Land use and status, desertification, agriculture
Oceans, seas, coasts	Coastal zone, fisheries, marine environment
Freshwater	Water quantity, water quality
Consumption and production patterns	Material consumption, waste generation and management, transportation

Source: UN. *Indicators of Sustainable Development: Guidelines and Methodologies*. United Nations, 3rd Edition, 2007.

were included in the document, such as "promoting empowerment, removing barriers to opportunity, and enhancing productive capacity" for the poor and people in vulnerable situations, including youth and children. Finally, the most recent UN resolution proposed in 2015 revised sustainability metrics, again highlighting poverty, health, education, and consumption, but also focusing on women, inequality, and institutions (UN, 2015). While few would argue that these are not important global issues, there has been little work in tying these concepts directly to civil engineering and even less in developing quantifiable metrics that could potentially be incorporated into engineering design. One serious attempt at developing a comprehensive framework within which to develop social sustainability metrics is sometimes known as "the Oxfam Doughnut."

EXAMPLE PROBLEM 4.2

List the potential social metrics that have been developed within the United Nations.

The potential social metrics that have been developed within existing civil engineering concepts include poverty, consumption, production, human development, uneven distribution, governance, health, education, people, empowerment, removing barriers, and women.

4.3 OXFAM DOUGHNUT

In 1942, Oxfam was founded in Oxford, England in order to promote food relief through the Allied blockade for Greece citizens during World War II. Over the years, it has transitioned to an umbrella organization made of 17 partner organizations in

94 countries. The current charge of Oxfam is to "find practical, innovative ways for people to lift themselves out of poverty and thrive." As a part of this mission, they began a campaign that focused in part on developing a broad definition of prosperity in a resource-constrained world. A primary deliverable from this work was the Oxfam Doughnut, which is seen in Figure 4.1.

The Oxfam Doughnut is constructed from concepts discussed earlier in both Chapters 3 and 4. Overall, the goal of the doughnut is to ensure a "safe and just space for humanity" that is inclusive of sustainable economic development. The heart of the Oxfam Doughnut focuses on societal issues and is directly related to concepts developed by the United Nations. The societal issues focus on critical human deprivations and outline societal foundations, including food, water, income, education, resilience, voice, jobs, energy, social equity, gender equality, and health. The outside of the doughnut focuses on environmental concerns and is directly related to concepts developed in the planet boundary theory, developed by Rockström et al. (2009). These concepts are the environmental ceiling of critical natural resources and planetary processes, including climate change, freshwater use, nitrogen/phosphorus cycles, ocean acidification, chemical pollution, atmospheric aerosol loading,

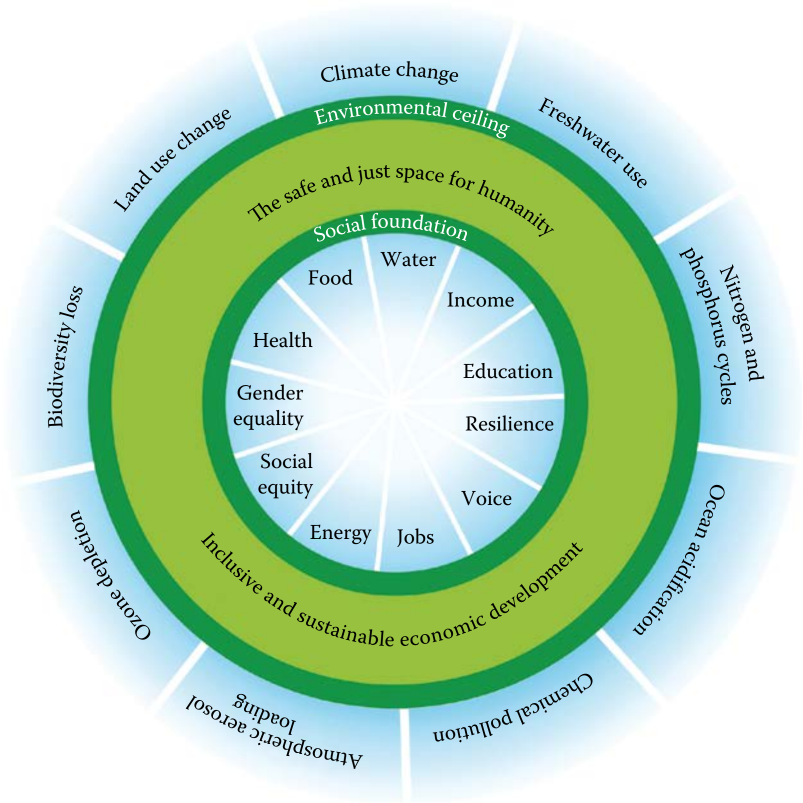

FIGURE 4.1 The Oxfam Doughnut. (Credit: Raworth, K. *A Safe and Just Space for Humanity, Can We Live within the Doughnut?* Oxfam International, February, 2012.)

ozone depletion, biodiversity loss, and land use change. While the inside and the outside of the Oxfam Doughnut are taken from existing resources, the interactions discussed could lead to better quantifications of social metrics in civil engineering.

One such interaction is the relationship between environmental stress and poverty. Poverty has again and again been shown to be a critically important social issue facing the world today. However, people who are in poverty often have the fewest tools available to deal with environmental stress, whether it be flooding, severe drought, or other extreme weather events. A second interaction is that policies aiming for sustainability in one area can exacerbate poverty in another area. A good example are biofuels. In theory, using a renewable resource that is plant based to fuel vehicles (as opposed to petroleum, which is nonrenewable) is a brilliant idea. However, this approach has a significant disadvantage in that the resources to produce biofuels are the same ones that are used to feed people. Biofuel production may negatively impact hungry people in two ways. First, biofuel production diverts food production, making less food available for those who are hungry. Second, increases in the price of food are linked to biofuel production, as in theory, there is less net food available for human consumption and competition for agricultural resources, so prices rise. Increased cost of food results in poor people being less able to afford the food that is produced. This does not mean that biofuels should stop being used, but it does mean that when new ideas and technologies are being implemented, care should be taken to evaluate potential repercussions and unintended consequences, especially in areas not generally associated with the problem at hand. The goal is to develop solutions and policies that promote both poverty eradication and sustainability.

One such success story includes insulating homes. By properly insulating homes, energy bills decrease, winter deaths decrease, and inhabitant productivity increases. Insulation, if done correctly, can easily be sustainable, by using either recycled or prefabricated materials and easy-to-ship designs that can be implemented at low costs with minimal tools. Successful insulation of homes achieves success in all three pillars of sustainability: economic, environmental, and social.

In closing, Oxfam does believe poverty can be ended, as their research suggests that poverty is a direct function of food, energy, and income. All three of these needs have tangible and deliverable solutions. Since a relatively small percentage of the world's population controls a relatively large percentage of the world resources (some sources claim that the richest 16% of the world's population consume 80% of the world's natural resources), this small segment of the population has tremendous control over solutions and distribution of resources. In addition to redistribution, however, reduction of inefficient use of natural resources and providing innovative solutions can result in less pressure on natural resources, reducing the impact on the planet and improving opportunities for those in need.

EXAMPLE PROBLEM 4.3

List the potential social metrics that have been developed within the Oxfam Doughnut.

The potential social metrics that have been developed within existing civil engineering concepts include education, resilience, voice, jobs, gender equality, social equality, energy, health, food, water, and income.

4.4 HUMAN DEVELOPMENT INDEX

The HDI began in 1990 as a part of the United Nations Development Programme (UNDP). The goal of the HDI was to expand beyond the traditional economic metrics of quantifying human development through the use of gross domestic product (GDP) and instead move into measuring human well-being in a more broadly and holistically defined manner. For example, activities such as unpaid care work (the production of goods or services in a household or community that are not sold on a market), voluntary work, and creative work may not enhance people's economic perspectives, but they do increase the richness of people's lives. These efforts by UNDP, along with the UN and Oxfam's approaches to expand the understanding of social sustainability, could be beneficial in the process of quantifying the social sustainability pillar.

The main premise behind UNDP's work is that people and capabilities should be the ultimate criteria for assessing development, not necessarily economic growth alone (UNDP, 2015). The capabilities were originally intended to stimulate debate about government policy priorities. In short, the UNDP worked toward creating a summary of average achievement for the following dimensions of human development (measurement for the dimension in parentheses):

- Long and healthy life (life expectancy at birth)
- Being knowledgeable (mean of years of schooling for ages 25+ and expected years for children entering school)
- Have decent standard of living (gross national income per capita)

The objective is that improvements in these three dimensions will create conditions for human development, allowing for participation in political and community life, environmental sustainability, human security and rights, and promoting equality and social justice.

Specific groups of people are targeted in the HDI. The first group is children, as they are the future of our race and also among the most vulnerable. It is important to recognize that across the world there are diverse experiences for children, including children who are in school, children who are not in school, and children who are working (whether by choice or forced). The second group is working-age people. Again, there are multiple groups included in the discussion, including employed non-poor, unpaid care workers, working poor, unemployed, forcibly displaced, and forced labor. The third group is persons older than 62 years. Like children and working-age people, older people have diverse circumstances, including people with sufficient pension, insufficient pension, or no pension. When considering social sustainability, often the differences in groups are glossed over, so classification is helpful with the development of effective social metrics.

According to the HDI, if people have an enlarged option of choices, it is possible that they could also have a higher chance of employment. By working, people potentially have significant benefits, from income and livelihood to long-term security. In addition, if women have more choices, they may be empowered in the professional workspace, which will increase participation and voice, dignity, and recognition, and most importantly for the HDI, creativity and innovation. As people are thriving in these conditions, their health could improve, the knowledge and skills could increase, and both awareness and opportunities should also increase. Once the cycle has begun, the two concepts of work and enlarged options of choices in theory will feed off each other and will both grow together. It is important to keep in mind, however, the importance of people having a solid-enough education in order to even being the positive cycle of work and enlarged option of choices. Therefore, HDI believes that increasing education must occur in order for the positive cycle to begin and thrive. In addition, HDI believes that if one of the three components is missing in a society, societal resources should be focused on that dimension.

There are several levels to sustainability and the HDI. At the most destructive end of the spectrum, the only opportunities available for people are degrading for the future and will destroy opportunities for the present. Examples of these include forced labor on deep-sea fishing boats, clearing rainforest, or trafficked workers. Moving up the spectrum, in the middle of constructive society activities, opportunities can be either limiting for the future while advancing human potential in the present or supporting opportunities for future while limiting present human potential. Examples of the first case include monocropping and/or traditional water- or fertilizer-intensive agriculture, which does help citizens today but is a mortgage of sorts for the future because of resource allocation and degradation. Examples of the second case include recycling to take pressure off natural resources but doing so without worker safeguards, protective gear, or removing contaminants, thereby threatening exposed people to health problems. Finally, at the other end of the spectrum, in ideal conditions, people could be exposed to expanding opportunities for the future while advancing human potential in the present. Examples that are being implemented today include poverty-reducing solar power or volunteer-led reforestation. These activities are not only preserving the future but also allowing for worker empowerment and increasing the standard of living in multidimensional ways not directly linked to increasing economic production.

While all of these concepts within HDI have merit, implementation will need additional innovative approaches. Government policies for enhancing human development through work could include strategies for ongoing education, entrepreneurship and wealth creation, or tax policies that recognize unpaid work. This could include formulating national employment strategies aimed at preparing the national labor force to seize opportunities in the changing world of work. Also critical are strategies for ensuring workers' well-being, which include guaranteeing workers' rights and benefits, extending social protection, and addressing inequalities. To capture the benefits of these policies, however, there must be an agenda for action that implements changing the traditional mechanisms for employment protection based on principles of sustainability (a "new social contract"), mobilization of all workers, businesses, and governments around the world (a "global deal"), or formalizing employment creation and enterprise development, standards and rights at work, social protection, and governance and social dialogue (a "decent work agenda"). Strategies should be developed for targeted actions, such as reducing gender or racial inequities in the workplace, moving toward sustainable work for more adults, and undertaking group-specific initiatives to improve the well-being of marginalized populations.

While the existing literature in civil engineering, work done by the UN and UNDP, and Oxfam have a plethora of potential metrics, there are other existing tools that have attempted to capture social impacts explicitly. Much like the popular environmental assessment tool for projects, an SIA has also been developed. This will be discussed in the following chapter.

EXAMPLE PROBLEM 4.4

List the potential social metrics that have been developed within the HDI.

The potential social metrics that have been developed within existing civil engineering concepts include health, lifespan, education, and standard of living.

4.5 SOCIAL IMPACT ASSESSMENT

An SIA reviews the social effects of infrastructure projects and other development interventions. The concept was derived from the environmental impact assessment model, which traditionally evaluates environmental effects of civil engineering projects. In an SIA, there are five main types of social impacts: lifestyle, cultural, community, quality of life, and health. These social metrics expand beyond economic metrics, much like the UN and Oxfam work, and focus instead on social issue parameters. Important inputs in an SIA analysis include demographic factors, socioeconomic determinants, social organization, sociopolitical context, and needs and values. An SIA is performed before a project is initiated to help decide which alternative to implement.

One example of an SIA is from 2006 by the Centre for Good Governance, which developed a guide for SIA (SIA, 2006). Their definition of the term "society impacts" is "the impacts of developmental interventions on human environment." This includes way of life, culture, community, political systems, environment, health and well-being, personal and property rights, and fears and aspirations. As a part of this guide, various variables were provided to relate project stage to social impact. The four project stages are planning/policy development, implementation/construction, operation/maintenance, and decommissioning/abandonment. Each of the four project stages were associated with five SIA variables. These five variables (population characteristics, community and institution structures, political and social resources, individual and family changes, and community resources) evaluated at each project stage are intended to provide a beginning point for the SIA. Underneath these five SIA variables were specific indicators, and these are summarized here:

- Population characteristics
  - Population change
  - Ethnic and racial distribution
  - Relocated populations
  - Influx/outflows of temporary workers
  - Seasonal residents
- Community and institution structures
  - Voluntary associations
  - Interest group activity

    - Size and structure of local government
    - Historical experience with change
    - Employment/income characteristics
    - Employment equity of minority groups
    - Local/regional/national linkages
    - Industrial/commercial diversity
    - Presence of planning and zoning activity
- Political and social resources
    - Distribution of power and authority
    - Identifications of stakeholders
    - Interested and affected publics
    - Leadership capability and characteristics
- Individual and family changes
    - Perceptions of risk, health, and safety
    - Displacement/relocation concerns
    - Trust in political and social institutions
    - Residential stability
    - Density of acquaintanceship
    - Attitudes toward policy/project
    - Family and friendship networks
    - Concerns about social well-being
- Community resources
    - Change in community infrastructure
    - Access to community infrastructure
    - Indigenous groups
    - Land use patterns
    - Effects on cultural, historical, and archaeological resources

A second example of an SIA is from Norway on a road construction project (NPRA, 2007). In this project, the socioeconomic analysis focused on nonmonetized impacts. These impacts included landscape and/or cityscape visual effects, community life, outdoor life, natural environment, cultural heritage (prehistoric deposits), and natural resources. In order to begin quantifying these impacts, values were assigned at three levels: small, medium, and large, in both the positive and negative directions. The project involved upgrading a road passing through a small town. Three different alternatives were explored: a do-nothing alternative, upgrading the existing roadway, and constructing a completely new roadway. Upgrading the new roadway suggested a positive economic effect but a negative social effect, while building a new highway suggested both a negative economic effect and a negative social effect. Noneconomic predicted benefits to upgrading the existing roadway included a neutral effect on community life, outdoor recreation, and natural resources, while the new-build roadway was predicted to have a positive effect on community life and outdoor recreation but a negative impact on natural resources. However, both options (upgrading and building new) in the SIA predicted a negative effect on landscape and cityscape, natural environment, and cultural heritage. Yet, both of these alternatives were ranked higher economically and socially versus doing nothing. Therefore, upgrading the existing roadway was ranked first and recommended for both economic and social benefits. While this example is somewhat broad, it does give some insight on the challenges to quantifying and qualifying social metrics, and shows that there is still significant work to be done.

EXAMPLE PROBLEM 4.5

List the potential social metrics that have been developed within the SIA.

The potential social metrics that have been developed within existing civil engineering concepts include lifestyle, cultural, community, and quality of life.

4.6 EMERGING AREAS OF SOCIAL SUSTAINABILITY

When considering the existing civil engineering concepts, work done at the UN, the Oxfam Doughnut, the HDI, and SIA, it is apparent that the concept of resiliency is becoming more pronounced. In terms of social–ecological systems, resiliency is the capacity of the system to sustain or absorb disturbances while still being able to maintain its structure and functions. In the context of social sustainability, a resilient society would be able to overcome barriers to common tasks such as commuting, prevail over issues such as poverty and natural hazards, and develop ways to thrive by moving into the safe and just space for humanity. Individuals' self-sufficiency, or the possession of sufficient resources to survive with enough excess to be able to participate meaningfully in society, is critical to resiliency. Conquering the impediments to social sustainability will only increase the successful virtuous cycle of social enhancements along with economic enhancements. In addition to the concept of resiliency, the four broad emerging areas are highlighted in social sustainability: human well-being, access to resources, self-government, and civil society. These four emerging areas provide a framework within which earlier attempts at social sustainability metrics can be evaluated and provide a starting point for a more comprehensive set of metrics.

All of these concepts that fall under the social pillar do not often intersect with civil engineering. But in order to begin the process of building social sustainability metrics for use with civil engineering, looking at the diverse portfolio of perspectives can help guide the development of effective metrics. The concepts listed in this chapter are a beginning, and as the concepts are more widely and better understood, applications toward civil engineering processes can begin, and, in time, a suite of social metrics can be developed that are as accepted as existing economic and environmental metrics.

HOMEWORK PROBLEMS

For all Chapter 4 homework problems, use the format provided under Sidebar 1.2 "Writing a High-Quality Essay" to discuss your answer.

1. Looking at existing potential social metrics in civil engineering concepts, the UN, Oxfam, HDI, and SDI, which three metrics do you think are most important, and why?
2. Why do you think it is important to develop social metrics of sustainability? What reasons can you think for developing metrics?

3. Do you think that data can be easily found for all of the existing potential social metrics? Choose two metrics that you believe data would be easy to find, and two metrics where data would be hard to find.
4. There are societal perspectives of sustainability. World societies are sometimes divided into high income (or developed countries) and low income (developing/undeveloped countries). Focus on two existing potential social metrics and discuss how they are similar and different, based on the income level of the country.
5. Of all of the existing potential social metrics, choose a list that you think is appropriate for high-income countries and low-income countries. You will need to justify the reasons for choosing the social metrics, and discuss how the data would be collected.

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5 Application
Environmental Sustainability

It does not matter how slowly you go as long as you do not stop.

Confucius

Environmental engineering is a broad topic. The breadth of environmental engineering topics includes chemistry, biology, ecosystems, air quality, hydraulics, hydrology, and groundwater. Environmental engineering topics also include highly engineered systems such as drinking water treatment and wastewater treatment. Other topics that may not be as intuitive, like air quality and built environment, also incorporate fundamental concepts of environmental engineering.

With such a diverse range of topics, it is not surprising that there are almost limitless applications of sustainability in environmental engineering. The environmental engineering topics discussed above are key to the United Nation's 2007 11 indicators from the Commission on Sustainable Development Sustainable Development Goals, including poverty, health, atmosphere, oceans, freshwater, and economic development. These indicators can be demonstrated through the close examination of four specific topics within environmental engineering:

1. Low-impact development
2. Drinking water treatment
3. Wastewater treatment
4. Outdoor air quality

These four topics will be discussed in detail in the following sections.

5.1 LOW-IMPACT DEVELOPMENT

The construction of any civil engineering structure, such as a landfill, a shopping center, or an airport terminal, alters the natural landscape. Existing vegetation is generally removed, the natural topography is modified, and new structures are installed. These types of activities are called development, and this development modifies the hydrological cycle at a local level. Instead of water falling onto the ground surface and naturally absorbing into the soil, it is often collected and diverted to retention ponds or storm sewers. These types of large water diversion systems not only move significant volumes of water to alternative locations, but they are also expensive to construct and maintain. A potential alternate to constructing these systems is to explore alternate methods of design that have a lower impact on the ecosystems. These methods are called low-impact development, or LID. As discussed above, one of the primary considerations of LID in civil engineering is runoff. The diversion of runoff has two downsides in addition to cost. First, this water often picks up pollutants and carries them downstream, creating smaller areas of higher concentrations of pollutants, and overloads nature's ability to filter pollutants from water. Second, the diversion of water can reduce the groundwater table, as water that would originally have percolated downward and naturally recharged the water table instead is transferred to another location. At some point during rain events, there will be a maximum amount of water moving across a field, a parking lot, or any other natural or engineered surface. This maximum amount of water is called the peak runoff.

There are two common methods of quantifying the peak runoff, which can be used for sizing culverts and storm drains. First, the rational method (also known as the rational formula, the rational equation, or the Lloyd–Davies equation), is typically used for relatively small areas, generally less than one-half square mile. The peak discharge is calculated from the rational method from Equation 5.1:

$$Q = C \times I \times A \tag{5.1}$$

where

Q = peak discharge (ft^3/s)
C = runoff coefficient
I = rainfall intensity (in/h)
A = watershed area (acres)

There are two important points to highlight in Equation 5.1. First, units must be carefully followed, as the runoff coefficient includes conversion factors from acres and inches to cubic feet, and hours to second. Second, there are many sources available for runoff coefficients, and usually there is a range associated with each surface and use as well. Table 5.1 shows various examples of typical values of runoff coefficients for the rational method compiled from various sources.

An important takeaway from Table 5.1 is the variability of runoff coefficients. Not only do many assumptions need to be made when choosing a runoff coefficient, but the calculation of runoff coefficient is not standard as well. As engineers, it is important to state the assumptions and choose a conservative yet reasonable value of runoff coefficients when performing a design.

A second method of calculating runoff, which can be applied to any size homogeneous watershed, is the Natural Resources Conservation Service (NRCS) rainfall-runoff method. The U.S. NRCS calculation method has been correlated to actual experience, and revolves around the concept of a curve number, which characterizes the land use and soil type. There are several assumptions necessary before applying the NRCS method. First, the method assumes that the initial abstraction (depression storage, evaporation, and interception losses) is equal to 20% of the maximum basin retention. Second, the precipitation must equal or exceed the initial abstraction. Third, the storage capacity must be large enough to absorb the initial abstraction plus any infiltration. Fourth, the method assumes a type II storm, which is the most common type of rain event in the United States (USDA, 1986). Finally, fifth, the

TABLE 5.1
Runoff Coefficients for the Rational Method

Surface	PE Reference Manual[a]	City of Fayetteville[b]	Washington State[c]	Florida State[d]
Forest	0.059–0.20	0.15–0.30	0.10–0.30	0.10–0.30
Lawn—sandy soil <2% slope	0.05–0.10	0.15	0.05–0.10	0.10–0.15
Lawn—sandy soil 2%–7% slope	0.10–0.15	0.25	0.07–0.15	0.20–0.25
Lawn—sandy soil >7% slope	0.15–0.20	0.30	0.10–0.20	0.25–0.35
Lawn—clay soil <2% slope	0.13–0.17	0.35	0.10–0.17	0.20–0.25
Lawn—clay soil 2%–7% slope	0.18–0.22	0.40	0.15–0.22	0.25–0.30
Lawn—clay soil >7% slope	0.25–0.35	0.45	0.20–0.35	0.30–0.40
Asphalt	0.70–0.95	0.95	0.90	0.95
Brick	0.70–0.85	0.85	0.90	0.75–0.95
Concrete	0.80–0.95	0.95	0.90	0.95
Shingle roof	0.75–0.95	0.95	0.90	0.95
Driveways, walkways	0.75–0.85	0.95	0.75–0.85	0.95

[a] From Lindeburg, M. *Civil Engineering Reference Manual*, 9th Edition, Professional Publications, Inc., 2003.
[b] From City of Fayetteville. *Drainage Criteria Manual*, Fayetteville, Arkansas, 2014.
[c] From Washington State. *Hydraulics Manual*, Washington State Department of Transportation, 1997.
[d] From Florida State. *Drainage Handbook Hydrology*, State of Florida Department of Transportation, 2012.

soil condition is assumed to be average (ARC II). The runoff is calculated using the following:

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} = \frac{(P - 0.2S)^2}{(P + 0.8S)} \tag{5.2}$$

$$S = \frac{1000}{CN} - 10 \tag{5.3}$$

where
Q = runoff (in)
I_a = initial abstraction (in)
P = precipitation (in)
S = maximum basin retention (in)
CN = curve number (ft^3/s)

Similar to the rational method, units must be carefully followed in Equations 5.2 and 5.3 to ensure that the final runoff answer is in inches. Table 5.2 shows some typical curve numbers for the same surfaces outlined in Table 5.1.

TABLE 5.2
Runoff Curve Numbers (CN, ft^3/s) of Urban Areas from NRCS

Surface	Soil Group A	Soil Group B	Soil Group C	Soil Group D
Forest	30–45	55–66	70–77	77–83
Lawn	39–68	61–79	74–86	80–89
Asphalt	98	98	98	98
Brick	98	98	98	98
Concrete	98	98	98	98
Shingle roof	98	98	98	98
Driveways, walkways	98	98	98	98

The hydrological soil group is determined by infiltration rate, with values and potential applications shown in Table 5.3.

Using these two methods of quantifying the peak runoff, several potential sustainable applications can be implemented in order to reduce peak runoff, so as to direct more of the rainfall directly downward in order to recharge the water table, reducing the need for built structures to redirect water. The applications discussed below include green roofs, porous pavements, and bioretention cells.

EXAMPLE PROBLEM 5.1

A forest in the City of Fayetteville will be replaced by a brick parking lot. Using runoff coefficients from the City of Fayetteville, calculate the change of peak discharge if the design rainfall intensity is 2.0 in/h and the area of the brick parking lot is designed to be 10,000 ft^2. State any assumptions that are needed to complete this calculation.

