Contents

Preface

The transportation system is the nation's lifeblood circulation system. Our complex system of roads and highways, railroads, airports and airlines, waterways, and urban transit systems provides for the movement of people and goods to and from the most remote outposts of the nation. It is the transportation network which allows for the concentrated production of food, goods, energy, and other material in an economically optimal manner, knowing that the systems needed to collect raw materials, and distribute final products throughout the nation are in place.

Traffic engineering deals with several critical elements of the transportation system: our streets and highways, and the transportation services they support. Because the transportation system is such a critical part of our infrastructure, the traffic engineer is involved in a wide range of issues, often in a very public setting, and must bring a broad range of skills to the table. Traffic engineers must have an appreciation for and understanding of planning, design, management, construction, operation, control, and system optimization. All of these functions involve traffic engineers at some level.

This text focuses on the key engineering skills required to practice traffic engineering in a broad setting. This is the fifth edition of the textbook, and it includes the latest standards and criteria of the *Manual on Uniform Traffic Control Devices* (2009, as updated through May 2012), the *Policy on Geometric Design of Highways and Streets* (2011), the *Highway Capacity Manual* (2016), the *Highway Safety Manual* (2010, with 2014 Supplement), and other critical documents. While this edition uses the latest versions of basic references, students must be aware that all of these are periodically updated, and (at some point), versions not available at this writing will become available, and should be used.

The text is organized into four major functional parts:

- Part I – Basic Concepts and Characteristics
- Part II – Traffic Studies and Programs
- Part III – Interrupted Flow Facilities: Design, Control, and Level of Service
- Part IV – Uninterrupted Flow Facilities: Design, Control, and Level of Service

The text is appropriate for an undergraduate survey course in traffic engineering, or for more detailed graduate (or undergraduate) courses focusing on specific aspects of the profession. A survey course might include all of Part I, a selection of chapters from Part II, and a few chapters focusing on signal design and/or capacity and level of service analysis. Over the years, the authors have used the text for graduate courses on Traffic Studies and Characteristics, Traffic Control and Operations, and Highway Capacity and Level of Service Analysis. Special courses on highway traffic safety and geometric design have also used this text.

Some chapters, particularly Traffic Impact and Mitigation Studies, are organized around case studies. These should only be used in a more advanced course with an instructor who is familiar with the many tools referenced.

What's New in This Edition

This edition of the textbook adds a significant amount of material, including, but not limited to:

1. More than 50% of the homework problems (and an available solutions manual) are new for most chapters.

2. New material on unsignalized intersections, roundabouts, alternative intersections, interchanges, operation and analysis of facilities, and more.
3. Material on signalized intersections, signal design and timing, and signal hardware has been updated and extended.
4. Material from the latest editions of key traffic engineering references is included, as noted previously.
5. Links to a number of new Web sites which students and instructors will find valuable.

There are some additional revisions. There is no overview chapter on statistics; undergraduate engineering degrees now require coursework in statistics. We have included supporting material on statistical analyses within the applications in which they are used. An overview chapter can't cover everything, and it should be expected that modern engineering students have been exposed to this material. The text still provides details on a number of capacity and level of service applications. The *2016 HCM*, however, has over 3,000 pages of printed and electronic material, and many complicated analyses can only be presented in outline or overview form. There is material from the *Highway Safety Manual*, but complete analysis material is included for only one type of application. Again, there is simply too much material to include more than an example of its procedures and applications.

We hope that students and instructors will continue to find this text useful in learning about the profession of traffic engineering, and about many of its key components. As in the past, comments are always welcome.

Roger P. Roess
Elena S. Prassas
William R. McShane

PART I

Basic Concepts and Characteristics

CHAPTER 1

Introduction

1.1 Traffic Engineering as a Profession

Traffic engineering has been defined in many ways over the years. It is currently described by the Institute of Transportation Engineers (ITE) in the following words [*1*]:

> A branch of civil engineering, traffic engineering concerns the safe and efficient movement of people and goods along roadways. Traffic flow, road geometry, sidewalks, bicycle facilities, shared lane markings, traffic signs, traffic lights, and more—all of these elements must be considered when designing public and private sector transportation solutions.

This description represents an ever-broadening profession that includes multimodal transportation systems and options, many of which use streets and highways. It also highlights that the simple objectives of safety and efficiency have become ever-more complex.

Historically, traffic engineering begins with early road-builders, which have existed since ancient times. The ancient Romans were prolific road-builders. The focus was on the physical and structural design of roadways. Civil engineering, with its focus on physical infrastructure, became the traditional home for traffic engineering.

With the advent of the automobile and its growing influence on modern transportation, the traffic engineer's purview was extended to the areas of traffic control and operations. Modern traffic engineering involves complex technologies employed to control and operate roadway facilities and networks, and touches upon virtually all of the fundamental engineering disciplines. While not technically "traffic engineering," the associated profession of transportation planning is integral, focusing on various aspects of human behavior and their impacts on travel, the forecasting of transportation demand, and the development and assessment of plans to accommodate society's travel and mobility needs.

1.1.1 Safety: The Primary Objective

The principal goal of the traffic engineer remains the provision of a safe system for highway traffic. This is no small task. Traffic fatalities peaked at 55,600 in 1972.

Improvements in vehicles, driver training, roadway design, and traffic control have helped bring that number significantly down beginning in the 1980s. The number of traffic fatalities has been less than 40,000 per year since 2008, with a low of 32,744 posted in 2014 [*2*].

Unfortunately, 2015 and 2016 fatalities show that the number is rising again. Traffic fatalities rose by 8.4% to 35,485 in 2015. Fatalities for 2016 show a further increase of 5.6%, resulting in 37,461 fatalities [*3*]. The National Safety Council (NSC) had predicted that fatalities would actually be more than 40,000 for 2016 [*4*]. The NSC uses a different basis to define traffic fatalities than the National Highway Transportation Administration (NHTSA), which may account for some of the discrepancy.

While total highway fatalities per year have fluctuated, accident rates based on vehicle-miles traveled have consistently declined. That is because U.S. motorists generally drive more miles each year, with the exception of 2008 and 2009, which saw a small reduction due to poor economic conditions. The increasing number of annual vehicle-miles traveled produces a declining fatality rate. The fatality rate reached its lowest point in memory in 2014, at 1.08 fatalities per 100 million vehicle-miles traveled (100 MVM). In 2015, the rate increased to 1.15, and in 2016 to 1.18.

Improvements in fatality rates reflect a number of trends, many of which traffic engineers have been instrumental in implementing. Stronger efforts to remove dangerous drivers from the road have yielded significant dividends in safety. Driving under the influence (DUI) and driving while intoxicated (DWI) offenses are more strictly enforced, and licenses are suspended or revoked more easily as a result of DUI/DWI convictions, poor accident record, and/or poor violations record. Vehicle design has greatly improved (encouraged by several acts of Congress requiring certain improvements). Today's vehicles feature padded dashboards, collapsible steering columns, seat belts with shoulder harnesses, air bags (some vehicles now have as many as eight), and antilock braking systems. Collision avoidance systems and other driver aids now exist in a growing number of vehicles. Highway design has improved through the development and use of advanced barrier systems for medians and roadside areas. Traffic control systems communicate better and faster, and surveillance systems can alert authorities to accidents and breakdowns in the system.

The increase in fatalities over the last 2 years has generally been attributed to higher incidence of "distracted driving." The modern vehicle has many more distractions for the driver, despite all of the technological advances made to assist drivers. Electronic devices, including Bluetooth phones and other devices, a vast variety of listening options, and an increasingly busy external environment tend to lure the driver's attention from his or her primary task. Nearly 40,000 people per year still die in traffic accidents. The objective of safe travel is always number one and is never finished for the traffic engineer.

1.1.2 Other Objectives

Traffic engineers have other objectives to consider.

- Travel time
- Comfort
- Convenience
- Economy
- Environmental compatibility

Most of these are self-evident desires of the traveler. Most of us want our trips to be fast, comfortable, convenient, cheap, and in harmony with the environment. All of these objectives are also relative and must be balanced against each other and against the primary objective of safety.

While speed of travel is much to be desired, it is limited by transportation technology, human characteristics, and the need to provide safety. Comfort and convenience are generic terms that mean different things to different people. Comfort involves the physical characteristics of vehicles and roadways, and is influenced by our perception of safety. Convenience relates more to the ease with which trips are made and the ability of transport systems to accommodate all of our travel needs at appropriate times. Economy is also relative. There is little in modern transportation systems that can be termed "cheap." Highway and other transportation systems involve massive construction, maintenance, and operating expenditures, most of which are provided through general and user taxes and fees. Nevertheless, every engineer, regardless of discipline, is called upon to provide the best possible systems for the money.

Harmony with the environment is a complex issue that has become more important over time. All transportation systems have some negative impacts on the environment. All produce air and noise pollution in some forms, and all utilize valuable land resources. In many modern cities, transportation systems utilize as much as 25% of the total land area. "Harmony" is achieved when transportation systems are designed to minimize negative environmental impacts, and where system architecture provides for aesthetically pleasing facilities that "fit in" with their surroundings.

The traffic engineer is tasked with all of these goals and objectives and with making the appropriate trade-offs to optimize both the transportation systems and the use of public funds to build, maintain, and operate them.

1.1.3 Responsibility, Ethics, and Liability in Traffic Engineering

The traffic engineer has a very special relationship with the public at large. Perhaps more than any other type of engineer, the traffic engineer deals with the daily safety of a large segment of the public. Although it can be argued that any engineer who designs a product has this responsibility, few engineers have so many people using their product so routinely and frequently and depending upon it so totally. Therefore, the traffic engineer also has a special obligation to employ the available knowledge and state of the art within existing resources to enhance public safety.

The traffic engineer also functions in a world in which a number of key participants do not understand the traffic and transportation issues or how they truly affect a particular project. These include elected and appointed officials with decision-making power, the general public, and other professionals with whom traffic engineers work on an overall project team effort. Because all of us interface regularly with the transportation system, many overestimate their understanding of transportation and traffic issues. The traffic engineer must deal productively with problems associated with naïve assumptions, plans, and designs that are oblivious to transportation and traffic needs, oversimplified analyses, and understated impacts.

Like all engineers, traffic engineers must understand and comply with professional ethics codes. Primary codes of ethics for traffic engineers are those of the National Society of Professional Engineers and the American Society of Civil Engineers. The most up-to-date versions of each are available online. In general, good professional ethics requires that traffic engineers work only in their areas of expertise; do all work completely and thoroughly; be completely honest with the general public, employers, and clients; comply with all applicable codes and standards; and work to the best of their ability. In traffic engineering, the pressure to understate negative impacts of projects, sometimes brought to bear by clients who wish a project to proceed and employers who wish to keep clients happy, is a particular concern. As in all engineering professions, the pressure to minimize costs must give way to basic needs for safety and reliability.

Experience has shown that the greatest risk to a project is an incomplete analysis. Major projects have been upset because an impact was overlooked or analysis oversimplified. Sophisticated developers and experienced professionals know that the environmental impact process calls for a fair and complete statement of impacts and a *policy decision by the reviewers* on accepting the impacts, given an overall good analysis report. The process does not require zero impacts; it does, however, call for clear and complete disclosure of impacts so that policy makers can make informed decisions. Successful challenges to major projects are almost always based on flawed analysis, not on disagreements with policy makers. Indeed, such disagreements are not a valid basis for a legal challenge to a project. In the case of the Westway Project proposed in the 1970s for the west side of Manhattan, one of the bases for legal challenge was that the impact of project construction on striped bass in the Hudson River had not been properly identified or disclosed. In particular, the project died due to overlooking the impact on the reproductive cycle of striped bass in the Hudson River. While this topic was not the primary concern of the litigants, it was the legal "hook" that caused the project to be abandoned.

The traffic engineer also has a responsibility to protect the community from liability by good practice. There are many areas in which agencies charged with traffic and transportation responsibilities can be held liable. These include (but are not limited to) the following:

- Placing control devices that do not conform to applicable standards for their physical design and placement.
- Failure to maintain devices in a manner that ensures their effectiveness; the worst case of this is a "dark" traffic signal in which no indication is given due to bulb or other device failure.
- Failure to apply the most current standards and guidelines in making decisions on traffic control, developing a facility plan or design, or conducting an investigation.
- Implementing traffic regulations (and placing appropriate devices) without the proper legal authority to do so.

A historic standard has been that “due care” be exercised in the preparation of plans, and that determinations made in the process be reasonable and “not arbitrary.” It is generally recognized that professionals must make value judgments, and the terms “due care” and “not arbitrary” are continually under legal test.

The fundamental ethical issue for traffic engineers is to provide for the public safety through positive programs, good practice, knowledge, and proper procedure. The negative (albeit important) side of this is the avoidance of liability problems.

1.2 Transportation Systems and Their Function

Transportation systems are a major component of the U.S. economy and have an enormous impact on the shape of the society and the efficiency of the economy in general. Table 1.1 illustrates some key statistics for the U.S. highway system for 2015 [*1*].

America moves on its highways. While public transportation systems are of major importance in large urban areas such as New York, Boston, Chicago, and San Francisco, it is clear that the vast majority of person-travel as well as a large proportion of freight traffic is entirely dependent on the highway system.

The system is a major economic force in its own right: Over $150 billion per year is spent by state and local governments on highways. The vast majority of disbursements applied to highways and streets is made by state and local governments. The federal government provides massive funding through aid to the states. The federal government spends directly on federally owned lands, such as military bases, national parks, national forests, and Indian (Native American) reservations.

The revenue to support these expenditures comes from a variety of sources. Federal aid is disbursed from the *Highway Trust Fund*, which is funded by the federal excise tax on fuels and other highway-related items, as well as from the federal general fund. State and local funds come from state and local taxes on fuels, and from state and local general funds. Table 1.2 summarizes the sources of national highway expenditures for the year 2011 [*5*].

When the United States embarked on the *National System of Interstate and Defense Highways* in 1956, it created the *Highway Trust Fund*, with a host of federal road-user excise taxes to fund it. The theory was that the users of these new facilities would be the primary beneficiaries, and should therefore pay the lion’s share of their cost.

Over the years, the general view of road-user taxes has changed. Many federal excise taxes were dropped in the mid-1970s—such as excise taxes on vehicle purchases, tires, oil, and parts. The federal fuel tax has not been raised since 1993. While the need for investment in highway and transportation infrastructure has greatly increased, more fuel-efficient cars have actually reduced federal fuel tax revenues. A political debate over raising the tax has been ongoing for almost a decade. On the one hand, more money for investment in this key infrastructure is badly needed. On the other hand, it is recognized that a user tax system is fairly regressive, one that hits those with lower incomes the hardest.

Table 1.1: Important Statistics on U.S. Highways

Statistic	2015 Value
Miles of public roadway	4.19 million
Vehicle-miles traveled	3.11 trillion
Total population of the United States	321 million
Licensed drivers	218 million
Registered vehicles	256 million
Fatalities	35,485

Table 1.2: Revenue Sources for 2011 Highway Disbursements

Revenue ($ billion)	Source	Percent of Total
41.2	State & local motor fuel taxes	26.9
28.0	Federal motor fuel & other excise taxes	18.3
23.2	State license fees	15.2
12.7	Tolls and other local user fees	8.3
105.1	***Subtotal road-user taxes***	**68.7**
30.0	State & local general fund allocations	19.6
18.0	Federal general fund allocations & deficit financing	11.7
48.0	***Subtotal general funds***	**31.3**
153.1	**TOTAL**	**100.0**

The American love affair with the automobile has grown consistently since the 1920s, when Henry Ford's Model T made the car accessible to the average wage earner. This growth has survived wars, gasoline embargoes, depressions, recessions, and almost everything else that has happened in society. As seen in Figure 1.1, annual vehicle-miles traveled reached the 1 trillion mark in 1968 and the 2 trillion mark in 1987, and is now over 3 trillion vehicle miles per year.

This growth pattern is one of the fundamental problems to be faced by traffic engineers. Given the relative maturity of our highway systems and the difficulty faced in trying to add system capacity, particularly in urban areas, the continued growth in vehicle-miles traveled leads directly to increased congestion on our highways. The inability to simply build additional capacity to meet the growing demand creates the need to address alternative modes, fundamental alterations in demand patterns, and management of the system to produce optimal results.

1.2.1 The Nature of Transportation Demand

Transportation demand is directly related to land-use patterns and to available transportation systems and facilities. Figure 1.2 illustrates the fundamental relationship, which is circular and ongoing. Transportation demand is generated by the types, amounts, and intensity of land use, as well as its location. The daily journey to work, for example, is dictated by the locations of the worker's residence and employer and the times that the worker is on duty.

Transportation planners and traffic engineers attempt to provide capacity for observed or predicted travel demand by building transportation systems. The improvement of transportation systems, however, makes the adjacent and nearby lands more accessible and, therefore, more attractive for development. Thus, building new transportation facilities leads to further increases

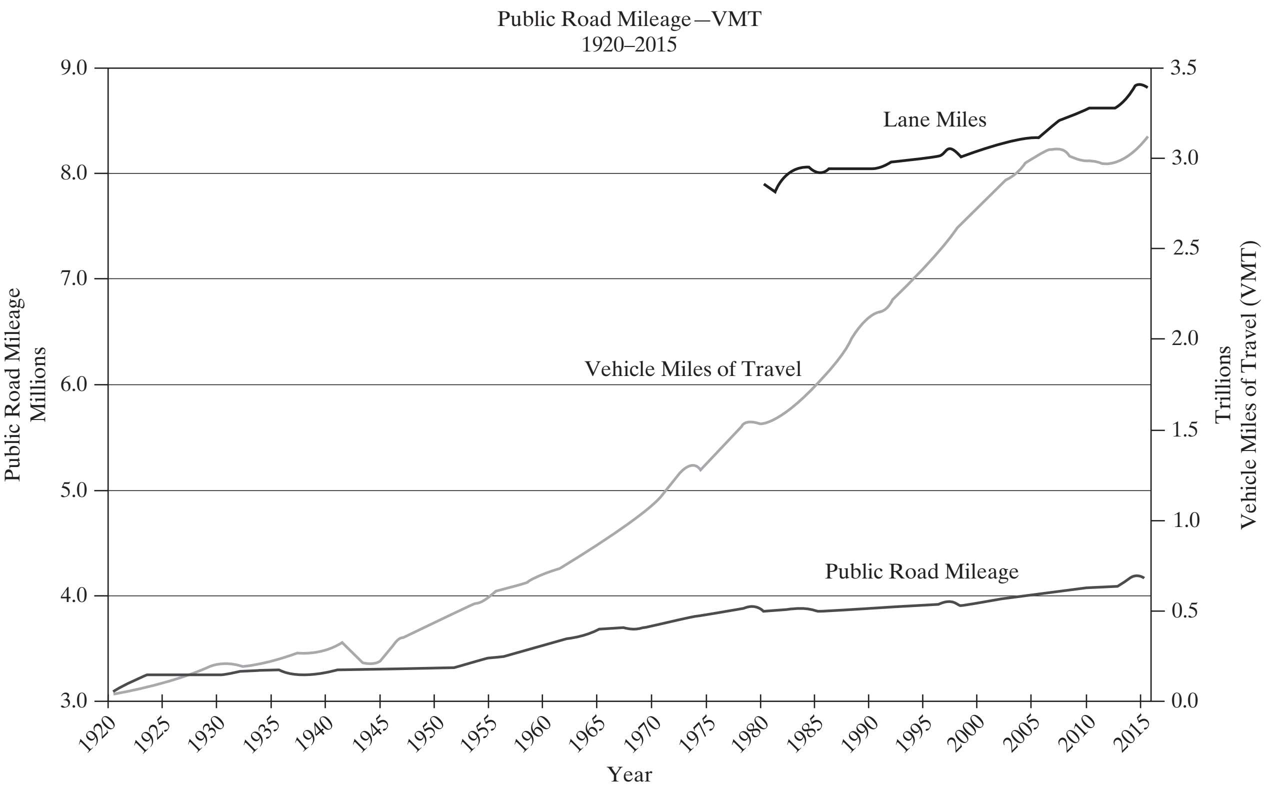

Figure 1.1: Public Highway Mileage and Annual Vehicle-Miles Traveled in the United States, 1920–2015 (*Source: Highway Statistics 2015*, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 2015, Table VMT 421C.)

