Introduction to TRANSPORTATION ENGINEERING

2nd Edition

James H. Banks

Introduction to TRANSPORTATION ENGINEERING

Second Edition

James H. Banks

San Diego State University

McGraw Hill

Boston Burr Ridge, IL Dubuque, IA Madison, WI New York San Francisco St. Louis
Bangkok Bogotá Caracas Kuala Lumpur Lisbon London Madrid Mexico City
Milan Montreal New Delhi Santiago Seoul Singapore Sydney Taipei Toronto

McGraw-Hill Higher Education

*A Division of The **McGraw-Hill** Companies*

INTRODUCTION TO TRANSPORTATION ENGINEERING
SECOND EDITION

Published by McGraw-Hill, a business unit of The McGraw-Hill Companies, Inc., 1221 Avenue of the Americas, New York, NY 10020.

This book is printed on acid-free paper.

International 1 2 3 4 5 6 7 8 9 0 FGR/FGR 0 9 8 7 6 5 4 3 2 1
Domestic 3 4 5 6 7 8 9 0 FGR/FGR 0 9 8 7 6 5 4 3

ISBN 0-07-243188-1
ISBN 0-07-112164-1 (ISE)

General manager: *Thomas E. Casson*
Publisher: *Elizabeth A. Jones*
Executive editor: *Eric M. Munson*
Developmental editor: *Amy Hill*
Marketing manager: *Ann Caven*
Project manager: *Joyce Watters*
Production supervisor: *Enboge Chong*
Coordinator of freelance design: *David W. Hash*
Senior photo research coordinator: *Lori Hancock*
Photo research: *Connie Gardner Picture Research*
Supplement producer: *Tammy Juran*
Media technology senior producer: *Phillip Meek*
Compositor: *Interactive Composition Corporation*
Typeface: *10.5/12 Times Roman*
Printer: *Quebecor World Fairfield, PA*

Library of Congress Cataloging-in-Publication Data

Banks, James H.
Introduction to transportation engineering / James H. Banks.—2nd ed.
p. cm.—(McGraw-Hill series in transportation)
Includes index.
ISBN 0-07-243188-1
1. Transportation engineering. I. Title. II. Series.

TA1145 .B33 2002
629.04—dc21 2001030687
CIP

INTERNATIONAL EDITION ISBN 0-07-112164-1

McGraw-Hill Series in Transportation

CONSULTING EDITOR

Edward K. Morlok, University of Pennsylvania

Banks: *Introduction to Transportation Engineering*
Horonjeff and McKelvey: *Planning and Design of Airports*
Kanafani: *Transportation Demand Analysis*
Meyer and Miller: *Urban Transportation Planning: A Decision-Oriented Approach*

PREFACE

Introduction to Transportation Engineering is intended as a text for a one-semester junior- or senior-level introductory course in transportation engineering, taught as part of a civil engineering curriculum. The book contains approximately fifty percent more material than can be covered in a single semester. This was done deliberately, to provide instructors with flexibility in the topics they cover. Some of this material is typically introduced in other courses, such as surveying (horizontal and vertical curve layout and earthwork), statistics, and engineering economy. Material on these topics is not intended to substitute for courses in these areas, but rather to provide students with a review and to demonstrate the application of these subjects to transportation engineering.

An introductory course in transportation engineering must serve the needs of at least three types of students. For most students, who will eventually practice some other civil engineering specialty, it will serve as a familiarization course. For others, who will practice in transportation-related jobs immediately after graduation, it will provide background for entry-level practice in transportation engineering. For still others, it will provide the background needed to pursue graduate studies.

In order to meet the needs of all three types of students, an introductory text needs to cover the basics of both theory and practice, convey a sense of the scope of transportation engineering, and maintain an appropriate balance between breadth and depth of coverage. This book emphasizes the social, economic, and political context of transportation engineering; places major emphasis on important practical topics such as geometric design, layer design for highway pavements, *Highway Capacity Manual* methods, and traffic signal timing; and also emphasizes important theoretical topics such as the fundamental techniques of traffic analysis and the economic theory underlying transportation demand modeling. It also provides overviews of several more specialized topics. These include environmental mitigation design for transportation projects, railroad track design, capacity analysis and traffic control for rail and air transportation, mass transit planning and operations, and specific demand analysis techniques.

