Dušan Teodorović and Milan Janić

TRANSPORTATION ENGINEERING

Theory, Practice and Modeling

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Transportation Engineering
Theory, Practice, and Modeling

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Transportation Engineering

Theory, Practice, and Modeling

To my wife, children, and grandchildren
Dušan Teodorović
To my wife and son
Milan Janić

About the Authors

Dr. Dušan Teodorović is Professor at the Faculty of Transport and Traffic Engineering, University of Belgrade, Serbia. He has been elected member of the *Serbian Academy of Sciences and Arts and the European Academy of Sciences and Arts*. Dr. Teodorović has been Honorable Senator of the University of Ljubljana, Slovenia since 2011. He was Vice Rector of the University of Belgrade. He has worldwide academic experience with formal appointments at Virginia Tech, United States. Professor Teodorović was visiting professor and visiting scholar at many universities in Europe, the United States, and Asia. Since 2006, he has been Professor Emeritus of Virginia Tech, United States. Dr. Teodorović has authored or coauthored numerous research publications in peer-reviewed international journals, book chapters, and conference proceedings. He has published the books *Airline Operations Research* and *Traffic Control and Transportation Planning*; *A Fuzzy Sets and Neural Networks Approach*. Professor Teodorović is the Editor of the *Routledge Handbook of Transportation*. His primary research interests are in operations research and computational intelligence applications in transportation engineering.

Dr. Milan Janić is a Senior Researcher at the Faculty of Civil Engineering and Geosciences (Department of Transport & Planning) of Delft University of Technology, The Netherlands. He is also Research Professor at the University of Belgrade, Serbia. Previously, he was a Leader of the Research Program and Senior Researcher at Manchester Metropolitan University, Loughborough University, and the Institute of Transport of the Slovenian Railways. Dr. Janić has been involved in many research and planning projects on both a national and international scale for almost 30 years. He has also published numerous papers in peer-reviewed journals. In addition to contributing to many edited books, he has published the following books: *Advanced Transport Systems*: *Analysis, Modelling, and Evaluation of Performances*, *Greening Airports*: *Advanced Technology and Operations*, *Airport Analysis, Planning and Design*: *Demand, Capacity and Congestion*, *The Sustainability of Air Transportation*: *A Quantitative Analysis and Assessment*, and *Air Transport System Analysis and Modelling*: *Capacity, Quality of Services and Economics*.

Foreword

It is with great pleasure that I am writing this foreword to *Transportation Engineering: Multi-Modal Transportation Networks, Theory, Practice and Modeling* by Dušan Teodorović and Milan Janić. I have known the two authors for a long time—close to 40 years by now. Both have enjoyed highly productive and distinguished careers at major universities, not only in their native lands of Serbia and Slovenia, but also in the United States, the United Kingdom, and the Netherlands. Their experience as educators and expertise as researchers are reflected in this valuable book. They have witnessed first-hand and have contributed themselves to the development and evolution of the transportation field during their professional lifetimes.

Since 2001, I have been co-teaching with various colleagues at MIT a course called "Transportation Systems Analysis: Supply and Performance," which introduces fundamental quantitative models and their application to first-year graduate students in our Transportation Program. The course attempts to provide an overview that spans all modes of transport and cuts across the disciplines of traffic engineering, transportation science, transportation economics, and operations research. While developing the course and in the years that have followed, I have been struck by the absence of a textbook that covers this material in an integrated fashion and at an adequate and consistent mathematical level. The available books tend to be focused primarily on a single mode and, usually, on only specific aspects of the mode, such as urban traffic, highway traffic, public transit, or air traffic management. Moreover, their mathematical level is all too often either elementary—so that the reader cannot appreciate the power of the existing analytical tools—or uneven, alternating between very basic and too advanced. As a result, my colleagues and I have relied on our own course notes, supplemented by selected readings of landmark papers or book chapters.

This new book therefore constitutes a most welcome addition to the transportation literature, as it addresses the central issue I identified in the previous paragraph—lack of integration across transportation modes, disciplines, and methodological approaches. Taking advantage of their complementary areas of expertise, the authors have managed to write a textbook that truly spans all modes. Having devoted a large part of my own research to air transportation, I am particularly pleased to see that airports and air traffic have been given their "fair share" of attention. Air transport has become the dominant mode of long-haul passenger transportation on a global scale and it is essential that transportation professionals and students become familiar with some of the most important models that describe air traffic movement and processes. An added benefit, in this respect, is that air traffic models typically treat vehicles (the airplanes) as discrete objects. Thus, these models expose the reader to a set of methodologies, such as integer programming, that focus on individual, "atomistic" entities. Air traffic models therefore offer a perspective different from the continuous flow models that are generally used to study road and highway traffic.

Another welcome feature of the book is that it does not draw a priori any dividing lines between modes of transport, but is structured around a set of major common themes, such as "traffic flow theory," "capacity and level of service," "traffic control," and "transportation planning" and "environmental impacts." This makes it possible to integrate the material better and facilitates the highlighting of the similarities and differences among the methodologies and modeling approaches used for each mode.