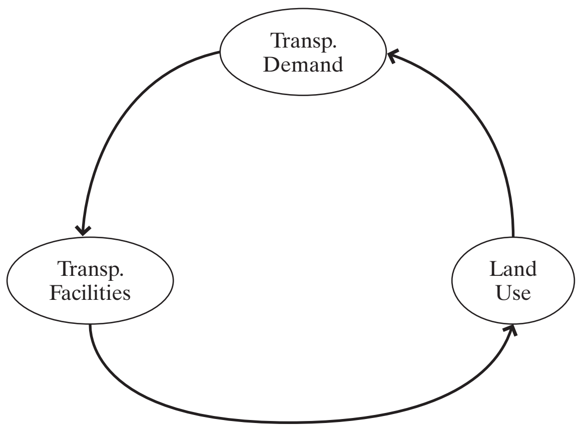

Figure 1.2: The Nature of Transportation Demand

in land-use development, which (in turn) results in even higher transportation demands. This circular, self-reinforcing characteristic of traffic demand creates a central dilemma: Building additional transportation capacity invariably leads to incrementally increased travel demands.

In many major cities, this has led to the search for more efficient transportation systems, such as public transit and car-pooling programs. In some of the largest cities, providing additional system capacity on highways is no longer an objective, as such systems are already substantially choking in congestion. In these places, the emphasis shifts to improvements within existing highway rights-of-way and to the elimination of bottleneck locations (without adding to overall capacity). Other approaches include staggered work hours and work days to reduce peak-hour demands, and even more radical approaches involve development of satellite centers outside of the central business district (CBD) to spatially disperse highly directional demands into and out of city centers.

Demand, however, is not constrained by capacity in all cities, and the normal process of attempting to accommodate demand as it increases is feasible in these areas. At the same time, the circular nature of the travel/demand relationship will lead to congestion if care is not taken to manage both capacity and demand to keep them within tolerable limits.

It is important that the traffic engineer understands this process. It is complex and cannot be stopped at any moment in time. Demand-prediction techniques (not covered in this text) must start and stop at arbitrary points in time. The real process is ongoing, and as new or improved facilities are provided, travel demand is constantly changing. Plans and proposals must recognize both this reality and the professional's inability to precisely predict its impacts. *A 10-year traffic demand forecast that comes within approximately $\pm 20\%$ of the actual value is considered a significant success*. The essential truth, however, is that traffic engineers cannot simply build their way out of congestion.

If anything, we still tend to underestimate the impact of transportation facilities on land-use development. Often, the increase in demand is hastened by development occurring simply as a result of the planning of a new facility.

One of the classic cases occurred on Long Island, in New York State. As the Long Island Expressway was built, the development of suburban residential communities lurched forward in anticipation. While the expressway's link to Exit 7 was being constructed, new homes were being built at the anticipated Exit 10, even though the facility would not be open to that point for several years. The result was that as the expressway was completed section by section, the 20-year anticipated demand was being achieved within a few years, or even months. This process has been repeated in many cases throughout the nation.

1.2.2 Concepts of Mobility and Accessibility

Transportation systems provide the nation's population with both mobility and accessibility. The two concepts are strongly interrelated but have distinctly different elements. *Mobility* refers to the ability to travel to many different destinations with relative ease, while *accessibility* refers to the ability to gain entry to a particular site or area.

Mobility gives travelers a wide range of choices as to where to go to satisfy particular needs, and provides for efficient trips to get to them. Mobility allows shoppers to choose from among many competing shopping centers and stores. Similarly, mobility provides the traveler with many choices for all kinds of trip purposes, including recreational trips, medical trips, educational trips, and even the commute to work. The range of available choices is enabled by having an effective transportation network that connects to many alternative trip destinations within a reasonable time, with relative ease, and at reasonable cost. Thus, mobility provides not only access to many travel opportunities but also relative speed and convenience for the required trips.

Accessibility is a major factor in the value of land. When land can be accessed by many travelers from many potential origins, it is more desirable for development and, therefore, more valuable. Thus, proximity of land to major highways and public transportation facilities is a major factor determining its value.

Mobility and accessibility may also refer to different portions of a typical trip. Mobility focuses on the through portion of trips and is most affected by the effectiveness of through facilities that take a traveler from one general area to another. Accessibility requires the ability to make a transfer from the transportation system to the particular land parcel on which the desired activity is taking place. Accessibility, therefore, relies heavily on transfer facilities, which include parking for vehicles, public transit stops, and loading zones.

Most transportation systems are structured to separate mobility and access functions, as the two functions often compete and are not necessarily compatible. In highway systems, mobility is provided by high-type facilities, such as freeways, expressways, and primary and secondary arterials. Accessibility is generally provided by local street networks. Except for limited-access facilities, which serve only through vehicles (mobility), most other classes of highway serve both functions to some degree. Access maneuvers, however (e.g., parking and unparking a vehicle, vehicles entering and leaving off-street parking via driveways, buses stopping to pick up or discharge passengers, trucks stopped to load and/or unload goods), retard the progress of through traffic. High-speed through traffic, on the other hand, tends to make such access functions more dangerous.

A good transportation system must provide for both mobility and accessibility, and should be designed to separate the functions to the extent possible to ensure both safety and efficiency.

1.2.3 People, Goods, and Vehicles

The most common unit used by the traffic engineer is "vehicles." Highway systems are planned, designed, and operated to move vehicles safely and efficiently from place to place. Yet the movement of vehicles is not the objective; the goal is the movement of the people and goods that occupy vehicles.

Modern traffic engineering now focuses more on people and goods. While lanes must be added to a freeway to increase its capacity to carry vehicles, its person-capacity can be increased by increasing the average vehicle occupancy. Consider a freeway lane with a capacity of 2,000 vehicles per hour (veh/h). If each vehicle carries one person, the lane has a capacity of 2,000 persons per hour as well. If the average car occupancy is increased to 2.0 persons per vehicle, the capacity in terms of people is doubled to 4,000 persons per hour. If the lane were established as an exclusive bus lane, the vehicle-capacity might be reduced to 1,000 veh/h due to the larger size and poorer operating characteristics of buses as compared with automobiles. However, if each bus carries 50 passengers, the people-capacity of the lane is increased to 50,000 persons per hour.

The efficient movement of goods is also vital to the general economy of the nation. The benefits of centralized and specialized production of various products are possible only if raw materials can be efficiently shipped to manufacturing sites and finished products can be efficiently distributed throughout the nation and the world for consumption. While long-distance shipment of goods and raw materials is often accomplished by water, rail, or air transportation, the final leg of the trip to deliver a good to the local store or the home of an individual consumer generally takes place on a truck using the highway system. Part of the accessibility function is the provision of facilities that allow trucks to be loaded and unloaded with minimal disruption to through traffic and the accessibility of people to a given site.

The medium of all highway transportation is the vehicle. The design, operation, and control of highway systems rely heavily on the characteristics of the vehicle and of the driver. In the final analysis, however, the objective is to move people and goods, not vehicles.

1.2.4 Transportation Modes

While traffic engineers focus their attention on the movement of people and goods in over-the-road vehicles, they must be keenly aware of the role of public transportation and other modes, particularly as they interface with the street and highway system. Chapter 2 presents an in-depth overview of the various transportation modes and their functions.

1.3 History of U.S. Highway Legislation

The development of highway systems in the United States is strongly tied to federal legislation that supports and regulates much of this activity. Key historical and legislative actions are discussed in the sections that follow.

1.3.1 The National Pike and the States' Rights Issue

Before the 1800s, roads were little more than trails cleared through the wilderness by adventurous travelers and explorers. Private roadways began to appear in the latter part of the 1700s. These roadways ranged in quality and length from cleared trails to plank roadways. They were built by private owners, and fees were charged for their use. At points where fees were to be collected, a barrier usually consisting of a single crossbar was mounted on a swiveling stake, referred to as a "pike." When the fee was collected, the pike would be swiveled or turned, allowing the traveler to proceed. This early process gave birth to the term "turnpike," often used to describe toll roadways in modern time.

In 1811, the construction of the first national roadway was begun under the direct supervision of the federal government. Known as the "national pike" or the "Cumberland Road," this facility stretched for 800 miles from Cumberland, MD, in the east, to Vandalia, IL, in the west. A combination of unpaved and plank sections, it was finally completed in 1852 at a total cost of $6.8 million. A good deal of the original route is now a portion of U.S. Route 40.

The course of highway development in the United States, however, was forever changed as a result of an 1832 Supreme Court case brought by the administration of President Andrew Jackson. A major proponent of states' rights, the Jackson Administration petitioned the court claiming that the U.S. constitution did not specifically define transportation and roadways as federal functions; they were, therefore, the responsibility of the individual states. The Supreme Court upheld this position, and the principal administrative responsibility for transportation and highways was forevermore assigned to state governments.

If the planning, design, construction, maintenance, and operation of highway systems is a state responsibility, what is the role of federal agencies—for example, the U.S. Department of Transportation and its components, such as the Federal Highway Administration, the National Highway Safety Administration, and others in these processes?

The federal government asserts its overall control of highway systems through the power of the purse string. The federal government provides massive funding for the construction, maintenance, and operation of highway and other transportation systems. States are not *required* to follow federal mandates and standards but must do so to qualify for federal funding of projects. Thus, the federal government does not force a state to participate in federal-aid transportation programs. If it chooses to participate, however, it must follow federal guidelines and standards. As no state can afford to give up this massive funding source, the federal government imposes strong control of policy issues and standards.

The federal role in highway systems has four major components:

1. Direct responsibility for highway systems on federally owned lands, such as national parks and Native American reservations.
2. Provision of funding assistance in accord with current federal-aid transportation legislation.
3. Development of planning, design, and other relevant standards and guidelines that must be followed to qualify for receipt of federal-aid transportation funds.
4. Monitoring and enforcing compliance with federal standards and criteria, and the use of federal-aid funds.

State governments have the primary responsibility for the planning, design, construction, maintenance, and operation of highway systems. These functions are generally carried out through a state department of transportation or similar agency. States are entrusted with:

1. Full responsibility for administration of highway systems.
2. Full responsibility for the planning, design, construction, maintenance, and operation of highway systems in conformance with applicable federal standards and guidelines.
3. The right to delegate responsibilities for local roadway systems to local jurisdictions or governmental agencies.

Local governments have general responsibility for local roadway systems as delegated in state law. In general, local governments are responsible for the planning, design, construction, maintenance, and control of local roadway systems. Often, assistance from state programs and agencies is available to local governments in fulfilling these functions. At intersections of state highways with local roadways, it is generally the state that has the responsibility to control the intersection.

Local organizations for highway functions range from a full highway or transportation department to local police to a single professional traffic or city engineer.

There are also a number of special situations across the United States. In New York State, for example, the state constitution grants "home rule" powers to any municipality with a population in excess of 1,000,000 people. Under this provision, New York City has full jurisdiction over all highways within its borders, including those on the state highway system.

1.3.2 Key Legislative Milestones

Federal-Aid Highway Act of 1916

The Federal-Aid Highway Act of 1916 was the first allocation of federal-aid highway funds for highway construction by the states. It established the "A-B-C System" of primary, secondary, and tertiary federal-aid highways, and provided 50% of the funding for construction of highways in this system. Revenues for federal aid were taken from the federal general fund, and the act was renewed every 2 to 5 years (with increasing amounts dedicated). No major changes in funding formulas were forthcoming for a period of 40 years.

Federal-Aid Highway Act of 1934

In addition to renewing funding for the A-B-C System, this act authorized states to use up to 1.5% of federal-aid funds for planning studies and other investigations. It represented the entry of the federal government into highway planning.

Federal-Aid Highway Act of 1944

This act contained the initial authorization of what became the National System of Interstate and Defense Highways. No appropriation of funds occurred, however, and the system was not initiated for another 12 years.

Federal-Aid Highway Act of 1956

The authorization and appropriation of funds for the implementation of the National System of Interstate and Defense Highways occurred in 1956. The act also set the federal share of the cost of the Interstate System at 90%, the first major change in funding formulas since 1916. Because of the major impact on the amounts of federal funds to be spent, the act also created the *Highway Trust Fund* and enacted a series of road-user taxes to provide it with revenues. These taxes included excise taxes on motor fuels, vehicle purchases, motor oil, and replacement parts. Most of these taxes, except for the federal fuel tax, were dropped during the Nixon Administration. The monies housed in the Highway Trust Fund may be disbursed only for purposes authorized by the current federal-aid highway act.

Federal-Aid Highway Act of 1970

Also known as the Highway Safety Act of 1970, this legislation increased the federal subsidy of non-Interstate highway projects to 70% and required all states to implement highway safety agencies and programs.

Federal-Aid Highway Act of 1983

This act contained the "Interstate trade-in" provision that allows states to "trade in" federal-aid funds designated for urban Interstate projects for alternative transit systems. This historic provision was the first to allow road-user taxes to be used to pay for public transit improvements.

ISTEA and TEA-21

The single largest overhaul of federal-aid highway programs occurred with the passage of the Intermodal Surface Transportation Efficiency Act (ISTEA) in 1991 and its successor, the Transportation Equity Act for the 21st Century (TEA-21), in 1998.

Most importantly, these acts combined federal-aid programs for all modes of transportation and greatly liberalized the ability of state and local governments to make decisions on modal allocations. Key provisions of ISTEA included the following:

1. Greatly increased local options in the use of federal-aid transportation funds.
2. Increased the importance and funding to Metropolitan Planning Organizations (MPOs) and requiring that each state maintain a state transportation improvement plan (STIP).

3. Tied federal-aid transportation funding to compliance with the Clean Air Act and its amendments.
4. Authorized $38 billion for a 155,000-mile National Highway System.
5. Authorized an additional $7.2 million to complete the Interstate System and $17 billion to maintain it as part of the National Highway System.
6. Extended 90% federal funding of Interstate-eligible projects.
7. Combined all other federal-aid systems into a single surface transportation system with 80% federal funding.
8. Allowed (for the first time) the use of federal-aid funds in the construction of toll roads.

TEA-21 followed in kind, increasing funding levels, further liberalizing local options for allocation of funds, further encouraging intermodality and integration of transportation systems, and continuing the link between compliance with clean-air standards and federal transportation funding.

The creation of the National Highway System (NHS) answered a key question that had been debated for years: What comes after the Interstate System? The new, expanded NHS is not limited to freeway facilities and is over three times the size of the Interstate System, which becomes part of the NHS.

SAFETY-LU

President Bush signed the most expensive transportation funding act into law on August 10, 2005. The act was a mile wide, and more than four years late, with intervening highway funding being accomplished through annual continuation legislation that kept TEA-21 in effect.

The Safe, Accountable, Flexible and Efficient Transportation Equity Act—A Legacy for Users (SAFETY-LU) has been both praised and criticized. While it retains most of the programs of ISTEA and TEA-21, and expands the funding for most of them, the act also adds many new programs and provisions, leading some lawmakers and politicians to label it "the most pork-filled legislation in U.S. history." Table 1.3

Table 1.3: Programs Covered by SAFETY-LU*

Interstate Maintenance Program	$25.1
National Highway System	$30.5
Surface Transportation System	$32.4
Congestion Mitigation/Air Quality Improvement Program	$8.5
Highway Safety Improvement Program	$5.1
Appalachian Development/Highway System Program	$2.4
Recreational Trails Program	$0.4
Federal Lands Highway Program	$4.5
National Corridor Infrastructure Improvement Program	$1.9
Coordinated Border Infrastructure Program	$0.8
National Scenic Byways Program	$0.2
Construction of Ferry Boats/Terminals	$0.3
Puerto Rico Highway Program	$0.7
Project of National and Regional Significance Program	$1.8
High-Priority Projects Program	$14.8
Safe Routes to School Program	$ 0.61
Deployment of MagLev Trans Projects	$ 0.45
Nat'l Corridor Planning/Dev of Coordinated Infrastructure Programs	$ 0.14
Highways for Life Program	$ 0.45
Highway Use Tax Evasion Projects	$ 0.12

*All amounts are stated in billions of dollars.

provides a simple listing of the programs covered under this legislation. The program, which authorizes over $248 billion in expenditures, includes many programs that represent items of special interest inserted by members of Congress.

The legislation does recognize the need for massive funding of Interstate highway maintenance, as the system continues to age, with many structural components well past their anticipated service life. It also provides massive funding for the new NHS, which is the successor to the Interstate System in terms of new highways. It also retains the flexibility for local governments to push more funding into public transportation modes.

MAP-21

The current (as of June 2017) transportation act is the "Moving Ahead for Progress in the 21st Century" (MAP) act, signed into law by President Obama on July 12, 2012. Unlike its immediate predecessors, MAP-21 was a limited 2-year stopgap that froze spending at the 2012 level for the 2-year period covered by the legislation. It consolidated 87 programs under SAFETY-LU into 30, and gave states greater flexibility in the allocation of funds. It authorized $105 billion for 27 months.

Like its immediate predecessors, MAP-21 has yet to be replaced. It has been extended on an annual basis by Congress to provide for ongoing federal transportation funding. A replacement piece of legislation has been under discussion for some time, and is now (June 2017) being considered as part of the Trump Administration's overall infrastructure plan.

