SI EDITION

Traffic & Highway Engineering

Nicholas J. Garber *Lester A. Hoel*

Fifth Edition

Traffic and Highway Engineering

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SI Edition prepared by

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CONVERSIONS BETWEEN U.S. CUSTOMARY UNITS AND SI UNITS

U.S. Customary unit		Times conversion factor		Equals SI unit	
		Accurate	Practical		
Acceleration (linear)					
foot per second squared	ft/s^2	0.3048*	0.305	meter per second squared	m/s^2
inch per second squared	$in./s^2$	0.0254*	0.0254	meter per second squared	m/s^2
Area					
circular mil	cmil	0.0005067	0.0005	square millimeter	mm^2
square foot	ft^2	0.09290304*	0.0929	square meter	m^2
square inch	$in.^2$	645.16*	645	square millimeter	mm^2
Density (mass)					
slug per cubic foot	$slug/ft^3$	515.379	515	kilogram per cubic meter	kg/m^3
Density (weight)					
pound per cubic foot	lb/ft^3	157.087	157	newton per cubic meter	N/m^3
pound per cubic inch	$lb/in.^3$	271.447	271	kilonewton per cubic meter	kN/m^3
Energy; work					
foot-pound	ft-lb	1.35582	1.36	joule (N·m)	J
inch-pound	in.-lb	0.112985	0.113	joule	J
kilowatt-hour	kWh	3.6*	3.6	megajoule	MJ
British thermal unit	Btu	1055.06	1055	joule	J
Force					
pound	lb	4.44822	4.45	newton ($kg·m/s^2$)	N
kip (1000 pounds)	k	4.44822	4.45	kilonewton	kN
Force per unit length					
pound per foot	lb/ft	14.5939	14.6	newton per meter	N/m
pound per inch	lb/in.	175.127	175	newton per meter	N/m
kip per foot	k/ft	14.5939	14.6	kilonewton per meter	kN/m
kip per inch	k/in.	175.127	175	kilonewton per meter	kN/m
Length					
foot	ft	0.3048*	0.305	meter	m
inch	in.	25.4*	25.4	millimeter	mm
mile	mi	1.609344*	1.61	kilometer	km
Mass					
slug	$lb-s^2/ft$	14.5939	14.6	kilogram	kg
Moment of a force; torque					
pound-foot	lb-ft	1.35582	1.36	newton meter	N·m
pound-inch	lb-in.	0.112985	0.113	newton meter	N·m
kip-foot	k-ft	1.35582	1.36	kilonewton meter	kN·m
kip-inch	k-in.	0.112985	0.113	kilonewton meter	kN·m

CONVERSIONS BETWEEN U.S. CUSTOMARY UNITS AND SI UNITS (Continued)

U.S. Customary unit		Times conversion factor		Equals SI unit	
		Accurate	Practical		
Moment of inertia (area)					
inch to fourth power	$in.^4$	416,231	416,000	millimeter to fourth power	mm^4
inch to fourth power	$in.^4$	0.416231×10^{-6}	0.416×10^{-6}	meter to fourth power	m^4
Moment of inertia (mass)					
slug foot squared	$slug\text{-}ft^2$	1.35582	1.36	kilogram meter squared	$kg{\cdot}m^2$
Power					
foot-pound per second	ft-lb/s	1.35582	1.36	watt (J/s or N·m/s)	W
foot-pound per minute	ft-lb/min	0.0225970	0.0226	watt	W
horsepower (550 ft-lb/s)	hp	745.701	746	watt	W
Pressure; stress					
pound per square foot	psf	47.8803	47.9	pascal (N/m^2)	Pa
pound per square inch	psi	6894.76	6890	pascal	Pa
kip per square foot	ksf	47.8803	47.9	kilopascal	kPa
kip per square inch	ksi	6.89476	6.89	megapascal	MPa
Section modulus					
inch to third power	$in.^3$	16,387.1	16,400	millimeter to third power	mm^3
inch to third power	$in.^3$	16.3871×10^{-6}	16.4×10^{-6}	meter to third power	m^3
Velocity (linear)					
foot per second	ft/s	0.3048*	0.305	meter per second	m/s
inch per second	in./s	0.0254*	0.0254	meter per second	m/s
mile per hour	mph	0.44704*	0.447	meter per second	m/s
mile per hour	mph	1.609344*	1.61	kilometer per hour	km/h
Volume					
cubic foot	ft^3	0.0283168	0.0283	cubic meter	m^3
cubic inch	$in.^3$	16.3871×10^{-6}	16.4×10^{-6}	cubic meter	m^3
cubic inch	$in.^3$	16.3871	16.4	cubic centimeter (cc)	cm^3
gallon (231 $in.^3$)	gal.	3.78541	3.79	liter	L
gallon (231 $in.^3$)	gal.	0.00378541	0.00379	cubic meter	m^3

