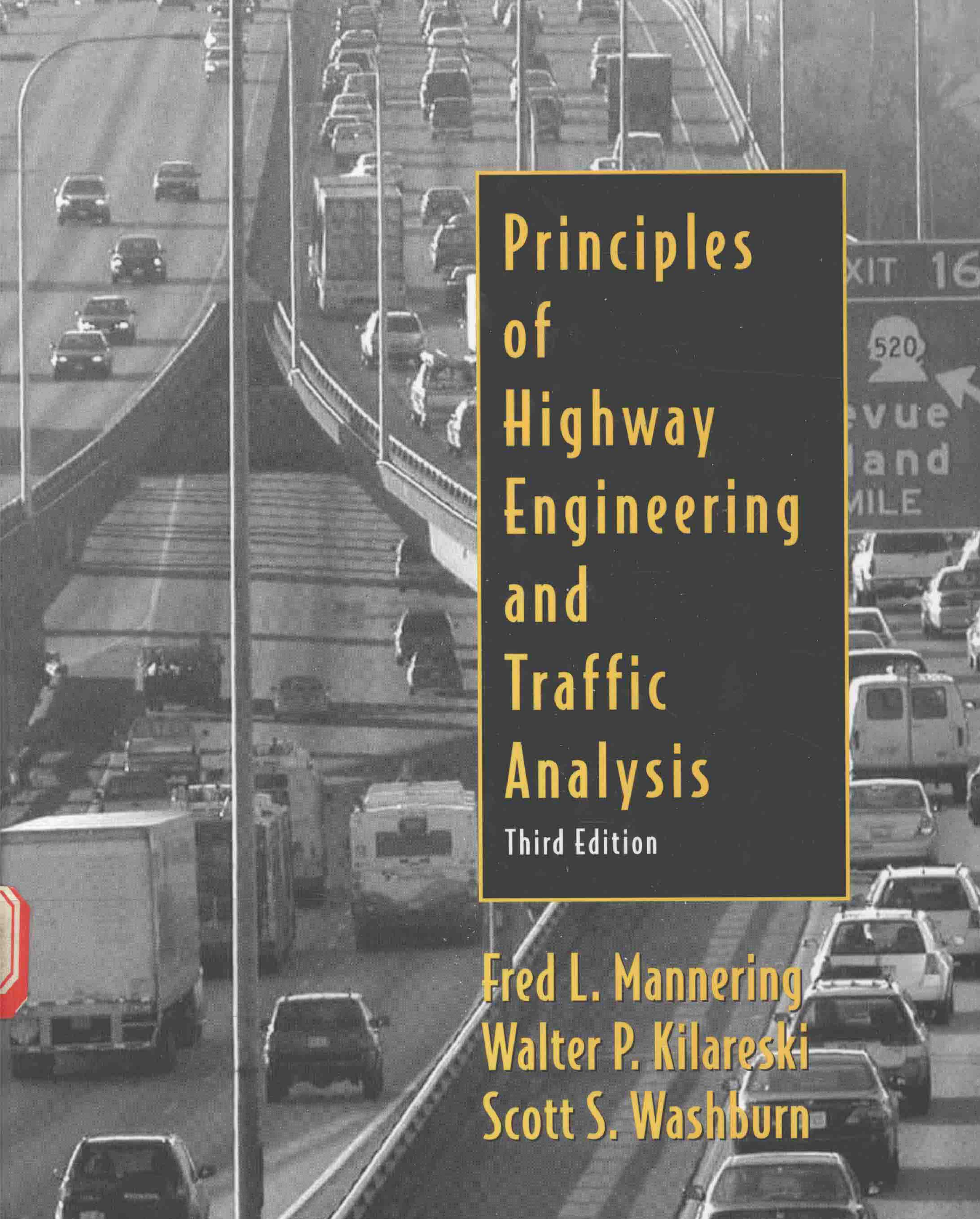

Principles of Highway Engineering and Traffic Analysis

Third Edition

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Preface

INTRODUCTION

The first two editions of *Principles of Highway Engineering and Traffic Analysis* sought to redefine how entry-level transportation engineering courses are taught. When the first edition was published, we saw the need for an entry-level transportation engineering book that focused on highway transportation and provided (1) the depth of coverage needed to serve as a basis for future transportation courses and (2) the material needed to answer questions likely to appear on the Fundamentals of Engineering (FE) or Principles and Practice of Engineering (PE) exams in civil engineering. The subsequent use of our book at some of the largest and most prestigious schools in the United States suggests that our vision of a highly focused, well-written, entry-level book was shared by many other educators.