1.3.3 The National System of Interstate and Defense Highways

The "Interstate System" has been described as the largest public works project in the history of mankind. In 1919, a young army officer, Dwight Eisenhower, took part in an effort to move a complete battalion of troops and military equipment from coast to coast on the nation's highways to determine their utility for such movements in a time of potential war. The trip took months and left the young officer with a keen appreciation for the need to develop a national roadway system. It was no accident that the Interstate System was implemented in the administration of President Dwight Eisenhower, nor that the system now bears his name.

After the end of World War II, the nation entered a period of sustained prosperity. One of the principal signs of that prosperity was the great increase in auto ownership along with the expanding desire of owners to use their cars for daily commuting and for recreational travel. Motorists groups, such as the American Automobile Association (AAA), were formed and began substantial lobbying efforts to expand the nation's highway systems. At the same time, the over-the-road trucking industry was making major inroads against the previous rail monopoly on intercity freight haulage. Truckers also lobbied strongly for improved highway systems. These substantial pressures led to the inauguration of the Interstate System in 1956.

The System Concept

Authorized in 1944 and implemented in 1956, the National System of Interstate and Defense Highways is a 42,500-mile national system of multilane, limited-access facilities. The system was designed to connect all standard metropolitan statistical areas (SMSAs) with 50,000 or greater population (at the time) with a continuous system of limited-access facilities. The allocation of 90% of the cost of the system to the federal government was justified on the basis of the potential military use of the system in wartime.

System Characteristics

Key characteristics of the Interstate System include the following:

1. All highways have at least two lanes for the exclusive use of traffic in each direction.
2. All highways have full control of access.
3. The system must form a closed loop: All Interstate highways must begin and end at a junction with another Interstate highway.
4. North–South routes have odd one- or two-digit numbers (e.g., I-95).
5. East–West routes have even one- or two-digit numbers (e.g., I-80).
6. Interstate routes serving as bypass loops or acting as a connector to a primary Interstate facility have three-digit route numbers, with the last two digits indicating the primary route.

A map of the Interstate System is shown in Figure 1.3.

Figure 1.3: A Map of the Interstate System

Status and Costs

By 1994, the system was 99.4% complete. Most of the unfinished sections were not expected to ever be completed for a variety of reasons. The total cost of the system was approximately $128.9 billion. This final estimate of cost was released in 1991. It is estimated that the cost would be over $500 billion in today's dollars.

The impact of the Interstate System on the nation cannot be understated. The system facilitated and enabled the rapid suburbanization of the United States by providing a means for workers to commute from suburban homes to urban jobs. The economy of urban centers suffered as shoppers moved in droves from traditional CBDs to suburban malls.

The system also had serious negative impacts on some of the environs through which it was built. Following the traditional theory of benefit-cost, urban sections were often built through the low-income parts of communities where land was the cheapest. The massive Interstate highway facilities created physical barriers, partitioning many communities, displacing residents, and separating others from their schools, churches, and local shops. Social unrest resulted in several parts of the country, which eventually leading to in important modifications to the public hearing process and in the ability of local opponents to legally stop many urban highway projects.

Between 1944 and 1956, a national debate was waged over whether the Interstate System should be built into and out of urban areas, or whether all Interstate facilities should terminate in ring roads built around urban areas. Proponents of the ring-road option (including, ironically, Robert Moses, who built many highways into and out of urban cities) argued that building these roadways into and out of cities would lead to massive urban congestion. The other side of the argument was that most of the road users who were paying for the system through their road-user taxes lived in urban areas and should be served. The latter view prevailed, but the predicted rapid growth of urban congestion also became a reality.

1.4 Elements of Traffic Engineering

There are a number of key elements of traffic engineering:

1. Traffic studies and characteristics
2. Performance evaluation
3. Facility design
4. Traffic control
5. Traffic operations
6. Transportation systems management
7. Integration of intelligent transportation system technologies

Traffic studies and characteristics involve measuring and quantifying various aspect of highway traffic. Studies focus on data collection and analysis that is used to characterize traffic, including (but not limited to) traffic volumes and demands, speed and travel time, delay, accidents, origins and destinations, modal use, and other variables.

Performance evaluation is a means by which traffic engineers can rate the operating characteristics of individual sections of facilities and facilities as a whole in relative terms. Such evaluation relies on measures of performance quality and is often stated in terms of "levels of service." Levels of service are letter grades, from A to F, describing how well a facility is operating using specified performance criteria. Like grades in a course, A is very good, while F connotes failure (on some level). As part of performance evaluation, the *capacity* of highway facilities must be determined.

Facility design involves traffic engineers in the functional and geometric design of highways and other traffic facilities. Traffic engineers, per se, are not involved in the structural design of highway facilities but should have some appreciation for structural characteristics of their facilities.

Traffic control is a central function of traffic engineers and involves the establishment of traffic regulations and their communication to the driver through the use of traffic control devices, such as signs, markings, and signals.

Traffic operations involves measures that influence overall operation of traffic facilities, such as one-way street systems, transit operations, curb management, and surveillance and network control systems.

Transportation systems management (TSM) involves virtually all aspects of traffic engineering in a focus on optimizing system capacity and operations. Specific aspects of TSM include high-occupancy vehicle priority systems, car-pooling programs, pricing strategies to manage demand, and similar functions.

Intelligent transportation systems (ITS) refers to the application of modern telecommunications technology to the operation and control of transportation systems. Such systems include automated highways, automated toll-collection systems, vehicle-tracking systems, in-vehicle GPS and mapping systems, automated enforcement of traffic lights and speed laws, smart control devices, and others. This is a rapidly emerging family of technologies with the potential to radically alter the way we travel as well as the way in which transportation professionals gather information and control facilities. While the technology continues to expand, society will grapple with the substantial "big brother" issues that such systems invariably create.

This text contains material related to all of these components of the broad and complex profession of traffic engineering.

1.5 Modern Problems for the Traffic Engineer

We live in a complex and rapidly developing world. Consequently, the problems that traffic engineers are involved in evolve rapidly.

Urban congestion has been a major issue for many years. Given the transportation demand cycle, it is not always possible to solve congestion problems through expansion of capacity. Traffic engineers therefore are involved in the development of programs and strategies to manage demand in both time and space and to discourage growth where necessary. A real question is not "how much capacity is needed to handle demand?" but rather "how many vehicles and/or people can be allowed to enter congested areas within designated time periods?"

Growth management is a major current issue. A number of states have legislation that ties development permits to level-of-service impacts on the highway and transportation system. Where development will cause substantial deterioration in the quality of traffic service, either such development will be disallowed or the developer will be responsible for general highway and traffic improvements that mitigate these negative impacts. Such policies are more easily dealt with in good economic times. When the economy is sluggish, the issue will often be a clash between the desire to reduce congestion and the desire to encourage development as a means of increasing the tax base.

Reconstruction of existing highway facilities also causes unique problems. The entire Interstate System has been aging, and many of its facilities have required major reconstruction efforts. Part of the problem is that reconstruction of Interstate facilities receives the 90% federal subsidy, while routine maintenance on the same facility is primarily the responsibility of state and local governments. Deferring routine maintenance on these facilities in favor of major reconstruction efforts has resulted from federal funding policies over the years. Major reconstruction efforts have a substantial major burden not involved in the initial construction of these facilities: maintaining traffic. It is easier to build a new facility in a dedicated undeveloped right-of-way than to rebuild it while continuing to serve 100,000 or more vehicles per day. Thus, issues of long-term and short-term construction detours as well as the diversion of traffic to alternate routes require major planning by traffic engineers.

Since 2001, the issue of security of transportation facilities has come to the fore. The creation of facilities and processes for random and systematic inspection of trucks and other vehicles at critical locations is a major challenge, as is securing major public transportation systems such as railroads, airports, and rapid transit systems.

As the fifth edition of this text is written, we are now in a new era with many unknowns. With the sharp rise in fuel prices through 2008, vehicle usage actually began to decline for the first time in decades. The upward trend, however, returned as economic conditions improved.

The economic crisis of 2008 and 2009 caused many shifts in the economy, even as the price of fuel came back to more normal levels. Major carmakers in the United States (Chrysler, GM) headed into bankruptcy, with major industry reductions and changes. Government loans to both banks and industries brought with it more governmental control of private industries. A shift of U.S. automakers to smaller, more fuel-efficient and "green" vehicles has begun, with no clear appreciation of whether the buying public will sustain the shift.

As the economy rebounded, however, some of these shifts were modified. While the emphasis on "green" vehicles continues, renewed interest and sales of sport-utility vehicles (SUVs), pickup trucks, and "muscle cars" occurred. While they still have some problems, the major U.S. automakers are more stable. Banks and other industries began to pay off their debt to the government, returning to more normal private control and management, albeit in a more stringent regulatory environment.

For perhaps the first time in many decades, transportation and traffic demand may be very much dependent upon the state of the general economy, not the usual motivators of improved mobility and accessibility. Will people learn new behaviors resulting in fewer and more efficient trips? Will people flock to hybrid or fully electric vehicles to reduce fuel costs? Will public transportation pick up substantial new customers as big-city drivers abandon their cars for the daily commute? It is an unsettling time that will continue to evolve into new challenges for traffic and transportation engineers. With new challenges, however, comes the ability for new and innovative approaches that might not have been feasible only a few years ago.

The point is that traffic engineers cannot expect to practice their profession only in traditional ways on traditional projects. Like any professional, the traffic engineer must be ready to face current problems and to play an important role in any situation that involves transportation and/or traffic systems.

1.6 Standard References for the Traffic Engineer

In order to remain up to date and aware, the traffic engineer must keep up with modern developments through membership and participation in professional organizations, regular review of key periodicals, and an awareness of the latest standards and criteria for professional practice.

Key professional organizations for the traffic engineer include the ITE, the Transportation Research Board (TRB), the Transportation Group of the American Society of Civil Engineers (ASCE), ITS America, and others. All of these provide literature and maintain journals, and have local, regional, and national meetings. TRB is a branch of the National Academy of Engineering and is a major source of research papers and reports.

Like many engineering fields, the traffic engineering profession has many manuals and standard references, most of which will be referred to in the chapters of this text. Major references include

- *Traffic Engineering Handbook, 7th Edition* [*1*]
- *Uniform Vehicle Code and Model Traffic Ordinance* [*6*]
- *Manual on Uniform Traffic Control Devices, 2009* (as updated through May 2012) [*7*]
- *Highway Capacity Manual, 6th Edition: A Guide for Multimodal Mobility Analysis* [*8*]
- *A Policy on Geometric Design of Highways and Streets* (The AASHTO Green Book), 6th *Edition* [*9*]
- *Traffic Signal Timing Manual, 2nd Edition* [*10*]
- *Transportation Planning Handbook, 4th Edition* [*11*]
- *Trip Generation, 8th Edition* [*12*]
- *Parking Generation, 4th Edition* [*13*]

All of these documents are updated periodically, and the traffic engineering professional should be aware of when updates are published and where they can be accessed.

Other manuals abound and often relate to specific aspects of traffic engineering. These references document the current state of the art in traffic engineering, and those most frequently used should be part of the professional's personal library.

There are also a wide variety of internet sites that are of great value to the traffic engineer. Specific sites are not listed here, as they change rapidly. All of the professional organizations, as well as equipment manufacturers, maintain web sites. The federal Department of Transportation (DOT), Federal Highway Administration (FHWA), National Highway Traffic Safety Administration (NHTSA), and private highway-related organizations maintain web sites. The entire *Manual on Uniform Traffic Control Devices* is available online through the FHWA web site, as is the *Manual of Traffic Signal Timing*.

Because traffic engineering is a rapidly changing field, the reader cannot assume that every standard and analysis process included in this text is current, particularly as the time since publication increases. While the authors will continue to produce periodic updates, the traffic engineer must keep abreast of latest developments as a professional responsibility.

1.7 Metric versus U.S. Units

This text is published in English (or Standard U.S.) units. Despite several attempts to switch to metric units in the United States, most states now use English units in design and control.

Metric and U.S. standards are not the same. A standard 12-ft lane converts to a standard 3.6-m lane, which is narrower than 12 ft. Standards for a 70-mi/h design speed convert to standards for a 120-km/h design speed, which are not numerically equivalent. This is because even units are used in both systems rather than the awkward fractional values that result from numerically equivalent conversions. That is why a metric set of wrenches for use on a foreign car is different from a standard U.S. wrench set.

Because more states are on the U.S. system than on the metric system (with more moving back to U.S. units) and because the size of the text would be unwieldy if dual units were included, this text continues to be written using standard U.S. units.

1.8 Closing Comments

The profession of traffic engineering is a broad and complex one. Nevertheless, it relies on key concepts and analyses and basic principles that do not change greatly over time. This text emphasizes both the basic principles and current (in 2017) standards and practices. The reader must keep abreast of changes that influence the latter.

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CHAPTER 2

Transportation Modes and Characteristics

The traffic engineer is involved in the planning, design, operation, and management of the street and highway system. While the street and highway system primarily serves vehicular traffic, it is actually multimodal in many ways.

Consider, for example, a typical major urban arterial. Within the right-of-way of the arterial and its intersections, service is provided to drivers and passengers in privately owned vehicles, passengers in bus transit operating on the arterial, goods moved in trucks along the arterial, pedestrians using the sidewalks and crosswalks, and bicyclists riding in vehicular lanes or in designated bike lanes. In some places, light rail transit may be sharing vehicular lanes. Even rapid transit lines, always on segregated rights-of-way (tunnels, elevated structures, separated facilities), interact by depositing large numbers of pedestrians onto the arterial at station locations.

Curb space along the arterial is shared by moving vehicles, bus-stops, truck loading zones, parking, and perhaps bicyclists. One of the principal functions of urban traffic engineers is the management of curb space, and its allocation to competing user groups.

On a more regional level, highway systems provide access to airports, railroad stations, ports, and other transportation facilities.

It is imperative, therefore, that traffic engineers clearly understand the many modes of transportation that impact their profession, and how these modes fit into the national and regional infrastructure that serves our total transportation needs.

2.1 Classifying Transportation Modes

There are many ways of classifying transportation modes. One significant factor is whether the transportation demand being serviced is intercity (between centralized areas) or intra-city (within a centralized area). Intercity trips typically involve longer travel distances and travel times, and occur less frequently than trips entirely within an area. Some modes of transportation serve one type of trip almost exclusively: Virtually all trips by air are intercity; virtually all pedestrian trips are local, or intra-city.

A second categorization involves whether the primary function is the movement of goods or people. While most transportation is dominated by the movement of people, goods movement is a vital function in the economy.

Both people and goods may travel intercity or intra-city. People use a wide variety of modes, but most person-travel is by private automobile. In major cities, public transportation (rapid transit, light rail, bus) can serve large components of the person-travel demand. Intercity person-trips occur in private automobiles, airplanes, on passenger railroads, and on intercity buses. Within urban centers, person-trips are accommodated by cars, bus or rail transit, and walking.

Goods move between cities in airplanes, over-the-road trucks, railroads, and ships. Where liquids are concerned, pipelines also play a major role. Within cities, most goods move by truck, but some may use a variety of rail services. One normally would not think of pipelines in an urban setting, yet they form a vital part of the urban transportation infrastructure in the delivery of natural gas and water to individual consumers, and in the removal of liquid waste.

A final way to categorize transportation modes is by whether the mode is privately or publicly operated. In intercity transportation, passenger cars are virtually always privately owned and operated. Airlines, railroads, ships, and pipelines are owned by mostly private or public operators who provide, maintain, manage, and operate the physical infrastructure. All are subject to government regulation. One might, however, consider such modes to be "public" in nature, as the individual traveler (or good) has no direct role in the operation of the service.

In urban areas, pedestrians, bicyclists, and drivers/passengers of privately owned vehicles form the core of "private" transportation, while "public" transportation includes transit and for-hire vehicles (taxis).

Table 2.1 summarizes the various transportation modes in terms of the categories discussed.

Table 2.1: Transportation Modes by Category

Function	Person-Transport	Goods Movement
Intercity	Private auto (private) Passenger railroad (public) Air (public) Intercity bus (public) Passenger boat—ferries (public)	Over-the-road trucks (public) Air freight (public) Railroad (public) Ships (public) Pipelines (public)
Intra-City	Pedestrian (private) Bicycle (private) Private auto (private) For-hire vehicle (public) Transit (public) Passenger boat—ferries (public)	Trucks (public) Railroad (public) Pipelines (public)

Note that "public" modes are so categorized because they are publicly accessible to users, whether or not the operator of the service is a private entity or a public one.

2.2 The Transportation Infrastructure and Its Use

To provide for the diverse transportation needs of the nation, a vast infrastructure must be in place. Much (but not all) of the basic infrastructure is publicly provided. Table 2.2 shows the miles of transportation infrastructure in place within the United States in 2014 [*1,2*].

The U.S. highway system is massive and serves intercity and intra-city transport of people and goods. The Interstate System (formally the Eisenhower National System of Interstate and Defense Highways) is of

Table 2.2: Transportation Infrastructure in the United States—2014

Category	System Mileage or Number
Public roads and highways (route mileage)	4,177,074
Interstate highway system	*47,622*
Other national highway system	*178,643*
Local	*3,950,809*
Railroad (route mileage)	127,012
Class I railroad	*94,362**
AMTRAK	*21,356*
Commuter rail	*7,795*
Heavy rail	*1,622*
Light rail	*1,877*
Navigable channels (route mileage)	25,000
Pipelines (route mileage)	2,368,436
Oil	*199,653*
Natural gas	*2,168,783*
Airports (number of airports)	19,294
Public use	*5,145*
Private use	*13,863*
Military	*286*

*Much of AMTRAK's mileage is shared with Class I railroads.

particular importance. Though it makes up a bit over 1.1% of the paved route-miles in the United States, it serves approximately 20% of all vehicle-miles traveled in the United States. The planning, design, and importance of this system are discussed in later chapters.

"Navigable channels" include commercially navigable rivers and inland passages and the Great Lakes–St. Lawrence Seaway. They do *not* include ocean-going routes, which are virtually limitless.

While we may tend to think of pipelines as conveying mostly oil, the vast majority of pipelines are devoted to the delivery of natural gas. Most of these are located within urbanized areas, and they deliver natural gas right to the individual homes of users.

Table 2.3 shows the annual tonnage of goods moved by the various modes in 2015 [*2*]. Note that Table 2.3 shows only domestic goods movement, that is, goods moved entirely within the United States, and does *not* include goods imported to the United States from abroad or goods exported from the United States to abroad.

Table 2.4 shows similar data for passenger transportation [*3*], which is quantified in terms of passenger-miles of travel. Some of the modes are exclusively intercity or intra-city, but a number span both categories.