*An asterisk denotes an exact conversion factor

Note: **To convert from SI units to USCS units, *divide* by the conversion factor**

Temperature Conversion Formulas

$$T(°C) = \frac{5}{9}[T(°F) - 32] = T(K) - 273.15$$

$$T(K) = \frac{5}{9}[T(°F) - 32] + 273.15 = T(°C) + 273.15$$

$$T(°F) = \frac{9}{5}T(°C) + 32 = \frac{9}{5}T(K) - 459.67$$

This book is dedicated to our wives,
Ada and Unni
and to our daughters,
Alison, Elaine, and Valerie
and
Julie, Lisa, and Sonja
With appreciation for the support, help, and encouragement that we received during the years that were devoted to writing this textbook.

Preface

PURPOSE IN WRITING AND REVISING THIS TEXTBOOK

The purpose of *Traffic and Highway Engineering,* Fifth Edition, is to serve as a resource textbook for students in engineering programs where courses in transportation, highway, or traffic engineering are offered. In most cases, these courses are usually taught in the third or fourth year but may also be covered at the graduate level.

Another purpose of this book is to serve as a reference for transportation engineers who are in practice or are preparing for a professional engineering examination.

The initial motivation for writing this textbook, which was first published in 1988, was many years of teaching highway and traffic engineering using textbooks that were primarily descriptive and lacked examples that illustrated the concepts presented. We also noted that none were comprehensive in dealing with all aspects of the subject and that some were written with transportation engineering titles but lacked specific focus. We also saw the need to demonstrate the challenges of the field and to explain the solid quantitative foundations that underlie the practice of transportation engineering. We wanted to select a mode that is ubiquitous and of worldwide application and one that students had contact with on a daily basis. Accordingly, we decided to focus on motor vehicle transportation and the highways that are an essential partner for this mode to exist. Our experience and instincts proved correct as the book became known and widely used.

The objectives of this textbook are: (1) To be a contemporary and complete text in highway and traffic engineering that can be used both at the undergraduate and at the graduate level for courses that emphasize highway and traffic engineering topics and (2) To serve as a reference for engineers in the highway and traffic field and as a study guide for use in preparing for the professional engineering license exam, review courses, and preparation for graduate comprehensive exams in transportation engineering.

The Fourth Edition of this textbook was published in 2009 and in the ensuing years there have been significant changes to the highway transportation literature that

mandated a major revision. Professors from transportation programs at twenty-one major universities reviewed various editions of the book and their comments and suggestions have been incorporated into the Fifth Edition.

The book is appropriate for a transportation curriculum or as an introductory transportation course because it provides an opportunity to present material that is not only useful to engineering students who may pursue careers in or related to transportation engineering, but is also interesting and challenging to those who intend to work in other areas. Furthermore, this book can serve as a reference for practicing transportation engineers and for use by students in graduate courses. Thus, the textbook provides a way for students to get into the area of transportation engineering, develop a feel for what it is about, and thereby experience the challenges of the profession

MAJOR ORGANIZING FEATURES OF THE TEXT

The scope of transportation engineering is broad and covers many modes and disciplines. Accordingly, several approaches have been used to introduce this topic to students.