APPROACH

In this, the third edition of *Principles of Highway Engineering and Traffic Analysis,* we continue the spirit of the first two editions by again focusing exclusively on highway transportation and providing the depth of coverage necessary to solve the highway-related problems that are most likely to be encountered in engineering practice. The focus on highway transportation seems a natural one in light of the dominance of the highway mode in the United States. Offering depth of coverage is a more risky proposition because, in order to keep the book at a manageable length, one must carefully choose the topics that most deserve coverage. Using the first two editions as a basis, along with the comments of other instructors and students who have used earlier versions of the book, we have carefully selected the topics that are fundamental to highway engineering and traffic analysis. This chosen material serves as a core upon which instructors can expand, if they wish, with material that they personally feel deserves additional attention. However, the core of material provided in the book is important for effective teaching because it allows instructors to be confident that students are learning the fundamentals necessary for them to undertake upper-level transportation courses, to enter transportation employment with a basic knowledge of highway engineering and traffic analysis, and to answer transportation-related questions on the civil engineering FE and PE exams.

Within the basic philosophical approach described above, this book addresses the complaint of some students that highway transportation is not as mathematically challenging or rigorous as other fields of study. This is not easily done because there is a dichotomy with regard to mathematical rigor, with relatively simple mathematics used in practice-oriented material and complex mathematics used in research. Thus it is common for instructors to either insult students' mathematical proficiency or vastly exceed it. This book makes an effort to find that elusive middle ground of mathematical rigor that matches junior and senior engineering students' mathematical abilities.

This third edition of *Principles of Highway Engineering and Traffic Analysis* has evolved from well over a decade of teaching introductory transportation engineering classes at the University of Washington, the University of Florida, Purdue University, and the Pennsylvania State University; feedback from users of the first two editions, and experiences in teaching engineering licensure exam review courses. The book's material and presentation style (which is characterized by the liberal use of example problems) are largely responsible for transforming much-maligned introductory transportation engineering courses into courses that are consistently rated by students as among the best civil engineering courses.

CHAPTER TOPICS AND ORGANIZATION

The book begins with a short introductory chapter that stresses the significance of highway transportation to the social and economic underpinnings of society. This chapter provides students with a basic overview of the problems facing the field of highway engineering and traffic analysis. The chapters that follow are arranged in sequences that focus on highway engineering (Chapters 2, 3, and 4) and traffic analysis (Chapters 5, 6, 7, and 8).

Chapter 2 introduces the basic elements of road vehicle performance. This chapter represents a major departure from the vehicle performance material presented in all other transportation and highway engineering books, in that it is far more involved and detailed. The additional level of detail is justified on two grounds. First, because students own and drive automobiles, they have a basic interest that can be linked to their freshman and sophomore coursework in physics, statics, and dynamics. The absence of such a link has been a common criticism of introductory transportation and highway engineering courses. Second, it is important that engineering students understand the principles involved with vehicle performance and the effect that continuing advances in vehicle technologies will have on engineering practice.

Chapter 3 presents current theory and design practices for the geometric alignment of highways. This chapter provides a high level of detail on vertical-curve design and the fundamental elements of horizontal-curve design. Basic material on highway classifications, turning radii, and so on is not included due to the great potential of alienating introductory-level students with too many design-oriented details.

Chapter 4 provides an overview of the current theory and practice of pavement design. The pavement-related material covers both flexible and rigid pavements in a thorough and consistent manner. The material in this chapter also links well with the geotechnical and materials courses that are likely to be part of the student's curriculum.