From Table 2.4, it can be observed that the U.S. population accounted for almost 5 *trillion* passenger-miles of travel in 2014. The vast majority of these (approximately 86%) occur on the nation's street and highway system. This emphasizes the significant dependence on the automobile as the principal means of mobility and access for the nation's population.

Much of the service and infrastructure for heavy rail is centered in a few major cities, like New York, Chicago, and Washington, D.C. Ferry service is not widespread, and again is largely focused on a few areas such as New York (the Staten Island Ferry) and the Puget Sound region around Seattle. For many, urban travel options are limited to the automobile, bus transit, taxi, and other on-call car services. Intercity travelers have a broader range of choices available, including air, rail, intercity bus, or highways.

Table 2.3: U.S. Domestic Goods Movement by Tonnage—2015

Mode	Tonnage
Truck	10,568,000,000
Rail	1,602,000,000
Water	884,000,000
Air (includes air + truck)	10,000,000
Multiple modes and mail	1,346,000,000
Pipelines	3,326,000,000
Other or unknown	33,000,000
TOTAL	**17,997,000,000**

Table 2.4: Passenger-Miles of Travel in the United States—2014

Mode	Passenger-Miles Traveled
Air (intercity domestic)	**607,772,000,000**
Highway	**4,092,575**
Passenger car (intercity & intra-city)	3,731,888,000,000
Motorcycle (intercity & intra-city)	21,510,000,000
Intercity bus (intercity)	339,177,000,000
Public Transit (intra-city)	**55,321,000,000**
Motor bus*	21,429,000,000*
Light rail	2,675,000,000
Heavy rail (rail rapid transit)	18,339,000,000
Commuter rail	11,600,000,000
Demand-responsive*	864,000,000*
Ferry boat	414,000,000
Other	1,692,000,000
Railroad—AMTRAK (intercity)	**6,675,000,000**
TOTAL	**4,762,343,000,000**

*Most motor bus and demand-responsive transit occurs on streets and highways, and therefore could also be included in the "Highway" category. It was not to avoid double-counting these passenger miles.

NOTE: Air figures do not include 244,373,000,000 passenger miles flown on international flights.

Note that there are no statistics shown in Table 2.4 for pedestrians, as it is almost impossible to collect meaningful data on how many pedestrian trips are made, and how far people walk for various purposes.

2.3 Modal Attributes

Travel modes for people can be divided into two general categories:

- Personal modes of transportation
- Public modes of transportation

The main characteristic of personal modes of transportation is that the traveler most often owns the "vehicle" in or on which the travel takes place. In some cases, the vehicle may be leased on a long-term basis or rented for a shorter period of time. In public modes, vehicles are generally owned and operated by an external agency that may be either publicly or privately owned. Personal modes of transportation include walking (no vehicle required), bicycling, and driving or riding in a privately owned and operated automobile. Public modes of transportation include taxi or other for-hire small vehicles, buses, light rail systems, and rail rapid transit (or "heavy rail" systems).

The primary features of personal modes of transportation are that they provide direct origin-to-destination service and are available at any time as needed. In public modes, taxis, for-hire vehicles, and other types of demand-responsive services closely mimic the characteristics of private modes. They, in general, do provide direct origin-to-destination service. They are available on call, but there may be waiting times and/or other time restrictions imposed, and come with a visible out-of-pocket cost.

Public modes of transportation, other than taxis and similar forms, primarily run on fixed routes according to a fixed schedule. The traveler must adjust his/her travel needs to accommodate these. Pickup and drop-off points may or may not be near the desired origin and destination, with the traveler responsible for making the connections between the origin and pickup location and the drop-off and destination location. Depending upon the specific circumstances, either or both of these could include significant travel time and/or travel cost.

Public modes of transportation can have numerous subcategories of characteristics that alter the type of service provided. Buses, for example, can be operated on local bus routes along local streets and arterials, or can make part or all of their trips on exclusive bus lanes or busways. Express bus services make pickups and drop-offs in defined areas, but travel nonstop between these areas to increase speed (and decrease travel time). Light rail services can operate on streets, mixed with other traffic, or in segregated lanes. They can also operate on separated rights-of-way with or without at-grade crossings.

Table 2.5 summarizes some of the fundamental service characteristics of personal and public transportation modes.

Table 2.5: Fundamental Service Characteristics of Personal and Public Transportation Modes

Type of Mode	Mode	Type of Service Provided	Typical Trip Lengths Served	Typical Average Speed of Service	Special Problems or Restrictions
Personal	Walking	– Door-to-door service provided. – Available on demand. – Limited control of personal environment.	0–1 miles	1–3 mi/h	– Depends on health/age. – Limited distance range. – Security. – Weather.
	Bicycling	– Door-to-door service provided. – Available on demand (assuming bike ownership). – Limited control of personal environment.	0–5 miles	5–15 mi/h	– Depends on health/age. – Secure storage for bike needed at both trip ends. – Limited dedicated bicycle facilities available in most areas. – Weather. – Safety of operation in mixed traffic.
	Automobile	– Door-to-door service provided. – Available on demand (assuming car ownership). – Full control of personal environment.	Unlimited	Highly variable 5–70 mi/h	– Parking needed at both ends of trip. – Safety (accident risk). – Costs of ownership, fuel, maintenance, insurance, etc.

Type of Mode	Mode	Type of Service Provided	Typical Trip Lengths Served	Typical Average Speed of Service	Special Problems or Restrictions
Public	Local bus	– Bus stop must be accessed; often within ½ mile of origin/destination. – Available on schedule (usually headway-based). – No control of personal environment.	0.5–10.0 mi	7–12 mi/h	– Affected by local traffic conditions. – Waiting a problem in bad weather. - Late-night security.
	Express bus	– Bus stop must be accessed; may be a considerable distance away. – Available on schedule (usually headway-based). – No control of personal environment.	3–20 mi	10–30 mi/h	– Affected by traffic while in mixed lanes. – Access to service may be a problem. – Weather (general). – Schedules may be limited to peak periods.
	Light rail	– Stop/station must be accessed; may be a considerable distance away. – Available on schedule (may be headway-based). – No control of personal environment.	3–20 mi	10–35 mi/h	– Power outages disrupt service. – May have to cross traffic lanes to get to stations. – Weather can cause disruptions. – There may not be night service.
	Heavy rail	– Station must be accessed; often a considerable distance from origin/destination. – Available on schedule (may be headway-based). – No control of personal environment.	5–30 mi	15–45 mi/h	– Power outages disrupt service. – Station security may be a problem. – Weather can cause disruptions if above surface. – There may not be night service.
	Commuter rail	– Station must be accessed, may be far away from origin. – Available on published schedule (may be limited). – No control of personal environment.	5–50 mi	30–80 mi/h	– If electrically powered, outages may disrupt service. – Station security and comfort may be a problem. – Outdoor lines subject to weather disruptions. – Schedules may be very limited. – Fares generally quite high.

2.4 The Capacity of Transportation Modes

How big is the bucket? This is a pretty important characteristic if you are carrying water. It is no less critical for transportation systems. The bucket has a capacity of some number of gallons of fluid. Transportation systems carry people and goods, so their "capacity" involves how many people or how many tons of freight they can accommodate.

While capacity is a generically understood phrase, it was formally defined for highways in the first edition of the *Highway Capacity Manual* (*HCM*) [*4*]. For a highway, *capacity* is currently defined as the maximum rate of flow at which vehicles or persons can be reasonably expected to pass a point or uniform segment of a highway or lane under prevailing conditions [*5*]. One can easily extend the concept to other modes of transportation as well—at least in terms of the ability to carry people.

There are four key concepts embedded in this definition:

1. *Rate of flow.* Capacity is defined not in terms of a full-hourly volume but as a maximum rate of flow. The standard unit of time used in most cases is 15 minutes. Fifteen minutes is believed to be the minimum unit of time in which statistically stable (or predictable) traffic flow exists, although some researchers have used time periods of 5 minutes or even 1 minute in their studies.
2. *Reasonable expectancy.* Capacity is not a static measure. A 5-gallon bucket always has a capacity of 5 gallons. Capacity of a transportation system element is, however, a random variable depending upon traveler behavior, which is not static over time or space. Capacity is defined in terms of values that can be "reasonably expected" to be replicated at different times and at different places with similar characteristics. Thus, it is quite possible to observe actual flow rates in excess of stated capacity values on some transportation facilities.
3. *Point or uniform segment.* Capacity depends upon the physical characteristics of the specific segment of the facility for which it is defined, as well as some characteristics of the travelers (or their vehicles) and control systems in place. Thus, along any given facility, capacity can only be stated for a point or a segment of limited length over which these characteristics are the same.
4. *Prevailing conditions.* Capacity is stated for whatever conditions prevail at the location. Prevailing conditions *for highways* fall into three broad categories:
   - *Physical conditions.* This includes the geometric characteristics of the horizontal and vertical alignments, and cross-sectional elements such as lane widths and lateral clearances at the roadsides.
   - *Traffic conditions.* This means the mix of vehicle types (cars, trucks, buses, etc.) making up the traffic stream.
   - *Control conditions.* This means all traffic controls and operational regulations, including signalization, speed limits, lane-use controls, and other control measures.

The key idea here is that when any one of the underlying prevailing conditions is changed, so is the capacity.

While the concept of capacity transfers relatively easily to other passenger transportation modes, the issue of "prevailing conditions" is more difficult. Capacity of a highway segment refers to the maximum flow rate that the highway can accommodate. This is also true for other modes, but the list of "prevailing conditions" becomes much longer.

For example, consider the capacity of a single track of rapid transit line. Its capacity (in persons/h) depends upon several categories of issues:

- *Design of the rail car.* How many people can fit into a single rail car? This depends primarily on the size of the car (floor dimensions) and the number and arrangement of seats. Rapid transit lines typically service more standees than seated passengers, so the interior layout becomes critical.
- *How many rail cars are in a train?* The number of cars that make up a train is limited primarily by the length of station platforms. Obviously, more cars per train = more people per train.
- *How many trains per hour can use a single track?* There are two limits on this: the control system and station dwell times. Control systems, whether old (using fixed block signaling) or new (using moving block technology), essentially limit how close trains can get to each other during operation. If a control system allows trains to operate 2 minutes apart, then a track can handle 60/2 = 30 trains/h.

  The control system, however, is sometimes not the limiting factor. If it takes a train 4 minutes to decelerate to a station stop, let passengers on and off, and accelerate back to normal speed, then a second train cannot enter the station for a minimum of 4 minutes—regardless of the control system.

- *Schedule.* Unlike highways, where users essentially bring their own vehicles, public transportation systems provide vehicles on a schedule. Thus, though the track and dwell time might accommodate 30 trains/h, if the schedule only provides 20 trains/h, then the capacity is limited to the number of passengers that can be transported by 20 trains/h.

These issues together control the capacity of a segment of rail line. The issues become far more complicated when a rapid transit system involves several branch lines merging to form a trunk line. The capacity of the trunk line limits the capacity of all of the branch lines, as the total number of trains scheduled must be less than the capacity of the trunk. There may be "excess" capacity available on the branch lines, but it cannot be used. The single trunk line is, essentially, the bottleneck of the entire system.

Transit buses are similarly limited by the size and interior design of the bus, the length and number of bus stops, dwell times, and schedules. Further, bus operations are limited by the general traffic conditions on the streets they use.

Capacity values are established based upon observed vehicle and passenger volumes, and on analytic models that describe key limiting values of various system elements. For highway facilities, the *Highway Capacity Manual, 6th Edition* [5], is the standard document specifying procedures to estimate capacities of various types of facilities and facility segments. For transit facilities, the third edition of the *Transit Capacity Manual* [6] defines current standards.

Table 2.6 shows the current criteria for capacities of various types of highway facilities as specified by the

Table 2.6: Ideal Capacities of Highway Facilities

Uninterrupted Flow Facilities				
Type of Facility	**Free-Flow Speed (mi/h)**	**Vehicle Capacity (pc/h/ln)**	**Person Capacity for Auto Occupancy of: (pers/h/ln)**	
			1.3 pers/car	**1.5 pers/car**
Freeways	≥ 70	2,400	3,120	3,600
	65	2,350	3,055	3,525
	60	2,300	2,990	3,450
	55	2,250	2,925	3,375
Multilane highways	≥ 60	2,200	2,860	3,300
	55	2,100	2,730	3,150
	50	2,000	2,600	3,000
	45	1,900	2,470	2,950
Two-lane highways	All, one lane	1,700	2,210	2,550
	All, total, both dir*	3,200	4,160*	4,800*
Interrupted Flow Facilities				
Type of Facility	**Green-to-Cycle Length Ratio (g/C)**	**Vehicle Capacity (pc/h/ln) *Based on:* (1,900 pc/hg/ln)**	**Person Capacity for Auto Occupancy of: (pers/h/ln)**	
			1.3 pers/car	**1.5 pers/car**
Arterials/streets	0.30	570	741	855
	0.40	760	988	1,140
	0.50	950	1,235	1,425
	0.60	1,140	1,482	1,710
	0.70	1,330	1,729	1,995

* Total for both lanes; on two-lane highways, the directional movements interact, restricting passing maneuvers and total capacity.

HCM. The values shown represent fundamentally "ideal" conditions, that is, the best possible values that apply when there are only passenger cars in the traffic stream, and where all geometric elements are the most desirable—that is, 12-ft lanes, adequate lateral clearances, and so on. Highway capacity values are stated in terms of maximum flow rates in passenger cars/hour/lane (pc/h/ln). Vehicle occupancies vary over both time and space, and the *HCM* does not specify a national standard. In most places, car occupancy is between 1.3 and 1.5 persons per vehicle.

For uninterrupted segments of highway facilities (freeways, multilane highways, two-lane highways), capacities are defined based upon the *free-flow speed* of the facility. An "uninterrupted" segment is any segment on a limited-access facility (no signals or other points of fixed interruption to the traffic stream) or a segment on a surface facility that is two miles or more from the nearest traffic signal. The "free-flow speed" of such a facility is the average speed that can be achieved when traffic is very light, that is, when there are few vehicles on the road. Recent studies show that free-flow speeds can exist over a wide range of flow rates, and that speeds do not begin to decline until flow rates exceed 1,000 pc/h/ln or more.

On interrupted flow facilities (arterials and streets), ideal capacities are stated in terms of *passenger cars per hour of green time per lane* (pc/hg/ln), as flow is restricted not only by prevailing geometric and traffic characteristics but also by signal timing. Thus, the capacity of an arterial, for example, is controlled by the traffic signal in the subject segment that has the minimum amount (or portion) of green time assigned. In Table 2.6, rough estimates of arterial and street capacity for green-to-cycle length (g/C) ratios of 0.30, 0.40, 0.50, 0.60, and 0.70 are shown. Other values are, of course, possible for different signal timings.

Generalized capacities for public transportation modes are shown in Table 2.7. Public transit capacities are based upon observations of highest-volume operations across the United States, documented by the American Public Transportation Association [*7*].

It is no accident that the highest transit flows are found, for most types of transit, in New York City (NYC) and its surrounding tri-state region (which includes parts of New Jersey and Connecticut). New York has one of the largest rail rapid transit systems in the world (by revenue track-miles), as well as *the* largest local bus system in the world.

The single highest rail transit passenger flows per track are found on the Queens Line in NYC. The express track of this subway carries two routes—the E and F trains—and regularly services a peak-hour passenger flow of 51,000 passengers on one track through the critical station at Queens Plaza. When the local track is added, this four-track (two in each direction) subway carries over 67,000 passengers per hour in one direction every weekday during peak hours.

Table 2.7: Highest Observed Transit Flows in North America

Type of Transit	Route/Service	No. of Tracks/ Lanes	Trains/Hour or Buses/Hour	Passengers per Hour
Rail rapid transit	Queens E, F Express (NYC)	1	29	51,084
	Lexington Ave 4,5 Express (NYC)	1	28	34,059
	Queens Express & Local (NYC)	2	47	67,234
	Lexington Ave Express & Local (NYC)	2	50	63,234
Commuter rail	Metro-North RR, New Haven Branch	1	20	15,282
	Long Island RR, Babylon Branch	1	14	12,980
Light rail	Green-Line Subway, Boston	1*	45	9,600
	South Line, Calgary, Alberta	1	11	4,950
Bus	Lincoln Tunnel (NYC, Excl Lane)	1**	735	32,600
	West Transitway (Ottowa, Busway)	1***	225	11,100
	Madison Avenue (NYC, Bus Lanes)	2	180	10,000
	Hillside Avenue (NYC, Mixed Traffic)	–	180	10,000

* Double-track stations.

** No stops.

*** Stops; passing of stopped buses by others is possible.

The highest single-track passenger flow on a commuter railroad is found on the Metro-North Railroad on its New Haven ranch. During peak hours, 20 trains per hour carrying over 15,000 persons per hour run every weekday. Capacities on commuter rail lines are limited primarily by schedules, but are affected by longer station dwell times than rapid transit (due to station configurations) and by railroad signal systems, which are generally less efficient than on modern rail rapid transit lines.

The highest hourly passenger flow observed on a light rail system is 9,600 passengers per hour, on Boston's Green-Line Subway. The Green-Line Subway accommodates several traditional trolley routes in downtown Boston. It has one track in each direction, but has double-track stations, which limits the impact of station dwell times. For a light rail system with single-track stations, the highest observed flows are on the South Line in Calgary, Alberta, Canada, where 4,950 persons per hour are carried during a typical weekday peak hour.

Bus system capacities are highly variable. The exclusive bus lane in the Lincoln Tunnel (New York–New Jersey) carries 735 buses per hour and 32,600 passengers per hour, but has no stops within it. Numerous bus routes converge on the bus lane, which connects directly to the Port Authority Bus Terminal in Manhattan, New York. In Ottawa, the West Transitway carries 225 buses per hour, and 11,100 passengers per hour. It is an exclusive roadway for buses, with stops. Buses may pass others while they are stopped. The highest on-street bus volumes are observed on Madison Avenue in Manhattan and Hillside Avenue in Queens, both in NYC. Both carry 180 buses per hour and approximately 10,000 passengers per hour. Madison Avenue has two exclusive bus lanes adjacent to the curb. On Hillside Avenue, buses operate in mixed traffic. These passenger volumes are extremely high, and represent multiple bus routes converging onto a common route. Bus schedules are usually the limit on capacity. A single bus per hour can carry as little as 50–60 passengers per hour, and typical single-route service can carry anything from several hundred passengers per hour to several thousand passengers per hour.

2.5 Multimodal Focus

The modern traffic engineer must keep the full range of transportation modes in mind in addressing transportation issues. Not every mode is appropriate for every demand, but in many urban cases, there may be different approaches that are feasible.