The basic approach of the book is intermodal. One of its underlying concepts is that the basic techniques and principles of transportation engineering are of wide application, particularly across modal lines. For practical reasons, the major emphasis is often on highways, but care is taken to show how basic concepts and techniques apply to different modes. This approach is followed in the presentation of material on geometric design in Chapter 4 and the introduction of traffic analysis techniques such as space-time diagrams, queuing analysis, and network analysis in Chapter 8. In the latter case, the strategy is to focus on the techniques themselves, and to present examples (from a variety of modal and operational contexts) that are intended to contribute to the students' understanding of them. The intended result is for students to grasp the underlying principles, and then be able to apply them flexibly in a variety of contexts.

ORGANIZATION OF THE TEXT

Material in the book is organized as follows: Chapters 1 and 2 serve as an introduction, with a focus on the scope and societal context of transportation engineering. Chapters 3–7 cover topics related to the design of transportation facilities. Chapters 8–12 focus on transportation system operation. Chapters 13–15 cover planning and evaluation of transportation systems. There is no one best order for these topics, and instructors should feel free to cover them whatever order they choose. In certain cases, however, the presentation of material in the later chapters assumes that the reader is familiar with topics presented earlier. Chapter 3 should be covered before Chapter 4. Chapters 8–11 should be covered in the order presented, and Chapter 12 should follow Chapter 8. Section 8.3 should be covered before Sections 13.6 and 13.7. Chapter 7, which deals with mitigation of environmental impacts, is placed where it is because the design of environmental mitigation is an important part of facility design; it is also related to the discussion of environmental impact assessment in Section 15.2, and might equally well be covered in conjunction with that material.

PEDAGOGY

Because experience shows that many students learn best by example, efforts have been made to provide numerous example problems and student exercises. Student exercises include written exercises, homework problems, computer exercises, and open-ended design exercises. Written exercises include both short answer questions and suggested term paper topics. As a general rule, homework problems include several versions of what is essentially the same problem. These are intended to provide instructors with flexibility in assigning problems, and to accommodate students who wish to gain extra practice by working several versions of the same problem. Computer exercises include both programming exercises, which require knowledge of FORTRAN or similar languages, and spread sheet exercises. A solutions manual has been provided for instructors; it contains solutions to the homework problems, answers for the short-answer written exercises, FORTRAN code for the programming exercises, and Excel spread sheets for the spread sheet exercises.

New Design Exercises. Design exercises are a major new feature of the second edition. These exercises introduce students to the thought processes and documentation involved in a variety of types of transportation design. They are intended to be relatively simple and straightforward and thus to serve as easily-documented introductory steps in a process that integrates design throughout the professional component of the curriculum, as required by the ABET civil engineering program criteria.

Every effort has been made to present up-to-date material. This includes reference to recent research related to speed-flow-density relationships for highway traffic, use of *Highway Capacity Manual 2000,* and use of metric design standards from the 1994 edition of the *AASHTO Policy on Geometric Design of Highways and Streets*. Metrication continues to pose a special problem because the United States is still in transition between traditional and metric units. The book reflects this state of transition; the system used for primary units is typically metric, but is occasionally traditional, depending on the usage of the principle references for the topic. Equivalent units for the other system are given in parentheses. The primary system of units for highway geometric design is metric, following the 1994 AASHTO *Policy.* In the case of highway capacity, the text of the second edition follows the metric version of *Highway Capacity Manual 2000,* but tables and figures from the U.S. customary unit version are included in an appendix to accommodate instructors who prefer them.