Chapter 5 presents the fundamentals of traffic flow and queuing theory, which provide the basic tools of traffic analysis. Relationships and models of basic traffic stream parameters are introduced, as well as queuing analysis models for deterministic and stochastic processes. Considerable effort was expended to make the material in this chapter accessible to junior and senior engineering students.

Chapter 6 presents some of the current methods used to assess highway levels of performance. Fundamentals and concepts are discussed along with the complexities involved in measuring and calculating highway level of service.

Chapter 7 introduces the basic elements of traffic control at a signalized intersection. It also builds upon the traffic analysis methods introduced in Chapter 5 and applies these to the analysis of signalized intersections. Using pretimed, isolated signals as the basis, this chapter covers both theoretical and practical elements associated with traffic signal phasing and timing.

Chapter 8, the final chapter, provides an overview of travel demand and traffic forecasting. This chapter uses a theoretically and mathematically consistent approach to travel demand and traffic forecasting. This chapter provides the student with an important understanding of the current state of travel demand and traffic forecasting, and some critical insight into the deficiencies of forecasting methods currently used.

NEW TO THIS EDITION

Dual Units

In this edition, an effort has been made to provide dual units (U.S. Customary and metric) throughout, with the primary units being U.S. Customary. This has been accomplished for all chapters except Chapter 4. Because the current pavement design guide is based only on U.S. Customary units, Chapter 4 provides only U.S. Customary units in a number of contexts where metric conversions are cumbersome.

Presentation Enhancements

Variable definitions for equations and figures are now presented in a tabular format to provide for quick accessibility and identification within the text.

New and Revised Problems

Over 50% of the problems are either new or have been revised. Users of the book will find the end-of-chapter problems to be extremely valuable in supporting the material presented in the book. Our intent has been to make these problems precise and challenging, a combination rarely found in transportation/highway engineering books.

Appendices for Problems in Metric

For those wishing to stress metric units, we have provided an appendix that contains the in-chapter example problems worked in metric units and an appendix that contains the end-of-chapter problems with metric units. It should be noted that these appendices include only problems that use units that can be converted to metric. For example, problems that deal only with units of vehicles or time are not repeated in these appendices. It should also be noted that some conversions are inexact in order to allow for consistent use of design tables, regardless of the units being used.

Some Chapter-Specific Enhancements

Chapter 1 The highway safety discussion has been updated to reflect current trends and has been integrated into the introductory section to better emphasize its significance to the entire field of transportation engineering.

Chapter 2 Section 2.9.5, Practical Stopping Distance, has been completely revised to be consistent with new design standards.

Chapter 3 Section 3.3.6, Underpass Sight Distance, has been added since this is often an important consideration in sag curve design. Numerous other revisions have been made to accommodate new design standards.

Chapter 5 Section 5.2, Traffic Stream Parameters, has been moderately expanded and revised to the provide the reader with a more thorough understanding of these concepts.

Chapter 6

- Section 6.3, Level-of-Service Determination, has been completely revised to provide a general overview of the process for determining level of service for all uninterrupted-flow highway segments.
- Sections 6.4–6.6, Basic Freeway Segments, Multilane Highways, and Two-Lane Highways, have been significantly revised in response to new design standards.

Chapter 7

- Section 7.2, Intersection and Signal Control Characteristics, has been added to introduce the reader to the basic concepts of the physical control of traffic signals.
- Section 7.3, Analysis of Traffic at Signalized Intersections, includes expanded coverage of interrupted traffic flow theory and concepts.
- Sections 7.3.3 and 7.6, Signalized Intersection Analysis for Level of Service and Level-of-Service Determination, provide explicit coverage of signal analysis for level of service.
- Section 7.5, Development of a Traffic Signal Phasing and Timing Plan, has been completely rewritten to be consistent with the latest guidelines and design standards.

Chapter 8

- Section 8.4.2, Trip Generation with Count Data Models, has been added to provide the reader with insight on a more mathematically consistent method for trip generation estimation.
- Appendix 8B, Maximum-Likelihood Estimation, has been added to introduce the reader to another method for estimating travel demand and traffic forecasting model coefficients.