In the final analysis, most of our facilities will serve several different modes. Streets will serve cars, trucks, transit buses, pedestrians, taxis, and bicycles. Further, the integration of modes is a critical issue for the traffic engineer. After parking their car, a motorist becomes a pedestrian. After leaving a rapid transit station, a user is pedestrian, but they may use a bus or a taxi to continue their journey. The interface between and among modes is as important as the modes themselves.

"Multimodal" is a critical concept in modern transportation planning and design. Users of all modes need to be provided with a safe and efficient set of facilities to handle their unique needs. Often, the optimal approach will involve several modes of transportation. The best plans and designs will be those that provide an appropriate mix of transportation modes in a means that efficiently links and integrates them into a seamless transportation system.

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7. *Transit Ridership Report* (Quarterly Publication), American Public Transportation Association, Washington, D.C., 2015.

Problems

2-1. What characteristics affect the capacity of a street or highway?

2-2. What characteristics affect the capacity of a rapid transit line?

2-3. A rapid transit line with one track in each direction uses rail cars that can accommodate 50 seated and 80 standing passengers. Stations are long enough to accommodate 10 car trains. The control system allows trains to travel 1.5 minutes apart. The critical station has a dwell time of 1.8 minutes. Estimate the capacity of one track.

2-4. A six-lane urban freeway (three lanes in each direction) has a free-flow speed of 55 mi/h. Traffic includes 10% trucks and 2% express buses. Each truck and express bus displaces 2.0 passenger cars from the traffic stream. If the occupancy of passenger cars is 1.5 people per vehicle, and buses carry an average of 50 people per bus, what is the person-capacity of the freeway (in one direction)? It may be assumed that trucks carry one person (the driver).

2-5. A travel demand of 30,000 people/h has been identified for a growing commercial corridor. What modal options might be considered to handle this demand, and what would (in general terms) be the advantages and disadvantages of each?

CHAPTER 3

Road-User, Vehicle, and Roadway Characteristics

The behavior of traffic is very much affected by the characteristics of the elements that comprise the traffic system, which are as follows:

- Road users—drivers, pedestrians, bicyclists, and passengers
- Vehicles—private and commercial
- Streets and highways
- Traffic control devices
- General environment

This chapter provides an overview of critical road-user, vehicle, and roadway characteristics. Chapter 4 provides an overview of traffic control devices and their role in the traffic system. Chapter 27 provides a more detailed look at the specific geometric characteristics of roadways.

The general environment also has an impact on traffic operations, but this is difficult to assess in any given situation. Such things as weather, lighting, density of development, and local enforcement policies all play a role in affecting traffic operations. These factors are most often considered qualitatively, with occasional supplemental quantitative information available to assist in making judgments.

3.1 Dealing with Diversity

Traffic engineering would be a great deal simpler if the various components of the traffic system had uniform characteristics. Traffic controls could be easily designed if all drivers reacted to them in exactly the same way. Safety could be more easily achieved if all vehicles had uniform dimensions, weights, and operating characteristics.

Drivers and other road users, however, have widely varying characteristics. The traffic engineer must deal with elderly drivers as well as 18-year-olds, aggressive drivers and timid drivers, and drivers subject to myriad distractions both inside and outside their vehicles. Simple subjects like reaction time, vision characteristics, and walking speed become complex because no two road users are the same.

Most human characteristics follow the normal distribution, which is discussed in Chapter 11. The normal distribution is characterized by a strong central tendency (i.e., most people have characteristics falling into a definable range). For example, most pedestrians crossing a street walk at speeds between 3.0 and 5.0 ft/s. However, there are a few pedestrians that walk either much slower or much faster. A normal distribution defines the proportions of the population expected to fall into these ranges. Because of variation, it is not practical to design a system for "average" characteristics. If a signal is timed, for example, to accommodate the average speed of crossing pedestrians, about half of all pedestrians would walk at a slower rate and be exposed to unacceptable risks.

Thus, most standards are geared to the "85th percentile" (or "15th percentile") characteristic. In general terms, a percentile is a value in a distribution for which the stated percentage of the population has a characteristic that is less than or equal to the specified value. In terms of walking speed, for example, safety demands that we accommodate slower walkers. The 15th percentile walking speed is used, as only 15% of the population walks slower than this. Where driver reaction time is concerned, the 85th percentile value is used, as 85% of the population has a reaction time that is numerically equal to or less than this value. This approach leads to design practices and procedures that safely accommodate 85% of the population. What about the remaining 15%? One of the characteristics of normal distributions is that the extreme ends of the distribution (the highest and lowest 15%) extend to plus or minus infinity. In practical terms, the highest and lowest 15% of the distribution represent very extreme values that could not be effectively accommodated into design practices. Qualitatively, the existence of road users who may possess characteristics not within the 85th (or 15th) percentile is considered, but most standard practices and criteria do not directly accommodate them. Where feasible, higher percentile characteristics can be employed.

Just as road-user characteristics vary, the characteristics of vehicles vary widely as well. Highways must be designed to accommodate motorcycles, the full range of automobiles, and a wide range of commercial vehicles, including double- and triple-back tractor-trailer combinations. Thus, lane widths, for example, must accommodate the largest vehicles expected to use the facility.

Over the past decade, much progress has been made in the design of vehicles to make them safer and more efficient. With this emphasis, cars are getting smaller and lighter. Their relative safety within a mixed traffic stream still containing large trucks and buses becomes an important issue requiring new planning and design approaches. The traffic professional must be prepared to deal with this and other emerging issues as they arise.

Some control over the range of road-user and vehicle characteristics is maintained through licensing criteria and federal and state standards on vehicle design and operating characteristics. While these are important measures, the traffic engineer must still deal with a wide range of road-user and vehicle characteristics.

While traffic engineers have little control over driver and vehicle characteristics, design of roadway systems and traffic controls is in the core of their professional practice. In both cases, a strong degree of uniformity of approach is desirable. Roadways of a similar type and function should have a familiar "look" to drivers; traffic control devices should be as uniform as possible. Traffic engineers strive to provide information to drivers in uniform ways. While this does not assure uniform reactions from drivers, it at least narrows the range of behavior, as drivers become accustomed to and familiar with the cues traffic engineers design into the system.

3.2 Road Users and Their Characteristics

Human beings are complex and have a wide range of characteristics that can and do influence the driving task. In a system where the driver is in complete control of vehicle operations, good traffic engineering requires a keen understanding of driver characteristics. Much of the task of traffic engineers is to find ways to provide drivers with information in a clear, effective manner that induces safe and proper responses.

The two driver characteristics of utmost importance are visual acuity factors and the perception–reaction process. The two overlap, in that reaction requires the use of vision for most driving cues. Understanding how information is received and processed is a key element in the design of roadways and controls.

There are other important characteristics as well. Hearing is an important element in the driving task (i.e., horns, emergency vehicle sirens, brakes squealing, etc.). While noting this is important, however, no traffic element can be designed around audio cues, as hearing-impaired and even deaf drivers are licensed. Physical strength may have been important in the past, but the evolution of power-steering and power-braking systems has eliminated this as a major issue, with the possible exception of professional drivers of trucks, buses, and other heavy vehicles.

Of course, one of the most important human factors that influences driving is the personality and psychology of the driver. This, however, is not easily quantified and is difficult to consider in design. It is dealt with primarily through enforcement and licensing procedures that attempt to remove or restrict drivers who periodically display inappropriate tendencies, as indicated by accident and violation experience.

3.2.1 Visual Characteristics of Drivers

When drivers initially apply for, or renew, their licenses, they are asked to take an eye test, administered either by the state motor vehicle agency or by an optometrist or ophthalmologist who fills out an appropriate form for the motor vehicle agency. The test administered is a standard chart-reading exercise that measures *static visual acuity*—that is, the ability to see small stationary details clearly.

While certainly an important characteristic, static visual acuity is hardly the only visual factor involved in the driving task. The *Traffic Engineering Handbook* [*1*] provides an excellent summary of visual factors involved in driving, as shown in Table 3.1.

Many of the other factors listed in Table 3.1 reflect the dynamic nature of the driving task and the fact that most objects to be viewed by drivers are in relative motion with respect to the driver's eyes.

As static visual acuity is the only one of these many visual factors that is examined as a prerequisite to issuing a driver's license, traffic engineers must expect and deal with significant variation in many of the other visual characteristics of drivers. Good static visual acuity is a key factor, as this is a prerequisite for other "good" vision characteristics. A driver with good static visual acuity could, for example, have poor dynamic visual acuity, poor depth perception, partial or complete color blindness, or other negative factors.

Table 3.1: Visual Factors in the Driving Task

Visual Factor	Definition	Sample Related Driving Task(s)
Accommodation	Change in the shape of the lens to bring images into focus.	Changing focus from dashboard displays to roadway.
Static visual acuity	Ability to see small details clearly.	Reading distant traffic signs.
Adaptation	Change in sensitivity to different levels of light.	Adjusting to changes in light upon entering a tunnel.
Angular movement	Seeing objects moving across the field of view.	Judging the speed of cars crossing our paths.
Movement in depth	Detecting changes in visual image size.	Judging the speed of an approaching vehicle.
Color	Discrimination between different colors.	Identifying the color of signals.
Contrast sensitivity	Seeing objects that are similar in brightness to their background.	Detecting dark-clothed pedestrians at night.
Depth perception	Judgment of the distance of objects.	Passing on two-lane roads with oncoming traffic.
Dynamic visual acuity	Ability to see objects that are in motion relative to the eye.	Reading traffic signs while moving.
Eye movement	Changing the direction of gaze.	Scanning the road environment for hazards.
Glare sensitivity	Ability to resist and recover from the effects of glare.	Reduction in visual performance due to headlight glare.
Peripheral vision	Detection of objects at the side of the visual field.	Seeing a bicycle approaching from the left.
Vergence	Angle between the eyes' line of sight.	Change from looking at the dashboard to the road.

(*Source:* Used with permission of the Institute of Transportation Engineers, Dewar, R, "Road Users," *Traffic Engineering Handbook*, 5th Edition, Chapter 2, Table 2-2, pg 8, 1999.)

Fields of Vision

Figure 3.1 illustrates three distinct fields of vision, each of which is important to the driving task [*2*]:

- *Acute or clear vision cone*—3° to 10° around the line of sight; legend can be read only within this narrow field of vision.
- *Fairly clear vision cone*—10° to 12° around the line of sight; color and shape can be recognized in this field.
- *Peripheral vision*—This field may extend up to 90° to the right and left of the centerline of the pupil, and up to 60° above and 70° below the line of sight. Stationary objects are generally not seen in the peripheral vision field, but the movement of objects through this field is detected.

These fields of vision, however, are defined for a stationary person. In particular, the peripheral vision field narrows, as speed increases, to as little as 100° at 20 mi/h and to 40° at 60 mi/h.

The driver's visual landscape is both complex and rapidly changing. Approaching objects appear to expand in size, while other vehicles and stationary objects are in relative motion both to the driver and to each other. The typical driver essentially samples the available visual information available and selects appropriate cues to make driving decisions.

The fields of vision affect a number of traffic engineering practices and functions. Traffic signs, for example, are placed so that they can be read within the acute vision field without requiring drivers to change their line of sight. Thus, they are generally placed within a 10° range of the driver's expected line of sight, which is assumed to be in line with the highway alignment. This leads to signs that are intended to be read when they are at a significant distance from the driver; in turn, this implies how large the sign and its lettering must be in order to be comprehended at that distance. Objects or other vehicles located in the fairly clear and peripheral vision fields may draw the driver's attention to an important event occurring in that field, such as the approach of a vehicle on an intersection street or driveway or a child running into the street after a ball. Once noticed, the driver may turn his/her head to examine the details of the situation.

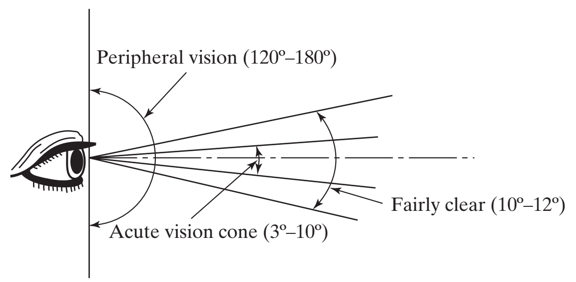

Figure 3.1: Fields of Vision Illustrated

Peripheral vision is the single most important factor when drivers estimate their speed. The movement of objects through the peripheral vision field is the driver's primary indicator of speed. Old studies have demonstrated time and again that drivers deprived of peripheral vision (using blinders in experimental cases) and deprived of a working speedometer have little idea of how fast they are traveling.

Important Visual Deficits

There are a number of visual problems that can affect driver performance and behavior. Unless the condition causes a severe visual disability, drivers affected by various visual deficits often continue to drive. Reference [*3*] contains an excellent overview and discussion of these.

Some of the more common problems involve cataracts, glaucoma, peripheral vision deficits, ocular muscle imbalance, depth perception deficits, and color blindness. Drivers who undergo eye surgery to correct a problem may experience temporary or permanent impairments. Other diseases, such as diabetes, can have a significant negative impact on vision if not controlled. Some conditions, like cataracts and glaucoma, if untreated, can lead to blindness.

While color blindness is not the worst of these conditions, it generally causes some difficulties for the affected driver, since color is one of the principal means to impart information. Unfortunately, one of the most common forms of color blindness involves the inability to discern the difference between red and green. In the case of traffic signals, this could have a devastating impact on the safety of such drivers. To ameliorate this difficulty to some degree, some blue pigment has been added to green lights and some yellow pigment has been added to red lights, making them easier to discern by color-blind drivers. Also, the location of colors on signal heads has long been standardized, with red on the top and green on the bottom of vertical signal heads. On horizontal heads, red is on the left and green on the right. Arrow indications are either located on a separate signal head or placed below or to the right of ball indications on a mixed signal head.

3.2.2 Perception–Reaction Time

The second critical driver characteristic is perception–reaction time (PRT). During perception and reaction, there are four distinct processes that the driver must perform [*4*]:

- *Detection or perception.* In this phase, an object or condition of concern enters the driver's field of vision, and the driver becomes consciously aware that something requiring a response is present.
- *Identification.* In this phase, the driver acquires sufficient information concerning the object or condition to allow the consideration of an appropriate response.
- *Decision or emotion.* Once identification of the object or condition is sufficiently completed, the driver must analyze the information and make a decision about how to respond.
- *Response or volition.* After a decision has been reached, the response is now physically implemented by the driver.

The total amount of time that this process takes is called the perception–reaction time. Some of the literature refers to this as "PIEV" time, named for the four individual actions making up the process.

Design Values

Like all human characteristics, PRTs vary widely among drivers, and are influenced by a variety of other factors, including the type and complexity of the event perceived and the environmental conditions at the time of the response.

Nevertheless, design values for various applications must be selected. The American Association of State Highway and Transportation Officials (AASHTO) mandates the use of 2.5 s for most computations involving braking reactions [*5*], based upon a number of research studies [*6–9*]. This value is believed to be approximately a 90th percentile criterion (i.e., 90% of all drivers will have a PRT as fast or faster than 2.5 s).

For signal timing purposes, the Institute of Transportation Engineers [*10*] recommends a PRT time of 1.0 s. Because of the simplicity of the response and the preconditioning of drivers to respond to signals, the PRT time is significantly less than that for a braking response on an open highway. While this is a lower value, it still represents an approximately 85th percentile for the particular situation of responding to a traffic signal.

Table 3.2: Recommended PRT Times (AAHSTO, ITE)

Situation	Recommended PRT
Normal stop at a traffic signal	1.0 s
Normal stop on a highway	2.5 s
Avoidance maneuver: stop on a highway	3.0 s
Avoidance maneuver: stop on an urban road	9.1 s
Avoidance maneuver: speed/path/direction change on a rural road	10.2 s–11.2 s
Avoidance maneuver: speed/path/direction change on a suburban road	12.1 s–12.9 s
Avoidance maneuver: speed/path/direction change on an urban road	14.0 s–14.5 s

AASHTO criteria, however, recognize that in certain more complex situations, drivers may need considerably more time to react than 1.0 s or 2.5 s. These are often referred to as *decision reaction times*. Table 3.2 summarizes PRT times in common use in traffic engineering.

Most of the "avoidance maneuver" categories involve complex situations requiring multiple actions from the driver. A driver might come up on a truck traveling at a very low speed, while weaving in and out of a lane. This information will take some time for the driver to process and make an appropriate decision on evasive actions.

Expectancy

The concept of expectancy is important to the driving task and has a significant impact on the perception–reaction process and PRT. Simply put, drivers will react more quickly to situations they *expect* to encounter as opposed to those that they *do not expect* to encounter. There are three different types of expectancies:

- *Continuity.* Experiences of the immediate past are generally expected to continue. Drivers do not, for example, expect the vehicle they are following to suddenly slow down, without an obvious reason.

- *Event.* Things that have not happened previously will not happen. If no vehicles have been observed entering the roadway from a small driveway over a reasonable period of time, then the driver will assume that none will enter now.
- *Temporal.* When events are cyclic, such as a traffic signal, the longer a given state is observed, drivers will assume that it is more likely that a change will occur.

The impact of expectancy on PRT is illustrated in Figure 3.2. This study by Olsen, et al. [*11*] in 1984 was a controlled observation of student drivers reacting to a similar hazard when they were unaware that it would appear, and again where they were told to look for it. In a third experiment, a red light was added to the dash to initiate the braking reaction. The PRT under the "expected" situation was consistently about 0.5 s faster than under the "unexpected" situation.

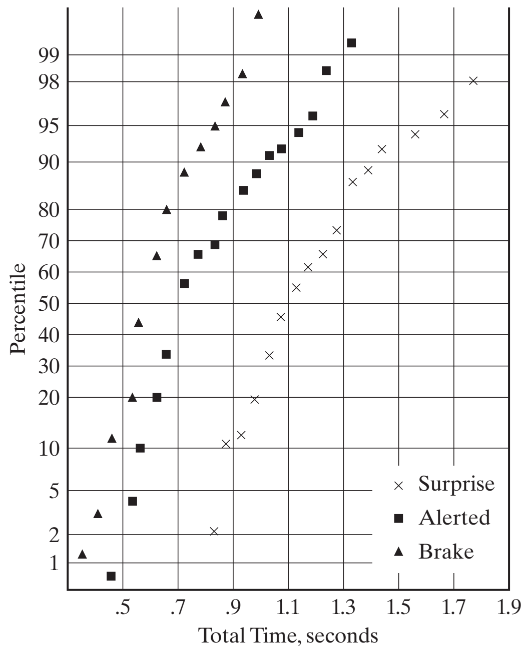

Figure 3.2: Comparison of Perception–Reaction Times Between Expected and Unexpected Events

(*Source:* Used with permission of the Transportation Research Board, National Research Council, Olson, P., et al., "Parameters Affecting Stopping Sight Distance," *NCHRP Report 270*, Washington, D.C., 1984.)