One approach is to cover all transportation modes-air, highway, pipeline, public, rail, and water, presented in an overview course. This approach ensures comprehensive coverage but tends to be superficial with uneven coverage of some modes and can be lacking in depth.

A second approach is to present the subject of transportation by generic elements, such as vehicle and guideway characteristics, capacity analysis, planning, design, safety, human factors, administration, finance, system models, information technology, operations, and so forth. This approach is appealing because each of the modes is considered within a common context and the similarities between various modes are emphasized. Our textbook, *Transportation Infrastructure Engineering: A Multi-Modal Integration,* is based on this concept.

A third approach is to select a single mode and cover the relevant disciplines to provide a comprehensive treatment focused on that mode. Our book follows this approached by emphasizing the subject of traffic and highway engineering, which is a major area within civil engineering. It is a topic that appeals to students because they can relate directly to problems created by motor vehicle travel and is useful to professionals employed by federal, state and local agencies as well as private consulting and construction organizations.

Each chapter presents material that will help students understand the basis for transportation, its importance, and the extent to which transportation pervades our daily lives. The text also provides information about the basic areas in which transportation engineers work: traffic operations and management, planning, design, construction, and maintenance. Thus, this book has been categorized into five parts

- Part 1: Introduction to the profession, its history, systems, and organizations
- Part 2: Traffic Operations
- Part 3: Transportation Planning
- Part 4: Location, Geometrics, and Drainage
- Part 5: Materials and Pavements.

The topical division of the book organizes the material so that it may be used in one or more separate courses.

For a single course in transportation engineering, which is usually offered in the third year where the emphasis is on traffic and highway aspects, we recommend that material from Parts 1, 2, and 3 (Chapters 1-13) be covered.

For a course in highway engineering, where the emphasis is on highway location, design, materials, and pavements, we recommend that material from Parts 2, 4, and 5 (Chapters 3 and 14-21) be used.

A single introductory course in transportation facilities design could include Chapters 1, 2, 3, 14, 15, 16, 19, and 21.

The book also is appropriate for use in a two-semester sequence in transportation engineering in which traffic engineering and planning (Chapters 3-13) would be covered in the first course, and highway design (Chapters 14-21) would be covered in the second course.

The principal features of this textbook are:

- Comprehensive treatment of the subject.
- Extensive use of figures and tables.
- Numbering of subsections for easy reference.
- Completed examples in each chapter that illustrate the concepts presented.
- Representative homework problems at the end of each chapter
- References and additional readings at the end of each chapter

CHANGES TO THE NEW EDITION

In addition to responding to reviewer comments on the Fourth Edition and updating each chapter, substantial changes were made in several chapters due to the availability of new editions of the following professional publications:

- *A Policy on Geometric Design of Highways and Streets,* 6th Edition, 2011, American Association of State Highway and Transportation Officials.
- *HCM 2010 Highway Capacity Manual,* Transportation Research Board
- *Highway Safety Manual,* 1st edition, American Association of State Highway and Transportation Officials, Washington, D.C., 2010.
- *Manual on Uniform Traffic Control Devices (MUTCD),* 2009 Edition, U.S. Department of Transportation, Federal Highway Administration
- *Roadway Design Guide,* 4th Edition 2011, American Association of Highway and Transportation
- *Transportation Planning Handbook,* 3rd Edition, Institute of Transportation Engineers

New Learning Objectives have been added for each chapter, and the Problem Sets have been thoroughly revised and updated to match the new content in the book.