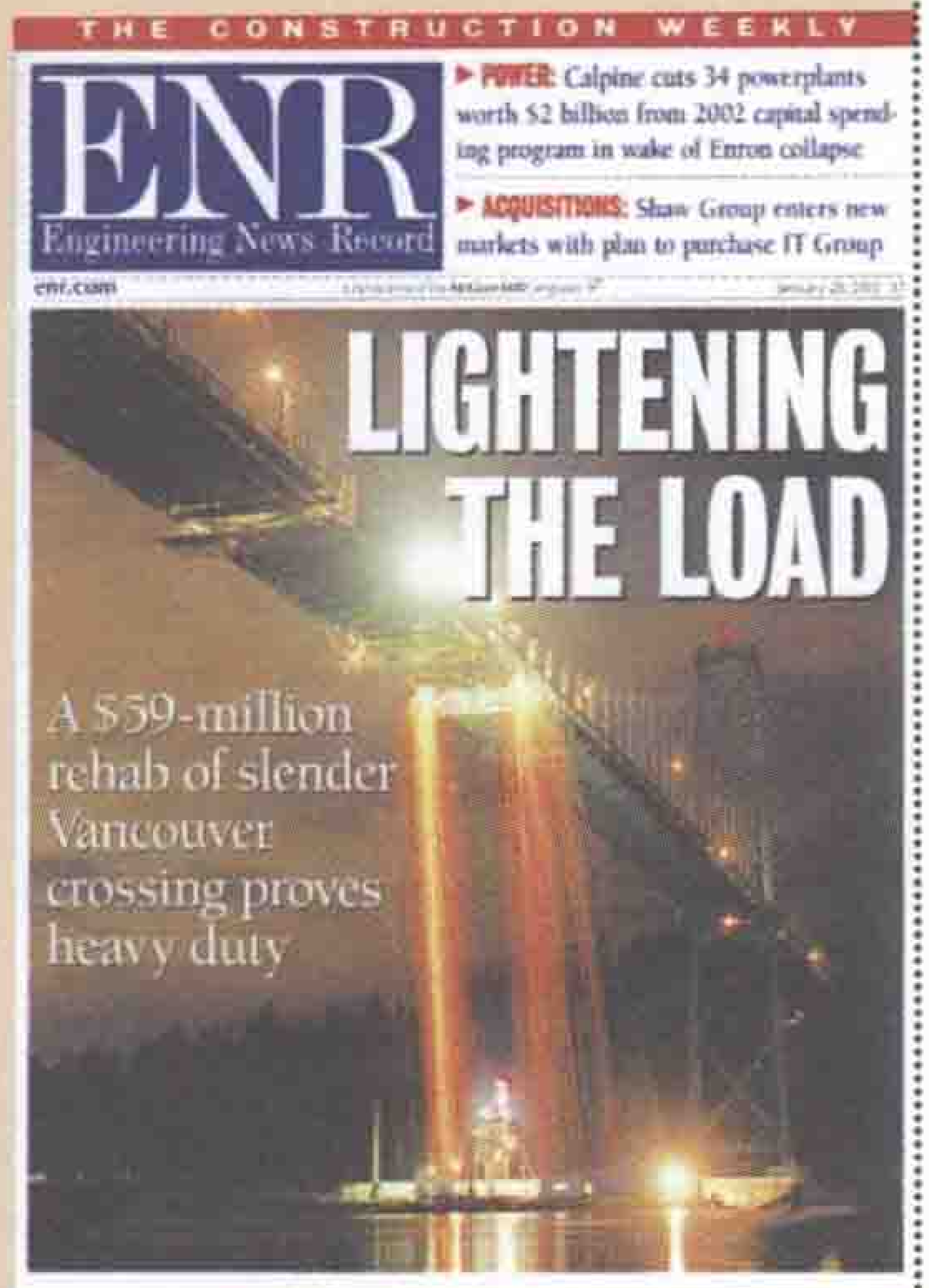
ACKNOWLEDGMENTS

This book began as a set of course notes that other instructors and I had developed at the University of California at Berkeley in the mid-1970s. Over the years, these notes were used at San Diego State University, California State University, Chico, and possibly other campuses in California. During this period, these notes were expanded and revised with contributions from a number of authors, including Thomas C. Ferrara, A. Reed Gibby, and several of their students at Cal State Chico, as well as myself. In 1994, I completely revised this material to turn what had previously been a disconnected set of course notes into a connected work. This was subsequently revised and expanded to produce the first edition of this book, which serves as the basis for this edition. In converting the original set of course notes into a book, I drew on several articles, otherwise unpublished, that were included in the course notes. I wish to acknowledge a particular debt to articles on various aspects of geometric design by V. F. Hurdle, an article on highway pavements by Thomas C. Ferrara, and an article on the use of mass diagrams in earthwork computations developed from material written by Prof. F. S. Foote.

I also wish to acknowledge my debt to the reviewers of this book, both those who contributed to the development of the first edition and those who assisted in this revision. These include several anonymous reviewers of the first edition, Richard G. McGinnis, and Edward K. Morlok, Jan L. Botha, William G. Buttlar, Jon D. Fricker, Mark Hickman, Xudong Jia, Martin R. Kane, Scott Keller, Arnim Meyburg, Mike Meyer, and Paul D. Shuldiner. I am particularly indebted to Dr. McGinnis for his extensive and detailed review of the first edition. I also wish to acknowledge the help, encouragement, and suggestions of B. J. Clark, Eric Munson, Amy Hill, Dennison Lee, and my colleague Janusz Supernak.