Equation 5.1, the rational method, is used to solve for the peak discharge. Using Table 5.1, it is assumed that the runoff coefficient falls in the middle of the runoff coefficient values, so 0.225 is used. The runoff coefficient for the bricks is given in Table 5.1 as 0.85. The rainfall intensity is given at 2.0 in/h (the correct units), but the area given must be converted to the proper units of acres:

$$\frac{10{,}000\,\text{ft}^2}{1} \times \frac{2.2957\text{e}^{-5}\ \text{acres}}{1.0\,\text{ft}^2} = 0.2296\ \text{acres}$$

TABLE 5.3
Hydrological Soil Group Classification

Group	Infiltration Rate (in/h)	Urbanized Classification
A	>0.30	Sand, loamy sand, sandy loam
B	0.15–0.30	Silty loam, loam
C	0.05–0.15	Sandy clay loam
D	<0.05	Clay loam, silty clay loam, sandy clay, silty clay, clay

Next, Equation 5.1 can be used to calculate the peak discharge for each surface:

$$\text{Forest} \rightarrow Q = C \times I \times A = 0.225 \times 2.0\ (\text{in/h}) \times 0.2296\ \text{acres} = 0.103\ \text{ft}^3/\text{s}$$

$$\text{Brick parking lot} \rightarrow Q = C \times I \times A = 0.85 \times 2.0\ (\text{in/h}) \times 0.2296\ \text{acres} = 0.390\ \text{ft}^3/\text{s}$$

$$\text{Difference} \rightarrow 0.390\ \text{ft}^3/\text{s} - 0.103\ \text{ft}^3/\text{s} = 0.287\ \text{ft}^3/\text{s increase in discharge}$$

5.1.1 Green Roofs

The tops of buildings are designed to be impermeable, so water does not infiltrate into the built structure. However, this impervious surface directs water away from where it would naturally absorb into the Earth, decreasing the water table beneath the building and increasing water flow away from the building. While a single structure is not likely to significantly influence an area's water table or runoff, the more urbanized an area becomes, the more significant the problems associated with the impervious surfaces are. Green roofs are a potential solution to these problems. Green roofs consist of multiple layers of natural vegetation, synthetic material, and impermeable material. The natural vegetation sits on the surface of the structure, with a filter and drainage layer directly underneath. With proper design, the drainage from the roof can be managed so that the majority of water is directed downward into the water table directly underneath the building, as opposed to flowing to another area. Finally, between the drainage layer and the structure's roof is a protection layer and root barrier to protect the structure itself. Figure 5.1 shows a green roof on top of Hillside Auditorium at the University of Arkansas. The green roof is over one of the two auditoriums inside the building. It is interesting to note in Figure 5.1a that a standard roof can be seen in the background (the Mechanical Engineering building at the University of Arkansas), complete with artificially engineered drainage to handle runoff.

The General Services Administration, or GSA, has been a leader of green roof implementation in the United States (GSA, 2011). The GSA has categorized green roofs into four main groups: single-course extensive, multicourse extensive, semi-intensive, and intensive. These categories are dependent on the thickness, the type of drainage layer, the type of vegetation layer, and the media type. The choice of green roof is dependent on the local environment, the level of management that the owner is willing to engage in, and the structural capacity of the structure that the green roof will sit on. Table 5.4 summarizes the four types of green roofs, and Figure 5.2a through d shows typical cross sections of each type.

With the relatively small footprint of each green roof, the rational method is often employed in order to calculate the difference in runoff for an area. Therefore, runoff coefficients need to be determined for green roofs. Several agencies and research groups have investigated potential runoff coefficients for green roof systems. Table 5.5 summarizes samples of these values. Two trends are apparent from Table 5.5. First, the runoff coefficients of green roofs are all lower than impervious roofs (Table 5.1, 0.75–0.95). Second, there is a significant range depending on the study and the roof

(a)

(b)

FIGURE 5.1 (a) University of Arkansas Hillside Auditorium green roof. (Credit: A. Braham.) (b) University of Arkansas Hillside Auditorium, green roof foreground, traditional roof background on the Mechanical Engineering building. (Credit: A. Braham.)

structure and roof geometry. However, this uncertainty is not uncommon in engineering and must be considered in design.

EXAMPLE PROBLEM 5.2

The University of Arkansas is planning on replacing the traditional shingle roof with a green roof that has an average soil media depth of 3 in. The approximate

TABLE 5.4
Summary of Types of Green Roof Systems

	Single-Course Extensive	Multicourse Extensive	Semi-Intensive	Intensive
Thickness (in)	3–4	4–6	6–12	>12
Drainage layer	Moisture management layer	Based on growth media thickness, plants, and local climate	Discrete drainage layer	Discrete drainage layer
Vegetation layer	Sedum, other succulents	Sedum, other succulents	Meadow species, ornamental varieties, woody perennials, turf grass	Similar to ground level
Media type	Coarse	Finer grained	Multicourse	Intensive growth media
Irrigation	None	First year only	Required for turf grass	Required
Prevalence	Common internationally	Most common in United States	Common internationally	Least common, structural capacity limiting

roof area of the Mechanical Engineering building is 2576 yd^2. Assuming the rainfall intensity is 1.8 in/h, what is the change in peak discharge? Use the PE reference manual runoff coefficient for the shingle roof. State any assumptions that you made.

Equation 5.1, the rational method, is used to solve for the peak discharge. Using Table 5.1, it is assumed that the runoff coefficient for the shingle roof falls in the middle of the runoff coefficient values, so 0.85 is used. The runoff coefficient for the green roof with an average soil media depth of 3 in is given in Table 5.5 as 0.50. The rainfall intensity is given at 1.8 in/h (the correct units), but the area given must be converted to the proper units of acres:

$$\frac{2576\,\text{yd}^2}{1} \times \frac{2.066e^{-4}\,\text{acres}}{1.0\,\text{yd}^2} = 0.5322\,\text{acres}$$

Next, Equation 5.1 can be used to calculate the peak discharge for each surface:

$$\text{Shingle roof} \rightarrow Q = C \times I \times A = 0.85 \times 1.8\ (\text{in/h}) \times 0.5322\,\text{acres} = 0.814\,\text{ft}^3/\text{s}$$

$$\text{Green roof} \rightarrow Q = C \times I \times A = 0.50 \times 1.8\ (\text{in/h}) \times 0.5322\,\text{acres} = 0.479\,\text{ft}^3/\text{s}$$

$$\text{Difference} \rightarrow 0.814\,\text{ft}^3/\text{s} - 0.479\,\text{ft}^3/\text{s} = 0.335\,\text{ft}^3/\text{s decrease in discharge}$$

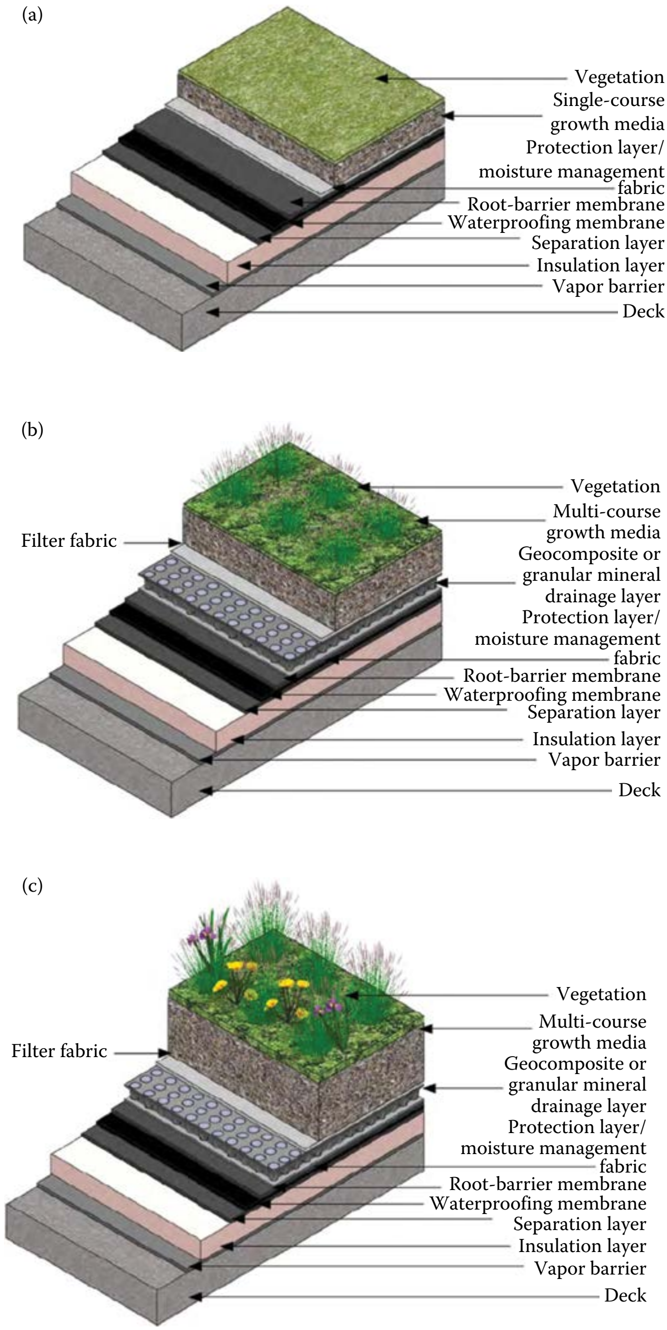

FIGURE 5.2 Examples of types of green roof systems. (a) Single-course extensive. (b) Multicourse extensive. (c) Semi-intensive. (*Continued*)

(d)

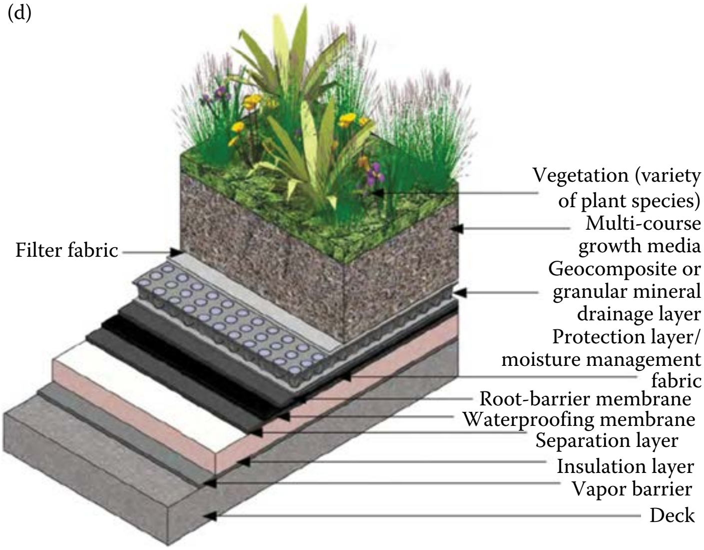

FIGURE 5.2 (Continued) (d) Intensive. (Credit: U.S. General Services Administration.)

TABLE 5.5
Green Roof System Runoff Coefficients for the Rational Method

Source	Description	Runoff Coefficient
NYC (2012)	Green roof with four or more inches of growing media	0.70
Moran et al. (2005)	Average soil media depth 3 in	0.50
Mobilia et al. (2014)	Layer depth of 15 cm, roof slope lower than 15°	0.35

5.1.2 Porous Pavements

Another sustainable application to reduce peak runoff is the use of porous, also called permeable, pavements. According to the Federal Highway Administration, there are 8.5 million lane-miles (13.7 million lane-kilometers) of road in the United States (FHWA, 2011). Assuming that each lane is 12 ft wide (3.65 m), approximately 19,300 square miles (49,320 square kilometers) of roadway covers the United States. This is equivalent to approximately 9.35 million American football fields, including the end zones. While soccer pitches are not a standard size, using the preferred size of 105 × 68 m, this is equal to 6.91 million soccer pitches. This immense amount of space provides an excellent opportunity to decrease the amount of impervious surfaces by using porous pavements.

Porous pavements typically come in three forms: porous asphalt, porous concrete, or pavers. Porous asphalt and porous concrete utilize gap-graded aggregate gradations with air voids typically between 15% and 25%. This allows for more water to pass through the pavement layer instead of running off the pavement layer. Additional benefits include filtering of the water and the potential to reduce heat island effect (the increase of temperature in urban areas due to the dark color of engineered structures). With the unique gradation and high air voids, porous pavements are not intended for high-volume or high-load roadway applications, so use on interstates or large state highways is not advised. However, the pavement surface is more than appropriate for lower-volume roads and residential areas, which make up the vast majority of roadways in the United States.

In brief, porous pavements are typically built over uncompacted subgrades (FHWA, 2015). This allows for natural infiltration into the existing groundwater table. Porous pavements can be placed in a typical pavement structure, but can also be placed on a choker course, stone reservoir, and a geotextile fabric. These reservoirs allow for the storage of water during storm events, allowing for the natural seepage of water down into the groundwater. Typically, the reservoirs are uniformly graded, clean crushed stone, with up to 40% voids. Immediately above the reservoir is the choker course, which provides a stabilized surface for the bound layer above. The geotextile is placed between the natural soil and reservoir in order to prevent the migration of fines up into the pavement layers. Figure 5.3 shows an example of a porous asphalt pavement structure.

There are three key considerations when designing the thickness of the porous pavement layers. The first consideration is the site of the project, which includes depth of bedrock, soil types, and pavement slope. The second consideration is the hydrology design, as the amount of storage needs to be adequate for anticipated precipitation and edge drains may be required to prevent the surface layers

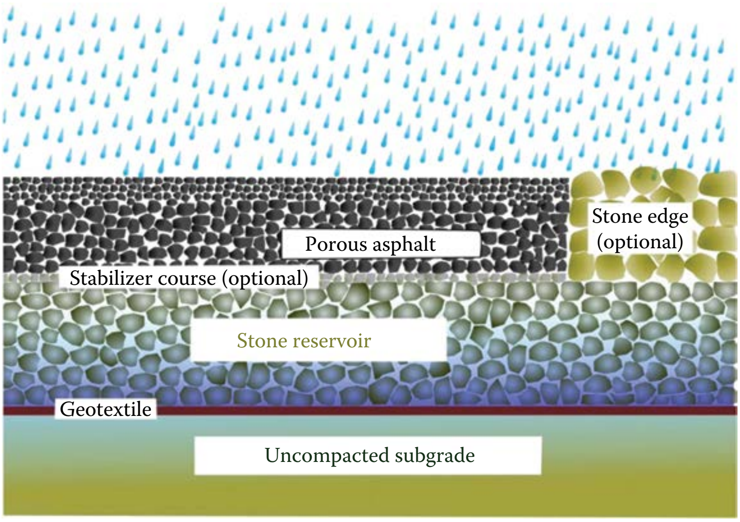

FIGURE 5.3 Potential porous asphalt pavement structure with a stone reservoir and geotextile layer. (Credit: National Asphalt Pavement Association.)

TABLE 5.6
Porous Pavement Runoff Coefficients for the Rational Method

Source	Description	Runoff Coefficient
Fassman and Blackbourn (2010)	10–90th percentile events	0.29–0.67
Fassman and Blackbourn (2010)	Porous pavement about one-half otherwise impervious catchment	0.41–0.74
St. John (1997)	Newly installed porous pavement	0.12–0.40
Wei (1986)	3–4 years after installation, porous pavement	0.18–0.29

TABLE 5.7
Porous Pavement Curve Numbers for Events Greater than 50 mm Using the NRCS Method

Pavement System	Description	Curve Number (Range, Mean)
Concrete grid pavers (CGP), 90 mm thick, filled with coarse grain sand	Slope 0.5%; above 50 mm bedding sand, geotextile, 70 mm washed marlstone	41–98, 70
Porous concrete (PC), 200 mm thick	Slope 0.3%; directly on native fine graded sand	60–91, 77
Permeable interlocking concrete pavements (PICP), 75 mm UNI Eco-Stone Pavers	Slope 0.4%; unlined; 75 mm No. 72 pea gravel, 200 mm No. 57 washed gravel	37–50, 43

Source: Bean, E. et al. *Journal of Irrigation and Drainage Engineering*, 2007, 133(6), 583–592.

from overflowing. Finally, the structural design must be addressed. Utilizing the AASHTO 1993 Design Guide for flexible pavements, typical asphalt concrete structural number coefficients generally are around 0.44. However, porous asphalt has slightly lower structural number coefficients, generally in the range of 0.40–0.42 (Hansen, 2008). This decrease in capacity needs to be taken into account during the structural design.

Several agencies and research groups have investigated potential runoff coefficients and curve numbers for porous pavement systems. Table 5.6 summarizes a sample of runoff coefficient values, and Table 5.7 summarizes a sample of curve numbers. Two trends are apparent from Table 5.6. First, the runoff coefficients of porous pavements are all lower than traditional roadways (Table 5.1, asphalt street = 0.70–0.95; concrete street = 0.80–0.95). Second, there is a significant range depending on the study and the roadway structure and roadway geometry. Again, this uncertainty is not uncommon in engineering and must be considered in design.

EXAMPLE PROBLEM 5.3

The University of Arkansas is considering replacing Parking Lot 71, which is currently a traditional asphalt surface, with a 200-mm-thick porous concrete pavement. Assuming that the old pavement will be completely removed and that the porous concrete pavement will be placed on native fine graded sand, and the precipitation is 2.6 in, what is the change in runoff? State any assumptions that are needed to complete this calculation.

Equation 5.2, the NRCS rainfall-runoff method, is used to solve for the runoff. Using Table 5.2 for the asphalt surface (CN = 98 ft^3/s), and assuming the average from Table 5.7 for the porous concrete (CN = 77 ft^3/s), the runoff can be calculated. First, the maximum basin retention is calculated for each surface using Equation 5.3:

$$\text{Asphalt surface} \rightarrow S = \frac{1000}{CN} - 10 = \frac{1000}{98\,\text{ft}^3/\text{s}} - 10 = 0.204\,\text{in}$$

$$\text{Porous concrete surface} \rightarrow S = \frac{1000}{CN} - 10 = \frac{1000}{77\,\text{ft}^3/\text{s}} - 10 = 2.987\,\text{in}$$

Next, the runoff can be calculated using

$$\text{Asphalt surface} \rightarrow Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} = \frac{(2.6 - 0.2 \times 0.204)^2}{(2.6 + 0.8 \times 0.204)} = 2.37\,\text{in}$$

$$\text{Porous concrete surface} \rightarrow Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} = \frac{(2.6 - 0.2 \times 2.987)^2}{(2.6 + 0.8 \times 2.987)} = 0.80\,\text{in}$$

$$\text{Change in runoff} \rightarrow 2.37\,\text{in} - 0.80\,\text{in} = 1.57\,\text{in decrease in runoff}$$

5.1.3 Bioretention Cells

The third application discussed to decrease peak runoff, directing more rainfall directly downward to recharge the water table, and reducing the need for built structures to redirect water, is the concept of bioretention cells. Bioretention cells are areas of plants and other porous materials placed near impervious surfaces that allow for the collection, filtration, infiltration, and recharge of water that runs off an impervious surface (ESD, 2007). For example, when a parking lot is constructed, a large area of land is generally covered by a relatively impervious surface. The runoff from this surface can be directed to a bioretention cell. Once at the cell, the runoff can be filtered and stored, so there is the slow recharge of the groundwater table. Figure 5.4a through c shows several views of a parking lot at the University of Arkansas, specifically designed to accommodate bioretention cells. These views can be contrasted to Figure 5.4d, which shows a "standard" drainage solution, involving high volumes of runoff and engineered systems to divert excess water to the storm sewer.

In general, there are four different types of bioretention cells: infiltration/recharge, filtration/partial recharge, infiltration/filtration/recharge, and filtration only. Infiltration/recharge cells are most useful in areas that require a high level of recharge of water, but the in-place soil must be able to accommodate the inflow levels. The term "recharge" is used when water moves directly downward from the ground surface into the groundwater. A filtration/partial recharge cell is used where there is a need for a high level of filtration of the water. Therefore, the plant type is critical to match the type of pollutants expected, and a drain is used in order to aid with controlling runoff, as all of the water is not designed to recharge the groundwater table. The third type of cell is an infiltration/filtration/recharge cell. This type of cell is used when high nutrient loadings, for example, nitrates,

(a)

(b)

FIGURE 5.4 (a) Water can run directly from parking spaces into a bioretention cell since curbs are not installed. (b) In some locations, curbs direct water to openings that flow to the bioretention cell. Note the sidewalk required a small bridge so pedestrians can cross water flow during heavy rains. (*Continued*)

(c)

(d)

FIGURE 5.4 (Continued) (c) Curbs can divert water to the bioretention cell. (d) A traditional drain leading to the storm sewer, where water is diverted from one location and moved to an alternate location. (Courtesy of A. Braham.)

may be present along with the ability of the water to recharge the groundwater table. In this configuration, a raised drain is available in case of several water loadings, but extra reservoir space is design for the ability to store water for maximum recharging. Finally, the fourth type of cell is utilized for areas that are known to have a high chance of significant runoff, such as gas stations, transload facilities, transportation depots, etc. Here, an impervious liner is used at the bottom of the system to ensure that a minimum amount of groundwater contamination would occur in a spill situation.

While bioretention cells are a viable component of LDI, they do not have specific runoff coefficients associated with them. An interesting concept, however, is the blend of different development types, or areas, and how bioretention cells can be incorporated into such spaces. In general, the size of the bioretention area is a function of the drainage area and runoff from the area. If the bioretention cell has a sand bed, the area of the cell should be approximately 5% of the drainage area multiplied by the runoff coefficient (EPA, 1999). If the bioretention cell does not have a sand bed, the area of the cell should be approximately 7% of the drainage area multiplied by the runoff coefficient.

EXAMPLE PROBLEM 5.4

The University of Washington athletic department is considering placing several bioretention cells in the asphalt parking lot directly adjacent to the football stadium (Husky Stadium). Assume the parking lot has 20,000 ft^2 of pavement and use the Washington State runoff coefficient. If the athletic department would like to use a sand bed bioretention cell, what is the required square footage of a sand bed bioretention cell?

First, use Table 5.1 to determine the runoff coefficient for asphalt, which is 0.90. Next, multiply the runoff coefficient by 20,000 ft^2 to obtain 18,000 ft^2. Finally, the sand bioretention cell should be designed as 5% of the drainage area multiplied by the runoff coefficient. Therefore, 5% of 18,000 ft^2 is $(18{,}000 \times 0.05) = 900$ ft^2 of sand bed bioretention cell required for the parking lot.

5.2 DRINKING WATER TREATMENT

According to the World Health Organization (WHO, 2013), humans require 2.5–3.0 L/day (0.7–0.8 gallons/day) for survival, 2–6 L/day (0.5–1.6 gallons/day) for basic hygiene practices, and 3–6 L/day (0.8–1.6 gallons/day) for basic cooking needs. For the water that is consumed uncooked, the treatment is required, as it may contain harmful microorganisms and organic or inorganic compounds that can cause physiological effects or negatively affect the taste. Evaluating drinking water can be split into two general categories, physical characteristics and contaminant regulation.

The physical characteristics of natural water include turbidity, particles, color, taste and odor, and temperature. Turbidity refers to the optical clarity of the water, and is reported in nephelometric turbidity units (NTU). Particles are solids (often not seen by the naked eye) that are suspended (>1 μm), colloidal (0.001–1 μm), and dissolved (<0.001 μm). Color is often influenced by dissolved organic matter, metallic ions, and turbidity, while taste and odor are generally from dissolved natural organic or inorganic constituents. In 1974, the United States Congress passed the Safe Drinking Water Act, which placed the responsibility of setting water quality regulations onto the Environmental Protection Agency, or EPA. After treatment, the water is potable and is safe for human consumption.

The regulated drinking water contaminants include microorganisms, disinfectants, disinfection by-products, inorganic chemicals, organic chemicals, and radionuclides. Each of these contaminants has a maximum contaminant level goal (MCLG) and maximum contaminant level (MCL). The MCLG is set, so there is no known or expected risk to health, while the MCL is the highest level of contaminant that is allowed in drinking water. In general, the MCLs are set as close to the MCLGs as possible, balancing the best technology with cost. Table 5.8 summarizes a sampling of contaminants and their MCLG and MCL according to the EPA (EPA, 2009).

TABLE 5.8
Sampling of Drinking Water Standards from the EPA

Contaminant	Maximum Contaminant Level (MCL)	Maximum Contaminant Level Goal (MCLG)
Asbestos (inorganic chemical, fibers >10 μm)	7 million fibers/L	7 million fibers/L
Benzene (organic chemical)	0.005 mg/L	0.0 mg/L
Chlorine as Cl_2 (disinfectant)	Maximum residual disinfectant level = 4.0 mg/L	Maximum residual disinfectant level goal = 4.0 mg/L
Chlorite (disinfection by-product)	1.0 mg/L	0.8 mg/L
Lead (inorganic chemical)	Less than 10% of tap water samples contain less than 0.015 mg/L	0.0 mg/L
Uranium (radionuclides)	30 μg/L	0.0 μg/L
Total coliforms, positive samples per month (microorganism)	5.0%	0.0%

There are many different ways to quantify the sustainability of water treatment technologies. The activated carbon adsorption, air stripping, clarifier/sedimentation basin design, settling characteristics of contaminants, softening mechanisms, flocculation design, osmosis, ultrafiltration, or disinfection all have been analyzed for sustainable technologies. As an example, the Langmuir isotherm, as a part of activated carbon adsorption, will be examined in more detail here.

The adsorption process can take place in either fixed-bed filtration units or suspended-media contactors. In the fixed-bed geometry, the water passes through 1–3 m of media (in this example, activated carbon). In the suspended-media contactors, the media is mixed with the water and travels with the water through the treatment plant. The media is usually removed by either sedimentation or filtration. During the adsorption process, various contaminants usually associated with taste and odor are transferred from the water to the media. When activated carbon is the media, the average diameter of activated carbon particles is 0.5–3.0 mm (granular particles) for fixed bed, while the average diameter is 20–50 μm (powdered particles) for suspended media.

Adsorption is an equilibrium process. In order to achieve and maintain equilibrium, the adsorbate is distributed between the aqueous and solid phases according to the adsorption isotherm. This is achieved by balancing the adsorbent surface (activated carbon) fixed sites where molecules of adsorbate (the contaminant) may be chemically bound. The Langmuir isotherm explains the variation of adsorption with pressure. In order to execute this isotherm, five assumptions need to be met:

- A fixed number of vacant (or adsorption) sites are available on the surface of the solid
- All of the vacant sites are the same size and shape

- Each site can hold one gaseous molecule and a constant amount of heat energy is released during the process
- There is a dynamic equilibrium between adsorbed gaseous molecules and the free gaseous molecule
- Absorption is unilayer or monolayer

The Langmuir isotherm can be represented using Equation 5.4:

$$\frac{x}{m} = X = \frac{aKC_e}{1 + KC_e} \tag{5.4}$$

where

x = mass of solute adsorbed
m = mass of adsorbent
X = mass ratio of the solid phase/mass of adsorbed solute per mass of adsorbent
a = mass of adsorbed solute required to saturate completely a unit mass of adsorbent
K = experimental constant
C_e = equilibrium concentration of solute, mass/volume

It is often quite convenient to portray the Langmuir isotherm in terms of the maximum sorption capacity, which is a function of both K and a. If this is done, Equation 5.4 can be rearranged to Equation 5.5:

$$\frac{1}{q} = \frac{1}{Q_{max}} + \frac{1}{(Q_{max}) \times b \times C_e} \tag{5.5}$$

where

q = amount of metal sorbed at equilibrium (mg/g)
Q_{max} = maximum sorption capacity of system (mg/g)
b = constant related to binding energy of sorption system (L/mg)
C_e = concentration of metal solution at equilibrium (mg/L)

The process required to produce activated carbon from virgin raw carbon requires several energy-intensive stages, including heating the carbon up to temperatures greater than 500°C several times during the production process. Therefore, it is advantageous to explore alternative materials to replace virgin carbon in hopes of reducing raw material usage and production energy. Various examples of agricultural by-products will be reviewed that discuss using the Langmuir isotherm in sustainable applications.