ANCILLARIES TO ACCOMPANY THE TEXT

An Instructor's Solutions Manual is provided with each problem completely solved. All figures and tables in the text are provided as PowerPoint slides. Also LectureBuilder PowerPoint slides are provided for all equations and examples so that instructors may easily and quickly build their own lectures. A digital version of the ISM and both sets of PPT slides are available for instructors through registration at www.cengagebrain.com

MINDTAP ONLINE COURSE AND READER

In addition to the print version, this textbook will also be available online through MindTap, a personalized learning program. Students who purchase the MindTap version will have access to the book's MindTap Reader and will be able to complete homework and

assessment material online, through their desktop, laptop, or iPad. If your class is using a Learning Management System (such as Blackboard, Moodle, or Angel) for tracking course content, assignments, and grading, you can seamlessly access the MindTap suite of content and assessments for this course.

In MindTap, instructors can:

- Personalize the Learning Path to match the course syllabus by rearranging content, hiding sections, or appending original material to the textbook content
- Connect a Learning Management System portal to the online course and Reader
- Customize online assessments and assignments
- Track student progress and comprehension with the Progress app
- Promote student engagement through interactivity and exercises

Additionally, students can listen to the text through ReadSpeaker, take notes and highlight content for easy reference, and check their understanding of the material.

ACKNOWLEDGMENTS

The success of our textbook has been a source of great satisfaction, because we believe that it has contributed to the better understanding of highway transportation in all its dimensions. We wish to thank our colleagues and their students for selecting this book for use in transportation courses taught in colleges and universities throughout the United States and abroad and for the many suggestions received during the preparation of all five editions.

The authors are indebted to many individuals who assisted in reviewing various chapters and drafts of the original manuscript and succeeding editions. We especially wish to thank the following individuals for their helpful comments and suggestions:

Maher Alghazzawi, Edward Beimborn, Rakim Benekohal, David Boyce, Stephen Brich, Chase Buchannan, Bernard Carlson, Christian Davis, Michael Demetsky, Brian Diefenderfer, Stacey Diefenderfer, Conrad Dudek, Lily Elefteriadou, Thomas Freeman, Ron Gallagher, Per Garder, Alan Gesford, Richard Gunther, Jiwan Gupta, Jerome Hall, Kathleen Hancock, Marvin Hilton, Jotin Khisty, Lydia Kostyniak, Michael Kyte, Feng-Bor Lin, Qun Liu, Yuan Lu, Tom Maze, Catherine McGhee, Kenneth McGhee, Richard McGinnis, Carl Monismith, Thomas Nelson, Ken O'Connell, Jack Page, Emelinda Parentela, Brian Park, Mofreh Saleh, Mitsuru Saito, Anthony Saka, Gerald Seeley, Robert Smith, Hamid Soleymani, James Stoner, Ed Sullivan, James Taylor, Egons Tons, Erol Tutumluer, Joseph Vidunas, Joseph Wattleworth, Peter Weiss, W James Wilde, F. Andrew Wolfe, Hugh Woo, Lewis Woodsen, Robert Wortman, Shaw Yu, Yihua Ziong and Michael Zmuda.

In the preparation of the Fifth Edition and earlier editions as well, we received reviews, comments and suggestions on individual chapters from several of our colleagues who have special expertise in the topics covered. We are most grateful for their willingness to devote this effort and for their help in validating and augmenting these chapters. They are: Richard Boaz, Michael Fontaine, Arkopal Goswami, Winston Lung, John Miller, Adel Sadek and Rod Turochy.

We also received a significant number of helpful comments from the reviewers of the fourth edition. We wish to thank them for their insightful comments and helpful suggestions many of which have been incorporated into this book. They are: Montasir Abbas, Virginia Tech, Mashrur Chowdhury, Clemson University, Shauna Hallmark, Iowa State University, David S. Hurwitz, Oregon State University, Wesley Marshall, University of

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The many organizations cited herein that permitted us to include material from their publications deserve special mention because, without their support, our book would not have been a reality. We also wish to thank our editor Hilda Gowans, for her help and guidance in the preparation of this edition, and Rose Kernan of RPK Editorial Services for her Production skills.