James H. Banks
San Diego State University

ISBN 0-07-243188-1 BANKS: INTRO TRANSPORTATION ENGINEERING



Student

Please enter my subscription for **Engineering News-Record**.

6 months ❑ $29.50 (Domestic)

Name

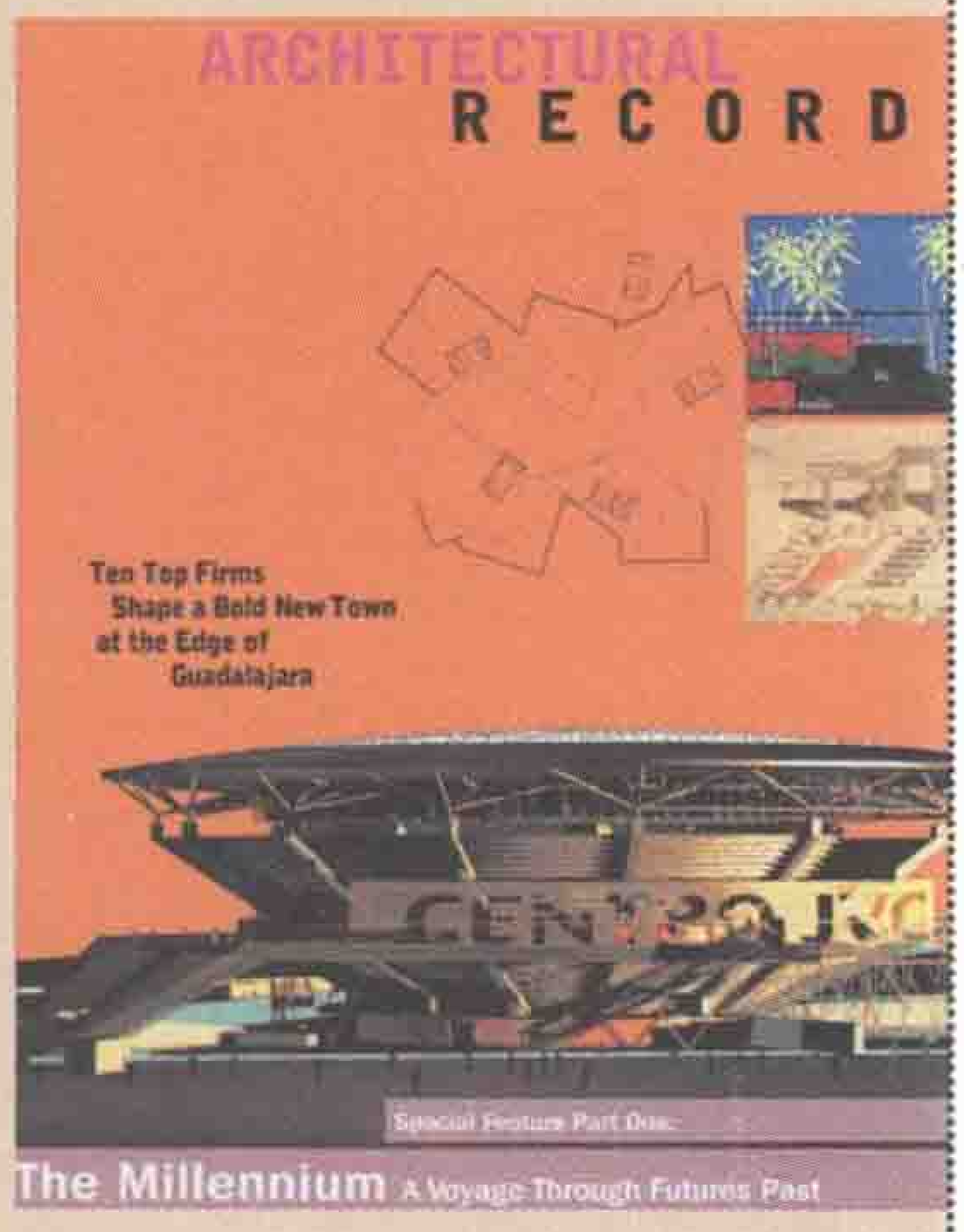
Address

City State Zip

❑ Payment enclosed ❑ Bill me later

McGraw_Hill CONSTRUCTION ENR

5EN2DMHE



Friendly

Please enter my subscription for **Architectural Record**.

6 months ❑ $19.50 (Domestic)

Name

Address

City State Zip

❑ Payment enclosed ❑ Bill me later

McGraw_Hill CONSTRUCTION Architectural Record

5AR2DMHE

Savings

Please enter my subscription for **Aviation Week & Space Technology**.