The first example examined the use of rice hulls for the sorption of cadmium (Kumar and Bandyopadhyay, 2006). Table 5.9 shows various examples of sorption

TABLE 5.9
Maximum Sorption Capacity of Cd(II) of Various Agricultural By-Products and Activated Carbon (Cd(II) EPA MCL = 0.005 mg/L)

Material	Sorption Capacity (Q_{max}, mg/g)	Material	Sorption Capacity (Q_{max}, mg/g)
Peanut hulls	5.96	Corncobs	8.89
Bark	8.00	Cornstarch	8.88
Powdered activated carbon	3.37	Granular activated carbon	3.37
Sawdust	9.26	Sugar beet pulp	17.2
Spent grain	17.3	RRH	8.58
Exhausted coffee	1.48	ERH	11.12
Sheath of palm	10.8	NCRH	16.18
		NRH	20.24

capacities of not only four rice hulls, but also other agricultural by-products, and the more traditional granular or powdered activated carbon. The four types are

- RRH—raw rice husk
- NRH—NaOH-treated rice husk
- ARH—acid-treated rice husk
- NCRH—sodium carbonate-treated rice husk

Modifying RRH improved the sorption capacity by 3–12 mg/g, and while NCRH and NRH both increased the uptake capacity, NCHR was potentially the best because of the relative low cost of sodium bicarbonate (three times less than NaOH), and the rapid uptake, where short contact time is common.

The second example utilized sunflower stalks as the raw material (Sun and Shi, 1998). The stalks were evaluated with three metals, two size ranges, and two temperatures. Table 5.10 shows the results.

These two studies demonstrate that the adsorption capacity of contaminants is influenced heavily by not only the type of media (whether coal or agricultural waste product based), but also the contaminant being removed, the size of the media, and the temperature of the filtration.

EXAMPLE PROBLEM 5.5

Washington County, in Northwest Arkansas, is evaluating alternative materials from powdered activated carbon (with an assumed value of b = 0.237) in order to adsorb contaminants from the drinking water. Since there is a significant amount of rice grown in southern Arkansas, they would like to explore using raw rice husk (with an assumed b value of 0.0496) as an alternative to powdered activated carbon. If the water currently has a level of 0.21 mg/L of Cd(II), how much powdered activated carbon and raw rice husk must be used in order to treat 1 L of water to meet the EPA maximum?

TABLE 5.10
Maximum Sorption Capacity of Sunflower Stalks

Metal Ions Contaminant	Size (Mesh, Openings/in)	Temperature (°C)	Sorption Capacity (Q_{max}, mg/g)
Cu^{2+} (EPA secondary[a] = 1.0 mg/L)	25–45	25	25.11
		50	24.75
	<60	25	29.30
		50	27.57
Zn^{2+} (EPA secondary = 5.0 mg/L)	25–45	25	27.27
		50	10.06
	<60	25	30.73
		50	11.61
Cd^{2+} (EPA MCL = 0.005 mg/L)	25–45	25	34.85
		50	27.24
	<60	25	42.18
		50	30.86
Cr^{3+} (EPA MCL = 0.10 mg/L)	25–45	25	15.20
		50	25.07
	<60	25	15.16
		50	21.48

[a] EPA secondary indicates a nonenforceable guideline regarding contaminants that may cause cosmetic effects (skin/tooth discoloration) or aesthetic effects (taste, odor, color); these limits are considered "secondary maximum contaminant levels."

First, let us explore the powdered activated carbon. To calculate q, the amount of metal sorbed at equilibrium, Equation 5.5 is used:

$$\frac{1}{q} = \frac{1}{Q_{max}} + \frac{1}{(Q_{max}) \times b \times C_e} = \frac{1}{3.37} + \frac{1}{3.37 \times 0.237 \times 0.21} = \frac{1}{6.253},$$
$$\text{so } q = 0.0040 \text{ (mg/g)}$$

Next, dividing the difference between the actual amount of Cd(II) and the desired amount (0.005 mg/L, given in Table 5.9) by q will of water:

Amount of activated carbon needed = (0.21 – 0.005)/(0.004) = 51.3 g of material/L.

Second, we use the same procedure to calculate the amount of raw rice husk needed. Using the unique values of Q_{max} and b, the amount of raw rick husk needed is 96.4 g of material/L.

These values are high, and demonstrate why activated carbon or alternate materials are rarely used to remove metals. Metals are typically removed by ion exchange or the precipitation process, where these types of materials are generally used to remove organics (such as pesticides, VOCs, etc.). Regardless, it is useful to see an example of how alternate materials can be utilized.

5.3 WASTEWATER TREATMENT

According to the EPA, the average U.S. citizen uses 100 gallons of water per day (375 L/day). Assuming a population of 320 million, and 85% of water consumption as an estimate of wastewater production (Henry and Heinke, 1989), the United States produces approximately 27 billion gallons of wastewater a day (103 billion L/day). This immense volume of wastewater provides a very good opportunity to implement sustainable practices.

There are typically five stages to wastewater treatment: pretreatment, primary treatment, secondary treatment, tertiary treatment, and disinfection (which is sometimes considered a tertiary treatment). The pretreatment generally removes floating debris (through screening) and grit (gravity), which are larger particulate material that could abrade piping and mechanical equipment in the treatment process. Primary treatment removes solids through gravity settling in a sedimentation tank, with retention times of approximately 2 h. Secondary treatment generally removes nutrients (such as nitrogen and phosphorus), while tertiary treatment polishes the treated wastewater, such as removing the remaining fine particles through filtration. In the end, disinfection removes pathogenic organisms. While each of these five stages can incorporate sustainable techniques, the focus in this section will be on the secondary treatment, specifically the aeration basin.

In the aeration basin of biological wastewater treatment, effluent from the primary treatment is mixed with activated sludge, including bacteria, fungi, rotifers, and protozoa. The total suspended solids (TSS) within the wastewater and activated sludge in the aeration basin is termed the mixed liquor suspended solids, or MLSS, in which the majority is a quantification of the biomass concentration. Most biochemical oxygen demand, or BOD, in wastewater, degrades in the presence of oxygen, so the addition of air or oxygen is critical for the success of the aeration basin. An important component of the activated sludge operation is the solids retention time (θ_c), or the mean cell residence time (MCRT). The MCRT is a function of the volume of the aeration basin (V), the MLSS (X_A), the waste sludge flow rate (Q_w), the waste sludge solids concentration (X_w), the effluent flow rate (Q_e), and the effluent suspended solids concentration (X_e). This relationship is shown through Equation 5.6:

$$\theta_c = \frac{V(X_A)}{Q_w X_w + Q_e X_e} \tag{5.6}$$

Aeration is highly energy intensive, amounting to 45%–75% of the plant energy cost (Rosso et al., 2008), so optimizing the aeration system is critical for reducing the impact of wastewater treatment on the environment.

There are two ways in which sustainability can be increased surrounding the secondary treatment. First, biomass can be produced during the wastewater treatment, and can be harvested during the aeration process. If properly managed, this biomass can be harvested for reuse in other sustainable applications such as biofuel. Second, since aeration is highly energy intensive, increasing the air transfer efficiency by changing the diffuser type can influence the amount of energy required to treat the water.

In regard to producing biomass, one potentially beneficial material that could be produced is material for biofuels (Valigore et al., 2012). As discussed briefly in Chapter 4, the use of land-based crops for biofuels has potential negative social impacts. But biomass produced from wastewater treatment could potentially be used as a biofuel feedstock. Wastewater contains a high level of nutrients required by microalgae and bacteria, two critical components of biomass production. Valigore et al. studied three streams of wastewater in the lab, with varying levels of chemical oxygen demand (COD), total Kjeldahl nitrogen (the combination of both organic and inorganic forms of nitrogen), total phosphorus, and TSS. In order to estimate the total productivity, the calculation for the solids retention time was slightly modified, obtaining Equation 5.7:

$$\text{Total productivity (g/m}^2\text{/day)} = \frac{Q_w X_w + Q_e X_e}{(A_s/10)} \quad (5.7)$$

where A_s = surface area of the reactor. With this information, it was found that with 31.2 g/m^2/day of total TSS productivity, approximately 114,000 kg/ha/year of biomass, 56,900 m^3/h/year of methane (CH_4), or 13,600 L/h/year of biodiesel could be produced. The authors acknowledged that these production rates may not be optimal for mass production in the field, but showed promise moving forward.

In addition to the production of harvestable biomass, the second area of sustainability in the secondary treatment is the type of aeration system. There are three general types of aeration systems: fine-pore diffusers, coarse bubble, or surface. While the fine-pore diffusers have a high level of aeration efficiency (mass of oxygen transferred per unit energy required), they are often more expensive and may foul (clog) if not cleaned. In addition, they decrease in aeration efficiency when dissolved surfactants are introduced. Therefore, older municipal treatment plants and industrial treatment plants often have the more traditional coarse-bubble or surface aerators.

However, even within the fine-pore diffusers, there are various levels of equipment that can be utilized, and choosing different equipment can significantly impact energy savings. For example, Bell and Abel (2011) found that changing conventional blower technology with direct-drive turbo blowers can save up to 35% of the energy. The key behind direct-drive turbo blowers is air bearing technology, which, in short, uses air as a bearing through the increase in pressure, which literally pushes mechanical components away from each other during operation. This creates a buffer of air, which eliminates wear associated with moving parts continually in contact. These concepts highlight the importance of civil engineers working closely with other disciplines, such as mechanical engineering. By working together, efficiencies can be made in several concurrent areas, thereby increasing the efficiency of the entire system.

Another set of data (Azapagic et al., 2004) has shown that the typical paddle aerator air-based system has an oxygen utilization efficiency of 5%–6%, which is identical to a coarse-bubble diffuser. In comparison, a fine-bubble diffuser has an oxygen utilization efficiency of 11%–18%, thus almost doubling the oxygen efficiency by using fine-bubble versus course-bubble or paddle mixing. While there are many variables associated with efficiency, these numbers give a broad indication of the potential for increased efficiency within a wastewater treatment plant.

EXAMPLE PROBLEM 5.6

Madison, Wisconsin's wastewater treatment plant (a part of Madison Metropolitan Sewerage District) is attempting to calculate their MCRT (or θ_c) with a paddle aerator. Using the information they have available below, calculate the MCRT for a paddle mixer:

Volume of the aeration basin (V) = 1.24 MGD (million gallons/day)
MLSS (X_A) = 2450 mg/L
Waste sludge flow rate (Q_w) = 0.065 MGD
Waste sludge solids concentration (X_w) = 9980 mg/L
Effluent flow rate (Q_e) = 5.71 MGD
Effluent suspended solids concentration (X_e) = 17.6 mg/L

In order to solve this problem, Equation 5.6 is utilized:

$$\theta_c = \frac{V(X_A)}{Q_w X_w + Q_e X_e} = \frac{1.24\,\text{MGD} \times 2450\,\text{mg/L}}{(0.065\,\text{MGD} \times 9980\,\text{mg/L}) + (5.71\,\text{MGD} \times 17.6\,\text{mg/L})}$$
$$= 4.1\,\text{days}$$

5.4 OUTDOOR AIR QUALITY

The first instance of pollution probably occurred when households began lighting fires indoors for heating the air and cooking food. Indoor fires with no release vents create highly unpleasant conditions, thus chimneys were created to divert the pollution out of the house and into outdoor air. In addition, very small point source pollution can occur from something as seemingly inconsequential as a personal grill in the backyard, as seen in Figure 5.5.

While the atmosphere has an incredibly high capacity to disperse pollutants, the arrival of the industrial revolution, and creation of factories, provided a pivot point in the history of air quality. With the combination of residential, commercial, and industrial pollution sources, the pollution began to outpace the ability of the atmosphere to disperse the pollutants. The problem was compounded by exponential growth of energy consumption. During the industrial revolution, most power was provided by coal power plants. Thus, the pollution from coal power plants for electricity and the pollution from residential, commercial, and industrial sources caused significant air quality issues. For example, the most famous instance of London Fog occurred in 1879, where for 4 months, the sun could not be seen because of the heavy pollution. The fogs continued into the 1950s, where in 1952, approximately 4000 London citizens were killed in a four-day fog. This event caused the English Parliament to enact the Clean Air Act in 1956, which has over time improved the air quality over London significantly.

FIGURE 5.5 Emissions from grilling hamburgers in the backyard. (Courtesy of A. Braham.)

The United States passed the Air Pollution Control Act in 1955, which was followed by the Clean Air Act of 1963, and subsequent amendments in 1970, 1977, and 1990. Along with the United Kingdom and the United States, most developed countries have passed some form of a Clean Air Act. However, developing countries still face significant challenges. For example, Beijing (China) is well known for air quality problems, as seen in Figure 5.6.

The World Health Organization considers particulate matter smaller than 2.5 μm (PM2.5) readings of 25 $\mu g/m^3$ as the maximum safe level, but in 2015, Beijing had several instances of readings just under 300 $\mu g/m^3$. This pollution is not only caused by traffic and factory pollution in Beijing, but also by the steel factories and power plants that surround Beijing in Hebei Province. The EPA has also established limits for PM2.5 with the following breakpoints for six air quality index categories:

- Good: 0.0–12.0 $\mu g/m^3$, 24-h average
- Moderate: 12.1–35.4 $\mu g/m^3$, 24-h average
- Unhealthy for sensitive groups: 35.5–55.4 $\mu g/m^3$, 24-h average
- Unhealthy: 55.5–150.4 $\mu g/m^3$, 24-h average
- Very unhealthy: 150.5–250.4 $\mu g/m^3$, 24-h average
- Hazardous: >250.5 $\mu g/m^3$, 24-h average

While strides are being made in improving air quality, there is still much work to be done.

(a)
(b)

FIGURE 5.6 A China Southern A380 on a bad pollution day (a) and on a good pollution day (b) at Beijing Capital International Airport. (Courtesy of A. Braham.)

The accumulation of pollution is a function of emission rates, dispersion rates, and generation/destruction rates by chemical reaction. Therefore, cities such as Los Angeles, which sit in a valley, may have lower emission rates than cleaner sites, but because of the surrounding mountains, the pollution is not able to disperse. While highly sophisticated tools have been developed to quantify air quality, modeling of the emissions is still essential for future pollution prediction. Another benefit to developing models is that physical tools are often very expensive (both time- and moneywise), and models can examine literally an infinite number of scenarios. Finally, modeling is 100% repeatable, which allows the ability to test various scenarios. While the accuracy of the models may not be perfect, exact conditions can be repeated.

In order to utilize models for emissions, there are several key dispersion principles that need to be followed. The pollutants generally come from a point source, such as a chimney or smoke stack. The wind will disperse the pollutants both horizontally and vertically into the air. Once in the air, the pollutants encounter both laminar and turbulent flow conditions. These conditions contain eddies and swirls, which are macroscopic random fluctuations from average flow and cause pollution to disperse in potentially unpredictable ways. The eddies form from thermal and mechanical influences. For example, thermal energy from the sun is absorbed into the ground, converted to heat, and the heat rises to lowest levels of air by conduction and convection creating thermal eddies. Mechanical eddies, on the other hand, are from shear forces when air flows over rough surfaces. In addition to the eddies, wind fluctuations (speed and direction) also influence pollution dispersion. In order to account for all of these random events, the pollution plume must be considered on time-averaged basis. In general, time-averaged distribution is normally distributed, both in horizontal and vertical directions. This horizontal and vertical direction is referred to as binormal distribution of pollutants.

A popular model that quantifies this binormal distribution is the Gaussian model. The Gaussian model models dispersion of nonreactive gaseous pollutant from elevated source and is the basis for almost all computer programs developed by environmental protection agencies. The Gaussian model is shown in Equation 5.8:

$$C = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right)\left[\exp\left(-\frac{1}{2}\frac{(z-H)^2}{\sigma_z^2}\right) + \exp\left(-\frac{1}{2}\frac{(z+H)^2}{\sigma_z^2}\right)\right] \quad (5.8)$$

where

C = steady-state concentration at a point (x, y, z) ($\mu g/m^3$)
Q = emissions rate ($\mu g/s$)
σ_y, σ_z = horizontal and vertical spread parameters (m)
u = average wind speed at stack height (m/s)
y = horizontal distance from plume centerline (m)
z = vertical distance from ground level (m)
$H = h + \Delta h$ effective stack height

- h = physical stack height (m)
- Δh = plume rise (m)

$\sigma_y = ax^b$
$\sigma_z = cx^d + f$
x = horizontal distance from plume origination (km)

and a, b, c, d, and f come from Tables 5.11 and 5.12.

TABLE 5.11
Atmospheric Stability under Various Conditions[a]

Wind Speed 10 m above Ground (m/s)	Daytime Solar Radiation			Night Cloudiness	
	Strong[b]	Moderate[c]	Slight[d]	Cloudy (≥50%)	Clear (<50%)
<2	A	A–B	B	E	F
2–3	A–B	B	C	E	F
3–5	B	B–C	C	D	E
5–6	C	C–D	D	D	D
>6	C	D	D	D	D

[a] Class D applies to heavily overcast skies, any wind speed day or night.
[b] Clear summer day with sun higher than 60° above horizon.
[c] Summer day with few broken clouds, clear day with sun 35–60° above horizon.
[d] Fall afternoon, cloudy summer day, clear summer day with sun 15–35° above horizon.

TABLE 5.12
Values of Curve-Fit Constants

			x < 1.0 km			x > 1.0 km		
Stability	a	b	c	d	f	c	d	f
A	213	0.894	440.8	1.941	9.27	459.7	2.094	–9.6
B	156	0.894	106.6	1.149	3.3	108.2	1.098	2.0
C	104	0.894	61.0	0.911	0	61.0	0.911	0
D	68	0.894	33.2	0.725	–1.7	44.5	0.516	–13.0
E	50.5	0.894	22.8	0.648	–1.3	55.4	0.305	–34.0
F	34	0.894	14.35	0.740	–0.35	62.6	0.180	–48.6

There are some general guidelines when using the Gaussian model that can help simplify the analysis of pollution dispersion. For example, downwind concentration at any location is directly proportional to the source strength (Q), and the downwind ground level (z = 0) concentration is generally inversely proportional to the wind speed. In addition, the elevated plume centerline concentrations decline continuously with increasing x, and the ground level centerline concentrations start at zero, increase to a maximum, and then begin decreasing. Finally, the dispersion parameters (σ_y, σ_z) increase with increasing atmospheric turbulence and the maximum ground-level concentration decreases as the effective stack height increases.

EXAMPLE PROBLEM 5.7

A coal power plant in Southwest Arkansas is looking to determine the EPA-established limit for PM2.5 from its primary emission stack, which is 35 m tall and is emitting 35 µg/s of PM2.5. Specifically, they are looking at the PM2.5 that a local soccer complex would be exposed to that is 1.2 km away from the emission stack. Assume the following conditions: strong daytime solar radiation, a wind speed of 4 m/s 10 m above ground, and the soccer complex is 100 m from the plume centerline.

The first step is calculating σ_y and σ_z. In order to calculate these two values, first the level of stability needs to be established. According to Table 5.11, with the given wind speed of 4 m/s at 10 m above ground, and the strong daytime solar radiation, the stability level is B. Next, using Table 5.12, since the distance from the emission stack to the soccer complex is greater than 1.0 km, the following values are used for a–d, f:

$a = 156$
$b = 0.894$
$c = 108.2$
$d = 1.098$
$f = 2.0$

With these values established, σ_y and σ_z can be calculated using

$\sigma_y = ax^b = (156) \times (1.2)^{0.894} = 183.6$ m
$\sigma_z = cx^d + f = (108.2) \times (1.2)^{1.098} + 2 = 134.2$ m

Finally, Equation 5.8 can be used to find the steady-state concentration at the soccer complex:

$$C = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right)\left[\exp\left(-\frac{1}{2}\frac{(z-H)^2}{\sigma_z^2}\right) + \exp\left(-\frac{1}{2}\frac{(z+H)^2}{\sigma_z^2}\right)\right]$$

$$C = \frac{35}{2\pi \times 4 \times 183.6 \times 134.2} \exp\left(-\frac{1}{2}\frac{100^2}{183.6^2}\right)\left[\exp\left(-\frac{1}{2}\frac{(35-35)^2}{134.2^2}\right) + \exp\left(-\frac{1}{2}\frac{(35+35)^2}{134.2^2}\right)\right] = 3.65^{-4}\,\mu g/m^3$$

$3.65^{-4}\,\mu g/m^3$ falls within the "good" air quality index according to the EPA's established limit.

SIDEBAR 5.1 CONSTRUCTING A HIGH-QUALITY GRAPH

A well-constructed graph must be easy to read and understand quickly and should be constructed so it can be read both in color and in black and white. The structure of the graph must include both horizontal (x-axis) and vertical (y-axis) axis titles and a legend. If the graph is within a document, it should not have an embedded chart title, as the caption provides the necessary information. However, if the graph is a stand-alone a chart title can be used. The axis titles and chart title should be bolded, and one font size larger than the axis labels. The legend font should be the same size as the axis label font and is not bolded. The axis labels should be large enough where you only have 4–6

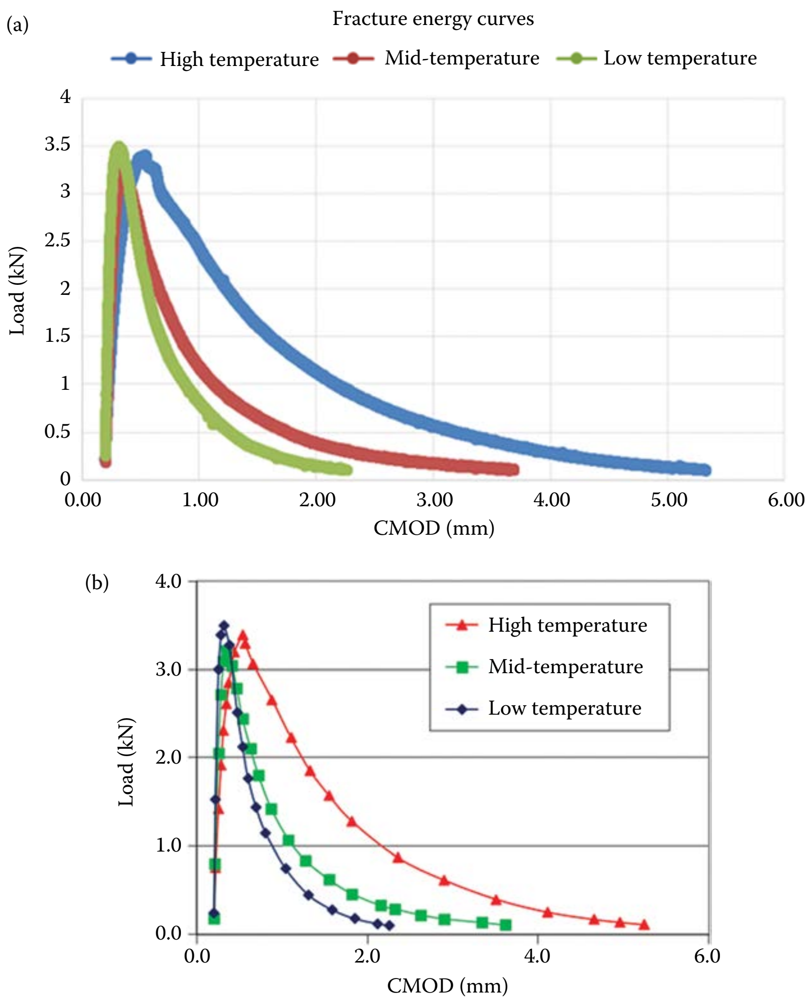

FIGURE S5.1 (a) Standard Excel output of fracture energy curves. (b) Modified Excel output of the same fracture energy curves. (Courtesy of A. Braham.)

delineations on the y-axis. Graphs are not used to convey precise numbers, but to show trends. With too many delineations, the axis becomes cluttered and unreadable. Within the delineations, the number of significant digits should remain the same, and the last digits should not be all zeros. If they are all zeros, remove significant digits until the last digits are not all zero, unless you are to the left of the decimal. Finally, rarely are all data points shown in a graph, especially one showing multiple data points per second over a time period of minutes. By only showing a portion of the data, the plotted points can be connected, which allows for clearer data presentation.

Let us take a look at calculating fracture energy. Fracture energy is the amount of energy required to create a new surface in a material. This is done in the lab by either pulling on, or pushing on, a sample to create a crack. The information recorded during this test is the load and some sort of displacement. The area under this load/displacement curve (the work) divided by the area of the cracked surface created is the fracture energy. However, it is often interesting to look at the load/displacement curves, and to show how they are different relatively to one another. For example, asphalt mixtures are viscoelastic material, meaning at higher temperatures they show more viscous behavior, and at lower temperatures, they show more elastic behavior. Therefore, it would be expected that the work required to create a crack surface would be higher at the higher temperatures, and lower at the lower temperatures. This trend is shown in Figure S5.1. Figure S5.1a has the standard output from Microsoft Excel, whereas Figure S5.1b is modified according to the "rules of thumb" outlined in this sidebar. It is obvious that by taking some care, graphs can become much easier to read and interpret, especially if shown in black and white.

HOMEWORK PROBLEMS

1. You have just graduated from college (congratulations!) and on the first day of work, your boss asks you to explore the variability of runoff coefficients on peak discharge. Assuming a rainfall intensity of 12.7 mm/h and a watershed area of 404,686 m^2, graph the minimum and maximum potential runoff for forest, lawn with clay soil and a slope between 2% and 7%, and asphalt. When establishing minimum and maximum potential runoff, utilize the PE reference manual, the City of Fayetteville, Washington State, and Florida State. Briefly describe the trends that you see, and use the format provided under Sidebar 5.1 "Constructing a High-Quality Graph."
2. Find a building with a flat roof nearby, and estimate the area of the roof. Assume the roof has shingles, and calculate the peak discharge of the roof currently, and how it will change if replaced by a green roof. Use a rainfall intensity of 0.75 in/h and state any assumptions you need to make.
3. The drinking water district of Salt Lake City, Utah, wants to compare bark, sugar beet pulp, and exhausted coffee to the traditional granular activated carbon for removing chlorite from their drinking water. Assuming the Q_{max} values in Table 5.9 can be used for chlorite, and that b = 0.237 for all four materials, how much material must be used in order to treat 1 L of water to meet the EPA maximum requirement? How much material must be used in order to treat 1 L of water to meet the EPA maximum goal?
4. Plot the change in maximum sorption capacity of sunflower stalks for metal ions contaminant, the size, and the temperature. Try to fit all of the data onto a single, easy-to-read graph, using the format provided under Sidebar 5.1 "Constructing a High-Quality Graph."

5. A wastewater treatment plant in Wichita, Kansas (the Lower Arkansas River Water Quality Reclamation Facility), is attempting to calculate their MCRT (or θ_c) with a paddle aerator. Using the information they have available below, calculate the MCRT for a paddle mixer:
   - Volume of the aeration basin (V) = 5.4 MGD (million gallons/day)
   - MLSS (X_A) = 10,350 mg/L
   - Waste sludge flow rate (Q_w) = 0.19 MGD
   - Waste sludge solids concentration (X_w) = 26,580 mg/L
   - Effluent flow rate (Q_e) = 24.71 MGD
   - Effluent suspended solids concentration (X_e) = 57.3 mg/L
6. Using the data in Example Problem 5.6, replace the paddle aerator with a fine-bubble diffuser. Assume that the change in retention time is linearly related to the change in efficiency of the aerator system.
7. A coal power plant in Champaign, Illinois is looking to determine the EPA-established limit for PM2.5 from its primary emission stack, which is 15 m tall and is emitting 412 μg/s of PM2.5. Specifically, they are looking at the PM2.5 that a local softball complex would be exposed to that is 0.3 km away from the emission stack. Assume the following conditions: nighttime, cloudy, wind speed of 5.5 m/s 10 m above ground, and the softball complex is 50 m from the plume centerline.
8. Using the data in homework problem 7, what is the minimum emission of PM2.5 (in μg/s) that would be required to fall into the "moderate" air quality index category established by the EPA?