Nicholas J. Garber
Lester A. Hoel

Preface to the SI Edition

This edition of ***Traffic and Highway Engineering*** has been adapted to incorporate the International System of Units (*Le Systeme Internationale d'Unites* or SI) throughout the book, wherever possible.

LE SYSTEME INTERNATIONAL D'UNITES

The United State Customary System (USCS) of units uses FPS (foot-pound-second) units (also called English or Imperial units). SI units are primarily the units of the MKS (meter-kilogram-second) system. However, CGS (centimeter-gram-second) units are often accepted as SI units, especially in textbooks.

USING SI UNITS IN THIS BOOK

In this book, we have used both MKS and CGS units. USCS units or FPS units used in the US Edition of the book have been converted to SI units throughout the text and problems, wherever possible. However, in the case of data sourced from handbooks, government standards, and product manuals, it is not only extremely difficult to convert all values to SI, it also encroaches on the intellectual property of the source. Some data in figures, tables, example, and references, therefore, remain in FPS units.

To solve problems that require the use of sourced data, the sourced values can be converted from FPS units to SI units before they are to be used in a calculation. To obtain standardized quantities and manufacturers' data in SI units, or country-specific codes and regulations, readers may need to contact the appropriate government agencies or authorities in their countries/regions.

INSTRUCTOR RESOURCES

A Printed Instructor's Solutions Manual in SI units is available on request. A digital version of the ISM, and PowerPoint slides of both figures, tables and images and examples and equations from the SI text are available for instructors registering on the book website.

Feedback from users of this SI Edition will be greatly appreciated and will help us improve subsequent editions.

The Publishers

About the Authors

Nicholas J. Garber is the Henry L. Kinnier Emeritus Professor of Civil Engineering at the University of Virginia and served as chairman of the Department from 1996 to 2002. Before joining the University of Virginia, Dr. Garber was Professor of Civil Engineering in the faculty of Engineering of the University of Sierra Leone, where he was also the Dean of the faculty of Engineering. He taught at the State University of New York at Buffalo, where he played an important role in the development of the graduate program in Transportation Engineering. Dr. Garber worked as a Design Engineer for consulting engineering firms in London between 1961 and 1964 and as an Area Engineer and Assistant Resident Engineer in Sierra Leone between 1964 and 1967.

Dr. Garber received the degree of Bachelor of Science (B.S.) in Civil Engineering from the University of London and the Masters (M.S.) and Doctoral (Ph.D.) degrees from Carnegie-Mellon University.

Dr. Garber's research is in the areas of Traffic Operations and Highway Safety. He has been the principal investigator for many federal-, state-, and private-agency-sponsored research projects. He is the author of over 120 refereed publications and reports. He is a co-author of the textbook *Transportation Infrastructure Engineering: A Multi-Modal Integration,* Thomson/Nelson, 2007.

Dr. Garber served as a member of the Executive Committee of the Transportation Research Board (TRB) and served for many years as chair of the TRB Committee on Traffic Safety in Maintenance and Construction Operations, currently the Committee on Work Zone Traffic Control. He has served as a member of several TRB Policy Studies on speed management, size and weight of large trucks, transportation of hazardous materials, and research priorities and coordination in highway infrastructure and operations safety. He also served as a member of the TRB Oversight Committee for the Strategic Highway Research Program II (SHRP II). Dr. Garber also has served as a member of several other national committees of the American Society of Civil Engineers (ASCE) and The Institute of Transportation Engineers (ITE). He also served as a member of the Editorial Board of the ASCE *Journal of Transportation Engineering.*

Dr. Garber is a member of the National Academy of Engineering. He is a recipient of many awards, including the TRB D. Grant Mickle Award, the ITE Edmund R. Ricker Transportation Safety Award, and the American Roads and Transportation Builders (ARTBA) S. S. Steinberg Outstanding Educator Award. He is listed in *Who's Who* in Science and Engineering and *Who's Who* in the world.