6 months ❑ $29.95 (Domestic)

Name

Address

City State Zip

❑ Payment enclosed ❑ Bill me later

Aviation Week's AVIATION WEEK & SPACE TECHNOLOGY www.AviationNow.com/awst

CAW34EDU

CONTENTS

Preface vii

1 Introduction 1
- 1.1 Transportation Engineering 1
- 1.2 The Transportation System 2
- 1.3 Modes of Transportation 6
- 1.4 Institutional Structure 17
- 1.5 Civil Engineering Involvement in Transportation 19
- 1.6 Careers in Transportation Engineering 20
- 1.7 Summary 21

References 22
Exercises 22

2 Transportation System Issues and Challenges 25
- 2.1 Traffic Congestion 25
- 2.2 Traffic Safety 27
- 2.3 Equality of Access 30
- 2.4 Environmental Protection 32
- 2.5 New Technology 34
- 2.6 Funding 38
- 2.7 Institutional Arrangements 42
- 2.8 Summary 44

References 44
Exercise 45

3 Introduction to Physical Design of Transportation Facilities 47
- 3.1 The Design Process 47
- 3.2 Design Standards 50
- 3.3 Design Speed and Sight Distance 52
- 3.4 Design Documents 57
- 3.5 Summary 60

References 61
Problems 61
Exercises 61
Computer Exercise 61

4 Geometric Design 63
- 4.1 Geometric Cross Section 63
- 4.2 Vertical Alignment 66
- 4.3 Horizontal Alignment 76
- 4.4 Superelevation 83
- 4.5 Coordination of Horizontal and Vertical Alignment 92
- 4.6 Intersections and Interchanges 94
- 4.7 Design Software 95
- 4.8 Summary 100

References 101
Problems 101
Computer Exercises 105
Design Exercises 106

5 Earthwork 111
- 5.1 Earthwork Cross Sections 111
- 5.2 Earthwork Volumes 115
- 5.3 Mass Diagrams 118
- 5.4 Summary 123

Reference 124
Problems 124
Computer Exercises 130
Design Exercise 130

6 Surfaces and Guideways 133
- 6.1 Highway Pavements 133
- 6.2 Railroad Track 154
- 6.3 Summary 164

Reference 164
Problems 164
Exercises 166

7 Mitigation of Environmental Impacts **169**
7.1 Noise 169
7.2 Encroachment on Natural Habitats 175
7.3 Stormwater Management 179
7.4 Hazardous Wastes and Soil Contamination 182
7.5 Summary 184

Reference 184
Problems 185
Exercises 185

8 Traffic-Analysis Techniques **187**
8.1 Space–Time Relationships 187
8.2 Queuing Analysis 199
8.3 Network Analysis 210
8.4 Summary 216

References 217
Problems 217
Computer Exercises 222

9 Traffic Flow **223**
9.1 Traffic Data 223
9.2 Traffic Flow Models 224
9.3 Traffic Data Analysis 236
9.4 Summary 245

References 246
Problems 246
Computer Exercises 250

10 Capacity and Level of Service **251**
10.1 Air Traffic Capacity 252
10.2 Rail Capacity 255
10.3 Highway Capacity 258
10.4 Summary 282

References 282
Problems 283
Computer Exercise 288
Design Exercise 289

11 Traffic Control **291**
11.1 Traffic Signals 292
11.2 Signal Timing 299
11.3 Signal Coordination 308
11.4 Freeway Management Systems 313
11.5 Rail Traffic Control 320
11.6 Air Traffic Control 321
11.7 Summary 325

References 325
Problems 326
Exercises 329
Design Exercises 330

12 Transit Operations **333**
12.1 Route Planning 333
12.2 Route Location 334
12.3 Stop Location 336
12.4 Route Schedules 339
12.5 Vehicle and Labor Scheduling 344
12.6 Control of Operations 346
12.7 Route Evaluation 347
12.8 Summary 348

References 349
Problems 349
Exercises 351
Computer Exercise 351
Design Exercise 352

13 Transportation Demand Analysis **355**
13.1 Travel Behavior 355

13.2 Travel Demand Modeling 356
13.3 Trip Generation Models 360
13.4 Trip Distribution Models 363
13.5 Mode Choice Models 366
13.6 Trip Assignment Models 368
13.7 Sequential Modeling Process: An Example 369
13.8 Summary 378