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6 Application
Geotechnical Sustainability

The function of education is to teach one to think intensively and to think critically. Intelligence plus character—that is the goal of true education.

Martin Luther King Jr

As many geotechnical engineers like to say, soils are the foundation of everything. In a sense this is true, because the vast majority of engineering structures are built on land, which is generally composed of some sort of soil. Therefore, a strong understanding of soil is absolutely necessary in order to then design the structure, roadway, or artificial body of water that rests on the soil because regardless of what you are designing or constructing, it will almost always eventually involve the ground. This understanding includes the plasticity and structure, the compaction and permeability characteristics, and the stresses and pressures that move through soil. When considering sustainability application in geotechnical areas, there are two primary paths, either the replacement of materials or the modification of a design in order to improve the economic, environmental, and social impact of the project. This chapter will cover both of these paths using the following four specific applications:

1. Alternate granular fill materials
2. Expanded polystyrene fill
3. Retaining wall design
4. Mechanically stabilized Earth walls

6.1 ALTERNATE GRANULAR FILL MATERIALS

The natural topography of a site is rarely appropriate for an engineering structure without first modifying the site grading in some manner. During the construction of highways, railways, buildings, landfills, dams, or levees, material often needs to be either removed (commonly known as "cut") or added (commonly known as "fill") in order to properly prepare a site. There are three typical formulas used to calculate the amount, or volume (V), of cut and fill of a site: the average end area formula, the prismoidal formula, and the pyramid formula. The average end area formula simply takes the area of one end of the cut or fill (A_1), adds this area to the opposite end (A_2), multiples by the length of the cut or fill (L), and divides by two, as shown in Equation 6.1.

$$V = \frac{L(A_1 + A_2)}{2} \tag{6.1}$$

The prismoidal formula uses a similar calculation, but includes the area of the mid-section of the cut or fill (A_m), creating a slightly more accurate estimation of the volume of material necessary, as shown in Equation 6.2.

$$V = \frac{L(A_1 + 4A_m + A_2)}{6} \tag{6.2}$$

The third formula, the pyramid or cone, is used if the site tapers to a single point with a known height (h) and area of base (A_b), and is shown in Equation 6.3.

$$V = \frac{h(A_b)}{3} \tag{6.3}$$

All of the areas can be calculated by using various methods, including the area by coordinates, the trapezoidal rule, or Simpson's 1/3 rule, all of which are generally learned in the first semester of college calculus. However, it is often necessary to switch from known volumes to known weights when dealing with cut and fill material. There are two reasons for this. First, properties of cut and fill material are highly dependent on the amount of water in the material. This water can be found either as a discrete phase (free water) or within the voids, so the knowledge of volume alone is often not adequate for a full understanding of the material. Second, it is very difficult to purchase or sell cut and fill material on the basis of volume. The transaction is usually conducted by weight, as trucks can easily pull on and off scales, but are rarely measured by height, width, and length, to establish quantities. Therefore, understanding phase relationships, between weight and volume, is critical. This can be done using a phase diagram, as seen in Figure 6.1.

The key to moving between the weight of a material and the volume of the material is the specific gravity (γ) and the moisture content (w). Beginning with the specific gravity of water ($\gamma_w = 62.4$ lb/ft^3 or 9.81 kN/m^3), and incorporating components of the phase diagram, various relationships can be established, including the specific gravity of the solids (G_s) in Equation 6.4.

$$G_s = \frac{(W_s/V_s)}{\gamma_w} \tag{6.4}$$

The void ratio (e) in Equation 6.5.

$$e = \frac{V_v}{V_s} \tag{6.5}$$

The saturated unit weight (γ_{sat}) in Equation 6.6.

$$\gamma_{sat} = \frac{(G_s + e)\gamma_w}{(1 + e)} \tag{6.6}$$

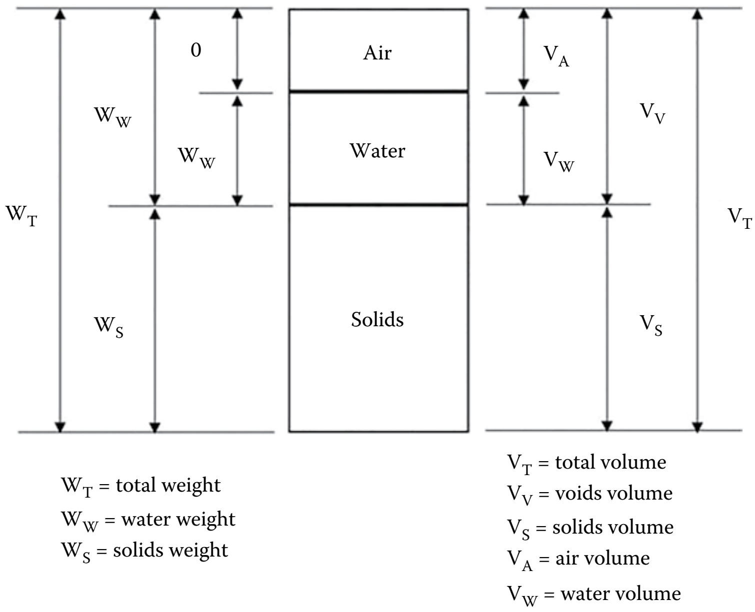

FIGURE 6.1 Phase diagram of cut or fill material (assumes volume of solids equals 1). (Credit: A. Braham.)

And finally, the porosity (n) in Equation 6.7.

$$n = \frac{V_v}{V} = \frac{e}{(1+e)} \tag{6.7}$$

These relationships, among others, allow for cut and fill to be fully evaluated and categorized in the laboratory to ensure proper behavior in the field.

Embankment refers to placing and compacting material to raise the existing grade above the level of existing surrounding ground surface, usually for a roadway, a railway, or the area under a building pad. Fill refers to placing and compacting material in a depression or hole, or the leveling of an existing site for preparation of a slab on grade foundation. When considering fill under a pavement structure, generally coarser and lower-quality material is placed at the bottom to provide a firm foundation and drainage, while the top portions are well-compacted, high-quality material that can support the structure being constructed directly above. However, fill under a building foundation is not as straightforward. Depending on the depth of the fill, the lower materials may need to be just as highly controlled as the upper materials or the foundation-bearing capacity and settlement design will be compromised. Important properties of alternate granular fill materials include gradation, unit weight/specific gravity, moisture-density characteristics (optimal moisture content, maximum dry density), shear strength (cohesion, internal friction), and compressibility (consolidation, settlement). Of these properties, the gradation is the only property that can be influenced, by crushing, screening, or washing.

Traditionally, cut and fill materials consist of natural soils. Ideally, cut material from one portion of the project is utilized as fill material in another part of the project (onsite borrow), which minimizes haul distance, thus reducing cost (economic pillar of sustainability) and emissions (environmental pillar of sustainability). However, another sustainable alternative is to use alternate granular fill materials, or by-product materials. This is not only potentially beneficial from an economic and environmental standpoint, but bringing in alternate material may be necessary if the existing material is not suitable for fill, such as if the area was formally a landfill or the existing soil is simply low quality. There are seven relatively common alternate granular fill materials that are used as either cut or fill material: blast furnace slag, coal fly ash, mineral processing wastes, nonferrous slags, reclaimed asphalt pavement, reclaimed concrete material, and scrap tires (Chesner et al., 1997). Table 6.1 summarizes properties of the seven alternate granular fill materials.

Table 6.2 shows similar properties for a sampling of the unified soil classification system (UCSC) soils. Table 6.2 was constructed from various resources, including textbooks and online information. While the trends are consistent (i.e., the optimal moisture content generally increases as you move down the table, while the compacted density, internal friction angle, and California Bearing Ratio [CBR] generally decrease), the actual data is provided as a general reference, and there may be exceptions.

When considering the use of alternative fill materials, there are three additional considerations that need special attention, including material process requirements, design considerations, and construction procedures. For example, special material process requirements for reclaimed concrete or scrap tires include removing any reinforcing steel. Both of these materials often utilize steel (concrete for tensile strength and tires for sidewall stiffness), but steel is not a desirable material to use as fill material because of its high weight and the potential to damage equipment during transport, placement, and compaction. Another example, for design considerations, is for

TABLE 6.1
Properties of Alternate Granular Fill Materials

	Optimum Moisture Content (%)	Compacted Density, lb/ft^3 (kg/m^3)	Internal Friction Angle (°)	CBR (%)
Blast furnace slag	9–19	70–120 (1120–1940)	40–45	>100
Coal fly ash	20–35	85–100 (1380–1600)	26–40	Increase soils ~20×
Nonferrous slags	4–8	175–237 (2800–3800)	40–53	>100
Recycled asphalt pavement	3–7	100–125 (1600–2000)	37	20–25
Reclaimed concrete	4–11	120–180 (1940–2900)	>40	90–140
Scrap tires	1	20–45 (320–720)	19–25	Increase soils ~10×

Source: Chesner, W., Collins, R., MacKay, M. User Guidelines for Waste and By-Product Materials in Pavement Construction. Federal Highway Administration, FHWA-RD-97-148, McLean, VA, 1997.

TABLE 6.2
Properties of Select USCS Fill Materials

USCS Classification (ASTM 2487)	Optimum Moisture Content (%)	Compacted Density, lb/ft³ (kg/m³)	Internal Friction Angle (°)	CBR (%)
GW—well-graded gravel	8–11	125–135 (2000–2160)	33–40	60–80
GM—silty gravel	8–12	120–135 (1920–2160)	30–40	40–80
SW—well-graded sand	9–16	110–130 (1760–2080)	33–43	20–40
SC—clayey sand	10–19	105–125 (1680–2000)	30–40	10–20
CL—lean clay	12–24	95–120 (1520–1920)	27–35	5–15
MH—elastic silt	24–40	70–95 (1120–1520)	23–33	4–8

coal fly ash. While it is similar in many respects to earthen backfill, it tends to wick water to itself, which reduces shear strength. Therefore, it often has to be delivered to the job site at near optimal moisture content to prevent the absorption of water. Finally, for construction procedures, an example of special consideration again comes from scrap tires, which should be wrapped with nonwoven geotextile fabric once the tires are placed and compacted. This will prevent expansion after compaction of the material, which will influence the volume calculations that were used during the design. Care must be taken with using all recycled material, however, ensuring that there are no existing environmental regulations that prohibit the use of any specific material.

EXAMPLE PROBLEM 6.1

Construct a phase diagram for recycled asphalt pavement, which generally has a specific gravity of 2.565. Use standard units; assume a soil volume of 1 ft³ and a total volume of 1.2 ft³. State any other assumption that you need to make.

The first assumption is for the moisture content. Using Table 6.1, the average optimal moisture content is assumed as the moisture content, so w = 5.0%. We know that $V_S = 1$, so we can calculate the weight of solids using Equation 6.4:

$$G_s = \frac{(W_s/V_s)}{\gamma_w} \rightarrow 2.565 = \frac{(W_s/1)}{62.4\,\text{pcf}} \rightarrow W_s = 160.1\,\text{pcf}$$

Next, the weight of the water can be calculated using

$$W_w = w \times G_s \times \gamma_w = 0.05 * 2.565 * 62.4\,\text{pcf} = 8.0\,\text{pcf}$$

The total weight is simply the combination of the solid weight and water weight, or 168.1 pcf. Now that the left side of the phase diagram is complete, the right side can be analyzed. First, the volume of water can also be calculated:

$$V_W = w \times G_s = 0.05 * 2.565 = 0.13\,\text{ft}^3$$

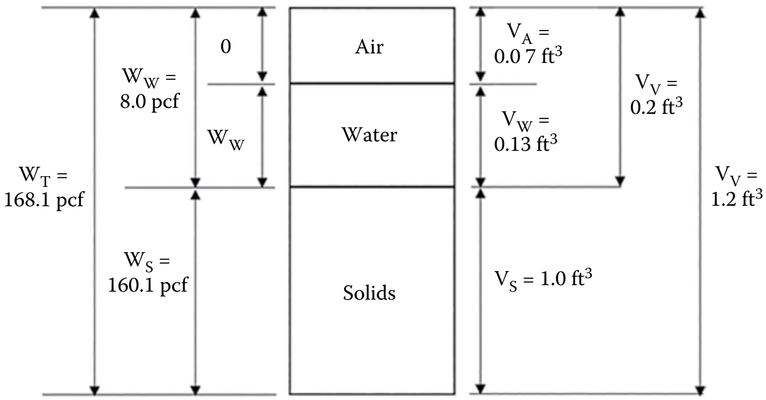

FIGURE EP6.1 Phase diagram for recycled asphalt pavement. (Credit: A. Braham.)

Next, the void volume can be calculated:

$$V_V = V_T - V_S = 1.2\ \text{ft}^3 - 1.0\ \text{ft}^3 = 0.2\ \text{ft}^3$$

And finally, the volume of air can be calculated, giving us the full phase diagram in Figure EP6.1.

$$V_A = V_V - V_W = 0.2\ \text{ft}^3 - 0.13\ \text{ft}^3 = 0.07\ \text{ft}^3$$

6.2 EXPANDED POLYSTYRENE FILL

As seen in Section 6.1, one of the benefits of using alternative fill materials is a lower unit weight versus traditional fill, which decreases the bearing support required on layers below the fill. In addition to alternative fill materials, engineering materials can also be used. Expanded polystyrene, also known as EPS, or geofoam, is an engineered material that can be fabricated off-site to exact size and performance specifications, and transported and placed in embankments. Figure 6.2 shows an application of geofoam as a fill material under a highway.

Specific benefits to using EPS geofoam include relative ease and speed of construction, placement in poor weather conditions, reduction of lateral stress, and high durability. Since the density of EPS is approximately 1/100th of conventional granular fill material, significant cost savings may be achieved, especially in soil removal and replacements. For example, the Daji Bridge in Taipei City, Taiwan, was evaluated for two traditional retaining walls with fill, priced at 28,438 New Taiwan dollars/m and 43,380 New Taiwan dollars/m (Lin et al., 2010). The same design was performed with EPS geofoam at a price of 25,059 New Taiwan dollars/m, a savings of 12% and 42% compared to the two traditional retaining wall design. This analysis included materials, equipment, and labor.

Another benefit of EPS geofoam is the consistency of the product. Fill materials, where earthen based or alternative materials, are often sensitive to moisture and variability of source material along with nonuniformity of construction practices

FIGURE 6.2 EPS geofoam as a fill material. (Credit: www.epsindustry.org.)

and procedures even within the same project. However, EPS geofoam, being manufactured off-site, can be highly controlled and engineered. The density of EPS geofoam for fill is generally 1.0–2.0 lb/ft^3 (16–32 kg/m^3); however, density variation (called density gradients) up to 10% can exist due to the manufacturing process. During construction, settlements up to 1% strain are often specified. After construction is complete, postconstruction settlement no greater than 2% strain may be specified (Farnsworth and Bartlett, 2007). The dimensions of the blocks are based on the mold, which in turn affects the delivery to a job site and the block layout more than engineering properties (Stark et al., 2004). However, the standard dimension of an EPS geofoam block is currently ~35 × 48 × 96 in (~900 × 1200 × 2400 mm), but dependent on manufacturers (in 2016, there were approximately 150 across the United States according to the EPS Industry Alliance website). EPS geofoam is generally covered immediately since if the material is exposed to UV radiation for extended periods (on a year scale), it will yellow and become brittle. According to Stark et al., (2004), EPS geofoam is inherently nonbiodegradable, and will not dissolve, deteriorate, or change chemically. In addition, EPS geofoam is not harmful or hazardous, no harmful gases are emitted during production, and the material will not interact with the ground/ground water. There have been instances where insects have tunneled/nested in EPS foam, but this can be deterred with chemical additives. Caution must also be taken with flammability. Flammability is expressed in oxygen index (OI—minimum relative proportion of oxygen in gas mixture required to support continuous combustion, percent). At sea level, a material will burn freely if the OI is less than 21%. EPS geofoam has OI of 18%, so it is inherently flammable. However, a bromine additive is generally added, so the OI is increased to approximately 24%, which adds approximately 10% more to the base material cost.

For design purposes, it is useful to have estimates of mechanical properties of EPS geofoam, for applications such as fill as seen in Figure 6.3. Table 6.3 summarizes

FIGURE 6.3 EPS geofoam as a fill material. (Credit: www.epsindustry.org.)

TABLE 6.3
Mechanical Properties of EPS Geofoam

Density, lb/ft³ (kg/m³)	Compressive Strength, lb/ft² (kPa)	Yield Stress, lb/ft² (kPa)	Poisson Ratio
1.5 (24)	3133 (150)	2477 (118.6)	0.14

Source: Stark, T. et al. *Geofoam Applications in the Design and Construction of Highway Embankments, NCHRP Web Document 65*, National Cooperative Highway Research Program, July 2004.

some useful mechanical properties. Note that the mechanical properties are dependent on loading rates, testing temperature, and specimen geometry. The properties listed in Table 6.3 are based on what would be considered typical field conditions.

One potential benefit of EPS geofoam is the reduction of emission from hauling material. Since geofoam has a much lower density than traditional fill materials, the corresponding emissions are also lower. Table 6.4 summarizes multiple heavy-duty vehicles, and their corresponding emissions.

EXAMPLE PROBLEM 6.2

A truck hauling fill material can carry approximately 20 tons of fill, which equates to 40,000 pounds, classifying it as a VIIIa truck. Assuming a loose density of 110 pcf of the clayey sand fill material (Table 6.2), and a density of 1.5 pcf of the geofoam (Table 6.3), what classification of truck would be required to haul the same volume of geofoam? What is the difference in VOC, CO, and PM2.5 emissions from these two trucks? State any assumptions that you need to make.

TABLE 6.4
Heavy-Duty Diesel Vehicle Classifications and Emissions

Classification	Gross Vehicle Weight (lbs)	VOC (g/mile)	THC (g/mile)	CO (g/mile)	NO_x (g/mile)	PM2.5 (g/mile)	PM10 (g/mile)
IIb	8501–10,000	0.189	0.194	0.839	3.088	0.091	0.099
III	10,001–14,000	0.201	0.204	0.908	3.298	0.073	0.079
IV	14,001–16,000	0.262	0.266	1.163	4.352	0.089	0.096
V	16,001–19,500	0.274	0.278	1.189	4.548	0.079	0.085
VI	19,501–26,000	0.365	0.370	1.367	5.990	0.172	0.186
VII	26,001–33,000	0.453	0.459	1.719	7.471	0.177	0.192
VIIIa	33,001–60,000	0.455	0.461	2.395	9.191	0.215	0.233
VIIIb	>60,000	0.545	0.552	3.109	10.990	0.238	0.259

Source: EPA. Average In-Use Emissions from Heavy-Duty Trucks. Environmental Protection Agency, Office of Transportation and Air Quality, EPA420-F-08-027, October 2008.

Note: Emissions are defined in Chapter 3.

The first step is to compute the volume of the fill, which is simply the weight divided by the density:

$$\text{Volume of fill} = \text{weight/density} = 40{,}000 \text{ lbs}/110 \text{ pcf} = 363.6 \text{ ft}^3$$

Next, the weight of the geofoam can be calculated by multiplying the volume of the fill by the density of the geofoam:

$$\text{Weight of geofoam} = \text{volume} \times \text{density} = 363.6 \text{ ft}^3 \times 1.5 \text{ pcf} = 545.5 \text{ lbs}$$

This weight is actually below any of the trucks listed in Table 6.4, so it is assumed that the smallest truck will be utilized, a *Class IIb heavy-duty diesel vehicle*.

The difference between a Class VIIIa and Class IIb truck for VOC, CO, and PM2.5 emissions is as follows:

VOC → 0.455–0.189 = 0.266 g/mile
CO → 2.395–0.839 = 1.556 g/mile
PM2.5 → 0.215–0.091 = 0.124 g/mile

6.3 RETAINING WALLS

While some job sites may be located in southern Florida, where stating that the land is flat is an understatement, many areas will be located in areas with elevation change. Whether designing a roadway or a structure, the topography may have to be modified, and the change in topography is frequently increased in order to create level areas for the engineering structure. A typical solution is to construct a concrete retaining wall, as shown in Figure 6.4a. However, an alternate solution can be a bio-engineered slope, which uses vegetation instead of concrete in order to restrain the

(a)

(b)

FIGURE 6.4 (a) A traditional concrete retaining wall on the University of Arkansas campus. (Credit: A. Braham.) (b) A bioengineered slope just north of Milwaukee, Wisconsin. (Credit: A. Braham.)

soil, as seen in Figure 6.4b. A brief review of Earth pressure is provided, followed by some examples of the sustainability of bioengineered slopes.

Rigid retaining walls are generally large masses of vertically constructed concrete or blocks that prevent Earth from moving laterally. A retaining wall without any steel reinforcement is a mass gravity retaining wall, and can be constructed out of plain concrete or stone masonry. As the name implies, their self-weight and any soil resting on the structure stabilize the structure. Lateral sliding of the wall is prevented by the friction between the base of the wall and the bearing soil (whether natural soil or fill material). This type of construction is only economical for wall heights that are no greater than 1.5 times the width of the footing. An example of three general stages of mass gravity wall construction is shown in Figure 6.5.

However, to either increase the height of the wall or to reduce the cross section of the concrete, steel reinforcement can be used. A steel-reinforced concrete wall is called a semigravity retaining wall. Instead of relying on the self-weight of the wall itself, semigravity walls utilize the steel reinforcement to resist bending and shear. However, from a design perspective, it is usually cheaper to excavate or construct a slightly bigger wall versus installing steel reinforcement. Nonetheless, as seen in Figure 6.6, by placing steel toward the Earth edge of the wall, the thickness of the stem can be reduced, thus reducing the quantity of concrete.

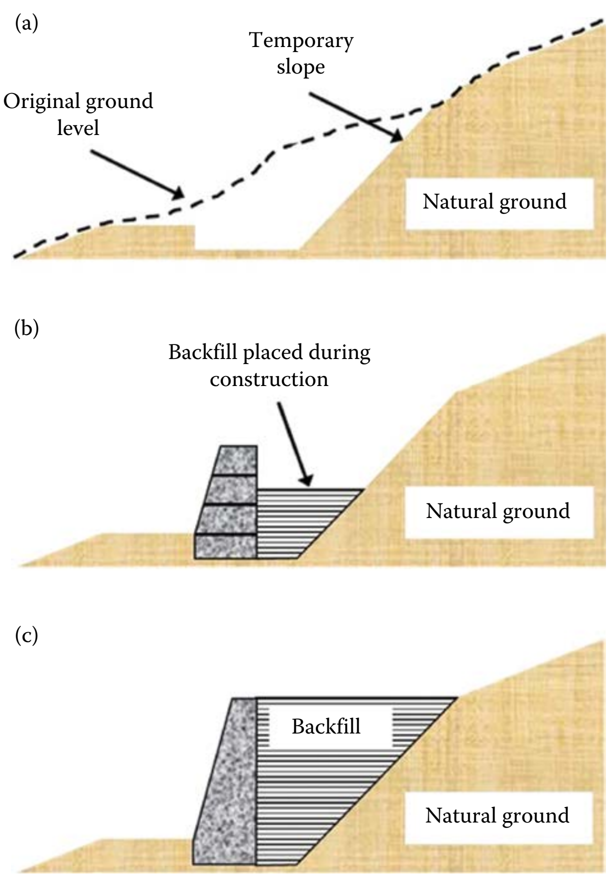

FIGURE 6.5 Simplified construction of a gravity wall: (a) excavation, (b) wall construction, (c) final product. (Credit: A. Braham.)

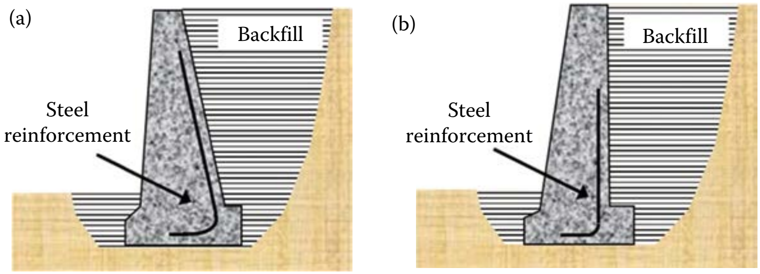

FIGURE 6.6 Typical semigravity concrete walls with steel reinforcement. (Credit: A. Braham.)

A cantilever retaining wall is also made of reinforced concrete, but consists of a thin stem and base foundation. The portion of the footing in front of the wall surface is known as the toe; the portion of the foundation behind the wall and covered with backfill is known as the heel. The names come from the cantilever action of the stem retaining the soil mass behind the wall. The weight of the soil on the heel as well as the wall's self-weight assists with achieving wall stability. The shape of a cantilever retaining wall is usually either a T-shape or an L-shape, as seen in Figure 6.7.

Finally, a counterfort retaining wall is similar to a cantilever wall, but also includes thin, vertical concrete slabs (known as counterfort) that tie the wall and base slab together. These counterforts reduce the shear and bending moments in the wall. Counterfort retaining walls are almost exclusively used for very tall walls, usually 30–36 ft (10–12 m) tall. While counterfort retaining walls are not as common as the other three, it is still an option during design. A simplified wall is shown in Figure 6.8.

Regardless of which of the four walls are used, all are designed to hold Earth back from an engineered area. When holding the Earth back, it is necessary to calculate the lateral Earth pressure, or how much the soil is pushing on the wall.

The first case of interest is when the soil is partially saturated. When the soil is partially saturated, an effective horizontal force is created. This effective horizontal force is a combination of the effective vertical stress and the pore water pressure. The effective horizontal force (P_o) can be solved for using Equation 6.8.

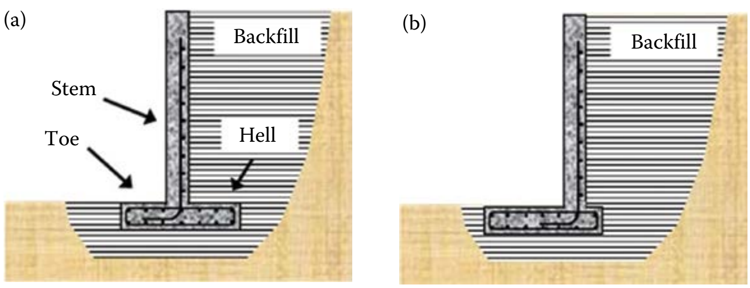

FIGURE 6.7 A T-shaped (a) and L-shaped (b) cantilever retaining wall. (Credit: A. Braham.)