Given the obvious importance of expectancy on PRT, traffic engineers must strive to avoid designing "unexpected" events into roadway systems and traffic controls. If there are all right-hand ramps on a given freeway, for example, left-hand ramps should be avoided if at all possible. If absolutely required, guide signs must be very carefully designed to alert drivers to the existence and location of the left-hand ramp, so that when they reach it, it is no longer "unexpected."

Other Factors Affecting PRT

In general, PRTs increase with a number of factors, including (1) age, (2) fatigue, (3) complexity of reaction, and (4) presence of alcohol and/or drugs in the driver's system. While these trends are well documented, they are generally accounted for in recommended design values, with the exception of the impact of alcohol and drugs. The latter are addressed primarily through enforcement of ever-stricter DWI/DUI laws in the various states, with the intent of removing such drivers from the system, especially where repeated violations make them a significant safety risk. Some of the more general effects of alcohol and drugs, as well as aging, on driver characteristics are discussed in a later section.

Reaction Distance

The most critical impact of PRT is the distance the vehicle travels while the driver goes through the process. In the example of a simple braking reaction, the PRT begins when the driver first becomes aware of an event or object in his or her field of vision and ends when his or her foot is applied to the brake. During this time, the vehicle continues along its original course at its initial speed. Only after the foot is applied to the brake pedal does the vehicle begin to slow down in response to the stimulus.

The reaction distance is simply the PRT multiplied by the initial speed of the vehicle. As speed is generally in units of mi/h and PRT is in units of seconds, it is convenient to convert speeds to ft/s for use:

$$\frac{1\ mi \times \left(\frac{5{,}280\ ft}{mi}\right)}{1\ h \times \left(\frac{3{,}600\ s}{h}\right)} = 1.466666\ldots\frac{ft}{s} = 1.47\ \frac{ft}{s}$$

Thus, the reaction distance may be computed as

$$d_r = 1.47\ S\,t \qquad [3\text{-}1]$$

where d_r = reaction distance, ft,
S = speed of vehicle, mi/h, and
t = perception–reaction time, s.

The importance of this factor is illustrated in the following example: A driver rounds a curve at a speed of 60 mi/h and sees a truck overturned on the roadway ahead. How far will the driver's vehicle travel before the driver's foot reaches the brake? Applying the AASHTO standard of 2.5 s for braking reactions:

$$d_r = 1.47 \times 60 \times 2.5 = 220.5 \text{ ft}$$

The vehicle will travel 220.5 ft (approximately 11–12 car lengths) before the driver even engages the brake. The implication of this is frightening. If the overturned truck is closer to the vehicle than 220.5 ft when noticed by the driver, not only will the driver hit the truck, he or she will do so at full speed—60 mi/h. Deceleration begins only when the brake is engaged—*after* the perception–reaction process has been completed.

3.2.3 Pedestrian Characteristics

One of the most critical safety problems in any highway and street system involves the interactions of vehicles and pedestrians. A substantial number of traffic accidents and fatalities involve pedestrians. This is not surprising, as in any contact between a pedestrian and a vehicle, the pedestrian is at a significant disadvantage.

Virtually all of the interactions between pedestrians and vehicles occur as pedestrians cross the street at intersections and at midblock locations. At signalized intersections, safe accommodation of pedestrian crossings is as critical as vehicle requirements in establishing an appropriate timing pattern. Pedestrian walking speed in crosswalks is the most important factor in the consideration of pedestrians in signal timing.

At unsignalized crossing locations, gap-acceptance behavior of pedestrians is another important consideration. "Gap acceptance" refers to the clear time intervals between vehicles encroaching on the crossing path and the behavior of pedestrians in "accepting" them to cross through.

Walking Speeds

Table 3.3 shows 50th percentile walking speeds for pedestrians of various ages. It should be noted that these speeds were measured as part of a controlled experiment [*12*] and not specifically at intersection or midblock crosswalks. Nevertheless, the results are interesting.

One problem with standard walking speeds involves physically impaired pedestrians. A study of pedestrians with various impairments and assistive devices concluded that average walking speeds for virtually all categories were lower than the standard used in signal timing until recently (4.0 ft/s) [*13*]. Table 3.4 presents some of the results of this study. These and similar results of other studies suggest that more consideration needs to be given to the needs of handicapped pedestrians.

Table 3.3: 50th Percentile Walking Speeds for Pedestrians of Various Ages

	50th Percentile Walking Speed (ft/s)	
Age (years)	**Males**	**Females**
2	2.8	3.4
3	3.5	3.4
4	4.1	4.1
5	4.6	4.5
6	4.8	5.0
7	5.0	5.0
8	5.0	5.3
9	5.1	5.4
10	5.5	5.4
11	5.2	5.2
12	5.8	5.7
13	5.3	5.6
14	5.1	5.3
15	5.6	5.3
16	5.2	5.4
17	5.2	5.4
18	4.9	N/A
20–29	5.7	5.4
30–39	5.4	5.4
40–49	5.1	5.3
50–59	4.9	5.0
60+	4.1	4.1

(*Source:* Compiled from Eubanks, J., and Hill, P., *Pedestrian Accident Reconstruction and Litigation*, 2nd Edition, Lawyers & Judges Publishing Co., Tucson, AZ, 1999.)

Table 3.4: Walking Speeds for Physically Impaired Pedestrians

Impairment/Assistive Device	Average Walking Speed (ft/s)
Cane/crutch	2.62
Walker	2.07
Wheelchair	3.55
Immobilized knee	3.50
Below-knee amputee	2.46
Above-knee amputee	1.97
Hip arthritis	2.44–3.66
Rheumatoid arthritis (knee)	2.46

(*Source:* Compiled from Perry, J., *Gait Analysis*, McGraw-Hill, New York, NY, 1992.)

Because of studies such as these, the approach to walking speeds has become more conservative where street crossings are involved. For pedestrian needs at signalized intersections, the *Manual on Uniform Traffic Control Devices*—referred to as the *MUTCD* [*14*]—now recommends the use of 3.5 ft/s for timing of pedestrian clearance intervals (flashing Upraised Hand), and 3.0 ft/s for total crossing time, which included the pedestrian WALK and the pedestrian clearance intervals.

Even lower speeds can be used where elderly or impaired pedestrians are thought to be present in significant numbers, such as near hospitals, senior residences, and similar types of facilities.

Gap Acceptance

When a pedestrian crosses at an uncontrolled (either by signals, STOP, or YIELD signs) location, either at an intersection or at a midblock location, the pedestrian must select an appropriate "gap" in the traffic stream through which to cross. The "gap" in traffic is measured as the time lag between two vehicles in any lane encroaching on the pedestrian's crossing path. As the pedestrian waits to cross, he or she views gaps and decides whether to "accept" or "reject" the gap for a safe crossing. Some studies have used a gap defined as the distance between the pedestrian and the approaching vehicle at the time the pedestrian begins his or her crossing. An early study [*15*] using the latter approach resulted in an 85th percentile gap of approximately 125 ft.

Gap-acceptance behavior, however, is quite complex and varies with a number of other factors, including the speed of approaching vehicles, the width of the street, the frequency distribution of gaps in the traffic stream, waiting time, and others. Nevertheless, this is an important characteristic that must be considered due to its obvious safety implications. Chapter 15, for example, presents warrants for (conditions justifying) the imposition of traffic signals. One of these is devoted entirely to the safety of pedestrian crossings.

Pedestrian Comprehension of Controls

One of the problems in designing controls for pedestrians is generally poor understanding of and poor adherence to such devices. One questionnaire survey of 4,700 pedestrians [*16*] detailed many problems of misunderstanding. The proper response to a flashing "DON'T WALK" (or flashing Upraised Hand) signal, for example, was not understood by 50% of road users, who thought it meant they should return to the curb from which they started. The meaning of this signal is to not start crossing while it is flashing; it is safe to complete a crossing if the pedestrian has already started to do so. Another study [*17*] found that violation rates for the solid "DON'T WALK" signal were higher than 50% in most cities, the use of the flashing "DON'T WALK" for pedestrian clearance was not well understood, and most pedestrians tend not to use pedestrian-actuated signals.

Most pedestrians do not understand the operation of a pedestrian push-button actuator at a signalized intersection. It does not provide an immediate WALK interval for the pedestrian. Rather, on the *next* signal cycle, the phase will be lengthened to accommodate a WALK interval. This may be anywhere between 30 s and 120 s after the time the pedestrian pushed the button. Most pedestrians don't wait that long, and try to make an unsafe crossing. When the WALK interval finally arrives, the pedestrian is often gone.

The task of providing for a safe environment for pedestrians is not an easy one. The management and control of conflicts between vehicles and pedestrians remains a difficult one. These issues will be discussed in some detail when the use and implementation of various forms of traffic control, including signals, is discussed in subsequent chapters.

3.2.4 Impacts of Drugs and Alcohol on Road Users

The effect of drugs and alcohol on drivers has received well-deserved national attention for many years, leading to substantial strengthening of DWI/

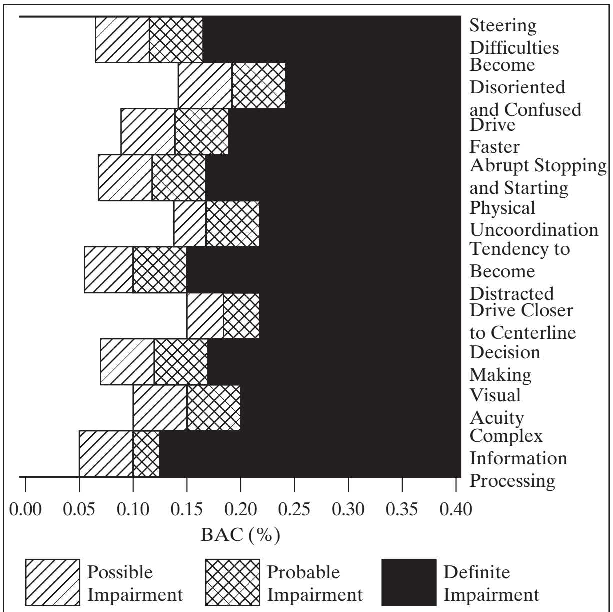

Figure 3.3: Effects of Blood-Alcohol Level on Driving Tasks

(*Source:* Used with permission of Institute of Transportation Engineers, Blaschke, J., Dennis, M., and Creasy, F., "Physical and Psychological Effects of Alcohol and Other Drugs on Drivers," *ITE Journal*, 59, Washington, D.C., 1987.)

DUI laws and enforcement. These factors remain, however, a significant contributor to traffic fatalities and accidents.

In 2015, there were 10,265 fatalities in crashes involving at least one driver with a blood-alcohol content (BAC) of 0.08 g/dL, the legal limit for impairment. This represented 29.3% of all traffic accident fatalities for the year. It is estimated that the economic cost of these fatalities was approximately $44 billion. The 2015 alcohol-related fatalities represented 3.2% increase over 2014. Total highway fatalities were 7.2% higher in 2015 than in 2014.

Of the 48,613 drivers involved in fatal crashes in 2015, 20% were legally impaired. This percentage is the same as it was in 2005 [*18*]. However, another 4% of these drivers had blood-alcohol levels between 0.01% and 0.08%. Of the 20% who were legally impaired, 13% had blood-alcohol levels over 0.15%.

Legal limits for DWI/DUI do not define the point at which alcohol and/or drugs influence the road user. Recognizing this is important for individuals to ensure safe driving, and is now causing many states to consider further reducing their legal limits on alcohol. Some states have instituted "zero tolerance" criteria (0.01%) for new drivers for the first year or two they are licensed.

Figure 3.3 is a summary of various studies on the effects of drugs and alcohol on various driving factors. Note that for many factors, impairment of driver function begins at levels well below the legal limits—for some factors at blood-alcohol levels as low as 0.05%.

Figure 3.4 shows the distribution of blood-alcohol levels for drivers (including all drivers with BACs over 0.01 g/dL) for 2014. Clearly, there are significant

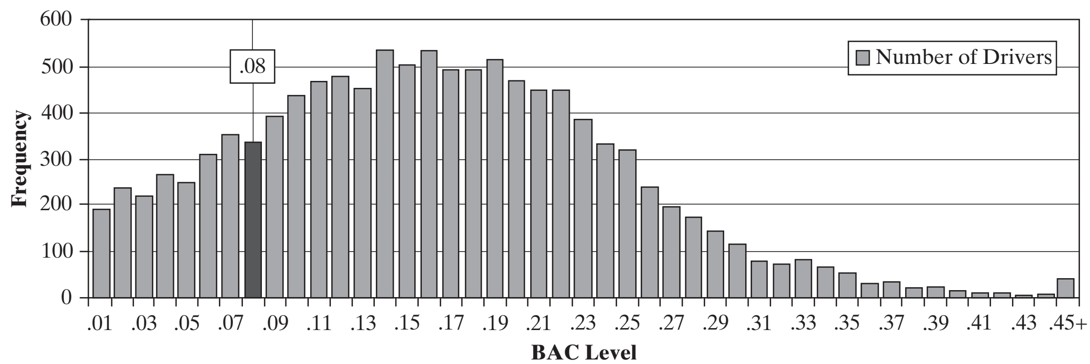

Figure 3.4: Distribution of Alcohol-Impaired Drivers in Fatal Crashes, 2014 (Drivers with BAC ≥ 0.01 g/dL)

(*Source: Traffic Safety Facts: 2014 Data*, National Highway Traffic Safety Administration, U.S. Department of Transportation, Washington, D.C., 2014, Fig 3.)

numbers of drivers involved in fatal accidents at alcohol levels below the legal limit for DWI/DUI.

Severe impairment is also a problem, with 65% of the impaired drivers in fatal crashes (in 2015) having BACs in excess of 0.15%.

The bottom line is that an impaired driver is a dangerous driver, even when their BACs are below the legal definition of impairment. Impairment leads to longer PRT times, poor judgments, and actions that can and do cause accidents. Since few of these factors can be ameliorated by design or control (although good designs and well-designed controls help both impaired and unimpaired drivers), enforcement and education are critical elements in reducing the incidence of DWI/DUI and the accidents and deaths that result.

If impaired drivers are a menace, then impaired pedestrians are even more so—although the danger is mostly to themselves. In 2015, 5,376 pedestrians were killed in traffic accidents, an increase of 9.59% over 2014. In accidents involving a pedestrian fatality, 48% included either a driver or pedestrian with a BAC in excess of 0.08 g/dL. Of the pedestrians involved in these accidents, 34% were legally impaired, while only 14% of the drivers involved were legally impaired. Drunk walking is obviously extremely dangerous [*19*].

While the nation has made substantial progress in reducing the number of traffic fatalities overall, the success in reducing pedestrian fatalities has been quite limited. Between 2003 and 2012, total traffic fatalities were reduced from 42,884 to 33,461 (22%), pedestrian fatalities only decreased from 4,774 to 4,743 (0.64%). At least some of this can be attributed to impaired pedestrians.

While there has been a great deal of research on alcohol and driving impairment, there is far less information available about the influence of other drugs on traffic fatalities and crashes. This, however, is becoming more of an issue, as several states have legalized the use of recreational marijuana. Efforts to develop a "fast test" (like a breathalyzer for alcohol) to detect marijuana-impaired drivers are now underway. In 2009, 12,055 drivers killed in traffic crashes were tested for drug involvement. Of these, 33% were found to be drug-impaired. This was an increase from the results in 2005, when only 28% were found to be drug-impaired [*20*]. Obviously, this is becoming a critical issue in traffic safety.

Both motorists and pedestrians should also be aware of the impact of common prescription and over-the-counter medications on their performance capabilities. Many legitimate medications have effects that are similar to those of alcohol and/or marijuana. Users of medications should always be aware of the side effects of what they use (a most frequent effect of many drugs is drowsiness), and exercise care and good judgment when considering whether or not to drive. Some legitimate drugs can have a direct impact on blood-alcohol levels and can render a motorist legally intoxicated without "drinking."

3.2.5 Impacts of Aging on Road Users

As life expectancy continues to rise, the number of older drivers has risen dramatically over the past several decades. Thus, it becomes increasingly important to understand how aging affects driver needs and limitations and how these should impact design and control decisions. Reference [*21*] is an excellent compilation sponsored by the National Academy of Sciences on a wide range of topics involving aging drivers.

Many visual acuity factors deteriorate with age, including both static and dynamic visual acuity, glare sensitivity and recovery, night vision, and speed of eye movements. Such ailments as cataracts, glaucoma, macular degeneration, and diabetes are also more common as people age, and these conditions have negative impacts on vision.

The increasing prevalence of older drivers presents a number of problems for both traffic engineers and public officials. At some point, deterioration of various capabilities must lead to revocation of the right to drive. On the other hand, driving is the principal means of mobility and accessibility in most parts of the nation, and the alternatives for those who can no longer drive are either limited or expensive. The response to the issue of an aging driver population must have many components, including appropriate licensing standards, consideration of some license restrictions on older drivers (e.g., a daytime only license), provision of efficient and affordable transportation alternatives, and increased consideration of their needs, particularly in the design and implementation of control devices and traffic regulations. Older drivers may be helped, for example, by such measures as larger lettering on signs, better highway lighting, larger and brighter signals, and other measures. Better education can serve to make older drivers more aware of the types of deficits they face and how to best deal with them. More frequent testing of key characteristics such as eyesight may also be helpful.

3.2.6 Psychological, Personality, and Related Factors

In the past few years, traffic engineers and the public in general have become acquainted with the term "road rage." Commonly applied to drivers who lose control of themselves and react to a wide variety of situations violently, improperly, and almost always dangerously, the problem (which has always existed) is now getting well-deserved attention. "Road rage," however, is a colloquial term, and is applied to everything from a direct physical assault by one road user on another to a variety of aggressive driving behaviors.

According to the testimony of Dr. John Larsen to the House Surface Transportation Subcommittee on July 17, 1997 (as summarized in Chapter 2 of Reference [*1*]), the following attitudes characterize aggressive drivers:

- The desire to get to one's destination as quickly as possible, leading to the expression of anger at other drivers/pedestrians who impede this desire.
- The need to compete with other fast cars.
- The need to respond competitively to other aggressive drivers.
- Contempt for other drivers who do not drive, look, and act as they do on the road.
- The belief that it is their right to "hit back" at other drivers whose driving behavior threatens them.

"Road rage" is the extreme expression of a driver's psychological and personal displeasure over the traffic situation he or she has encountered. It does, however, remind traffic engineers that drivers display a wide range of behaviors in accordance with their own personalities and psychological characteristics.

Once again, most of these factors cannot be addressed directly through design or control decisions and are best treated through vigorous enforcement and educational programs.