References 378
Problems 378
Computer Exercises 382

14 Transportation Planning 385

14.1 Perspectives on the Planning Process 386
14.2 Planning Regulations 390
14.3 Transportation and Air Quality Planning 393
14.4 Planning Studies 397
14.5 Planning Study Organization 402
14.6 Summary 404

References 404
Exercises 405

15 Transportation Project Evaluation 407

15.1 Economic Evaluation Techniques 408
15.2 Environmental Impact Assessment 417
15.3 Summary 429

References 430
Problems 431
Exercises 433
Computer Exercises 433

Appendix A: Statistical Tables 435

Appendix B: Tables and Charts for Pavement Design 438

Appendix C: Highway Capacity Manual Materials (Metric) 455

Appendix D: Highway Capacity Manual Materials (Traditional) 469

Index 485

CHAPTER 1

Introduction

1.1 TRANSPORTATION ENGINEERING

Transportation engineering is the application of scientific principles to the planning, design, operation, and management of transportation systems. As commonly used, however, the term refers to a subspecialty of civil engineering. Since the purpose of this book is to introduce civil engineering students to the practice of transportation engineering, such topics as vehicle design will be ignored, even though they are extremely important applications of engineering to the transportation system. At the same time, the transportation field practiced by civil engineers is inherently multidisciplinary, overlapping such diverse fields as economics, psychology, geography, city planning, public administration, political science, industrial engineering, and electrical engineering. In addition, major theoretical contributions to transportation engineering have been made by people with backgrounds in physics and mathematics.

This breadth of interaction with other disciplines stems from the fact that the scope of transportation engineering is determined more by society's need to provide an adequate transportation system than by the backgrounds of its practitioners. Thus it involves synthesis of several different intellectual perspectives and scientific knowledge bases to solve perceived technical, economic, social, and environmental problems. Among the civil engineering specialties, it is similar in this respect to environmental engineering, but differs from hydraulic engineering or structural engineering, which are more closely tied to particular bodies of scientific knowledge.

This breadth of material presents a challenge, especially in an introductory course. Any such course needs to serve at least three purposes: (1) to provide general information about the practice of transportation engineering for students who will practice other civil engineering specialties, (2) to prepare students who will practice in transportation-related jobs immediately upon graduation, and (3) to provide the necessary background for students who wish to pursue graduate studies in transportation engineering. In order to meet the needs of all three types of students, it is necessary to introduce a wide variety of topics, but at the same time to pursue them with enough rigor and in enough detail to prepare students for the challenges of real-world practice or graduate studies. This makes for a fast-paced course, and requires a certain amount of mental flexibility on the part of the student.

The material presented in this book may be organized in various ways. For instance, introductory texts in transportation engineering are often organized in terms of the different transportation modes (highways, air, rail, etc.—see Section 1.3), and some focus exclusively on one of these modes, usually highways. In contrast, the approach here is to organize the material in terms of the different types of design and analysis that transportation engineers engage in—for instance, geometric design of facilities, traffic analysis, analysis and design of traffic control systems, transportation demand analysis, or transportation planning—and to discuss these in terms of basic concepts and techniques that often can be applied in a wide variety of situations to different transportation modes. The objective in presenting the material in this way is not only to emphasize the many similarities among the transportation modes but (more importantly) to help students experience the intellectual power and efficiency that can result from being able to apply abstract concepts and techniques to a range of concrete situations. At the same time, most of us learn abstract ideas best by first being exposed to concrete examples. Consequently, the approach that will be followed is to introduce basic concepts and techniques by means of examples. Students are expected to understand that these examples are applications of basic principles that can be used in many other situations; and students should strive to understand the principles and imagine their full range of application, rather than merely memorizing the solution to specific problems.

1.2 THE TRANSPORTATION SYSTEM

1.2.1 Scope and Functional Organization

Transportation is one of the major functional systems of modern society. A *system,* in the sense intended here, is something that may be thought of as a whole consisting of parts or *components.* The description of a system involves identification of the system itself as distinct from its *environment* (that is, the rest of the world), identification of its components, and a description of how the components interact. In the case of the transportation system, the components may be conceived of in various ways. For instance, they may be thought of as entities that perform various *functions* (or tasks) in the provision of transportation, as in this section, or as being the different *modes* of transportation described in Section 1.3.