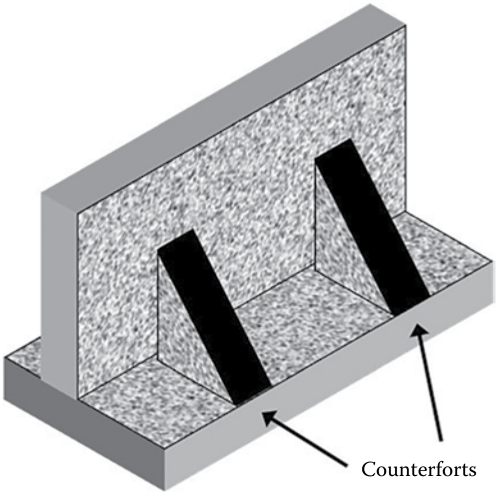

FIGURE 6.8 A simplified counterfort retaining wall. (Credit: A. Braham.)

$$P_o = (P_{A1}) + (P_{A2}) = \left(\frac{1}{2}\sigma_1' K_o H_1\right) + \left(\frac{1}{2}(\sigma_1' + \sigma_2') K_o H_2\right) \quad (6.8)$$

where:

P_o = force per unit length of wall, or effective horizontal force
P_{A1} = force per unit length of unsaturated Earth
P_{A2} = force per unit length of saturated Earth
σ'_1 = lateral pressure of unsaturated Earth
= unit weight of unsaturated Earth (γ_1) multiplied by height of unsaturated Earth (H_1)
K_o = Earth pressure coefficient at rest = 1 – sin φ' for coarse-grained soils
σ_2' = lateral pressure of saturated Earth
$= (\gamma_1 \times H_1) + (\gamma_2 \times H_2) - (\gamma_w \times H_2)$
γ_2 = unit weight of saturated Earth
γ_w = unit weight of water
H_2 = height of saturated Earth

The general case of the Earth pressure coefficient at rest (K_o) is the ratio of the horizontal effective stress and the vertical effective stress. However, various other functions for coarse-grained soils, loose sand, compacted sand, and clays. In addition, work has been done for overconsolidation conditions as well.

The calculation of the effective horizontal force is shown graphically in Figure 6.9.

A specific case for the Earth pressure coefficient is when every point in a soil mass is about to fail, which is the plastic equilibrium in soil. This was explored by Rankine, who looks at both the active and passive forces on a retaining wall (Rankine, 1857). The active force condition, or K_A, is when the retaining wall is allowed to *move away* from the retained soil mass. Conversely, the passive force

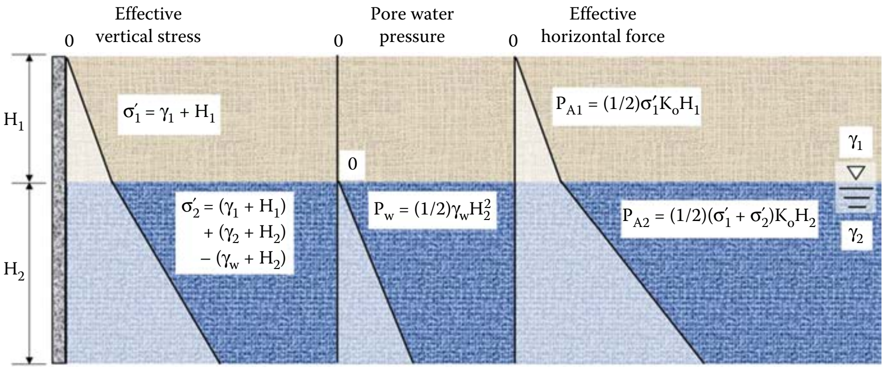

FIGURE 6.9 Horizontal stress profiles and forces. (Credit: A. Braham.)

condition, or K_P, is when the retaining wall *is pushed into* the soil mass. These conditions are represented by Equations 6.9 and 6.10.

$$K_A = \tan^2\left(45° - \phi/2\right) \tag{6.9}$$

$$K_P = \tan^2(45° + \phi/2) \tag{6.10}$$

where a smooth wall is assumed, the backfill is level, the cohesion (c) of the soil is zero, and φ is the angle of internal friction.

From a sustainable standpoint, there have been several studies that have compared a traditional concrete retaining wall versus a bioengineered slope. For example, Storesund et al. (2008) examined the LCCA, energy consumption, and GWP during the planning, design, construction, and operation and maintenance of a creek restoration site. The following life cycle components were included for each stage:

- Planning
  - Permits, permit preparation, configuration and layout, cost and schedule, environmental impact, site characterization: concrete and bioengineered
- Design
  - Scour evaluation, design analysis, plans/specifications/schedule, material quantities, stormwater runoff: concrete and bioengineered
- Construction
  - Earthwork, formwork, steel and concrete, backfill: concrete only
  - Earthwork, vegetation implementation, erosion control: bioengineered only
- Operation and maintenance
  - Graffiti removal: concrete only
  - Pruning and weeding, vegetation replacement, insect and disease control: bioengineered only

TABLE 6.5
Summary of Reinforced Concrete versus Bioengineered Retaining Wall

	Reinforced Concrete			Bioengineered		
Life Cycle Stage	**Value ($)**	**Energy, ft-lb (GJ)**	**Global Warming Potential lb (kg)**	**Value ($)**	**Energy, ft-lb (GJ)**	**Global Warming Potential, lb (kg)**
Planning	50,300	8.26×10^{10} (112)	20,966 (9510)	50,300	8.26×10^{10} (112)	20,966 (9510)
Design	63,400	1.84×10^{11} (249)	42,274 (19,175)	60,900	9.00×10^{10} (122)	25,510 (11,571)
Construction	80,879	2.80×10^{11} (380)	72,757 (33,002)	47,100	3.25×10^{10} (44)	7628 (3460)
Operation and Maintenance	50,000	1.50×10^{11} (203)	32,628 (14,800)	200,000	7.01×10^{10} (95)	17,066 (7741)
Total	244,579	7.07×10^{11} (959)	168,625 (76,487)	358,300	2.77×10^{11} (375)	71,240 (32,314)

A summary of the analysis is provided in Table 6.5.

In Table 6.5, the consecution cost of the bioengineered slope is actually less than the reinforced concrete wall, but because of the higher operation and maintenance cost, the LCCA is actually higher. However, it is important to realize the assumptions that went into the operation and maintenance of the reinforced concrete wall. It was assumed that there would be no deterioration of the concrete, which is certainly possible, assuming proper design and construction. However, if deterioration were included, the LCCA results may have been different. While the economic pillar is higher for the bioengineered slope, the environmental pillar is much lower. The energy of the bioengineered slope is almost 1/3 of the reinforced concrete, and the GWP is just under 1/2. Therefore, a decision must be made by the owner: is the economic pillar or the environmental pillar more important?

While reinforced concrete walls and bioengineered slopes are two options for designing a retaining wall, a third option exists, a mechanical stabilized earth (MSE) wall.

EXAMPLE PROBLEM 6.3

Determine the effective horizontal force on a retaining wall 10 ft tall of two types of fill material on unsaturated fill material. Compare blast furnace slag and well-graded gravel, assuming both are coarse-grained soils. State any assumptions that you make.

Since the fill material is unsaturated, Equation 6.8 can be simplified to read:

$$P_o = (P_{A1}) = \left(\frac{1}{2}\sigma_1' K_o H_1\right)$$

H1 is given as 10 ft, so only σ_1' and K_o need to be calculated for each material. For σ_1', the unit weight of each material needs to be provided. Assuming the average value of 95 pcf for the blast furnace slag (Table 6.1) and an average value of 130 pcf for the well-graded gravel (Table 6.2):

$$\text{Slag} \rightarrow \sigma_1' = \gamma \times H_1 = 95 \text{ pcf} \times 10 \text{ ft} = 950 \text{ psf}$$

$$\text{Gravel} \rightarrow \sigma_1' = \gamma \times H_1 = 130 \text{ pcf} \times 10 \text{ ft} = 1{,}300 \text{ psf}$$

Next, the Earth pressure coefficient at rest is used (again using average internal friction angles from Tables 6.1 and 6.2 for each material, acknowledging that these two materials are both coarse-grained soils:

$$\text{Slag} \rightarrow K_o = 1 - \sin\varphi' = 1 - \sin 42.5 = 0.324$$

$$\text{Gravel} \rightarrow K_o = 1 - \sin\varphi' = 1 - \sin 36.5 = 0.405$$

Finally, we can solve the two effective horizontal forces on the wall:

$$\text{Slag} \rightarrow P_o = (P_{A1}) = \left(\frac{1}{2}\sigma_1' K_o H_1\right) = \left(\frac{1}{2} \times 950 \text{ psf} \times 0.324 \times 10 \text{ ft}\right) = 1540.9 \text{ lb/ft}$$

$$\text{Gravel} \rightarrow P_o = (P_{A1}) = \left(\frac{1}{2}\sigma_1' K_o H_1\right) = \left(\frac{1}{2} \times 1300 \text{ psf} \times 0.405 \times 10 \text{ ft}\right) = 2633.7 \text{ lb/ft}$$

6.4 MECHANICALLY STABILIZED EARTH WALLS

As more retaining walls were designed and installed, a new concept was developed that used the mass of the soil behind the wall to maintain the shape of the soil mass. This concept is referred to as an MSE wall. MSE walls are built in layers, where one to two foot lifts of select backfill are placed and compacted, and strips are laid on the soil. These strips can be made of metal, geogrid, or geotextile. A geogrid is generally made of a rigid plastic (i.e., polyester) that is arranged in a grid pattern, which allows for soil or aggregate interlock within the grid while still increasing the tensile strength of the soil or aggregate. A geotextile is more of a fabric that not only provides tensile strength from friction between the soil and fabric, but can also filter and drain water, or separate different materials without fear of contamination. Both geogrids and geotextiles fall within the geosynthetic family of materials.

After the geosynthetic is laid, a second lift of soil is placed, and a second layer of strips is placed. As the wall moves upward, the soil either slowly steps back with stone facing or is vertical, with typically a precast concrete panel facing. The concrete panels are pinned to the strips, which means the panels are hanging from the strips that are embedded in the Earth. The weight of the soil provides friction for the strips and prevents the soil wall from failing. Figure 6.10 shows two schematics

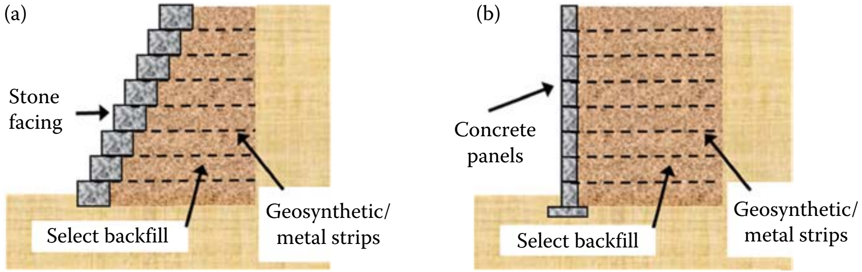

FIGURE 6.10 Stepped (a) versus vertical (b) MSE walls. (Credit: A. Braham.)

of MSE walls, while Figure 6.11 shows an example stepped MSE wall in Northwest Arkansas and Figure 6.12 shows an example vertical MSE wall. Figure 6.12 is a vertical MSE wall with concrete panels being constructed in Little Rock, Arkansas, with a close-up of the back of a concrete panel with ties for the metal strips (a) and an overview with select fill (b). For vertical MSE walls, there is a narrow continuous footing underneath the concrete panels, which only provides support for the panels, as seen in Figure 6.10b.

On both stepped and vertical MSE walls, the stone facing and concrete panels are mainly for aesthetic purposes and for preventing erosion of the retained soil. Also of interest, in Figure 6.12b, is the sheet piles that are behind the MSE wall being constructed. The pictures of Figure 6.12 are of I-630 in Little Rock, Arkansas. The MSE wall was being constructed because in order to keep the entire width of the interstate at the same grade, the westbound lanes needed to be elevated significantly. The sheet piles just behind the MSE wall are holding up the existing soil material,

FIGURE 6.11 Stepped MSE wall. (Credit: A. Braham.)

(a)
(b)

FIGURE 6.12 (a) MSE wall construction concrete panel with ties for the metal strips. (Credit: A. Braham.) (b) MSE wall construction overview with select fill. (Credit: A. Braham.)

while the MSE wall is being constructed. At the end of construction, the sheet piles will be removed and the MSE wall will hold the exiting soil material in place. This demonstrates the importance of recognizing temporary structures on construction sites that are necessary to maintain functionality of the infrastructure during the construction phase.

Another important discussion point when considering MSE walls is their social benefit, especially when considering vertical MSE walls. Many vertical MSE walls are used in locations where there is little excess space on either side of the project. On roadways, this is termed the right of way (ROW). State agencies must design and construct their infrastructure within the ROW, or they need to purchase land adjacent to the ROW. Many existing highways within urban centers are overcapacity with very poor level of service. However, owing to economic and social issues, two of the three pillars of sustainability, it is not feasible to acquire land adjacent to the ROW. Therefore, vertical MSE walls can fully utilize ROW space, even when there are elevation changes along the project. In Figure 6.12b, a vertical MSE wall was probably constructed because AHTD could not acquire additional land as I-630 passed through Little Rock.

MSE walls must satisfy both internal and external stability. Internal stability governs reinforcement spacing, while external stability governs reinforcement length. Internally, the reinforced soil structure (the select backfill plus strips) must be coherent and self-supporting under its own weight and any externally applied forces. The reinforcements should not fail either in tension or by pulling out of the select backfill. Externally, the structure must resist overturning (or toppling), sliding at the base, sliding below the base (deep-seated failure), or global instability (bearing capacity failure). In general, the length of reinforcement is 70%–80% of the wall height, and the wall is embedded approximately 5%–10% of the wall height.

While there are entire books written about the design of retaining walls (Brooks and Nielsen, 2013), it is worthwhile to have a single, simple example of vertical MSE wall design in order to get a flavor of more advanced design principles. For example (Abramson et al., 1996), when designing an MSE wall that utilizes galvanized steel strip reinforcement, the strip length must be long enough in order to support the concrete panel wall and provide a stable mass. The minimal length (L_{min}) of the steel strip can be calculated using Equation 6.11.

$$L_{min} = \frac{F_s K S \Delta H}{2W \tan \delta} \tag{6.11}$$

where

F_s = safety factor (usually 1.5–2.0)
K = Earth pressure coefficient
S = horizontal spacing of steel strips
ΔH = vertical spacing of steel strips
W = width of steel strips
δ = angle of friction of backfill (note that in the MSE wall, design δ is used instead of the traditional φ that is usually used for the angle of friction in soil applications)

According to Abramson et al., typical dimensions for the horizontal spacing of steel strips (S) is 24 in, the vertical spacing of steel strips (ΔH) is 10–12 in, and the width of the steel strips (W) is 3 in.

EXAMPLE PROBLEM 6.4

Using the same two materials and conditions as in Example Problem 6.3, determine the minimum strap length for an MSE wall. State any assumptions you must make.

Utilizing Equation 6.11, the factor of safety will be assumed to be in the middle of the given range, so $F_s = 1.75$. For slag, $K = 0.324$ and for gravel, $K = 0.405$. Finally, assuming the strap spacing and width that Abramson utilized, $S = 24$ in, $\Delta H = 11$ in (the average value), and $W = 3$ in. Therefore, the minimum strap lengths can be estimated:

$$\text{Slag} \rightarrow L_{min} = \frac{F_s K S \Delta H}{2W \tan\delta} = \frac{1.75 \times 0.324 \times 24 \text{ in} \times 11 \text{in}}{2 \times 3 \text{ in} \times \tan 42.5} = 27 \text{ in}$$

$$\text{Gravel} \rightarrow L_{min} = \frac{F_s K S \Delta H}{2W \tan\delta} = \frac{1.75 \times 0.405 \times 24 \text{ in} \times 11 \text{in}}{2 \times 3 \text{ in} \times \tan 36.5} = 42.2 \text{ in}$$

This calculation shows how for a relatively short wall, and with an especially cohesive fill material (gravel), the use of metal strips may not be most appropriate.

HOMEWORK PROBLEMS

1. Using the data from Example Problem 6.1, calculate the void ratio, the saturated unit weight, and the porosity.
2. Create a phase diagram for reclaimed concrete. Assume a specific gravity of 2.678, a soil volume of 1 ft^3 and a total volume of 1.3 ft^3. In addition, calculate the void ratio, the saturated unit weight, and the porosity. State any assumptions that need to be made.
3. A truck hauling fill material can carry approximately 40 tons of fill, which equates to 40,000 pounds. Assuming a loose density of 120 pcf of the well-graded sand material (Table 6.2), and a density of 1.5 pcf of the geofoam (Table 6.3), what classification of truck would be required to haul the well-graded sand material, and the same volume of geofoam? What is the difference in VOC, CO, and PM2.5 emissions from these two trucks? State any assumptions that you need to make.
4. Geofoam seems to have many beneficial characteristics. However, there are challenges during the design and construction of fill when using geofoam. Identify what you believe the two largest challenges are, and discuss using the format provided under Sidebar 1.2 "Writing a High-Quality Essay."
5. Determine the effective horizontal force on a retaining wall 20 ft tall of two types of fill material on unsaturated fill material for the top 10 ft and saturated fill material for the bottom 10 ft. Compare blast furnace slag

and well-graded gravel, assuming both are coarse-grained soils. State any assumptions that you make.

6. Bioengineered slopes seem to have many beneficial characteristics. However, there are challenges during the design, construction, and maintenance of bioengineered slopes. Identify what you believe the two largest challenges are, and discuss using the format provided under Sidebar 1.2 "Writing a High-Quality Essay."
7. Determine the minimum strap length for an MSE wall with lean clay is the fill material (note: assume you can estimate the Earth pressure coefficient using the equation given for coarse-grained soils). The wall will need to be 20 ft tall. State any assumptions you must make.
8. In total, six types of retaining walls were explored. List the six types, and choose which type you think is most sustainable. Give one example of economic, environmental, and social reasons for your choice. Discuss using the format provided under Sidebar 1.2 "Writing a High-Quality Essay."

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7 Application
Structural Sustainability

Don't let schooling interfere with your education.

Mark Twain

Many young aspiring civil engineers enter the discipline because of structures. Whether soaring skyscrapers or elegant bridges, structures is the extroverted side of civil engineering. The area of structures also has many different perspectives for sustainability. Whether looking at materials, design, or evaluation, there are many applications to incorporate sustainable practices. This chapter will cover two material-related themes, one design theme, and finish with a discussion about how to evaluate the sustainability of structural systems. Specifically, this chapter will cover these four areas:

1. Fly ash
2. Bamboo
3. Steel diagrids
4. Certification and rating systems

7.1 FLY ASH

It is estimated that there are over 600 coal power plants in the United States that produced over 52 million short tons of fly ash in 2012 (EPA, 2015). Fly ash is both inorganic and noncombustible, and is a residue of coal after burning in power plants. Fly ash is a pozzolanic material, and can be used as a supplement of Portland cement in PCC. During combustion of coal, the volatile matter and carbon are burned off, while the mineral impurities melt and are fused together. These mineral impurities include clay, feldspar, and quartz. The fused material is moved to low-temperature zones where it solidifies into spherical particles of glass. The material that falls is bottom ash (from agglomeration), while the rest of the material are light enough to be lifted out with the flue gas stream. This light material is the fly ash, and it is removed from the gas by cyclone separation, electrostatic precipitation, and baghouse filtration.

There are two categories of fly ash: Class C (high calcium) and Class F (low calcium). The mean size of both Class C and F fly ash is 10–15 μm, the surface area is 1–2 m^2/g, and the specific gravity is 2.2–2.4. Table 7.1 shows some differences in mineral composition between the two classes. Class C fly ash comes from anthracite and bituminous coal, whereas Class F fly ash comes from lignite and subbituminous coal. In general, if the amount of carbon in fly ash is greater than 5%, it is not desirable for use in PCC.

TABLE 7.1
Common Characteristics of Fly Ash

	mg $Ca(OH)_2$ consumed/gram	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	Carbon (%)
Class C	500	>30	15–25	<10	20–30	<1
Class F	850	>50	20–30	<20	<5	<5

Fly ash with higher amounts of calcium display cementitious behavior, and will react with water to perform hydrates when calcium hydroxide is not available. This reaction benefits PCC as it increases the cementitious binder phase (calcium-silicate hydrates, or C-S-H), improving the long-term strength and decreasing the permeability. Fly ash is generally used as a partial substitute for Portland cement.

Not only are there physical differences between the two materials, as seen in Figure 7.1, but the two materials also influence both the fresh and hardened concrete properties. These influences are summarized nicely in a publication put out by the Portland Cement Association (Thomas, 2007), and summarized in the following paragraphs.

When examining fresh concrete, fly ash can affect the workability, water demand, setting time, heat of hydration, and finishing and curing. In terms of workability, the addition of fly ash increases workability, making the concrete easier to place, consolidate, and finish. The increase of workability comes from the fact that fly ash has a relatively high fineness and low carbon content, which reduces the need for water. Therefore, in general, less water is needed when substituting either Class F or Class C fly ash for Portland cement. A rule of thumb is for each 10% of fly ash substituted for Portland cement, the water can be reduced 3%.

In addition to the workability and water content, the setting time can also be decreased. In general, low-calcium fly ashes extend both the initial and final set

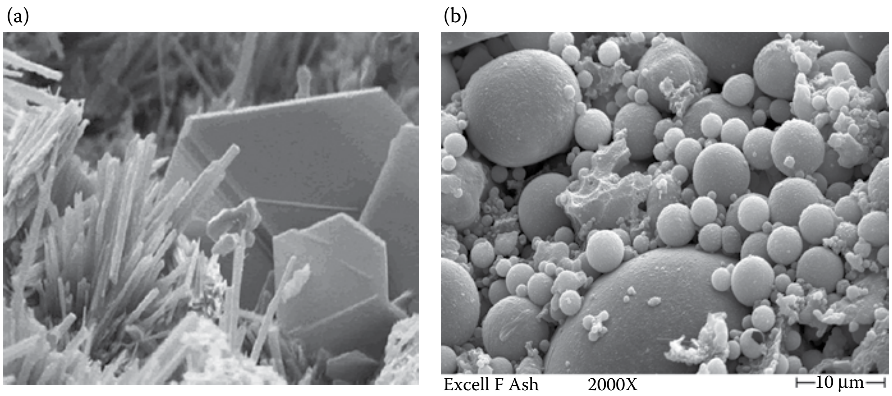

FIGURE 7.1 (a) Portland cement hardened paste, plates of calcium hydroxide, and needles of ettringite, micron scale. (Credit: US DOT.) (b) Fly ash. (Credit: PMET Lab Service.)

times of PCC. This influence, however, is dependent on ambient temperature. During hotter weather, the extension of time is reduced and may actually become a benefit, whereas in colder weather, the extended set time can cause delays and thus complicate placement and finishing operations. Conversely, higher-calcium fly ashes do not retard setting time as much as lower-calcium fly ashes because of the increase of hydraulic reactivity. However, this trend is more difficult to predict, so a full laboratory evaluation is recommended before incorporating a new fly ash source.

The next fresh PCC characteristic, heat of hydration, is an incentive for using fly ash, especially in mass concrete construction. Large-scale structures, such as dams or large bridge columns, can cure improperly due to the high heat within the concrete mass, which could lead to cracking and other temperature-related damage. However, if early age strengths are not necessary, the use of fly ash can reduce the heat of hydration, thus reducing potentially harmful high temperatures. Studies have shown that replacing approximately half of Portland cement with Class F fly ash, for example, can reduce the maximum temperature in large concrete blocks by almost 30% (Langley et al., 1992).

While the workability, setting, and heat of hydration can all be influenced by fly ash, the final finishing and curing should also be considered. The rate of pozzolanic reaction is slower than the rate of cement hydration, and more care must be taken in order to ensure proper curing. When using fly ash, the concrete should be moist cured for a minimum of 7 days, and ideally, a curing member should be added after 7 days and curing should be extended to 14 days. Table 7.2 summarizes the trends of fresh properties of concrete using fly ash.

In addition to fresh concrete, hardened concrete properties must also be accounted for. Important hardened properties include compressive strength development, permeability, and alkali–silica reaction (ASR). In general, the initial compressive strength of concrete is lower with fly ash, and the strength continues to decrease with an increase of fly ash. However, long-term strength is actually increased with the use of fly ash.

The permeability of PCC is important for durability and long-term performance in the field, especially in the presence of chlorides. Chlorides are especially destructive to reinforcing steel, and will destroy the passive oxide fill on steel if able to permeate into the PCC. Therefore, it is beneficial to have low permeability. With the addition of fly ash, the permeability decreases in PCC.

TABLE 7.2
Fly Ash Impact on Fresh Properties of Concrete

Fly Ash Type	Workability	Water Demand	Setting Time	Heat of Hydration	Finishing and Curing
Class F	Increases	Decreases	Increases	Decreases	Increase
Class C	Increases	Decreases	May increase or decrease	May increase or decrease	May increase or decrease

TABLE 7.3
Fly Ash Impact on Hardened Properties of Concrete

Fly Ash Type	Compressive Strength—Short Term	Compressive Strength—Long Term	Permeability	Alkali–Silica Reaction
Class F	Decreases	Increases	Decreases	Decreases
Class C	May increase or decrease	Increases	Decreases	Decreases

Class F fly ash can control damaging ASR at intermediate levels of replacement (20%–30%). ASR occurs when the alkalis in the cement paste react with certain types of silica in the aggregate. The concrete expands during this reaction, which causes cracking. While Class C fly ashes are less effective, both essentially reduce the concentration of alkali hydroxides in the pore solution when fly ash is present. Table 7.3 summarizes the trends of hardened properties of concrete using fly ash.

Overall, fly ash influences both the fresh and hardened properties of PCC, and if properly managed, can increase the performance of the PCC. In addition to these material benefits, fly ash is also very beneficial from both an economic and environmental standpoint.

From an economic standpoint, fly ash has shown to have an advantage over Portland cement. Lippiatt and Ahmad (2004) performed an LCCA that incorporated costs from the product purchase onward, which encompasses all out-of-pocket costs. They calculated that both first and future costs would be approximately 10% lower with the incorporation of 35% fly ash into a PCC mix (with 65% Portland cement) compared to a PCC mix containing 100% Portland cement. A second study by Santero et al. (2011) anticipated an average savings of approximately $15,000/lane-km when going from 10% to 30% fly ash replacement for Portland cement in PCC pavements. Finally, a study by Lu (2007) found an optimal value of 23% fly ash replacement for use in footpaths and bicycle lanes. These studies all show that replacing virgin Portland cement can potentially save money over the life of the application.

Similarly, environmental benefits of utilizing fly ash have been found. Ondova and Estokova (2014) performed an LCA on 15% replacement of fly ash for Portland cement, and examined the extraction, production, application, and disposal/recycling phase of PCC. Overall, the research found that utilizing 15% fly ash reduced the GWP from 1763 to 1668 kg CO_2 equivalent/kg (a reduction of over 5%) and the acidification potential from 3.4 to 3.2 kg SO_2 equivalent/kg (a reduction of over 6%). A second study used the PaLATE LCA tool, which incorporates the production of materials, construction, maintenance, and end-of-life processes (Ahlman et al., 2015). The research took findings from six state Department of Transportations (Colorado, Georgia, Illinois, Minnesota, Pennsylvania, Virginia, and Wisconsin), and found that the environmental benefits from the use of fly ash provided 81% savings in energy, 88% savings in water consumption, and 82% in CO_2. Overall, these studies show significant environmental benefits of fly ash as a replacement of Portland cement.