Solutions Manual

The Solutions Manual includes solutions both in U.S. Customary and metric units. The Solutions Manual is available only to instructors. Instructors who are using this book for their course should visit the book's Web site (www.wiley.com/college/mannering), and go to the Instructor Companion Site portion of the Web site to register for a password and download the Solutions Manual.

Text Figures in Electronic Format

The figures from the text are available to instructors in electronic format, for easy creation of lecture slides. Visit the Instructor Companion Site portion of the book's Web site (www.wiley.com/college/mannering) to register for a password and download the text figures.

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Contents

Chapter 1

Introduction to Highway Engineering and Traffic Analysis

1.1 INTRODUCTION

The importance of highway transportation to the industrial and technological complex of the United States and other industrialized nations cannot be overstated. Virtually every aspect of modern economies, and the ways of life they support, can be tied directly or indirectly to highway transportation. From the movement of freight and people to the impact on residential, commercial, and industrial locations, highways have had, and continue to have, a profound effect on the world economy and societal development. In the United States, the manner in which highways have come to dominate the transportation system has been studied for decades as a cultural, political, and economic phenomenon. Without a doubt, the demand for unrestricted mobility and unlimited access to resources has played an important role and helped to quickly move highway transportation to its dominant position from the middle of the 20th century onward. The construction of the U.S. interstate highway system remains to this day the largest infrastructure project in human history. At the time, it underscored the nation's commitment to the unrestricted mobility of its populace and to the economic opportunities that such a system would provide its industrial and service industries. Today, additional highway expansion and maintenance of existing highway systems continue to represent an enormous investment in public infrastructure—an investment with an immeasurable impact on society in terms of mobility, economic opportunities, and environmental implications, including consumption of resources and pollution.

The mobility and opportunities that highway infrastructure provides also has a human cost. Although safety has always been a primary consideration in highway design and operation, highways continue to exact a terrible toll in terms of loss of life, injuries, property damage, and reduced productivity as a result of vehicle accidents. To be sure, the elements of highway safety are complex. They involve technical and behavioral components and the complexities of the human-machine interface. Because of the high costs of highway accidents, efforts to improve highway safety have intensified dramatically in the last decade. This has resulted in the implementation of new highway design guidelines and countermeasures (some technical and some behavioral) aimed at reducing the frequency and severity of highway accidents. These efforts sought to reverse an upward trend in U.S. highway fatalities and injuries that saw such fatalities exceed 50,000 per year in the 1970s. Fortunately, efforts aimed at improving highway design (such as more stringent design guidelines and breakaway signs), vehicle occupant protection (safety belts, padded dashboards, collapsible steering columns, driver- and passenger-side airbags, and improved bumper design), and vehicle accident avoidance (antilock braking and traction control systems), combined with accident countermeasures (campaigns to reduce drunk driving), have reduced annual U.S. highway fatalities to around 40,000 in the 1990s. However, in spite of continuing efforts and unprecedented advancements in vehicle safety technologies, the number of fatalities in recent years has begun to rise again (although fatalities per mile driven continue to decline).

To explain this, evidence points to a number of potential factors: an increase in the overall level of aggressive driving; increasing levels of disrespect for traffic control devices (running of red lights and stop signs being two of the more notable examples); in-vehicle driving distractions, such as cell phones; and poor driving skills in the younger and older driving populations. Two other phenomena are being observed that may be contributing to the increased number of fatalities. One is that some people drive more aggressively in vehicles with advanced safety features, thus leveraging some of the benefits of new safety technologies against the desire for increased mobility (speed). The other is that many people are more influenced by style and function than by safety features when making vehicle purchase decisions. This is evidenced by the growing popularity of vehicles such as sport utility vehicles (SUVs), minivans, and pickup trucks, despite their consistently overall lower rankings in certain safety categories, such as rollover probability, relative to sedan-style passenger cars. These issues underscore the importance of the highway engineer's need to consider the complex interaction between human behavior/factors and technology in highway design.