The transportation system is a *functional* system in the context of society as a whole because it provides a service—the movement of goods and people from place to place—that is essential to the functioning of the community as a whole. It is a *major* functional system because it is an essential feature in the economy and the personal lives of people everywhere, most especially in the developed nations. A highly developed transportation system makes possible the abundance and variety of goods and the high levels of personal mobility that are the hallmarks (for better or for worse) of a wealthy society. The economic scope of the transportation system is indicated by the fact that in 1998, transportation accounted for 11.2 percent of the gross domestic product and 19 percent of the average household expenditures in the United States. Its impact on the lives of individuals is revealed by the fact that in 1995 the average American made 1,568 local trips, and traveled over 27,500 km, 5,000 km of which was for long-distance travel (trips of more than 160 km). At the same time, the transportation system is a major source of resource consumption and environmental impact. Transportation accounts for almost two-thirds of the petroleum consumption in the United States and is a major contributor to environmental problems such as air pollution, noise, and destruction of natural habitats.

If viewed in functional terms, the transportation system includes the following components:

- *Physical facilities,* including streets, roads, and highways; railroads, airports, sea and river ports, pipelines, and canals.
- *Fleets* of vehicles, vessels, and aircraft.
- *Operating bases and facilities,* including vehicle maintenance facilities and office space.
- *Organizations.* These may be classified roughly as *facility-oriented organizations* and *operating organizations. Facility-oriented organizations* are primarily involved in planning, designing, constructing, maintaining, and operating fixed facilities. They include the United States Department of Transportation; state departments of transportation (or equivalent agencies); metropolitan planning organizations (organizations responsible for transportation planning at the level of the metropolitan region); local departments of public works, departments of transportation, and similar organizations; port authorities, and private land developers. *Operating organizations,* also known as *carriers,* are primarily concerned with operating fleets to provide transportation services. They include railroads, airlines, ship or barge lines, truck lines, transit operators, and private individuals who operate automobiles, motorcycles, and bicycles.
- *Operating strategies,* including vehicle routing, scheduling, and traffic control.

Figure 1.1 illustrates the ways in which the functional components of the commercial air transportation system are interrelated. Major *organizations* include the Federal Aviation Agency (FAA), the airlines, metropolitan planning organizations (MPOs), and airport authorities or other owners and operators of airports. Of these, the FAA, the MPOs, and the airport authorities are primarily concerned with providing facilities, and hence would be considered *facility-oriented organizations.* The FAA is responsible for design standards for air transportation facilities and provides some funding, the MPOs are involved in planning airport facilities at the local level, and the airport authorities actually own and construct the airports. The airlines are primarily concerned with operating commercial air service, and hence are *operating organizations.* In addition, the FAA provides safety regulation (including certification of aircraft and pilots) and air traffic control. The airlines own and operate *fleets* of aircraft