EXAMPLE PROBLEM 7.1

A local contractor is investigating replacing 30% virgin Portland cement with fly ash. The concrete with 100% Portland cement has a compressive strength of 33 MPa at 3 days and a compressive strength of 52 MPa at 90 days. The concrete with 30% fly ash has a compressive strength of 28 MPa at 3 days and 60 mPa at 90 days. Using the common relationship between compressive strength and modulus of elasticity, calculate the secant modulus of elasticity (E_c) at these four strength levels.

The common relationship is $E_c = 0.043w_c^{1.5}\sqrt{f_c'}$, where the unit weight of concrete is usually assumed to be 2320 kg/m_3, giving $E_c = 4730\sqrt{f_c'}$. Therefore

100% Portland cement, 3 day cure → $E_c = 4730\sqrt{33\text{ MPa}} = 27.2\text{ GPa}$
100% Portland cement, 90 day cure → $E_c = 4730\sqrt{52\text{ MPa}} = 34.1\text{ GPa}$
30% Fly ash, 3 day cure → $E_c = 4730\sqrt{28\text{ MPa}} = 25.0\text{ GPa}$
30% Fly ash, 90 day cure → $E_c = 4730\sqrt{60\text{ MPa}} = 36.6\text{ GPa}$

7.2 BAMBOO

Wood is a common building material, especially in the United States and Europe, with the added benefit of being a renewable resource and a location for carbon storage. The United States has approximately 746 million acres of forest land that provides collection of carbon through absorption. With the continued use of carbon dioxide emissions, these types of "terrestrial pools" are beneficial in absorbing carbon from the atmosphere (EPA, 1995). However, another renewable resource that could be used as a building material is bamboo. Bamboo, like wood, is renewable and has mechanical properties similar to timber (Widenoja, 2007). In fact, according to Sharma et al. (2015), bamboo has a faster growth rate and shorter harvest cycle versus wood, and has four times the carbon density versus spruce forests. Wood is most frequently found in the northern hemisphere (North America, Europe, Russia), while the majority of developing areas in the world are in the equatorial regions or in the southern hemisphere, locations where bamboo is more common than wood. The general structure of bamboo is similar to wood, as it is an anisotropic material, where the properties vary in the longitudinal, radial, and transverse directions. The structure of bamboo, where longitudinal fibers align with a lignin matrix, is what causes this anisotropic behavior. These longitudinal fibers are divided by solid diaphragms along the longitudinal length, as seen in Figure 7.2.

Overall, there are 1200 species of bamboo worldwide, with a variation in both geometrics and mechanical properties, making it difficult to design connects and joints suitable for various sections of construction material, such as columns, beams, or other permanent, loading-bearing structures. However, bamboo composites are of interest because of the standardization of shape, low variability of material properties.

Similar to plywood and particle board, bamboo can be broken down and reassembled in a more beneficial form (Sharma et al., 2015). There are two types

FIGURE 7.2 Solid diaphragms dividing the longitudinal fibers. (Credit: Alain Van den Hende.)

of bamboo composites available, laminated and scrimber. Laminated bamboo preserves both the longitudinal and culm (radial) matrix. The bamboo is split and planed, bleached, and caramelized. After lamination, it is pressed to form a board product. This process uses approximately 30% of the raw inputs, as much of the input material is lost during the planing process.

The second bamboo composite is scrimber, which maintains only the longitudinal matrix. The scrimber bamboo is produced by weaving the longitudinal strands, crushing the woven strands, and saturating in resin. This compressed, dense block maintains the longitudinal direction of the fibers and the resin matrix connects the fiber bundles. A benefit to this technique is that the scrimber process utilizes approximately 80% of the raw inputs.

Sharma et al. (2015) performed a study that compared various material properties of both scrimber and laminated bamboo with raw bamboo, spruce lumber, and laminated veneer lumber. This allowed for direct comparison between not only the two different forms of composite bamboo (laminated and scrimber), but also the raw materials alone (bamboo and spruce) and two different laminated materials (lumber and bamboo). The results are shown in Figure 7.3a through d. Note that the compressive, tensile, and shear strengths are all measured parallel to the material's primary orientation.

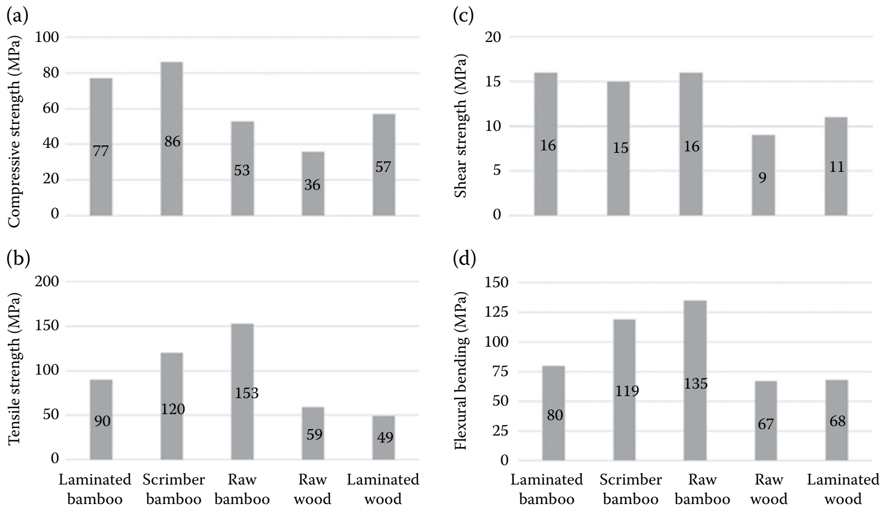

FIGURE 7.3 Mechanical properties of laminated bamboo, scrimber bamboo, raw bamboo, raw wood, and laminated wood. (From Sharma, B. et al. *Construction and Building Materials*, 81, 2015, 66–73.)

In Figure 7.3, the scrimber bamboo has higher values in all four mechanical properties versus laminated (except the shear strength, which is essentially the same in the two materials). Therefore, it would appear that since scrimber bamboo has better performance and uses a higher percentage of raw inputs, it would be the preferable method of utilizing composite bamboo. When comparing the laminated bamboo to the laminated wood, the laminated bamboo has higher values in all four mechanical properties without exception, indicating that it is a stronger and more versatile material. Finally, the raw bamboo also has higher values in all four mechanical properties versus raw wood. From this data set, it would appear that bamboo is a stronger material than wood. However, when thinking about sustainability, it is also critical to think of the cost (economic pillar) and the processing requirements (economic and environmental pillar). In the United States, the costs and processing requirements would be higher for bamboo since the supply is lower, but in southeast Asia, where bamboo is more commonly used than wood, the economic and environmental impacts are most likely lower.

The discussion up to now has focused on comparing bamboo to wood, but there are also applications where bamboo is a reasonable replacement of steel. A common form of scaffolding in the United States and Europe is steel, but in China and Southeast Asia, bamboo is much more prevalent as a scaffolding material. For example, Figure 7.4 shows a construction site in Hefei, Anhui province, China that utilized bamboo as a scaffolding material.

A mode of failure that is important when constructing scaffolding is buckling failure. When considering elastic buckling stresses, the calculations for bamboo and steel are a bit different, but they have a similar starting point. Buckling, regardless

FIGURE 7.4 Bamboo used as a scaffolding material in Hefei, China. (Credit: A. Braham.)

of material, is generally represented by Euler's formula, which is seen in Equation 7.1:

$$F_e = \frac{\pi^2 E}{(KL/r)^2} \tag{7.1}$$

where
F_e = elastic buckling force
E = modulus of elasticity
K = column effective length factor
L = unsupported length of column
r = radius of gyration

The column effective length factor is dependent on the end conditions. When both ends are pinned, K = 1. When both ends are fixed, K = 0.50. If one end is fixed and the other end is pinned, K = 0.7071. Finally, if one end is fixed and the other end is free to move laterally, K = 2.0.

While Equation 7.1 provides the foundation for both the bamboo and steel buckling equation, when considering bamboo, an alpha value is placed in front of the equation, creating Equation 7.2:

$$F_e = \frac{\alpha\pi^2 E}{(KL/r)^2} \tag{7.2}$$

where α is a function of the second moment of area, and depends on the moisture content. Alpha ranges from 1.00 to 2.35, and increases as the moisture content increases.

EXAMPLE PROBLEM 7.2

A firm in Central Arkansas would like to explore using bamboo as a substitute to steel for scaffolding. However, they are concerned about the load-carrying ability of the bamboo versus the steel. Assume that both materials are pinned connected at each end, the length of the column will be 12 ft, and the radius of gyration of each material is 1.25 in. Also, assume that the modulus of elasticity of the steel is 28.8×10^6 psi. Compare the steel to bamboo in a wet state ($\alpha = 2.35$, $E = 0.97 \times 10^6$ psi) and in a dry state ($\alpha = 2.35$, $E = 1.50 \times 10^6$ psi).

Using Equation 7.1, the elastic buckling force can be calculated for steel:

$$\text{Steel} \rightarrow F_e = \frac{\pi^2 E}{(KL/r)^2} = \frac{\pi^2 \times 28.8E^6 \text{ psi}}{(1.0 \times 144\text{in}/1.25\text{in})^2} = 21.4 \text{ ksi}$$

Using Equation 7.2, the elastic buckling force can be calculated for the bamboo:

$$\text{Bamboo dry} \rightarrow F_e = \frac{\alpha\pi^2 E}{(KL/r)^2} = \frac{1.00 \times \pi^2 \times 1.50E^6 \text{ psi}}{\left(1.0 \times 144\text{in}/1.25\text{in}\right)^2} = 1.1 \text{ksi}$$

$$\text{Bamboo wet} \rightarrow F_e = \frac{\alpha\pi^2 E}{(KL/r)^2} = \frac{2.35 \times \pi^2 \times 0.97E^6 \text{ psi}}{(1.0 \times 144\text{in}/1.25\text{in})^2} = 1.7 \text{ ksi}$$

7.3 STEEL DIAGRIDS

When considering the potential life cycle stages of steel, a manufactured product, you have five stages:

1. Material extraction
2. Material processing
3. Manufacturing
4. Product use
5. End of life

Recycling consists of going from the end-of-life stage to the material processing. According to the Steel Recycling Institute (www.recycle-steel.org), if steel is made in North America, it contains a minimum of 28% recycled content. By essentially skipping step one of the life cycle stages of steel, it is estimated that recycling steel saves 74% of the energy required in the life cycle. From 1990 to 2013, the steel recycling rates have increased in North America from 67% to 81%.

The steel recycling process begins with the delivery of the steel to a recycling process center. All of the metal material is sent through a series of rollers, hammer mills, and other crushing mechanisms, in order to reduce the size and begin the separation of material into ferrous metal, nonferrous metal, and nonmetallic material (such as plastic, rubber, cloth, etc.). The crushed material is passed through a magnetic drum, which attracts the ferrous metal while the other material is diverted to another stream. Through other sorting mechanisms, such as air separation or even human evaluation, pick out material (such as copper) that would degrade the quality of the recycled steel. During all of these stages, the material can also be scanned for any radioactive properties to ensure that the newly formed steel will not have radioactive characteristics. The high-quality ferrous materials are sent to steel mills and incorporated into new finished steel products.

A unique and innovative design strategy, moving away from traditional moment frame design as support structures, is a diagrid structure (Moon et al., 2007). In this design, perimeter diagonals are used. These structures have been used on buildings as tall as 123 stories and as short as six stories. Some of the more iconic buildings include the CCTV Tower in Beijing (referred to by locals as “Big Shorts” or 大裤衩, dàkùchǎ), the Swiss Re building in London, and the Hearst Tower in New York (Korsavi and Maqhareh, 2014). The CCTV Tower and Hearst Tower can be seen in Figure 7.5a and b, respectively.

In traditional moment frame buildings, the goal is to eliminate yielding and lateral-torsional buckling in beams while minimizing shear. In the columns, the design compressive strength prevents buckling. While designing diagrids, the building is divided into two sets of faces, the web and the flange. The web planes are parallel to dominant wind directions, while the flange planes are perpendicular to dominant wind directions. This orientation is shown in Figure 7.6.

In the design for the amount of steel for each diagonal on the web, the shear force and the transverse shear strain are necessary. For the flange, the moment, the bending rigidity, and the curvature are necessary. The following equation solves for the area of each diagonal on the web facing of the building:

$$A_{d,w} = \frac{V \times L_d}{2 \times N_{d,w} \times E_d \times h \times \gamma \times \cos^2\theta}$$

where

$A_{d,w}$ = area of each diagonal on the web
V = shear force
L_d = length of diagonal
$N_{d,w}$ = number of diagonals on each web plane
E_d = modulus of elasticity of steel
h = height of diagonal
γ = transverse shear strain
θ = angle of diagonal member

A similar equation has been developed for the area of steel needed on the flange diagonal members:

$$A_{d,f} = \frac{2 \times M \times L_d}{(N_{d,f} + \delta) \times B^2 \times E_d \times h \times \chi \times \sin^2\theta}$$

(a) (b)

FIGURE 7.5 (a) 大裤衩 [Big Shorts] in Beijing, China. (Credit: A. Braham.) (b) Hearst Tower in New York. (Credit: A. Braham.)

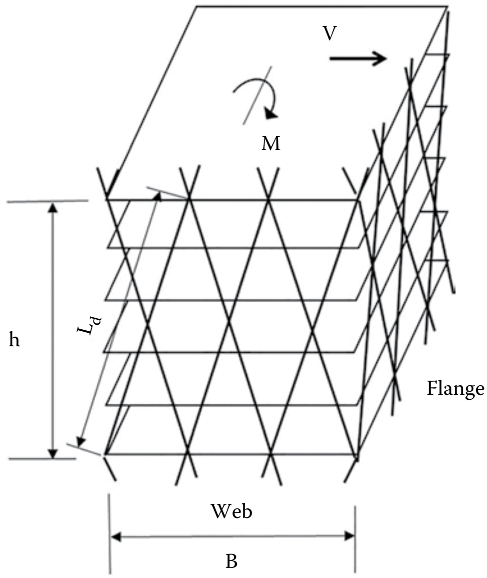

FIGURE 7.6 Diagrid structural elements. (Credit: A. Braham.)

where
$A_{d,f}$ = area of each diagonal on the flange
M = moment
$N_{d,f}$ = number of diagonals on each flange plane
δ = contribution of web diagonals for bending rigidity
B = building width in the direction of applied force
χ = curvature

An example of comparing a moment frame design to a diagrid design was performed by Deshpande et al. in 2015. A 60-story building was designed using a moment frame with I-beams and a diagrid frame with tube members. The moment frame incorporated the web depth and flange width of the columns, the length of the columns, and the number of sections. The diagrid frame included the outer diameter, inner diameter, thickness, length, sections, and connections within the structure. Each story on the moment frame building was 9 ft high, and each story on the diagrid building was 12 ft high. The diagrid angle was 72° for the first 20 stories, and then was reduced to 56° from 20–60 stories. In addition to the steel necessary for the exterior columns, both buildings required 7900 tons of steel for core beams and 630 tons for facade beams. Table 7.4 summarizes the amount of steel needed for the exterior columns and the total amount of steel needed for the full design.

Table 7.4 shows that the diagrid frame uses approximately 25% less steel than a traditional moment frame structure. While this single analysis was performed using ETABS software, this number is representative of actual projects. For example, the Hearst Tower in New York City reportedly used approximately 20% less

TABLE 7.4
Exterior Steel Necessary for 60-Story Building

Story	Moment Frame (Tons Steel)	Diagrid Frame (Tons Steel)	Diagrid Angle (θ)
1–20	3500	2700	72°
20–40	2100	356	56°
40–60	1050	130	56°
Total steel—including beams	15,250	11,248	

steel (2000 tons, Boniface, 2006) in its diagrid design versus a moment frame design.

However, the concept of moment frames is not efficient over approximately 15–20 stories. While moment frames have good lateral stiffness at lower heights, for resisting wind and earthquake loads, in order to be resistant to these loads in taller structures, the beams become unreasonably deep. This depth decreases the available height between floors and increases the cost. Therefore, tall buildings are generally a framed tube structure, where the interior core (of elevator shafts, stairwells, and building utilities are housed) provides the stiffness, and the exterior is just facing. Buildings are complex structures, and the examples provided in this section are intended to introduce a different type of structural design not commonly found in college curriculum.

EXAMPLE PROBLEM 7.3

Utilizing the data for the 60-story building in Table 7.4, calculate the difference in emissions using the following data (from WSA, 2011):

- Primary energy demand (PED): 4.82×10^7 lbf/ton
- Global warming potential (GWP): 1.6 ton CO_2 equiv./ton
- Acidification potential (AP): 0.0045 ton SO_2 equiv./ton
- Eutrophication potential (EP): 0.00036 ton phosphate/ton
- Photochemical ozone creation potential (POCP): 0.0008 ton ethene/ton

For PED:	Moment frame: 15,250 tons × 4.82E10^7 lbf/ton = 7.35×10^{11} lbf
	Diagrid: 11,248 tons × 4.82E10^7 lbf/ton = 5.42×10^{11} lbf
For GWP:	Moment frame: 15,250 tons × 1.6 ton CO_2 equiv./ton = 2.44×10^4 ton CO_2 equiv.
	Diagrid: 11,248 tons × 1.6 ton CO_2 equiv./ton = 1.80×10^4 ton CO_2 equiv.
For AP:	Moment frame: 15,250 tons × 0.0045 ton SO_2 equiv./ton = 68.6 ton SO_2 equiv.
	Diagrid: 11,248 tons 0.0045 ton SO_2 equiv./ton = 50.6 ton SO_2 equiv.
For EP:	Moment frame: 15,250 tons × 0.00036 ton phosphate/ton = 5.49 ton phosphate
	Diagrid: 11,248 tons × 0.00036 ton phosphate/ton = 4.05 ton phosphate
For POCP:	Moment frame: 15,250 tons × 0.0008 ton ethene/ton = 12.2 ton ethene
	Diagrid: 11,248 tons × 0.0008 ton ethene/ton = 9.00 ton ethene

7.4 CERTIFICATION AND RATING SYSTEMS

In Chapter 5, sustainable concepts around drinking water and wastewater treatment were discussed, from a standpoint of the processing of the water. In Chapter 6, various types of retaining walls were explored to hold back Earth fills. These three applications, however, not only have applications in the environmental and geotechnical areas of civil engineering, but also structural engineering, as a structure needs to be designed in order to allow for the water and wastewater to be treated, and the soil to be retained. Since structures are so prevalent within civil engineering, the United States Green Building Council (USGBC) established a certification program for sustainability. In 1993, USGBC released The Leadership in Energy and Environmental Design, or LEED, certification system.

The LEED system is based on points. In short, various categories have been established that quantify the sustainability of a building, and those points are added up for a final score. As LEED has been developed, some credits within the categories have moved from optional to required. Based on the final score, a rating is established. In 2016, there were four levels of LEED certification based off of 110 points (following version 4). If a building earned 80 or more points, it is considered LEED Platinum certified. If the building earned 60–79 points, it is considered LEED Gold certified. 50–59 points earns a LEED Silver certification, and finally, 40–49 points earns LEED certified. Certification can be applied to eight different types of building construction:

1. New construction and major renovation
2. Core and shell
3. Schools
4. Retail
5. Data centers
6. Warehouse and distribution centers
7. Hospitality
8. Health care

Each of these eight types of building construction is then broken down into eight categories:

1. Location and transportation
2. Sustainable sites
3. Water efficiency
4. Energy and atmosphere
5. Materials and resources
6. Indoor environmental quality
7. Innovation in design
8. Regional priority

Each type of building construction has slightly different requirements under the eight categories, but general concepts and themes are similar for each type of building construction. Table 7.5 summarizes the checklist for new construction and

TABLE 7.5
Summary of LEED New Construction and Major Renovation Credits

Category (110 Points Total)	Credit	Points Possible
No category (1 point total)	Integrative process	1
Location and transportation (16 points total)[a]	Sensitive land protection	1
	High-priority site	2
	Surrounding density and diverse uses	5
	Access to quality transit	5
	Bicycle facilities	1
	Reduced parking footprint	1
	Green vehicles	1
Sustainable sites (10 points total)	Construction activity pollution prevention	Required
	Site assessment	1
	Site development—protect or restore habitat	2
	Open space	1
	Rainwater management	3
	Heat island reduction	2
	Light pollution reduction	1
Water efficiency (11 points total)	Outdoor water use reduction, indoor water use reduction, building-level water metering	Required
	Outdoor water use reduction	2
	Indoor water use reduction	6
	Cooling tower water use	2
	Water metering	1
Energy and atmosphere (33 points total)	Fundamental commissioning and verification, minimum energy performance, building-level energy metering, fundamental refrigerant management	Required
	Enhanced commissioning	6
	Optimized energy performance	18
	Advanced energy metering	1
	Demand response	2
	Renewable energy production	3
	Enhanced refrigerant management	1
	Green power and carbon offsets	2
Materials and resources (13 points total)	Storage and collection of recyclables, construction and demolition waste management planning	Required
	Building life-cycle impact reduction	5
	Building product disclosure and optimization—environmental product declarations	2
	Building product disclosure and optimization—sourcing of raw materials	2

(*Continued*)

TABLE 7.5 (*Continued*)
Summary of LEED New Construction and Major Renovation Credits

	Building product disclosure and optimization—material ingredients	2
	Construction and demolition waste management	2
Indoor environmental quality (16 points total)	Minimum indoor air quality performance, environmental tobacco smoke control	Required
	Enhanced indoor air quality strategies	2
	Low-emitting materials	3
	Construction indoor air quality management plan	1
	Indoor air quality assessment	2
	Thermal comfort	1
	Interior lighting	2
	Daylight	3
	Quality views	1
	Acoustic performance	1
Innovation (6 points total)	Innovation	5
	LEED accredited professional	1
Regional priority (4 points total)	Regional priority: specific credit	4

[a] A project applying for a LEED Neighborhood Development Location applies for an umbrella 16 points, and does not need to pursue each subcredit.

major renovation, and the total number of points possible under each category and credit.

For new construction and major renovation, there are 57 credits that can be achieved. On the USGBC website, each credit has an intent and requirement list. For example, for new construction, the intent of the outdoor water use reduction, which is required, is to reduce outdoor water consumption. The requirement can be met with one of the following options: no irrigation required or reduce irrigation. For the first option, no irrigation required, the "landscape should not require a permanent irrigation system beyond a maximum two-year establishment period." For the second option, the "project's landscape water requirement must be reduced by at least 30% from the calculated baseline for the site's peak watering month." This can be achieved through plant species selection and irrigation system efficiency, and can be calculated using the EPA's WaterSense Water Budget Tool. There are additional requirements that nonvegetaged surfaces (permeable or impermeable pavement) should be excluded from the landscape area calculations, and athletic fields, playgrounds, and food gardens may or may not be included.

Another credit example for new construction is the bicycle facilities. This credit is not required, but one point can be obtained if followed. The intent of the bicycle facilities is to "promote bicycling and transportation efficiency and reduce vehicle distance traveled" and to "improve public health by encouraging utilitarian and recreational physical activity." A summary of the requirements for bicycle facilities is that the project is within 200 yards (180 m) of a bicycle network and that various requirements for bicycle storage and shower rooms are met, including short- and long-term bicycle storage, location of bicycle storage, and a bicycle maintenance program. While the USGBC website is not quite the most intuitive website to navigate around, googling the phrase "usgbc bicycle facilities new construction" brings the summary discussion above up as the first link. Therefore, if any of the credits in Table 7.5 are of particular interest, it is recommended to google the credit inside the phrase provided above, and a full intent and requirement should be one of the first links provided.

Another interesting feature is the ability to search LEED certified buildings within USGBC's website. By going to www.usgbc.org/projects, or by googling the name of a building, the state, and LEED, it is possible to examine the checklists of all LEED certified buildings. Table 7.6 provides a summary of the LEED certified checklist for Hillside Auditorium at the University of Arkansas.

Hillside Auditorium received 53/110 points, which places it as LEED Silver certified. Another example of a LEED certified building is the Nanoscale Science Engineering Building, which was awarded certification in May 2012. The Nanoscale Science Engineering Building is LEED Gold certified, receiving 42/69 points at the time of certification. This certification utilized a previous LEED rating system, which had a different point value than Hillside Auditorium. These two buildings are shown in Figure 7.7.

While the LEED system has been utilized in over 80,000 projects (as of July 2016), there is another certification that has gained traction in civil engineering: Envision. According to ASCE, Envision was founded in 2010 by ASCE, the American Council of Engineering Companies, and the American Public Works Association. Envision is administered by the Institute for Sustainable Infrastructure. Similar to LEED, the Envision system is based on points. In 2016, there were four levels of Envision certification based off of 845 total points (following version 2.0). If a project earned greater than 50% of the points, it is considered Envision Platinum certified. If the project earned 40%–50% of the points, it is considered Envision Gold certified. 30%–40% of the points earns an Envision Silver certification, and finally, 20%–30% of the points earns Envision Bronze certified. Certification can be applied to nine

TABLE 7.6
Summary of LEED Certified Checklist for Hillside Auditorium

Category	Points (53/110)
Sustainable sites	18/26
Water efficiency	6/10
Energy and atmosphere	12/35
Materials and resources	6/14
Indoor environmental quality	8/15
Innovation	1/6
Regional priority credits	2/4
Integrative process credits	0/3

(a)
(b)

FIGURE 7.7 Hillside Auditorium (LEED Silver) (a) and the Nanoscale Science Engineering Building (LEED Gold) (b) on the University of Arkansas campus. (Credit: A. Braham.)

different specific types of infrastructure, or can fall under an “other” category. The types of infrastructure are

1. Roads
2. Bridges
3. Pipelines

4. Railways
5. Airports
6. Dams
7. Levees
8. Landfills
9. Water treatment systems

Each of these nine types of infrastructure is broken down into five categories. Each category also has multiple subcategories. Under each subcategory are several credits that are available. The categories, subcategories, and credits available under each category are as follows:

1. Quality of life: purpose, community, well-being—13 credits
2. Leadership: collaboration, management, planning—10 credits
3. Resource allocation: materials, energy, water—14 credits
4. Natural world: siting, land and water, biodiversity—15 credits
5. Climate and risk: emission, resilience—8 credits

Finally, each credit has up to five levels of achievement, with increasing point value for each level of achievement. All five levels of achievement are not applicable to all credits. The five levels of achievement are

1. Improved (1–4 points): performance above conventional, slightly exceeds regulatory requirements
2. Enhanced (2–9 points): indications that superior performance is within reach
3. Superior (4–13 points): noteworthy sustainable performance
4. Conserving (5–20 points): performance with essentially zero negative impact
5. Restorative (11–25 points): performance restores natural or social systems

Table 7.7 summarizes the checklist for Envision, and the total number of points possible under each category and credit.