3.3 Vehicle Characteristics

In 2015, there were 263,610,219 registered vehicles in the United States. With a 2015 population of 320,000,000, this means that there was one registered vehicle for every 0.82 people in the United States, including children [*22*]. The characteristics of these vehicles vary as widely as those of the motorists who drive them. Table 3.5 summarizes these vehicles by type in four broad categories.

Table 3.5: U.S.-Registered Vehicles in 2015

Vehicle Type	Registered Vehicles
Passenger cars	112,864,228
Buses (school, transit, and intercity)	888,907
Trucks	141,256,148
Motorcycles	8,600,936
Total	**263,610,219**

Trucks and buses are not generally owned by individuals, but are more likely to be part of commercial fleets owned by various businesses, including trucking firms, transit systems, and the like. Nevertheless, there are more registered vehicles in the United States than there are licensed drivers (218,084,219 in 2015).

In general, motor vehicles are classified by AASHTO [*5*] into four main categories:

- *Passenger cars*—all passenger cars, SUVs, minivans, vans, and pickup trucks
- *Buses*—intercity motor coaches, transit buses, school buses, and articulated buses
- *Trucks*—single-unit trucks, tractor-trailer, and tractor-semi-trailer combination vehicles
- *Recreational vehicles*—motor homes, cars with various types of trailers (boat, campers, motorcycles, etc.)

This categorization is somewhat different from the national statistical summary of Table 3.5. Recreational vehicles are generally treated as trucks in national statistics. Motorcycles are not isolated as a separate category in AASHTO, as their characteristics do not usually limit or define design or control needs.

There are a number of critical vehicle properties that must be accounted for in the design of roadways and traffic controls. These include the following:

- Braking and deceleration
- Acceleration
- Low-speed turning characteristics
- High-speed turning characteristics

In more general terms, the issues associated with vehicles of vastly differing size, weight, and operating characteristics sharing roadways must also be addressed by traffic engineers.

3.3.1 Concept of the Design Vehicle

Given the immense range of vehicle types using street and highway facilities, it is necessary to adopt standard vehicle characteristics for design and control purposes. For geometric design, AASHTO has defined 20 "design vehicles," each with specified characteristics. The 20 design vehicles are defined as follows:

P	=	passenger car
SU-30	=	single-unit truck with two axles
SU-40	=	single-unit truck with three axles
BUS-40	=	intercity bus with a 40-ft wheelbase
BUS-45	=	intercity bus with a 45-ft wheelbase
CITY-BUS	=	transit bus
S-BUS 36	=	conventional school bus for 65 passengers
S-BUS 40	=	large school bus for 84 passengers
A-BUS	=	articulated bus
WB-40	=	intermediate semi-trailer with 40-ft wheelbase
WB-62	=	interstate semi-trailer with a 62-ft wheelbase
WB-67	=	interstate semi-trailer with a 67-ft wheelbase
WB-67D	=	"double-bottom" semi-trailer/trailer with a 67-ft wheelbase
WB-92D	=	Rocky Mountain double semi-trailer/trailer with a 92-ft wheelbase
WB-100T	=	triple semi-trailer/trailers with a 100-ft wheelbase
WB-109D	=	turnpike double semi-trailer/trailer with a 109-ft wheelbase
MH	=	motor home
P/T	=	passenger car and camper trailer
P/B	=	passenger car and boat trailer
MH/B	=	motor home and boat trailer

Wheelbase dimensions are measured from the frontmost axle to the rearmost axle, including both the tractor and trailer in a combination vehicle.

Design vehicles are primarily employed in the design of turning roadways and intersection curbs, and are used to help determine appropriate lane widths, and such specific design features as lane-widening on curves. Key to such usage, however, is the selection of an appropriate design vehicle for various types of facilities and situations. In general, the design should consider the largest vehicle likely to use the facility with reasonable frequency.

In considering the selection of a design vehicle, it must be remembered that all parts of the street and highway network must be accessible to emergency vehicles, including fire engines, ambulances, emergency evacuation vehicles, and emergency repair vehicles, among others. Therefore, the single-unit truck is usually the minimum design vehicle selected for most local street applications. The mobility of hook-and-ladder fire vehicles is enhanced by having rear-axle steering that allows these vehicles to negotiate sharper turns than would normally be possible for combination vehicles; so the use of a single-unit truck as a design vehicle for local streets is not considered to hinder emergency vehicles.

The passenger car is used as a design vehicle only in parking lots, and even there, access to emergency vehicles must be considered. For most other classes or types of highways and intersections, the selection of a design vehicle must consider the expected vehicle mix. In general, the design vehicle selected should easily accommodate 95% or more of the expected vehicle mix.

The physical dimensions of design vehicles are also important considerations. Design vehicle heights range from 4.3 ft for a passenger car to 13.5 ft for the largest trucks. Overhead clearances of overpass and sign structures, electrical wires, and other overhead appurtenances should be sufficient to allow the largest anticipated vehicles to proceed. As all facilities must accommodate a wide variety of potential emergency vehicles, use of 14.0 ft for minimum clearances is advisable for most facilities.

The width of design vehicles ranges from 7.0 ft for passenger cars to 8.5 ft for the largest trucks (excluding special "wide load" vehicles such as a tractor pulling a prefabricated or motor home). This should influence the design of such features as lane width and shoulders. For most facilities, it is desirable to use the standard 12-ft lane width. Narrower lanes may be considered for some types of facilities when necessary, but given the width of modern vehicles, 10 ft is an absolute minimum for virtually all applications, and 11 ft is a commonly used reasonable minimum.

3.3.2 Turning Characteristics of Vehicles

There are two conditions under which vehicles must make turns:

- Low-speed turns (≤10 mi/h)
- High-speed turns (>10 mi/h)

Low-speed turns are limited by the characteristics of the vehicle, as the minimum radius allowed by the vehicle's steering mechanism can be supported at such speeds. High-speed turns are limited by the dynamics of side friction between the roadway and the tires, and by the superelevation (cross-slope) of the roadway.

Low-Speed Turns

AASHTO specifies minimum design radii for each of the design vehicles, based on the centerline turning radius and minimum inside turning radius of each vehicle. While the actual turning radius of a vehicle is controlled by the front wheels, rear wheels do not follow the same path. They "off-track" as they are dragged through the turning movement.

Reference [*5*] contains detailed low-speed turning templates for all AASHTO design vehicles. An example (for a WB-40 combination vehicle) is shown in Figure 3.5. Note that the minimum turning radius is defined by the track of the front outside wheel. The combination vehicle, however, demonstrates considerable "off-tracking" of the rear inside wheel, effectively widening the width of the "lane" occupied by the vehicle as it turns. The path of the rear inside wheel is not circular, and has a variable radius.

Turning templates provide illustrations of the many different dimensions involved in a low-speed turn. In designing for low-speed turns, the minimum design turning radius is the minimum centerline radius plus one-half of the width of the front of the vehicle.

Minimum design turning radii range from 23.8 ft for a passenger car to a high of 82.0 ft for the WB-92D double tractor-trailer combination vehicle. Depending upon the specific design vehicle, the minimum inside curb radius is generally considerably smaller than the minimum design turning radius, reflecting the variable radius of the rear-inside wheel's track.

Table 3.6 summarizes the minimum turning radii and minimum inside curb radii for the various defined design vehicles.

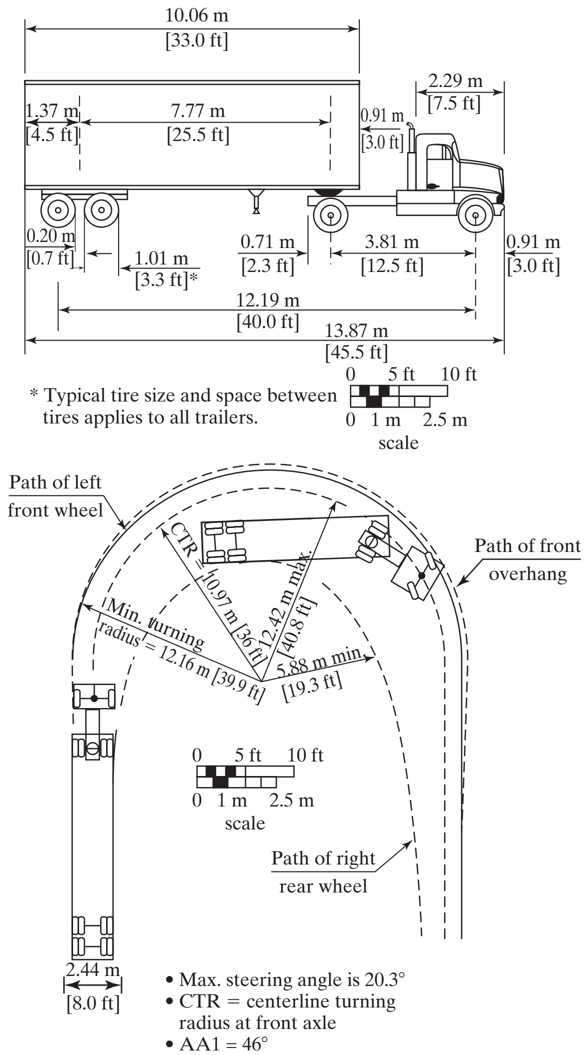

Figure 3.5: Low-Speed Turning Template for WB-40 Combination Vehicles

(*Source:* Adapted from *A Policy on Geometric Design of Highways and Streets,* 2011, by the American Association of State Highway and Transportation Officials, Washington, D.C. U.S.A)

In designing intersections, off-tracking characteristics of the design vehicle should be considered when determining how far from travel lanes to locate (or cut back) the curb. In a good design, the outside wheel of the turning design vehicle should be able to negotiate its path without "spilling over" into adjacent lanes as the turn

Table 3.6: Minimum Low-Speed Turning Radii for AASHTO Design Vehicles

Design Vehicle	Minimum Turning Radius (ft)	Minimum Inside Curb Radius (ft)
P	23.8	14.4
SU-30	41.8	28.4
SU-40	51.2	36.4
BUS-40	41.7	24.3
BUS-45	44.0	24.7
CITY-BUS	41.6	24.5
S-BUS 36	38.6	23.8
S-BUS 40	39.1	25.3
A-BUS	39.4	21.3
WB-40	39.9	19.3
WB-62	44.8	7.4
WB-67	44.8	7.9
WB-67D	44.8	19.1
WB-92D	82.0	55.6
WB-100T	44.8	9.7
WB-109D	59.9	13.8
MH	39.7	26.0
P/T	32.9	18.8
P/B	23.8	8.0
MH/B	49.8	35.0

is negotiated. This requires that the curb setback must accommodate the maximum off-tracking of the design vehicle.

High-Speed Turns

When involved in a high-speed turn on a highway curve, centripetal forces of momentum are exerted on the vehicle to continue in a straight path. To hold the curve, these forces are opposed by side friction and superelevation.

Superelevation is the cross-slope of the roadway, always with the lower edge in the direction of the curve. The sloped roadway provides an element of horizontal support for the vehicle. Side-friction forces represent the resistance to sliding provided across the plane of the surface between the vehicle's tires and the roadway. From the basic laws of physics, the relationship governing vehicle operation on a curved roadway is

$$\frac{e + f}{1 - ef} = \frac{S^2}{gR} \qquad [3\text{-}2]$$

where e = superelevation rate of the roadway, ft/ft (dimensionless),
f = coefficient of side friction (dimensionless),
S = speed of the vehicle, ft/s,
R = radius of curvature, ft, and
g = acceleration rate due to gravity, 32.2 ft/s^2.

The superelevation rate is the total rise in elevation across the travel lanes of the cross-section (ft) divided by the width of the travel lanes (ft), expressed as a decimal. Some publications, including AASHTO, express superelevation rate as a percentage.

Equation 3-2 is simplified by noting that the term "*ef*" is extremely small, and may be ignored for the normal range of superelevation rates and *side-friction factors*. It is also convenient to express vehicle speed in mi/h. Thus:

$$\frac{e + f}{1} = \frac{(1.47S)^2}{32.2R}$$

This yields the more traditional relationship used to depict vehicle operation on a curve:

$$R = \frac{S^2}{15(e + f)} \qquad [3\text{-}3]$$

where all terms are as previously defined, except that "*S*" is the speed in mi/h rather than ft/s, as in Equation 3-2.

The normal range of superelevation rates is from a minimum of approximately 0.005 to support side drainage to a maximum of 0.12. As speed increases, higher superelevation rates are used. Where icing conditions are expected, the maximum superelevation rate is generally limited to 0.08 to prevent a stalled vehicle from sliding toward the inside of the curve.

Coefficients of side friction for design are based upon wet roadway conditions. They vary with speed and are shown in Table 3.7.

Theoretically, a road can be banked to fully oppose centripetal force without using side friction at all. This is, of course, generally not done, as vehicles travel at a range of speeds and the superelevation rate required in many cases would be excessive. High-speed

Table 3.7: Side-Friction Factors (f) for Wet Pavements at Various Speeds

Speed (mi/h)	30	40	50	60	70
f	0.16	0.15	0.14	0.12	0.10

turns on a flat pavement may be fully supported by side friction as well, but this generally limits the radius of curvature or speed at which the curve may be safely traversed.

Chapter 27 treats the design of horizontal curves and the relationships among superelevation, side friction, curve radii, and design speed in greater detail.

Equation 3-3 can be used in a number of ways as illustrated in the following sample problems. In design, a minimum radius of curvature is computed based on maximum values of *e* and *f*.

Sample Problem 3-1: Estimating Minimum Radius of Curvature

A roadway has a design speed of 65 mi/h, with maximum values of $e = 0.08$ and $f = 0.11$, determine the minimum radius of curvature that can be used.

The minimum radius is found as:

$$R = \frac{65^2}{15(0.08 + 0.11)} = 1{,}482.5\,ft$$

Sample Problem 3-2: Estimating Maximum Safe Speed on a Horizontal Curve

If a highway curve with radius of 800 ft has a superelevation rate of 0.06, estimate the maximum safe speed. This computation requires that the relationship between the *coefficient of side friction, f*, and speed, as indicated in Table 3.7, be taken into account. Solving Equation 3-3 for *S* yields

$$S = \sqrt{15R(e + f)} \quad [3\text{-}4]$$

For the example given, the equation is solved for the given values of *e* (0.06) and *R* (800 ft) using various values of *f* from Table 3.7. Computations continue until there is closure between the computed speed and the speed associated with the coefficient of side friction selected. Thus:

$$S = \sqrt{15 \times 800 \times (0.06 + f)}$$

$$S = \sqrt{15 \times 800 \times (0.06 + 0.10)}$$
$$= 43.8 \text{ mi/h (70 mi/h assumed)}$$

$$S = \sqrt{15 \times 800 \times (0.06 + 0.12)}$$
$$= 46.5 \text{ mi/h (60 mi/h assumed)}$$

$$S = \sqrt{15 \times 800 \times (0.06 + 0.14)}$$
$$= 49.0 \text{ mi/h (50 mi/h assumed)}$$

$$S = \sqrt{15 \times 800 \times (0.06 + 0.15)}$$
$$= 50.2 \text{ mi/h (40 mi/h assumed)}$$

The correct result is obviously between 49.0 and 50.2 mi/h. If straight-line interpolation is used:

$$S = 49.0 + (50.2 - 49.0) \times \left[\frac{(50.0 - 49.0)}{(50.2 - 49.0) + (50.2 - 40.0)}\right] = 49.1\ mi/h$$

Thus, for the curve as described, 49.1 mi/h is the maximum safe speed at which it should be negotiated.

It must be noted that this is based on the design condition of a wet pavement and that higher speeds would be possible under dry conditions.

3.3.3 Braking Characteristics

Another critical characteristic of vehicles is their ability to stop (or decelerate) once the brakes have been engaged. Again, basic physics relationships are used. The distance traveled during a stop is the average speed during the stop multiplied by the time taken to stop, or

$$d_b = \left(\frac{S}{2}\right) \times \left(\frac{S}{a}\right) = \frac{S^2}{2a} \quad [3\text{-}5]$$

where d_b = braking distance, ft,
S = initial speed of the vehicle, ft/s, and
a = deceleration rate, ft/s^2.

It is convenient, however, to express speed in mi/h, yielding:

$$d_b = \frac{(1.47\,S)^2}{2a} = \frac{1.075\,S^2}{a}$$

where *S* is the speed in mi/h. Note that the 1.075 factor is derived from the more exact conversion factor between mi/h and ft/s, 1.46666..... It is often also useful to express this equation in terms of the coefficient of forward rolling or skidding friction, *F*, where $F = a/g$ (or $a = Fg$), where *g* is the acceleration due to gravity, 32.2 ft/s^2. Then:

$$d_b = \frac{1.075\,S^2}{Fg} = \frac{1.075\,S^2}{32.2\,F} = \frac{S^2}{30\,F}$$

When the effects of grade are considered, and where a braking cycle leading to a reduced speed other than "0" are considered, the equation becomes

$$d_b = \frac{S_i^2 - S_f^2}{30(F \pm G)} \quad [3\text{-}6]$$

where S_i = initial speed of the vehicle, mi/h,
S_f = final speed of the vehicle (after the deceleration action), mi/h,
F = coefficient of forward rolling or skidding friction, and
G = grade, expressed as a decimal.

When there is an upgrade, a "+" is used; a "–" is used for downgrades. This results in shorter braking distances on upgrades, where gravity helps deceleration, and longer braking distances on downgrades, where gravity causes acceleration.

In previous editions of AASHTO, braking distances were based on coefficients of forward skidding friction on wet pavements that varied with speed. In the latest standards, however, a standard deceleration rate of 11.2 ft/s^2 is adopted as a design rate. This is viewed as a rate that can be developed on wet pavements by most vehicles. It is also expected that 90% of drivers will decelerate at higher rates. This, then, suggests a standard friction factor for braking distance computations of $F = 11.2/32.2 = 0.348$ and Equation 3-6 becomes

$$d_b = \frac{S_i^2 - S_f^2}{30(0.348 \pm G)} \quad [3\text{-}7]$$

Sample Problem 3-3: Estimating Braking Distance

Consider the following case: Once the brakes are engaged, what distance is covered bringing a vehicle traveling at 60 mi/h on a 0.03 downgrade to a complete stop ($S_f = 0$). Applying Equation 3-7:

$$d_b = \frac{60^2 - 0^2}{30(0.348 - 0.03)} = 377.4\,ft$$

The braking distance formula is also a favorite tool of accident investigators. It can be used to estimate the initial speed of a vehicle using measured skid marks and an estimated final speed based on damage assessments. In such cases, actual estimated values of F are used, rather than the standard design value recommended by AASHTO. Thus, Equation 3-6 is used.