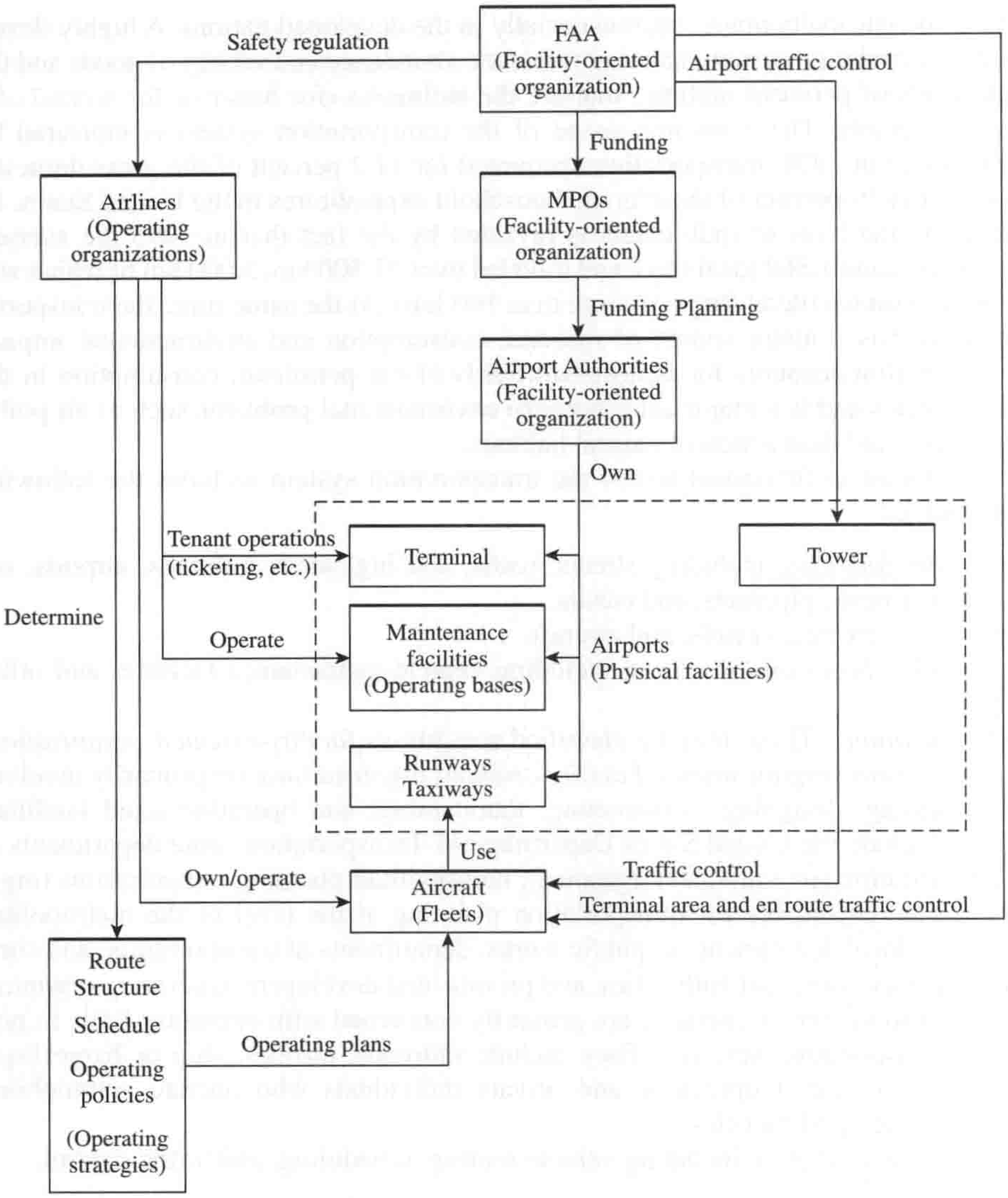


FIGURE 1.1
Interrelationship of functional components of a commercial air transportation system.

and determine *operating strategies,* including route structures (that is, which airport pairs are served directly and how the overall network is linked together), schedules, and various other operating policies. The major *physical facilities* are the airports, which consist of terminal buildings, maintenance facilities (hangers, etc.), runways and taxiways, and airport towers. The towers are part of the air traffic control system and are staffed by the FAA. Most activities in the terminals are carried out by tenant organizations, including the airlines, who use them for functions such as ticketing, baggage handling, and loading and unloading aircraft. The airlines also operate the maintenance facilities, which serve as their *operating bases*.

The provision of transportation service results when various organizations construct physical facilities and deploy fleets in accordance with their operating strategies. In order for the system to function effectively, the interactions of the various components must be understood. For instance, in order to design a highway effectively, it is necessary to know the characteristics of both the vehicles and the drivers that will use it, and to be aware of the traffic control strategies that will be employed. To give another example, to design an effective air traffic control system, it is necessary to understand the operating strategies of the airlines; the physical devices used to implement air traffic control; and the characteristics of aircraft, pilots, and airports.

1.2.2 Objectives and Constraints

From a historical point of view, there have been several motives for public and private investment in transportation systems. The most important of these have military, political, or economic bases.

Examples of transportation systems motivated primarily by military considerations include the road networks built by Romans and Napoleon, and the German autobahns built by Hitler in the 1930s. Another traditional motivation for establishing transportation systems is to "knit together" the inhabitants of a territory by providing mutual access and communication. This was, for instance, a major concern in providing the first intercontinental railroads in the United States and is still a concern in some of the developing countries of the world.

More commonly, transportation is thought of as an economic activity, and decisions about transportation systems are motivated by economic concerns. The most basic function of the transportation system is to create what in economic jargon is called *time* or *place utility* through the physical transfer of persons or goods from one location to another—in other words, the value of goods depends on where they are and when they are there. Basic economic resources and human population are scattered widely over the face of the earth; in order for a complex economy to exist, raw materials must be extracted, brought together in some form of manufacturing process, and then brought to market. Normally, all steps in this process will require some form of transportation.

This leads to two major conclusions about the economic role of transportation systems. First, an adequate transportation infrastructure is necessary for a high level of economic activity to exist. Second, most transportation is not something undertaken for its own sake (although some passenger travel may be purely for pleasure), but is what is referred to as a *secondary good* (in this case *secondary service* might be more appropriate), whose value depends on the value of the goods transported or the services performed by passengers at their destinations.