Similar to LEED, each credit has a summary of characteristics that includes the intent, definitions of the level of achievement, a description, a discussion on advancing to higher achievement levels, and evaluation criteria and documentation. For example, the credit preserve views and local character's intent is to "design the project to maintain the local character of the community and to not negatively impact community views." The levels of achievement are as follows:

- Improved: understanding and balance
- Enhanced: alignment with community values
- Superior: community preservation and enhancement
- Conserving: community connections and collaboration
- Restorative: restoration of community and character

TABLE 7.7
Summary of Envision Credits

Category	Subcategory	Credit	Maximum Points
Quality of life	Purpose	Improve community quality of life	25
		Stimulate sustainable growth and development	16
		Develop local skills and capabilities	15
	Well-being	Enhance public health and safety	16
		Minimize noise and vibration	11
		Minimize light pollution	11
		Improve community mobility and access	14
		Encourage alternative modes of transportation	15
		Improve site accessibility, safety, and wayfinding	15
	Community	Preserve historic and cultural resources	16
		Preserve views and local character	14
		Enhance public space	13
Leadership	Collaboration	Provide effective leadership and commitment	17
		Establish a sustainability management system	14
		Foster collaboration and teamwork	15
		Provide for stakeholder involvement	14
	Management	Pursue by-product synergy opportunities	15
		Improve infrastructure integration	16
	Planning	Plan for long-term monitoring and maintenance	10
		Address conflicting regulations and policies	8
		Extend useful life	12
Resource allocation	Materials	Reduce net embodied energy	18
		Support sustainable procurement practices	9
		Use recycled materials	14
		Use regional materials	10
		Divert waste from landfills	11
		Reduce excavated materials taken off site	6
		Provide for deconstruction and recycling	12
	Energy	Reduce energy consumption	18
		Use renewable energy	20

(*Continued*)

TABLE 7.7 (*Continued*)
Summary of Envision Credits

		Commission and monitor energy systems	11
		Protect freshwater availability	21
		Reduce potable water consumption	21
		Monitor water systems	11
Natural world	Siting	Preserve prime habitat	18
		Protect wetlands and surface water	18
		Preserve prime farmland	15
		Avoid adverse geology	5
		Preserve floodplain functions	14
		Avoid unsuitable development on steep slopes	6
		Preserve greenfields	23
	Land and water	Manage stormwater	21
		Reduce pesticide and fertilizer impacts	9
		Prevent surface and groundwater contamination	18
		Preserve species biodiversity	16
		Control invasive species	11
		Restore disturbed soils	10
		Maintain wetland and surface water functions	19
Climate and risk	Emissions	Reduce greenhouse gas emissions	25
		Reduce air pollutant emissions	15
	Resilience	Assess climate threat	15
		Avoid traps and vulnerabilities	20
		Prepare for long-term adaptability	20
		Prepare for short-term hazards	21
		Manage heat islands effects	6

The description of each credit includes a discussion about the project design, and ensures that the context of the credit is clear. An urban setting example of context would be the inclusion of traditional streetscapes, building material choices, or height limitations. A rural example would include discussion about views and vistas of natural landscapes, along with other prominent natural features. The main concept behind the advancing to higher achievement levels revolves around the concept of simply minimizing impacts to preservation and restoration, toward a more comprehensive planning process that takes stakeholder input into account. Finally, evaluation criteria and document would include plans and drawings, specific documents that emphasize specific contextual features, and a summary of existing policies and regulations. While this is just one example of one credit, a comprehensive summary has been put together by the Institute for Sustainably Infrastructure (ITS, 2015).

A good example of the Envision certification process can be found in Eugene, Oregon, along the Alder Street Active Transportation Corridor (Rodrigues, 2013). Alder Street has a high level of pedestrian and bicycle traffic. In order to maximize safety and promote travel by these two modes, the City of Eugene partnered with the University of Oregon and Lane Transit District to completely reconstruct the corridor. By incorporating new bicycle features (two-way buffered and contraflow bicycle lanes, colored pavement), new pedestrian features (widened sidewalks, comprehensive tree canopy), and improved signalization, the city executed their goal of not only providing a safe space to travel, but also enhancing the facilities to encourage nonmotorized modes of transportation. The self-assessment provided a 65% "yes" rating for the quality of life, a 74% "yes" rating for leadership, a 34% "yes" rating for resource allocation, a 11% "yes" rating for natural world, and a 45% "yes" rating for climate. Taken together, the assessment provided an overall 59.8% "yes" rating, which would place the project at an Envision Platinum certification. Recall, however, that this was simply the self-assessment and not the certified assessment. To continue the example above, under the credit "preserve views and local character," the city scored a 2/2 by answering yes to the two assessment questions. The commentary stated that "the project team worked closely with stakeholders to replace streetlights and construct sidewalk and tree plantings that preserved and enhanced the local character." This commentary showed specific examples of how the team achieved the credit. Figure 7.8 shows a before and after image of the corridor.

Since LEED was developed approximately 20 years before Envision, there are far more LEED projects across the world versus Envision projects. However, there are similarities and differences between the two certification systems. There are several areas of overlap in application areas, which fall under credits for both systems, such as light pollution, stormwater runoff quality, and alternative transportation. In fact, when looking at the overall content, Envision essentially covers all of LEED through the resource allocation, natural world, and climate categories. The interesting comparison comes from the differences from the two systems. Overall, LEED is a binary system, where questions are either "yes" or "no." However, Envision has the five levels of achievement, which allows for not only more of a spectrum of ratings to be established, but also allows owners and agencies to strive for incremental improvements instead of simply getting an all or nothing. When filling out the checklist, LEED is more straightforward, but on a smaller scope, while Envision is more subjective on the level of each category, but provides a larger and more flexible scope.

Another difference is that taken as a whole, LEED tends to redevelop sites and materials, while Envision tends to focus on preserving resources. This may stem from the fact that LEED focuses exclusively on buildings, where Envision strives to include multiple different types of infrastructure (including buildings, roads, bridges, pipelines, levees, etc.) This brings up the last point that LEED is focused almost primarily on the environmental pillar of sustainability, while Envision covers both the environmental and social pillar. While there are pros and cons to each certification system, it is interesting to compare them directly, and will be even more interesting to see how they will evolve over time.

(a)

(b)

FIGURE 7.8 Before (a) and after (b) of the Alder Street Active Transportation Corridor. (Credit: Rodrigues, M. Applying the ISI Envision Checklist, Post project analysis of the Alder Street Active Transportation Corridor Project. City of Eugene, Public Works Engineering, July 19, 2013.)

EXAMPLE PROBLEM 7.4

Summarize in bullet form the similarities and differences between LEED and Envision.

- Similarities
  - Overlap in application areas
  - Envision covers majority of LEED content (but not vice versa)
- Differences
  - LEED is binary (yes or no), Envision a spectrum of five levels
  - LEED questions tend to be more straightforward, Envision more subjective
  - LEED redevelops sites and focuses on materials, Envision focuses on preserving resources
  - LEED focuses exclusively on buildings, Envision infrastructure
  - LEED focuses on environmental pillar of sustainability, Envision splits between environmental and social pillar

HOMEWORK PROBLEMS

1. A local contractor is investigating replacing 50% virgin Portland cement with fly ash. The concrete with 100% Portland cement has a compressive strength of 25 MPa at 3 days and a compressive strength of 50 MPa at 90 days. The concrete with 50% fly ash has a compressive strength of 22 MPa at 3 days and 55 MPa at 90 days. Using the common relationship between compressive strength and modulus of elasticity, calculate the secant modulus of elasticity (E_c) at these four strength levels.
2. Using the fly ash replacement levels in problem 1, along with data comparing the use of fly ash versus Portland cement, prepare a summary of the economic and environmental benefits of using fly ash versus Portland cement. Discuss your findings using the format provided under Sidebar 1.2 "Writing a High-Quality Essay."
3. A firm in central Illinois would like to explore using bamboo as a substitute to steel for scaffolding. However, they are concerned about the load-carrying ability of the bamboo versus the steel. Assume that both materials have a fixed connection at each end, the length of the column will be 20 ft, and the radius of gyration of each material is 1.15 in. Also, assume that the modulus of elasticity of the steel is 25.8×10^6 psi. Compare the steel to bamboo in a wet state ($\alpha = 2.35$, $E = 1.25 \times 10^6$ psi) and in a dry state ($\alpha = 2.35$, $E = 1.75 \times 10^6$ psi).
4. A firm in Nanjing, China would like to explore using steel as a substitute to bamboo for scaffolding. However, they are concerned about the load-carrying ability of the steel versus the bamboo. Assume that both materials have one end fixed and the other end pinned, the length of the column will be 15 ft, and the radius of gyration of each material is 1.20 in. Also, assume that the modulus of elasticity of the steel is 26.7×10^6 psi. Compare the steel to bamboo in a wet state ($\alpha = 2.35$, $E = 1.15 \times 10^6$ psi) and in a dry state ($\alpha = 2.35$, $E = 1.65 \times 10^6$ psi).

5. Construct a graph from the data calculated in Example Problem 7.3. Use the format provided under Sidebar 5.1 “Constructing a High-Quality Graph.” Choose two sets of data that you find are the most interesting and discuss your thoughts using the format provided Sidebar 1.2 “Writing a High-Quality Essay” to formulate your answer.
6. Diagrid buildings appear to have many advantages during the design and building process, but they are still relatively uncommon. Using the format provided under Sidebar 1.2 “Writing a High-Quality Essay,” discuss why you think diagrid buildings are not more common.
7. Choose a LEED certified building in your area and find the score on the USGBC website. List how you think the building achieved this points received in the LEED certification.
8. Which certification system do you think is better, LEED or Envision? Pick two primary arguments, and use the format provided under Sidebar 1.2 “Writing a High-Quality Essay” to build your argument.

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8 Application

Transportation Sustainability

It is the mark of an educated mind to be able to entertain a thought without accepting it.

Aristotle

The Transportation and Development Institute (T&DI) is one of the specialty institutes of the American Society of Civil Engineers. Like many institutes, T&DI has a host of committees that track and further areas of interest for the institute. The committees of T&DI address topics such as aviation, freight and logistics, infrastructure systems, rail and public transit, roadways, and development. As a part of the development council, T&DI has a committee on sustainability and the environment. This committee on sustainability addresses all facets of sustainability within transportation engineering. This chapter will cover four of those areas to provide a glimpse into how sustainability can be applied in the fourth and final application area of sustainability, which is transportation:

1. Material reuse: RAP and RAS
2. Multimodal transportation
3. Intelligent transportation systems
4. Crash modification factors

8.1 MATERIAL REUSE: RAP AND RAS

Asphalt mixtures are made of both aggregate and asphalt binder. The aggregate, which is approximately 93%–97% of the asphalt mixture by weight, is designed to provide a skeleton to carry the weight of vehicles passing over the pavement. The asphalt binder, 3%–7% of the asphalt mixture by weight, is designed to hold the aggregate together and to provide flexibility to the pavement structure during traffic loading and ground movement. However, over time, the asphalt pavement loses its flexibility due to natural weathering. Weathering can include oxidation from the sun and wind, moisture damage, and traffic damage. This weathering is usually confined to the upper layer of the asphalt pavement structure and does not typically extend more than 1.5–2.0 in into the pavement. Therefore, it is common to mill off the existing surface course of a pavement and replace it with a new asphalt mixture. The material that was milled off the existing surface course of the pavement is called recycled asphalt pavement, or RAP. RAP, though weathered, still contains properties that could be beneficial to asphalt concrete. According to the National Asphalt Pavement Association (NAPA), over 68.3 million tons of RAP was used in asphalt mixtures in 2012 (Hansen and Copeland, 2013). This RAP not only replaces aggregate, but also partially replaces asphalt binder. The use of RAP is quite well established in asphalt mixtures. The National Cooperative Highway Research Program (NCHRP) performed an extensive study examining the mix design, performance, and materials management for RAP in asphalt mixtures (West et al., 2013). The report states that the use of RAP, even in high quantities, is perfectly acceptable with the proper design process, but good management practices are essential for proper performance. Figure 8.1 shows a front-end loader collecting load of RAP during asphalt mixture production.

Another material that can supplement asphalt binder in asphalt mixtures is recycled asphalt shingles, or RAS. Asphalt shingles can either come from scrap during manufacturing or they are ripped off roofs after their service life on buildings is over. After some processing, RAS can be incorporated into asphalt mixtures. In 2012, NAPA estimated that 1.9 million tons of RAS was placed in asphalt mixtures (Hansen and Copeland, 2013). While RAS does not replace aggregate in asphalt mixtures, using RAS in U.S. roadways in 2012 conserved approximately 2.1 million barrels of asphalt binder, saving approximately $228 million. Even more material and economic savings were seen for RAP, which conserved over 19 million barrels of asphalt binder in U.S. roadways, saving approximately $2 billion. While the use of RAS in asphalt mixtures is not quite as prevalent as RAP, there is still much research indicating that, again, with proper design and management practice of the material, RAS can be successfully utilized in asphalt mixtures (Ozer et al., 2013; Zhou et al., 2013; Cooper et al., 2014).

While both RAP and RAS have been proven to be a quality substitute for virgin material, the binder portion of the RAP and RAS tends to oxidize, which makes it stiffer. RAP and RAS are both petroleum based, but during their in-service life, they

FIGURE 8.1 A stockpile of RAP in northwest Arkansas. (Credit: A. Braham.)

are exposed to oxygen, and the asphalt binder goes through what is called oxidative hardening. In short, oxidative hardening occurs when polar, oxygen-containing chemical groups are introduced to asphalt molecules. More details on oxidative hardening and other forms of hardening can be found in Peterson (2009). Four examples of oxidative hardening on the molecular scale are shown in Figure 8.2.

The hardening of asphalt binder influences the classification of the binder. In the United States, the Superpave system is used to classify binder, and binder is classified by "grading" the binder. The performance grade (PG), or PG binder grading system, has a high and low temperature. The high temperature of the PG grade is related to the anticipated high air temperature that the road will be exposed to. Improperly designed roads may rut under higher temperatures. The low temperature of the PG grade is related to the anticipated low pavement surface temperature that the road will be exposed to. Improperly designed roads may crack under low temperatures. Stiffer binder increases the high-temperature binder grade and also increases the lower-temperature binder grade. In theory, this makes the mixture less susceptible to rutting, but more susceptible to cracking. Therefore, care must be taken to ensure that the mixture's binder grade stays within the proper design range, which is one of the recommendations from research for using both RAP and RAS.

There are several challenges associated with using RAP and RAS in asphalt mixtures. The largest challenge is providing a consistent product. RAP is obtained from milling an existing roadway. A common rehabilitation strategy for asphalt roadways is to mill 2 in off the top of a pavement surface and then lay down 2 in of new asphalt mixture. This eliminates any surface distresses and provides a new traveling surface. However, after a road is milled, the material is generally taken back to an asphalt plant, where it is crushed and mixed with other millings. The millings are obtained from many different roads, all of which may have had different original aggregate and asphalt binders, and that which likely are of different ages. This means that RAP stock piles are a very diverse pile of materials; hence, it can prove difficult to ensure a consistent product going into the asphalt mixture. RAS can be even more diverse, as there are two primary types of RAS: waste from asphalt shingle production and tear-off shingles. Waste from the production of asphalt shingles is preferred, as the material is not exposed to weathering or oxidation. However, tear-off shingles, shingles that are removed from roofs, are highly oxidized, and also highly variable. While consistent RAP and RAS products are a challenge to produce, if properly managed with suppliers, they can be successfully incorporated into a roadway as a useful recycled material.

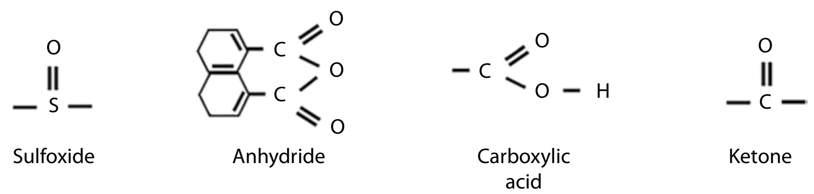

FIGURE 8.2 Oxidative hardening of four asphalt binder molecules. (Credit: A. Braham.)

EXAMPLE PROBLEM 8.1

On the website www.pavementinterative.org, there is a section on Superpave Performance Grading. About a half of the way down the page is Figure 2—PG binder specification taken from NAPA. Using this chart, record the testing temperatures for each test when evaluating a PG64-22 binder. In addition, if you add a stiffer material to an asphalt mixture (such as RAP or RAS), what do you anticipate would happen to the low (–22°C) and high binder (+64°C) temperature?

Going through the chart, the test temperatures are within each box of the table. For a PG64-22, the following tests require the following test temperatures:

- Original binder:
  - Flash point: 230°C
  - Viscosity: 135°C
  - Dynamic shear: 64°C
- Rolling thin film oven (RTFO) residue:
  - Dynamic shear: 64°C
- Pressure aging vessel (PAV) residue:
  - Dynamic shear: 25°C
  - Creep stiffness: –12°C
  - Direct tension: –12°C

In regard to the high and low binder temperature, if you add RAP and RAS to an asphalt mixture, it will make the mixture stiffer, which will increase the high-temperature binder grade, and will also increase the low-temperature binder grade. So, for example, if you add RAP or RAS to an asphalt mixture with a PG64-22 binder, adding enough RAP or RAS may increase the binder grade to a PG70-16.

8.2 MULTIMODAL TRANSPORTATION

When considering modes of transportation, two perspectives should be examined: passenger travel and freight movement. In terms of passenger travel, travel by car versus bus versus self-propelled travel (e.g., bicycles) is frequent. For example, the European Cyclist Federation looked at the impact of biking, taking a bus, and driving a car. By examining the fuel CO_2 emissions, they found that driving produced 0.81 pounds/mile (assuming an occupancy of 1.16 passengers per vehicle), taking a bus produced 0.34 pounds/mile (assuming an occupancy of 10 passengers per bus), while biking produced 0.6 pounds/mile (assuming one person per bicycle). The CO_2 emissions for cars and buses were calculated for emissions linked to production, distribution, and consumption of fuel, while the CO_2 emissions for biking was calculated by food production for the bicyclist. Another benefit of utilizing mass transit and bicycles is the reduction of vehicle volume on the roadway. A famous picture from the City of Munster, Germany, shows the density of vehicles on a city street for 60 people (Figure 8.3).

It is clear that the 60 bicycles and one bus take up far less space on the roadway versus the 60 individual vehicles. In essence, reducing the density of vehicles on the

FIGURE 8.3 Bicycle versus car versus bus vehicle density. (Credit: Carlton Reid.)

roadway generally increases the flow of traffic and enhances the level of service. However, many of these traditional studies assume the use of conventionally powered and individually owned vehicles. In addition, studies have been very one dimensional, looking at either just the economic or environmental impact of transit. More recent studies have investigated hybrid cars and buses and have incorporated concepts of ride-sharing into their analyses. In addition, some recent studies have expanded the scope of their analyses to include more sustainability metrics. For example, a study in 2014 (Mitropoulos and Prevedouros, 2014) looked at conventional internal combustion cars versus hybrid electric cars, both with and without car sharing, and ranked these four groups versus a traditional diesel bus and a hybrid diesel–electric bus. These six vehicle configurations were explored across five sustainability concepts:

1. Minimize environmental impacts
2. Minimize energy consumption
3. Maximize and support a vibrant economy
4. Maximize user and community satisfaction
5. Maximize technology performance to help a community meet its needs

While many assumptions went into the analysis, it was found that when looking at both passenger miles traveled (PMT) and vehicle miles traveled (VMT), the car sharing and hybrid cars performed better than the buses.

Along with passenger mobility, another subject to consider is freight, which must also be transported around the country. A convenience that freight has versus passengers is that travel time is often less restricted and factors such as comfort do not need to be addressed. Assuming that perishable or time-sensitive material is not being hauled, there are five primary modes of freight transportation: waterways, rails, highways, air, and pipelines. However, the majority of freight in the United States is generally shipped by either railroad or truck. This data is shown in Figure 8.4, which was compiled from data available online from the Bureau of Transportation Statistics.

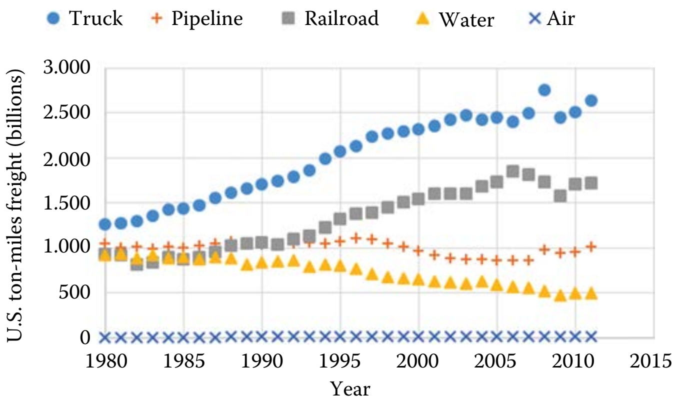

FIGURE 8.4 Freight shipping by mode in the United States. (Credit: A. Braham.)

Studies have shown that for a typical barge movement of freight on water, the same CO_2 emissions would be generated for hauling the same ton-miles of freight on 25 train cars or 297 trucks on the highway. Costs are also less for movement on water, as rail was found to be about 1.7 times higher than ship, while trucks were found to be 2.8 times higher (Cenek et al., 2012). Other studies have seen even higher cost differences, with trucks costing 5–10 times more per ton-mile versus rail (Rasul, 2014). In this study, Rasul determined that it costs an estimated \$0.10–\$0.20 per ton-mile to ship by truck, yet only \$0.01–\$0.04 per ton-mile by rail.

In addition to the potential environmental and economic savings of shipping freight by rail and ship versus truck, highway pavement materials could potentially be reduced as well. One of critical inputs into pavement design is the number of equivalent single-axle loads, or ESALs. In general, higher ESALs mean that a thicker pavement structure is required, increasing the economic and environmental impact of the roadway. ESALs can be computed using Equation 8.1:

$$ESAL_i = f_d \times G_{rn} \times AADT_i \times 365 \frac{\text{days}}{\text{year}} \times N_i \times F_{Ei} \tag{8.1}$$

where

$ESAL_i$ = equivalent accumulated 18,000-lb single-axle load for the axle category i per year

f_d = design lane factor (percent truck volume on design lane)

G_{rn} = growth factor for a given growth rate r and design period n = $[(1 + r)^n - 1]/r$

$AADT_i$ = first-year annual average daily traffic for axle category i

N_i = number of axles on each vehicle in category i

F_{Ei} = load equivalency factor for axle category i

The design lane factor (f_d), the growth factor (G_{rn}), the first-year annual average daily traffic for axle category i ($AADT_i$), and the number of axles on each vehicle (N_i) are all relatively straightforward, and usually given, yet, the load equivalency factor (F_{Ei}) is a critical input. Tables are available in the 1993 AASHTO pavement design guide that relate the terminal serviceability index and the pavement structural number to the load equivalency factor. For example, one table is provided in the Fundamentals of Engineering (FE) reference manual for the load equivalency factor. The table is built from a roadway that has a terminal serviceability index of 2.5 and a pavement structural number of 5.0. In the table, the load equivalency factors for a passenger car (1000 lb or 4.45 kN) is only 0.00002, whereas the standard semitruck weight for a single axle is 18,000 lb (80.0 kN), with a load equivalency factor of 1.0. This means that a standard loaded semitruck has approximately 50,000 times more ESAL influence on a road compared to a passenger car. This clearly shows that trucks are what deteriorate pavements, so agencies must design for the "worst-case" scenario, which are the trucks. By shifting freight movement from highways to either rail, water, or pipelines, the life expectancy of pavements would be extended.

EXAMPLE PROBLEM 8.2

A six-lane interstate is being built through Fayetteville, Springdale, Rogers, and Bentonville in Northwest Arkansas. Traffic volume forecasts estimate that there will be 62,000 average annual daily traffic (AADT) in both directions during the first year of operation. The following vehicle mix is expected:

1. Passenger cars (2000 lbs/axle, $F_{Ei} = 0.0002$) = 60%
2. Three-axle single-unit trucks (10,000 lb/axle, $F_{Ei} = 0.0877$) = 25%
3. Five-axle tandem-unit trucks (20,000 lb/axle, $F_{Ei} = 0.1206$) = 15%

If the growth factor is anticipated to be 33.06 (from an annual growth rate of 5% and a 20 year design period), and the percent truck volume on the design lane is 35%, compute the total ESALs for the roadway.

To solve the problem, Equation 8.1 must be solved for each vehicle class.

Passenger cars (pc):

$$\begin{aligned}ESAL_{pc} &= f_d \times G_{rn} \times AADT_i \times 365 \times N_i \times F_{Ei}\\ &= 0.35 \times 33.06 \times 62{,}000 \times 365 \times 0.60 \times 2 \times 0.0002 = 0.063 \times 10^6\end{aligned}$$

Three-axle single-unit trucks (3t):

$$ESAL_{3t} = 0.35 \times 33.06 \times 62{,}000 \times 365 \times 0.25 \times 3 \times 0.0877 = 17.2 \times 10^6$$

Five-axle tandem-unit trucks (5t):

$$ESAL_{5t} = 0.35 \times 33.06 \times 62{,}000 \times 365 \times 0.15 \times 5 \times 0.1206 = 23.7 \times 10^6$$

$$\text{Total ESALs} = \text{ESAL}_{pc} + \text{ESAL}_{3t} + \text{ESAL}_{5t} = 0.63 \times 10^6 + 17.2 \times 10^6 + 23.7 \times 10^6 = 41.0 \times 10^6$$

It is interesting to note that the passenger cars, while taking up 60% of the traffic stream, have essentially a negligible impact on the ESAL count, and hence, have a negligible impact on the deterioration of the roadway structure as well.

8.3 INTELLIGENT TRANSPORTATION SYSTEMS

In 2013, the National Academies and the Executive Committee of the Transportation Research Board published a discussion of six critical issues in transportation (TRB, 2013). In the first paragraph of the first page of text, there is a discussion about the lost time in traffic congestion. Just a couple of paragraphs later, the second critical issue discusses road safety, and the third critical issue identifies transportation's unsustainable impact on the environment. These three points, interestingly, are almost identical to comments made by Ban Ki-moon in the UN's sustainable mobility discussion (UN, 2012). Ki-moon's comments revolved around the need to improve road safety, reduce congestion for people and freight, and minimize environmental impact of transportation systems. One potential solution to addressing these three comments and the discussion of critical issues is intelligent transportation systems, or ITS.

ITS collects, stores, analyzes, and distributes data on the movement of people and freight. ITS provides real-time travel information services and provides management models across all modes of transportation. ITS can help with incident/crash management, emergency response systems, crash prevention, and roadway maintenance systems. Some examples of ITS for drivers include variable message signs along the side of the road, onboard vehicle systems (such as lane departure warning systems), advanced emergency braking systems, and onboard diagnostics. Other types of ITS resources for drivers are apps, such as IDrive Arkansas, which can provide construction, weather, and traffic information in real time to travelers on their cell phones. An example of a variable message sign in Missouri is shown in Figure 8.5. While the sign in Figure 8.5 did not display any emergency information at the time of the picture, it can quickly be changed from a remote location to warn drivers of issues coming up on the roadway. These signs also can be used for emergency messages such as America's Missing: Broadcast Emergency Response (AMBER) alerts.