Sample Problem 3-4: Use of Braking Formula in Crash Investigations

An accident investigator estimates that a vehicle hit a bridge abutment at a speed of 20 mi/h, based on his or her assessment of damage. Leading up to the accident location, he or she observes skid marks of 100 ft on the pavement ($F = 0.35$) and 75 ft on the grass shoulder ($F = 0.25$). There is no grade. An estimation of the speed of the vehicle at the beginning of the skid marks is desired.

In this case, Equation 3-6 is used to find the initial speed of the vehicle, S_i, based upon a known (or estimated) final speed, S_f. Each skid must be analyzed separately, starting with the grass skid (for which a final speed has been estimated from the observed vehicle damage). Then:

$$d_b = 75 = \frac{S_i^2 - 20^2}{30(0.25)}$$

$$S_i = \sqrt{(75 \times 30 \times 0.25) + 20^2} = \sqrt{962.5}$$
$$= 31.0 \text{ mi/h}$$

This is the estimated speed of the vehicle at the *start* of the grass skid; it is also the speed of the vehicle at the *end* of the pavement skid. Then:

$$d_b = 100 = \frac{S_i^2 - 962.5}{30 \times 0.35}$$

$$S_i = \sqrt{(100 \times 30 \times 0.35) + 962.5} = \sqrt{2012.5}$$
$$= 44.9 \text{ mi/h}$$

It is, therefore, estimated that the speed of the vehicle immediately before the pavement skid was 44.9 mi/h. This, of course, can be compared with the speed limit to determine whether excessive speed was a factor in the accident.

3.3.4 Acceleration Characteristics

The flip side of deceleration is acceleration. Passenger cars are able to accelerate at significantly higher rates than commercial vehicles. Table 3.8 shows typical maximum acceleration rates for a passenger car with a weight-to-horsepower ratio of 30 lbs/hp and a tractor-trailer with a ratio of 200 lbs/hp.

Acceleration is highest at low speeds and decreases with increasing speed. The disparity between passenger cars and trucks is significant.

Consider the distance required for a vehicle to accelerate to target speed. The distance is the time taken to accelerate to the target speed x the average speed during acceleration, or

$$d_a = \left(\frac{S}{a}\right) \times \left(\frac{S}{2}\right) \quad [3\text{-}8]$$

where d_a = acceleration distance, ft,
S = target speed, ft/s, and
a = acceleration rate, ft/s^2.

Again, it is useful to convert the equation for the use of speed in mi/h:

Table 3.8: Acceleration Characteristics of a Typical Car versus a Typical Truck on Level Terrain

Speed Range (mi/h)	Acceleration Rate (ft/s^2) for:	
	Typical Car (30 lbs/hp)	Typical Truck (200 lbs/hp)
0–20	7.5	1.6
20–30	6.5	1.3
30–40	5.9	0.7
40–50	5.2	0.7
50–60	4.6	0.3

(*Source:* Used with permission from *Traffic Engineering Handbook,* 5th Edition, Institute of Transportation Engineers, Washington, D.C., 2000, Chapter 3, Tables 3-9 and 3-10.)

$$d_a = \left(\frac{1.47S}{a}\right) \times \left(\frac{1.47S}{2}\right) = 1.075\left(\frac{S^2}{a}\right) \quad [3\text{-}9]$$

where S is now in units of mi/h.

Once again, note that the 1.075 factor is derived using the more precise factor for converting mi/h to ft/s (1.466666.....).

Sample Problem 3-5: Acceleration Impacts

Consider the difference in acceleration distance for a passenger car and truck to accelerate from a standing stop to 20 mi/h. From Table 3.8, the acceleration rate for a passenger car is 7.5 ft/s^2, while the acceleration rate for a typical truck is 1.6 ft/s^2. Then:

For the passenger car:

$$d_a = 1.075\left(\frac{20^2}{7.5}\right) = 57.3\,ft$$

For the truck:

$$d_a = 1.075\left(\frac{20^2}{1.6}\right) = 268.8\,ft$$

The disparity is striking. If a car is at a "red" signal behind a truck, the truck will significantly delay the car. If a truck is following a car in a standing queue, a large gap between the two will occur as they accelerate.

Unfortunately, there is not much that can be done about the disparity indicated in Sample Problem 3-5 in terms of design and control. In the analysis of highway capacity, however, the disparity between trucks and cars in terms of acceleration and in terms of their ability to sustain speeds on upgrades leads to the concept of "passenger car equivalency." Depending on the type of facility, severity and length of grade, and other factors, one truck may consume as much roadway capacity as six to seven or more passenger cars. Thus, the disparity in key operating characteristics of trucks and passenger cars is taken into account in design by providing additional capacity as needed.

3.3.5 Total Stopping Distance and Applications

The total distance to bring a vehicle to a full stop, from the time the need to do so is first noted, is the sum of the reaction distance, d_r, and the braking distance, d_b. If Equations 3-1 (for d_r) and 3-8 (for d_b) are combined, the total stopping distance becomes

$$d_S = d_r + d_b$$

$$d_S = 1.47S_i t + \frac{S_i^2 - S_f^2}{30(0.348 \pm G)} \quad [3\text{-}10]$$

where all variables are as previously defined.

The concept of total stopping distance is critical to many applications in traffic engineering. Three of the more important applications are discussed in the sections that follow.

Safe Stopping Sight Distance

One of the most fundamental principles of highway design is that the driver must be able to see far enough to avoid a potential hazard or collision. Thus, on all roadway sections, the driver must have a sight distance that is at least equivalent to the total stopping distance required at the design speed.

Essentially, this requirement addresses this critical concern: A driver rounding a horizontal curve and/or negotiating a vertical curve is confronted with a downed tree, an overturned truck, or some other situation that completely blocks the roadway. The only alternative for avoiding a collision is to stop. The design must provide visibility for one safe stopping distance at every point along the roadway. By ensuring this, the driver can never be confronted with the need to stop without having sufficient distance to do so.

Sample Problem 3-6: Safe Stopping Distance

Consider a section of rural freeway with a design speed of 70 mi/h. On a section of level terrain, what safe stopping distance must be provided? Equation 3-10 is used with a final speed (S_f) of "0" and the AASHTO standard reaction time of 2.5 s. Then:

$$d_S = 1.47(70)(2.5) + \frac{70^2 - 0^2}{30(0.348 \pm 0.0)}$$

$$= 257.3 + 469.3 = 726.6\,ft$$

The results of Sample Problem 3-6 mean that for the entire length of this roadway section drivers must be able to see at least 726.6 ft ahead. Providing this safe stopping sight distance will limit various elements of horizontal and vertical alignment, as discussed in Chapter 27. Not doing so exposes drivers to the risk of seeing an object blocking the road without adequate time to stop. This is explored in Sample Problem 3-7.

Sample Problem 3-7: The Cost of Not Providing Safe Stopping Sight Distance

What could happen, if a section of the roadway described in Sample Problem 3-6 provided a sight distance of only 500 ft? It would now be possible that a driver would initially notice an obstruction when it is only 500 ft away. If the driver were approaching at the design speed of 70 mi/h, a collision would occur. Again, assuming design values of reaction time and forward skidding friction, Equation 3-10 could be solved for the collision speed (i.e., the final speed of the deceleration cycle), using a known deceleration distance of 500 ft:

$$500 = 1.47 \times 70 \times 2.5 + \frac{70^2 - S_f^2}{30(0.348)}$$

$$500 - 257.3 = 242.7 = \frac{70^2 - S_f^2}{10.44}$$

$$2{,}533.8 = 4{,}900 - S_f^2$$

$$S_f = \sqrt{4{,}900 - 2{,}533.8} = 48.6 \text{ mi/h}$$

If the assumed conditions hold, a collision at 48.6 mi/h would occur. Of course, if the weather were dry and the driver had faster reactions than the design value (remember, 90% of drivers do), the collision might occur at a lower speed, and might be avoided altogether. The point is that such a collision *could* occur if the sight distance were restricted to 500 ft.

Decision Sight Distance

While every point and section of a highway must be designed to provide at least safe stopping sight distance, there are some sections that should provide greater sight distance to allow drivers to react to potentially more complex situations than a simple stop. Previously, reaction times for collision avoidance situations were cited [5].

Sight distances based upon these collision-avoidance decision reaction times are referred to as "decision sight distances." AASHTO recommends that decision sight distance be provided at interchanges or intersection locations where unusual or unexpected maneuvers are required: changes in cross-section such as lane drops and additions, toll plazas, and intense-demand areas where there is substantial "visual noise" from competing information (e.g., control devices, advertising, roadway elements).

The decision sight distance is found by using Equation 3-10, replacing the standard 2.5 s reaction time for stopping maneuvers with the appropriate collision avoidance reaction time for the situation from Table 3.2.

Sample Problem 3-8: Decision Sight Distance, Assuming a Stop is Required

Consider the decision sight distance required for a freeway section with a 60 mi/h design speed approaching a busy urban interchange with many competing information sources. The approach is on a 0.03 downgrade. For this case, Table 3.2 suggests a reaction time up to 14.5 s to allow for complex path and speed changes in response to conditions. The decision sight distance is still based on the assumption that a worst case would require a complete stop. Thus, the decision sight distance would be

$$d = (1.47 \times 60 \times 14.5) + \left[\frac{60^2 - 0^2}{30(0.348 - 0.03)}\right]$$
$$= 1{,}278.9 + 377.4 = 1{,}656.3\,ft$$

AASHTO criteria for decision sight distances do not assume a stop maneuver for the speed/path/direction changes required in the most complex situations. The criteria, which are shown in Table 3.9, replace the braking distance in these cases with maneuver distances consistent with maneuver times between 3.5 and 4.5 s. During the maneuver time, the initial speed is assumed to be in effect. Thus, for maneuvers involving speed, path, or direction change on rural, suburban, or urban roads, Equation 3-11 is used to find the decision sight distance.

$$d = 1.47\,(t_r + t_m)\,S_i \qquad [3\text{-}11]$$

where t_r = reaction time for appropriate avoidance maneuver, s, and

t_m = maneuver time, s.

The criteria for decision sight distance shown in Table 3.9 are developed from Equations 3-10 and 3-11 for the decision reaction times indicated for the five defined avoidance maneuvers.

Table 3.9: Decision Sight Distances Resulting from Equations 3-10 and 3-11

Design Speed (mi/h)	Assumed Maneuver Time (s)	Decision Sight Distance for Avoidance Maneuver (ft)				
		A (Eqn 3-10)	B (Eqn 3-10)	C (Eqn 3-11)	D (Eqn 3-11)	E (Eqn 3-11)
Reaction Time (s)		3	9.1	11.2	12.9	14.5
30	4.5	219	488	692	767	838
40	4.5	330	688	923	1023	1117
50	4.0	460	908	1117	1242	1360
60	4.0	609	1147	1341	1491	1632
70	3.5	778	1406	1513	1688	1852
80	3.5	966	1683	1729	1929	2117

A: Stop on a rural road.
B: Stop on an urban road.
C: Speed/path/direction change on a rural road.
D: Speed/path/direction change on a suburban road.
E: Speed/path/direction change on an urban road.

Sample Problem 3-9: Decision Sight Distance Based on AASHTO Criteria

Consider the result of Sample Problem 3-8. What decision distance would be required for the roadway described in Sample Problem 3-9 using AASHTO criteria? AASHTO would not assume that a stop is required. At 60 mi/h, a maneuver time of 4.0 s is used with the 14.5 s reaction time, and

$$d = 1.47(14.5 + 4.0)60 = 1{,}631.7\,ft$$

Note that the result is not very different from Sample Problem 3-8 in this case.

Other Sight Distance Applications

In addition to safe stopping sight distance and decision sight distance, AASHTO also sets criteria for (1) passing sight distance on two-lane rural highways and (2) intersection sight distances for various control options. Intersection sight distances are treated in Chapter 15.

Passing sight distance on two-lane rural highways is a critical issue in the safe design of these types of facilities. On multilane highways, the objective is to always provide the driver with at least the safe stopping distance. This is also true of two-lane highways.

An additional issue arises on two-lane highways, however: passing maneuvers take place in the opposing lane of traffic when the opportunity exists. In this situation, the passing vehicle must assess the availability of a safe gap in the opposing traffic, move into the opposing lane, overtake and pass the slower vehicle(s), and safely return to the proper lane. All of this must be done as a potential vehicle in the opposing lane is approaching at considerable speed.

Passing on two-lane highways is not permitted at all locations. It is only permitted when the *passing sight distance* is available. Passing sight distance is sufficient for a driver to assess the desired maneuver and safely complete all aspects of it before an opposing vehicle imposes a hazard. Many models have been used over the years to analyze required passing sight distances for safety. For some time, criteria presented in the *MUTCD* conflicted with criteria presented in AASHTO. The current AASHTO criteria [*5*] now align with those of the *MUTCD* [*14*]. These criteria are summarized in Table 3.10.

Table 3.10: Passing Sight Distances for Two-Lane Rural Highways

Design Speed (mi/h)	Assumed Maneuver Speeds (mi/h)		Passing Sight Distance (ft)
	Passed Vehicle	Passing Vehicle	
20	8	20	400
25	13	25	450
30	18	30	500
35	23	35	550
40	28	40	600
45	33	45	700
50	38	50	800
55	43	55	900
60	48	60	1,000
65	53	65	1,100
70	58	70	1,200
75	63	75	1,300
80	68	80	1,400

(*Source:* Adapted from (*A Policy on Geometric Design of Streets and Highways*), (2011), by the American Association of State Highway and Transportation Officials, Washington, D.C. U.S.A.)

Note that assumed maneuver speeds are somewhat conservative. The passed vehicle is assumed to be traveling at a speed 12 mi/h below the design speed of the facility, while the passing vehicle is assumed to travel at the design speed. In reality, passing vehicles often travel at higher speeds, particularly while in the opposing lane.

Wherever these passing sight distances are *not* available, passing must be prohibited. Signs and markings are used to mark "No Passing" zones on such highways.

Change (Yellow) and Clearance (All-Red) Intervals for a Traffic Signal

The yellow interval for a traffic signal is designed to allow a vehicle that cannot comfortably stop when the green is withdrawn to enter the intersection legally. Consider the situation shown in Figure 3.6.

In Figure 3.6, d is the safe stopping distance. At the time the green is withdrawn, a vehicle at d or less feet from the intersection line will not be able to stop, assuming normal design values hold. A vehicle further away than d would be able to stop without encroaching into the intersection area. The yellow signal is timed to allow a vehicle that cannot stop to traverse distance d at the approach speed (S). A vehicle may legally enter the intersection on yellow (in most states).

Having entered the intersection legally, the all-red period must allow the vehicle to cross the intersection width (W) and clear the back end of the vehicle (L) past the far intersection line (at a minimum).

Thus, the yellow interval must be timed to allow a vehicle to traverse the safe stopping distance. Sample Problem 3-10 illustrates how the length of the yellow and all-red intervals can be determined.

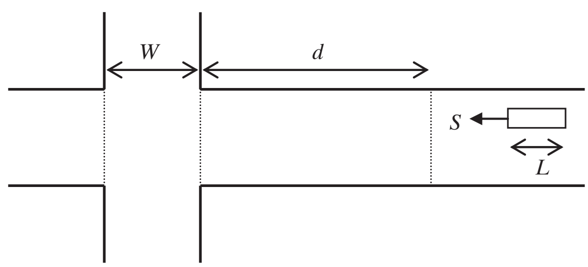

Figure 3.6: Timing Yellow and All-Red Intervals at a Signal

Sample Problem 3.10: Timing "Yellow" and "All-Red" Signal Intervals

Consider a case in which the approach speed to a signalized intersection is 40 mi/h. The grade is level, and the standard reaction time for a "Red" signal is 1.0 s. How long should the yellow and all-red intervals be?

The safe stopping distance is computed using a standard reaction time of 1.0 s for signal timing and level grade:

$$d = 1.47 \times 40 \times 1.0 + \frac{40^2 - 0^2}{30(0.348)}$$
$$= 58.8 + 153.3 = 212.1 \text{ ft}$$

The length of the yellow signal is the time it takes an approaching vehicle to traverse 212.1 ft at 40 mi/h, or

$$y = \frac{212.1}{1.47 \times 40} = 3.6 \text{ s}$$

A vehicle can, therefore, legally enter the intersection during the last instant of the yellow signal. Such a vehicle must be allowed to safely cross the intersection width (W) and the length of the vehicle (L) before conflicting vehicles are allowed to enter the intersection. This is the purpose of the all-red signal. If the street width in this case was 50 ft, and the length of the vehicle 20 ft, it would have to be

$$ar = \frac{50 + 20}{1.47 \times 40} = 1.2\ s$$

In signal timing applications, the yellow signal is computed using a time-based equation and a standard deceleration rate. Also, for greater safety, the yellow signal uses an 85th percentile speed (speed below which 85% of all vehicles travel), rather than an average speed. For the same reason, the all-red signal uses a 15% speed. In the equation for the yellow, speed is in the numerator, and faster vehicles would be at greater risk. In the equation for the all-red, speed is in the denominator, and slower vehicles would be at greater risk.

Sample Problem 3-10 shows how the concept of safe stopping distance is incorporated into signal timing methodologies, which are discussed in detail in Chapters 19 and 20.

3.4 Roadway Characteristics

Roadways are complex physical elements that have important impacts on traffic behavior. Roadways are, in fact, structures that bear the weight load of highway traffic. Further, roadways involve ancillary structures such as bridges, underpasses, embankments, drainage systems, and other features. This text does not treat the physical structural qualities of roadways.

Vehicle operations, however, are greatly influenced by the geometric characteristics of roadways, including horizontal and vertical curvature, and cross-sectional design elements (such as lanes, lane widths, shoulders). An overview of the specific geometric design elements of highways is presented in Chapter 27.

In this chapter, an overview of how roadway systems are organized, developed, and used by motorists is presented.

3.4.1 Highway Functions and Classification

Roadways are a major component of the traffic system, and the specifics of their design have a significant impact on traffic operations. There are two primary categories of service provided by roadways and roadway systems:

- Accessibility
- Mobility

"Accessibility" refers to the direct connection to abutting lands and land uses provided by roadways. This accessibility comes in the form of curb parking, driveway access to off-street parking, bus stops, taxi stands, loading zones, driveway access to loading areas, and similar features. The access function allows a driver or passenger (or goods) to depart the transport vehicle to enter the particular land use in question. "Mobility" refers to the through movement of people, goods, and vehicles from Point A to Point B in the system.

The essential problem for traffic engineers is that the specific design aspects that provide for good access—parking, driveways, loading zones, and so on—tend to retard through movement, or mobility. Thus, the two major services provided by a roadway system are often in conflict. This leads to the need to develop roadway systems in a hierarchal manner, with various classes of roadways specifically designed to perform specific functions.