Dr. Garber is a Distinguished member of the American Society of Civil Engineers, a Fellow of the Institute of Transportation Engineers, a Fellow of the Institution of Civil

Engineers of the United Kingdom, a member of the American Society for Engineering Education, and a member of Chi Epsilon.

Lester A. Hoel is the L. A. Lacy Distinguished Professor of Engineering Emeritus, at the University of Virginia. He held the Hamilton Professorship in Civil Engineering from 1974 to 1999. From 1974 to 1989 he was Chairman of the Department of Civil Engineering and from 2002 to 2009 was Director of the Center for Transportation Studies. Previously, he was Professor of Civil Engineering and Associate Director, Transportation Research Institute at Carnegie-Mellon University. He has been a registered professional engineer in California, Pennsylvania, and Virginia. His degrees are: BCE from the City College of New York, MCE from the Polytechnic Institute of New York, and the Doctorate in Engineering from the University of California at Berkeley.

Dr. Hoel's area of expertise is the management, planning, and design of surface transportation infrastructure with emphasis on highway and transit systems. He is an author of over 150 publications and was co-editor (with G.E. Gray) of the textbook *Public Transportation,* and co-author (with N.J. Garber and A.W. Sadek) of the textbook *Transportation Infrastructure Engineering: A Multi-Modal* Integration and Lead Editor of the Textbook, Intermodal Transportation: Moving Freight in A Global Economy.

Dr. Hoel is a member of the National Academy of Engineering, a Distinguished Member of the American Society of Civil Engineers, a Fellow of the Institute of Transportation Engineers, a member of the American Society for Engineering Education and the Norwegian Academy of Technical Sciences. As a student, he was elected to the national honor societies Chi Epsilon, Tau Beta Pi, and Sigma Xi. He was a member of the Executive Committee of the Transportation Research Board (TRB) from 1981 to 1989 and from 1995 to 2004 and served as its Chairman in 1986. He was an ex-officio member of the National Research Council (NRC) Governing Board of the National Academies and the Transportation Research Board Division Chairman for NRC Oversight from 1995 to 2004. In that capacity, he was responsible for oversight of the NRC review process for all TRB policy studies produced during that period. He served as the Chairman of two congressionally mandated policy studies. He also has served on TRB technical committees and NCHRP/TCRP panels. He was a member of the TRB Transit Research Analysis Committee, whose purpose is to advise the Federal Transit Administration on its research program, and was a member of the National Research Council Report Review Committee, in which he oversees the review process for policy studies prepared by the National Research Council of the National Academies.

He is a recipient of the American Society of Civil Engineers' Huber Research Prize, the Transportation Research Board Pyke Johnson Award, the Highway Users Federation Stanley Gustafson Leadership Award, the TRB W.N. Carey, Jr. Distinguished Service Award, the ASCE Frank Masters Transportation Engineering Award, the ASCE James Laurie Prize, the Virginia Society of Professional Engineers Service Award, the Institute of Transportation Engineers' Wilbur Smith Distinguished Educator Award, the American Road and Transportation Builders S. S. Steinberg Outstanding Educator Award, and the Council of University Transportation Centers Distinguished Professor Award. He is listed in *Who's Who in America* and *Who's Who in the World.* He resides in Saint Helena, California.

Dr. Hoel has served as president of the Council of University Transportation Centers and on the ASCE accreditation board for engineering and technology. He was chairman of the Board of Regents of the Eno Transportation Foundation Leadership Center and served on its Board of Advisors. He is Senior Editor of the *Journal of Transportation of the Institute of Transportation Engineers* and has served on the editorial boards of transportation journals, including *Transportation Research, Journal of Advanced Transportation, Journal of Socio-Economic Planning Sciences, Journal of Specialized Transportation, Computer-Aided Civil and Infrastructure Engineering,* and *Urban Resources.*

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