It is against this backdrop that engineers must strive to provide high levels of mobility (minimizing travel times and delays) and high levels of safety. These two goals are not only often contradictory (higher speeds minimize travel time but may also decrease safety), but must be achieved while giving full consideration to the complex impacts that are likely to result from highway-related projects. Such impacts can be broadly classified as economic (the cost and economic impact of these projects), political (the community-related impacts of projects), and environmental (the impact of projects on the environment measured in terms of air, water, land, noise, and quality of life).

Although attempting to provide higher levels of both mobility and safety may seem an impossible task at times, it is a task that engineers have an ethical responsibility to undertake. In so doing, they must use all of the technologies at their disposal while giving full consideration to the associated effects on human behavior.

1.2 TECHNOLOGY

As with all fields of engineering, technological advances offer the promise of solving complex problems and achieving lofty goals. For highways, technologies can be classified into those impacting infrastructure, vehicles, and traffic control.

1.2.1 Infrastructure Technologies

Investments in highway infrastructure have been made continuously throughout the twentieth and twenty-first centuries. Such investments have understandably varied over the years in response to need, and political and national priorities. For example, in the United States, an extraordinary capital investment in highways during the 1960s and 1970s was undertaken in constructing the interstate highway system and upgrading and constructing many other highways. The economic and political climate that permitted such an ambitious construction program was unprecedented and has not been replicated since. It is difficult to imagine, in today's economic and political environment, that a project of the magnitude of the interstate highway system would ever be seriously considered. This is because of the prohibitive costs that are associated with land acquisition and construction and the community and environmental impacts that would result.

It is also important to realize that highways are durable, long-lasting investments that require maintenance and rehabilitation at regular intervals. The legacy of a major capital investment in highway infrastructure is the proportionate maintenance and rehabilitation schedule that will follow. For example, most of the U.S. interstate system was designed with pavements that had a finite lifetime before major rehabilitation became necessary. Thus an unfortunate consequence of the extensive interstate construction program is the maintenance and rehabilitation programs that are needed today. Although there are sometimes compelling reasons to defer maintenance and rehabilitation (including the associated construction costs and the impact of the reconstruction on traffic), such deferral can result in unacceptable losses in mobility and safety.

Engineers must now deal with new construction and infrastructure maintenance and rehabilitation by developing and applying new technologies to extend the life of new facilities and to economically combat aging infrastructure. Included in these technologies are the extensive development and application of new sensing technologies in the emerging field of structural health monitoring. There are also opportunities to extend the life expectancy of new infrastructure with the ongoing nanotechnology advances in material science. Such technological advances are essential elements in the future of highway infrastructure.

1.2.2 Vehicle Technologies

Until the 1970s, vehicle technologies evolved slowly and often in response to mild trends in the vehicle market as opposed to an underlying trend toward technological development. Beginning in the 1970s, three factors began a cycle of unparalleled advances in vehicle technology that continues to this day: (1) government regulations on air quality, fuel efficiency, and vehicle occupant safety; (2) energy shortages and fuel price increases; and (3) intense competition from foreign vehicle manufacturers. The aggregate effect of these factors has been vehicle consumers demanding new technology. Vehicle manufacturers have found it necessary to reallocate resources and to restructure manufacturing and inventory control processes to meet this demand. In recent years, consumer demand and competition among vehicle manufacturers has resulted in the widespread implementation of new technologies including supplemental restraint systems, antilock brake systems, traction control systems, and a host of other applications to improve safety and comfort in highway vehicles. There is little doubt that the combination of consumer demand and intense competition in the vehicle industry will continue to spur technological innovations.

Although the development of new vehicle technologies usually lies in the domain of disciplines such as mechanical and electrical engineering, the influence of such technologies on highway design and traffic analysis is an important concern for highway engineers. This is because highway engineers must be able to account for new technologies in the design and rehabilitation of highways in their ongoing effort to provide the highest possible levels of mobility and safety.