A specific application that can be explored related to ITS is the effect of driver reaction time on stopping sight distance (SSD). The SSD is a combination of the distance associated with driver reaction time (D_{rt}) and braking distance (D_b), which can be shown in Equation 8.2:

$$\text{SSD} = D_{rt} + D_b = 1.47Vt + \frac{V^2}{30\left(\left(\frac{a}{32.2}\right) \pm G\right)} \tag{8.2}$$

FIGURE 8.5 ITS variable message sign in Missouri. (Credit: A. Braham.)

where
V = design speed (mph)
t = driver reaction time (s)
a = deceleration rate (assume AASHTO recommended value of 11.2 ft/s^2)
G = percent grade divided by 100 (will be in decimal form)

One study on reaction time (Porter et al., 2008) examined the effect of sound warnings on braking distance in younger male drivers and older male drivers. The young males were 30–50 years old, and the old males were 70+ years old. Sound warnings included auditory alerts 100 m before crosswalks, school zones, playgrounds, red light cameras, and deer crossings, in addition to the traditional visual signage from the *Manual of Uniform Traffic Control Devices* (MUTCD). Four scenarios were examined with the two age groups: expected events with and without sound warnings (expected meaning a person crossing at a crosswalk, a light changing from green to red on approach, etc.) and unexpected events with and without sound warnings (unexpected meaning a car entering the roadway just after a school zone alert, a pedestrian in the street not at a crosswalk, etc.). Some general characteristics were examined to determine statistical differences and similarities between younger and older drivers:

- Differences
  - Age—the age difference between the older and younger drivers was statistically significant
  - Driving experience—older drivers had more driving experience
  - Number of days driven in the past week—older drivers had driven more in the past week

TABLE 8.1
Effect of Sound Warnings on Reaction Times and Distances

Age	Event	Alert	Average Reaction Time (s)	Average Reaction Distance (ft)
Younger	Expected	Sound warning	1.8	98
		No sound warning	2.2	120
	Unexpected	Sound warning	2.5	137
		No sound warning	2.4	131
Older	Expected	Sound warning	2.3	126
		No sound warning	3.1	170
	Unexpected	Sound warning	2.5	137
		No sound warning	2.8	153

- Leg strength—younger drivers had higher leg strength
- Mobility—younger drivers had higher mobility
- Visual information processing—younger drivers processed information more quickly

- Similarities
  - Visualizing missing information—both age groups were able to visualize missing information in a similar manner

Using a driving simulator, 16 younger drivers and 14 older drivers were put through multiple driving situations that explored the expected and unexpected events, with and without sound warnings. Table 8.1 summarizes the average reaction times, along with the corresponding reaction time distances, with the design speed of the simulations set at 37.2 mph.

Table 8.1 clearly demonstrates that older drivers had longer reaction distances versus younger drivers and that both sets of age groups had longer reaction distances when events were unexpected versus expected. In general, the sound warning also assisted in reducing reaction distances, except with younger drivers in an unexpected event, where the distances were essentially the same. This is one example of how an ITS technology onboard a vehicle can reduce reaction distances, and thus SSD, creating safer environments on the roadway. It is interesting to note that the default value for reaction time used by AASHTO is 2.5 s, which comes from the combination of 1.5 s to perceive the need to brake and 1.0 s to begin the braking process. This 2.5 s falls at the very long end of the younger drivers in Porter's study, while it falls quite near the short end for the older drivers.

EXAMPLE PROBLEM 8.3

Determine the difference in SSD for an older driver between receiving a sound warning and not receiving a sound warning with an expected event. Assume a speed of 72 mph, on a downward grade of 2.3%.

In order to solve this problem, Equation 8.2 is utilized. Recall that the standard AASHTO value for deceleration rate can be used (11.2 ft/s^2) and that the grade must be in decimal form.

With sound warning:

$$\mathrm{SSD} = 1.47\mathrm{Vt} + \frac{\mathrm{V}^2}{30\left(\left(\frac{\mathrm{a}}{32.2}\right) \pm \mathrm{G}\right)} = 1.47 \times 72 \times 2.3 + \frac{72^2}{30\left(\left(\frac{11.2}{32.2}\right) - 0.025\right)} = 741\ \mathrm{ft}$$

Without sound warning:

$$\mathrm{SSD} = 1.47\mathrm{Vt} + \frac{\mathrm{V}^2}{30\left(\left(\frac{\mathrm{a}}{32.2}\right) \pm \mathrm{G}\right)} = 1.47 \times 72 \times 3.1 + \frac{72^2}{30\left(\left(\frac{11.2}{32.2}\right) - 0.025\right)} = 826\ \mathrm{ft}$$

Therefore, the difference for older drivers with and without a sound warning is 826–741 = 85 ft.

8.4 CRASH MODIFICATION FACTORS

The discussion on transportation applications of sustainability has so far covered material reuse (RAP and RAS), multimodal transportation (passenger travel by car, bus, bicycle; freight travel by truck, rail, water, pipeline, and air), and ITS. These concepts all had components of the economic, environmental, and social pillars of sustainability. Crash modification factors (CMFs) are a bit unique however, as they revolve primarily around the social pillar of sustainability (with the concept of safety) and secondly around the economic pillar (litigation associated with crashes, injury, and even death); with CMFs, there is less to be said about environmental impacts.

The concept of safety has become so important in the United States that, in 2010, the first edition of the *Highway Safety Manual* was released by AASHTO (AASHTO, 2010). This manual is similar to other AASHTO publications, such as the *Manual for Bridge Element Inspection* or *A Policy on Geometric Design of Highways and Streets* (the green book), but AASTHO's *Highway Safety Manual* focuses exclusively on safety. Two of the largest subjects covered in this book are safety performance functions and CMFs. In the United States, according to the National Highway Traffic Safety Administration (NHTSA), there were over 32,000 traffic crash fatalities in 2014. For the purpose of giving an important glimpse into the social and economic pillars of sustainability, as related to the field of transportation engineering, this chapter will focus exclusively on CMFs, which are implemented in the AASHTO *Highway Safety Manual* on the following roadway types:

- Roadway segments
- Intersections
- Interchanges

- Special facilities and geometrics situations
- Road networks

In order to discuss CMFs, a general overview of vehicle crash considerations is helpful. Broadly speaking, there are four generally categorized factors involved with crashes: human factors, vehicle conditions, roadway conditions, and the environment. Human factors revolve around the driver and the driver's actions. For example, younger drivers have less experience in driving and therefore may make unexpected decisions while driving, whereas older drivers' reaction times increase (as seen in Section 8.3). External factors that engineers can control, however, also play a factor. For example, crashes can occur as a result of information overload to drivers, through roadway design and signage. Therefore, it is important that information is provided in an orderly and consistent way. Avoiding information overload to drivers can be achieved, for instance, by placing a series of signs that give information in a progressive, orderly manner, which helps drivers rank the importance of information. These concepts are discussed in more detail in the MUTCD. The MUTCD can be downloaded for free from FHWA's website; simply google "Manual of Uniform Traffic Control Devices" and FHWA's website with the .pdf download should be one of the first links.

The second factor of crashes is the vehicle condition. Obviously, if a car has bad breaks or the steering is not fully responsive, there is an increased likelihood of a crash. In addition, as technology progresses, technology such as power steering and antilock brakes have reduced the number of crashes, while technology such as seat belts and airbags have reduced the amount of injuries and fatalities associated with crashes. As these technologies degrade over time in a vehicle, the number of crashes and injuries increases.

The third factor of crashes is the roadway condition. Conditions of the roadway can be broken down into four parts: the pavement, the shoulders, intersections, and the traffic control system. When considering the pavement, there must be enough surface friction between the roadway and the tires so that drivers can maintain control of the vehicle, while wide shoulders give space for disabled vehicles to move off active lanes of traffic. Intersections must be properly designed for easy lines of sight for drivers to observe cars approaching from different directions. Finally, components of the traffic control system, such as stop lights, must be easily visible as vehicles approach the intersection and are waiting at the intersection.

The fourth and last factor generally recognized about crashes is the environment. Weather, for instance, plays a significant role in crashes. Sitting water on the pavement surface can cause hydroplaning or can freeze and form ice, both of which result in a loss of friction between the tire and pavement surface. Fog can reduce the visibility of the driver, which reduces the SSD. Besides weather, another environmental factor that is not commonly addressed is the level of lighting. It is estimated that the number of fatal crashes during daylight is about the same as the number that occur in darkness, but only 25% of the vehicle miles traveled occur at night (Lutkevich et al., 2012). This means that fatal crashes are three times as likely to occur when it is dark versus when it is light. While transportation engineers have only partial control over these four factors of crashes, the roadway infrastructure should be designed in ways that minimize the external factors of crashes.

With the dangerous and significant ramifications of crashes, two methods of quantifying crash rates have been developed, one for intersections and one for roadways. For intersections, crash rates are presented as crash rate per million entering vehicles (RMEV), which is calculated by Equation 8.3:

$$\text{RMEV} = \frac{\text{A} \times 1{,}000{,}000}{\text{V}} \tag{8.3}$$

where
A = number of crashes, total/type occurring in a single year
V = average daily traffic (ADT) entering the intersection × 365 days/year.

A similar equation has been developed for roadway segments. For roadway segments, crash rates are presented as crash rate per hundred million vehicle miles (RMVM), which is calculated by Equation 8.4:

$$\text{RMVM} = \frac{\text{A} \times 100{,}000{,}000}{\text{VMT}} \tag{8.4}$$

where
A = number of crashes, total/type occurring in a single year
VMT = vehicle miles of travel during a given period
= ADT on roadway segment × number of days in study period × length of road

Using these two calculations, an examination of CMFs can begin.

In this chapter, roadway segments is the only type of roadway that will be examined in the AASHTO *Highway Safety Manual*. Roadway segments consist of the following types of roads:

- Rural
  - Two-lane road
  - Multilane highway
  - Frontage road
- Freeway
- Expressway
- Urban arterial
- Suburban arterial

Each of these road types has various treatments, also called countermeasures, associated with reducing crashes, including modifying the lane width, adding lanes by narrowing existing lanes and shoulders, removing lanes, adding/widening a paved shoulder, providing a raised median, changing the width of the existing median, and increasing the median width. These treatments can then be associated with CMFs, from which the number of crashes prevented can be calculated. In order to calculate the number of crashes prevented, Equation 8.5 is used:

$$\text{Crashes prevented} = N \times CR \frac{(\text{ADT after improvement})}{(\text{ADT before improvement})} \tag{8.5}$$

where

- N = expected number of crashes if countermeasure is not implemented and traffic volume remains the same
- CR = overall crash reduction factor for multiple mutually exclusive countermeasures at a single site
  $= CR_1 + (1 - CR_1) \times CR_2 + (1 - CR_1) \times (1 - CR_2) \times CR_3 + \cdots + (1 - CR_1) \times \cdots \times (1 - CR_{m-1}) \times CR_m$
  $= (1 - CMF) \times 100$
- CR_i = crash reduction factor for a specific site
- m = number of countermeasures at the site

Therefore, the influence of countermeasures such as modifying the lane width and incorporating rumble strips into the shoulder can be incorporated into a calculation for the number of crashes prevented.

EXAMPLE PROBLEM 8.4

For a rural, two-lane, two-way highway, determine the crash reduction factor for reducing the lane width from 12 ft to 9 ft, for adding centerline rumble strips, and for the combination of these two treatments.

First, for reducing the lane width, using Table 10-8 on page 10–24 of the *Highway Safety Manual*, we assume that the AADT is greater than 2000 vehicles, which provides a CMF = 1.50. The crash reduction factor is

$$CR = (1 - CMF) \times 100 = (1 - 1.50) \times 100 = -50\%$$

Reducing the lane width from 12 ft to 9 ft increases the crashes by 50% if the ADT stays constant.

Second, for adding centerline rumble strips, on p. 10–29, the CMF = 0.94. The crash reduction factor is

$$CR = (1 - CMF) \times 100 = (1 - 0.94) \times 100 = 6\%$$

Adding centerline rumble strips decreases the crashes by 6% if the ADT stays constant.

Finally, looking at the two treatments combined:

$$CR_T = CR_1 + (1 - CR_1) \times CR_2 = -0.50 + (1 - -0.50) \times 0.06 = -0.41 \rightarrow -41\%$$

Therefore, reducing the lane width and adding centerline rumble strips is expected to increase the crashes by 41% if the ADT stays constant.

HOMEWORK PROBLEMS

1. Asphalt Incorporated, a laboratory testing firm of asphalt materials, received two samples for testing. The mixtures were identical, except that one mixture contained 78% virgin material, 20% RAP, and 2% RAS, while the second mixture contained 100% virgin material. Indicate which mixture you believe has the recycled material based on Superpave Performance-Graded (PG) Binder Grading testing run off extracted asphalt binder (extraction testing following ASTM D2172), and justify your reasoning. Note that you must explain the process that you followed to grade the binder.

Extracted asphalt binder 01:

Flash point		237°C
Viscosity at 135°C		2.84 Pa-s
Dynamic shear G*/sin δ (unaged)	64°C	0.47 kPa
	58°C	0.94 kPa
	52°C	1.67 kPa
RTFO mass loss		0.97%
Dynamic shear G*/sin δ (RTFO aged)	64°C	2.13 kPa
	58°C	2.97 kPa
	52°C	3.31 kPa
Dynamic shear G* × sin δ (PAV aged)	19°C	5012 kPa
	22°C	4942 kPa
	25°C	4855 kPa
Creep stiffness (S/m-value)	–24°C	324 MPa/0.301
	–18°C	298 MPa/0.305
	–12°C	253 MPa/0.322
Direct tension (failure strain)	–18°C	0.87%
	–12°C	1.02%
	–6°C	1.21%

Extracted asphalt binder 02:

Flash point		239°C
Viscosity at 135°C		2.73 Pa-s
Dynamic shear G*/sin δ (unaged)	64°C	0.95 kPa
	58°C	1.32 kPa
	52°C	1.87 kPa
RTFO mass loss		0.84%
Dynamic shear G*/sin δ (RTFO aged)	64°C	1.79 kPa
	58°C	2.22 kPa
	52°C	2.91 kPa
Dynamic shear G* × sin δ (PAV aged)	19°C	5113 kPa
	22°C	5017 kPa
	25°C	4922 kPa

(*Continued*)

Creep stiffness (S/m-value)	–24°C	312 MPa/0.285
	–18°C	295 MPa/0.302
	–12°C	275 MPa/0.311
Direct tension (failure strain)	–18°C	0.71%
	–12°C	0.92%
	–6°C	1.04%

2. A laboratory testing firm of asphalt materials in Madison, Wisconsin received two samples for testing. The mixtures were identical, except that one mixture contained 65% virgin material and 35% RAP, while the second mixture contained 100% virgin material. Indicate which mixture you believe has the recycled material based on Superpave Performance-Graded (PG) Binder Grading testing run off extracted asphalt binder (extraction testing following ASTM D2172), and justify your reasoning. Note that you must explain the process that you followed to grade the binder.

Extracted asphalt binder 01:

Flash point		274°C
Viscosity at 135°C		2.88 Pa-s
Dynamic shear G*/sin δ (unaged)	64°C	0.55 kPa
	58°C	1.03 kPa
	52°C	1.57 kPa
RTFO mass loss		0.85%
Dynamic shear G*/sin δ (RTFO aged)	64°C	2.03 kPa
	58°C	2.17 kPa
	52°C	2.51 kPa
Dynamic shear G* × sin δ (PAV aged)	13°C	5112 kPa
	16°C	4822 kPa
	19°C	4735 kPa
Creep stiffness (S/m-value)	–24°C	325 MPa/0.311
	–18°C	288 MPa/0.315
	–12°C	254 MPa/0.322
Direct tension (failure strain)	–24°C	0.97%
	–18°C	1.03%
	–12°C	1.11%

Extracted asphalt binder 02:

Flash point		242°C
Viscosity at 135°C		2.67 Pa-s
Dynamic shear G*/sin δ (unaged)	64°C	0.85 kPa
	58°C	1.23 kPa
	52°C	1.57 kPa

(*Continued*)

RTFO mass loss		0.87%
Dynamic shear G*/sin δ (RTFO aged)	64°C	1.87 kPa
	58°C	2.31 kPa
	52°C	2.88 kPa
Dynamic shear G*×sin δ (PAV aged)	13°C	5203 kPa
	16°C	5032 kPa
	19°C	4971 kPa
Creep stiffness (S/m-value)	–24°C	312 MPa/0.295
	–18°C	302 MPa/0.312
	–12°C	300 MPa/0.321
Direct tension (failure strain)	–24°C	0.78%
	–18°C	0.98%
	–12°C	1.08%

3. A minor arterial road is being reconstructed through Urbana, Illinois. Traffic volume forecasts estimate that there will be 13,500 AADT in both directions during the first year of operation. The following vehicle mix is expected:

   a. Passenger cars (2000 lbs/axle, $F_{Ei} = 0.0002$) = 75%
   b. Three-axle single-unit trucks (12,000 lb/axle, $F_{Ei} = 0.189$) = 20%
   c. Five-axle tandem-unit trucks (18,000 lb/axle, $F_{Ei} = 0.0773$) = 5%

If the growth factor is anticipated to be 14.49 (from an annual growth rate of 8% and a 10 year design period), and the percent truck volume on the design lane is 55%, compute the total ESALs for the roadway.

4. Using Figure 8.4, calculate the approximate cost of shipping by truck and train in the United States in 2010. What would happen to the costs if 10% of the truck freight was switched to rail? Describe your process of estimating the costs, along with assumptions you had to make. Use the format provided under Sidebar 1.2 "Writing a High-Quality Essay" to formulate your answer.
5. Make a graph of the SSD for all eight scenarios and describe the trends. Assume a speed of 45 mph and an upward grade of 0.7%. State other assumptions you make, and use the format provided under Sidebar 5.1 "Constructing a High-Quality Graph." Choose two sets of data that you find are the most interesting and discuss your thoughts using the format provided under Sidebar 1.2 "Writing a High-Quality Essay" to formulate your answer.
6. As mentioned, the assumed perception reaction time that AASHTO uses is 2.5 s. Assume a speed of 45 mph and an upward grade of 0.7% and find the SSD. Compare this stopping distance to the data calculated in problem 5. Do you think that AASHTO's value for perception reaction time is appropriate? Discuss your thoughts using the format provided under Sidebar 1.2 "Writing a High-Quality Essay" to formulate your answer.

7. For an undivided roadway segment (Section 11.7.1 of the *Highway Safety Manual*), determine the crash reduction factor for increasing the lane width from 10 ft to 12 ft (Table 11-11), for increasing the shoulder width from 2 ft to 4 ft (Table 11-12), and for the combination of these two treatments. Assume the AADT is between 400 and 2000 vehicles, and the CMFs within these two tables can be used directly in the equations utilized in Example Problem 8.4.
8. According to the *Highway Safety Manual*, the comprehensive societal crash cost of a fatal collision is $4,008,900, while a disabling injury is $216,000 (Table 7-1). Do you think that these dollar amounts are reasonable? Do you think it is appropriate to assign a dollar amount to a fatality? Discuss your thoughts using the format provided under Sidebar 1.2 "Writing a High-Quality Essay" to formulate your answer.

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9 Tomorrow's Sustainability

> The principal goal of education in the schools should be creating men and women who are capable of doing new things, not simply repeating what other generations have done.
>
> **Jean Piaget**

While the concept of sustainability has been in existence for a millennium, it is only in the past 30 years that there has been significant movement toward the qualification and quantification of sustainability. From a qualitative standpoint, the United Nations, the American Society of Civil Engineers, Oxfam, and various other groups have taken strides to defining sustainability. The concept of three pillars of sustainability is common through this work, with the three pillars being economic, environmental, and social. From a quantitative standpoint, concepts such as life cycle cost analysis, benefit/cost ratio, life cycle analysis, and ecological footprint have captured economic and environmental metrics of sustainability, and the field of social metrics is young but developing rapidly. Through all of this work, however, many would agree that sustainability is not a straightforward issue, and overall, it is a relatively undeveloped field. The advancement of sustainability in civil engineering is not an exception. In addition, many believe that in order to truly succeed in implementing sustainable practices in civil engineering, a paradigm shift will need to occur with innovative and applicable solutions.

When reviewing the plethora of resources available that discuss the future of sustainability, three stood out as both thoughtful and comprehensive in their analysis. These three documents were the United Nation's "2030 Agenda for Sustainable Development" (UN, 2015), Global Reporting Initiative's "Sustainability and Reporting Trends in 2025" (GRI, 2015), and the World Conservation Union's "Future of Sustainability" (IUCN, 2006). These three documents are broken down in the pages that follow to discuss how sustainability is not a straightforward issue, how it is underdeveloped, and how a paradigm shift will need to occur moving forward.

9.1 SUSTAINABILITY IS NOT A STRAIGHTFORWARD ISSUE

Starting with the UN, their 2030 Agenda contained seventeen goals, four of which are directly related to civil engineering. The four goals directly related to civil engineering are

- Goal 6—ensure availability and sustainable management of water and sanitation for all
- Goal 9—build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation

- Goal 11—make cities and human settlements inclusive, safe, resilient, and sustainable
- Goal 17—strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development

Just looking at these four goals brings a whole host of questions. Can the water and sanitation system currently installed in high-income (i.e., developed) counties simply be replicated and placed into low-income (i.e., undeveloped) countries, as outlined in the sixth goal? In the ninth goal, how can resilient infrastructure be built while achieving all three of the pillars: economic, environmental, and social? How can we as civil engineers incorporate safety into all of our designs, whether buildings or roads, as charged by goal 11? These are not easy, nor trivial, questions. But as civil engineers, following ASCE's code of ethics, we must "use [engineer's] knowledge and skill for the enhancement of human welfare and the environment." More challenges are presented by GRI, which presents ten sustainable economic challenges, three of which are directly related to civil engineering:

- Challenge 1—shortage of raw materials
- Challenge 3—reduce waste and ecosystem contamination
- Challenge 7—define regional sustainable development plans

Here, things appear a bit more straightforward. In regard to the first challenge, civil engineers are well aware that so many of our tools are finite resources; this is why fly ash is substituted for Portland cement in Portland cement concrete, and recycled asphalt pavement is substituted for aggregate and asphalt binder in asphalt mixtures. For the second challenge, the United States has made tremendous strides in reducing ecosystem contamination with the passage of the Clean Air Act in 1963 and the Federal Water Pollution Control Act Amendments of 1972, which led to the Clean Water Act of 1977. Yet, these examples provide a contradiction of sorts. If civil engineers were truly achieving a reduction in raw materials by using fly ash and RAP, the shortage of raw materials continues to be an issue since GRI listed this as the number one challenge? Another question comes from the seventh challenge. Regional planning is rarely performed by civil engineers, but instead it is usually directed by government-appointed planning commissions. Therefore, how can civil engineers use their skills to introduce options to these commissions, armed with the knowledge of the economic, environmental, and social perspectives of the long-term projects that will be constructed from the regional plan? The situation does not become any simpler when examining the thirteen regulating and cultural services put forth by IUCN, four of which are directly related to civil engineering:

- Service 1—air quality regulation
- Service 4—water regulation
- Service 5—erosion regulation
- Service 6—water purification and waste treatment

Here, we see similar themes to the UN and GRI, with air quality and water taking three of the four services. The fifth service, however, is new, but no less important.

Erosion takes many forms, from runoff of construction sites to high-quality topsoil being washed away on cleared farmland. Therefore, between the UN, the GRI, and IUCN, all four application areas of civil engineering have been covered, with discussion and challenges in environmental, geotechnical, structural, and transportation. But the challenges reviewed were only those directly related to civil engineering and did not weigh in on the "soft" issues, such as poverty, hunger, climate change, wealth inequality, gender inequality, social conflict, human rights, education of workers, or anticorruption policies. Therefore, in addition to the challenges associated directly with civil engineering, challenges that fall outside of the traditional realm of civil engineering must be faced. The bright side to these challenges, both within and outside of civil engineering, is that there are tremendous opportunities available for improvement of existing practices and the development of new practices to move toward a more sustainable future.

9.2 SUSTAINABILITY IS AN UNDEVELOPED FIELD

While there has been progress in both the economic and environmental pillar of sustainability and there is an acknowledged need for progress in the social pillar, there is another existing opportunity that allows for impactful opportunities for advancement of sustainable practices. As asked in Section 9.1, is it appropriate for sanitation systems in high-income countries to simply be placed in low-income countries? These highly complicated and expensive sanitation systems require a complex collection system to move the wastewater from buildings to the treatment plant, and then the wastewater must be treated through a multistep process that includes pretreatment, primary treatment, secondary treatment, tertiary treatment, and disinfection. Finally, the fully treated water needs to be returned to the ecosystem. All of these stages require extensive equipment and chemicals in order to execute. Interestingly, some of our youngest, and unpaid, workers are providing opportunities to solve these problems in low-income countries using more appropriate solutions.

Engineers Without Borders USA is a student group that has chapters in many universities across the United States. Generally, small groups of students with a faculty member or two travel to a low-income country in order to complete an engineering-based volunteer project. For example, two groups of civil engineering students went to Costa Rica to install bathrooms in a new computer center at a small school in San Juan de San Isidro (Texas A&M, 2010). Obviously, the students would not be building a full scale wastewater distribution system and wastewater treatment plant, so they instead installed a small septic tank with an onsite leach field. The total cost for the plumbing material was just under $3,700, a cost achievable for a low-income community.

This is just one example of the over 650 community-driven projects in over 40 countries around the world headed by Engineers Without Borders USA. However, just like wastewater treatment technology from high-income countries should not be applied to low-income countries, the wastewater project in Costa Rica may not work in other low-income countries. The challenges associated with students building tailor-made projects for specific communities, while still utilizing engineering principles learned in the classroom, show the possibilities of future potential developments in the field of sustainability.

9.3 PARADIGM SHIFT REQUIRED FOR SUSTAINABILITY

A couple of years ago, I invited an industry representative to talk in my sustainability class. During the question and answer portion of the class, I asked if the company of the representative would ever consider environmental impact on a level playing field as economic impact. The answer was a flat out "no." While not surprising, many people answer that question more along the lines of "both the environment and economic impact are important, but of course, if we are to stay in business, the economic case must be strong." I give the industry representative credit for answering truthfully, but it shows the work that needs to be done in changing how we, as civil engineers, approach our work.

GRI agrees that progress needs to be made in the area of environmental and social sustainability. In its report, GRI discusses how companies must be held accountable, and that the business decision makers need to take sustainability issues into account more profoundly. The IUCN agrees, calling for "new concepts, new thinking." The challenge for incorporating the environmental pillar into our civil engineering design process will be difficult, but chances are, incorporating the social pillar will be even more difficult. Therefore, existing employees of our civil engineering companies and agencies must continue to move toward economic, environmental, and social improvements in our design and execution of infrastructure projects.

Our future rests with the students of today and tomorrow. The primary purpose of this book is to provide tools for students to begin tackling these complicated, non-straightforward issues. However, this book also strives to embrace the wide open field of sustainability. To change the mindset of graduating civil engineers. To demonstrate that the economic pillar of sustainability is only 1/3 of the picture. To convince that the environmental and social pillars of sustainability are just as important as the economic pillar in civil engineering. All of these changes will probably not happen today, but they need to happen. Hopefully, the reader now has a more complete toolbox to tackle and address sustainability, so that tomorrow, the changes will happen, and the world will be a better place for all of the inhabitants of the world.

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