1.2.3 Traffic Control Technologies

Intersection traffic signals are a familiar traffic control technology. At signalized intersections, the trade-off between mobility and safety is brought into sharp focus. Procedures for developing traffic signal control plans (allocating green time to conflicting traffic movements) have made significant advances over the years. Today, signals at critical intersections respond quickly to prevailing traffic flows, groups of signals are sequenced to allow for a smooth through-flow of traffic, and in some cases, computers control entire networks of signals. In addition to signal controls, numerous safety, navigational, and congestion mitigation technologies are now reaching the market under the broad heading of Intelligent Transportation Systems (ITS). Such technological efforts offer the potential to significantly reduce traffic congestion and improve safety on highways by providing an unprecedented level of traffic control. There are, however, many obstacles associated with ITS implementation, including system reliability, human response, and the human-machine interface. It is therefore important not only that highway engineers participate in the development and implementation of new traffic control technologies, but that they also recognize the limitations associated with these technologies.

1.3 HUMAN BEHAVIOR

The volume and speed of highway traffic determines both highway mobility and safety and is a behavioral phenomenon that is an outgrowth of people's travel-related choices. Over the years, these choices have resulted in crippling congestion in many urban areas and millions of highway injuries and deaths, as well as property and productivity losses that have easily exceeded a trillion dollars. Despite congestion and safety problems, the trend in traffic growth continues upward. This is rather surprising because one would expect the supply-demand effect (a congested highway infrastructure should restrain the growth of private-vehicle use) to be an effective factor in limiting urban traffic congestion. However, it has been found that people are willing to tolerate high amounts of congestion just to continue to use private vehicles, most of which only have a single occupant. The continued growth in traffic congestion is a serious obstacle to improving mobility.

Addressing traffic growth is a perplexing problem. Current economic and political environments do not favor large-scale construction programs aimed at increasing highway capacity. Technological innovations in traffic control have the potential to offer some relief, but it is questionable whether such innovations can keep pace with the growth in traffic volume. This points toward the more fundamental issue of the behavioral processes and preferences that generate highway traffic.

1.3.1 Dominance of Single-Occupant Private Vehicles

Of the available urban transportation modes (bus, commuter train, subway, and private vehicle), private vehicles (and single-occupant private vehicles in particular) offer a level of mobility that is unequaled. The single-occupant private vehicle is such an overwhelmingly dominant choice that travelers are willing to pay substantial capital and operating costs, confront high levels of congestion, and struggle with parking-related problems, just to have the flexibility in travel departure time and destination choices that is uniquely provided by private vehicles. The dominance of the private-vehicle mode is supported by historical data that shows continuing trends toward its use. For example, in the last 40 years, the percentage of trips taken in private vehicles has risen from about 69% to over 90% (public transit, walking, and other modes make up the balance). Over this same period, average private-vehicle occupancy has dropped from 1.22 to 1.09 persons per vehicle, reflecting the fact that the single-occupant vehicle is becoming the increasingly dominant mode of travel.

Dealing with extensive private-vehicle use and low vehicle occupancy presents engineers with a classic mobility dilemma. On one hand, programs that encourage travelers to take alternative modes of transportation (bus fare incentives and increases in private-vehicle parking fees) or to increase vehicle occupancy (high-occupancy vehicle lanes and employer-based ride sharing programs) have the potential to provide some traffic congestion relief on highways and provide remaining highway users with higher mobility. However, such programs have the adverse effect of directing people toward travel modes that inherently provide lower levels of mobility because no other mode offers the departure time and destination choice flexibility provided by private, single-occupant vehicles. With this mobility dilemma in mind, it is clear that controversial congestion-related compromises must be reached.

1.3.2 Demographic Trends

Travelers' commuting patterns are inextricably intertwined with their socioeconomic characteristics, such as age, income, household size, education, and job type, as well as the distribution of residential, commercial, and industrial developments within the region. Many American metropolitan areas have experienced population declines in central cities accompanied by a growth in suburban areas. Many have argued that the population shift from the central cities to the suburbs was made possible by the