The major common themes are themselves arranged in a logical sequence, so that the reader can progress from an understanding of the "physics" of the *individual elements* of transportation networks—e.g., flows in a road segment, traffic light settings at an isolated intersection, capacity of a runway—to studying the performance of the *networks* as a whole. In this respect, the authors take great pains to emphasize the importance of considering how the pieces fit together into *systems*. The book is definitely "network-centric" and discusses the design of transportation networks, including multi-modal ones, their optimization at the planning level and the operations level, their control in the long run ("demand management") and in real time, and the economics and environmental impacts of the different modes.

The centerpiece of the book lies, I believe, in the presentation of fundamental *models*, i.e., mathematical abstractions and constructs that are used to represent essential features of actual transportation systems. In the transportation field, we are fortunate at this point to have an abundance of such models. As the authors make clear, the appropriate model to use depends on the questions that one wishes to answer. Any given transportation system can be modeled in several different ways, according to the question at hand. One can have models that are: deterministic or probabilistic/stochastic, depending on the extent to which one wishes to account for uncertainty; static or dynamic over time; macroscopic or microscopic depending on the level of detail one wishes to capture; and analytically based or simulation-based depending on the methodology used—with numerous additional subcategories when it comes to analytical models. The reader will find all these types of models in different parts of this book.

During the second half of the 20th century, studies in transportation engineering and transportation science made huge strides toward developing a knowledge base of methodologies and models for studying, quantifying, and predicting the behavior of transportation systems. As a result, we now have a much better understanding of how to plan, design, manage, and operate transportation networks. The first two decades of the 21st century have added to this arsenal of tools the ability to collect and process, often in real time, enormous amounts of data about the state of transportation networks. However, to take full advantage of this newfound capability, one must be familiar with this knowledge base of methodologies and models. This book, I believe, makes an important contribution toward providing this crucial background for students and professionals alike, including a much-needed historical perspective. I am quite certain that the readers will agree with this assessment.

Amedeo R. Odoni

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March 2016

When once you have tasted flight, you will forever walk the earth with your eyes turned skyward, for there you have been, and there you will always long to return.
Leonardo da Vinci

Preface

Joint writing a book is not a simple task. It is similar to playing the piano with four hands. We met, for the first time, in 1974, at the University of Belgrade, Serbia, when the first author was a teaching assistant, and another undergraduate student. We had a different professional careers in the countries in which we lived. During occasional meetings, we have been strengthened in our belief that we have similar views on important transportation engineering issues. During our professional careers, we were professors, and visiting scholars at the universities in Europe, the United States, and Asia.

For many years, we have been studying fascinating traffic phenomena. We thought, at one point, that it was time to write our book about transportation engineering fundamentals. We strongly believe that each new book in a certain area opens up new views to the reader. We have tried in this book to touch on urban and road transportation, air transportation, railways, inland water transportation, and logistics. This book begins with the story about the earliest discovered paths, made by animals, and adapted by humans, found near *Jericho*, and arrives at the issues related to the autonomous car (self-driving car, driverless car, robotic car) that are now around us. The following is a brief description of the book chapters.

Chapter 2 introduces the reader to the field of transportation engineering. The chapter covers the history of transportation, offers basic definitions and classification of the transportation systems, and describes the most important transportation systems issues: planning, control, congestion, safety, and environment protection.

Chapter 3 deals with traffic and transportation analysis techniques. This chapter covers object motion and time-space diagrams, transportation networks basics, mathematical programming applications in traffic and transportation, the relationship between the probability theory and traffic phenomena, queueing theory, simulation techniques, and computational intelligence techniques.

Chapter 4 covers traffic flow theory basics. The chapter describes measurements of the basic flow variables, speed-density relationship, flow-density relationship, speed-flow relationship, fundamental diagram of traffic flow, micro-simulation traffic models, car following models, and network flow diagram.

Chapter 5 involves capacity and level of service of different transportation modes (highways, urban transit systems, urban freight transport systems, rail interurban transport systems, inland waterway freight/cargo transport systems, maritime freight/cargo transport systems, air transport systems, and air traffic control systems).

Chapter 6 describes traffic control techniques related to the road, rail, and air traffic control systems. The chapter covers a variety of traffic control measures, methods, and strategies that should be implemented in order to use the existing transportation infrastructure optimally.

Chapter 7 deals with public transportation systems. The chapter describes public transportation basics, public transit network types, public transit network design, vehicle scheduling in public transit, public transit planning process, demand-responsive transportation systems, and air transportation basics.

Chapter 8 covers transportation planning methods and techniques. The chapter describes transportation demand modeling, the four step planning procedure (trip generation, trip distribution, modal split, and route choice), Wardrop's principles and traffic networks equilibrium conditions, the Braess paradox and transportation capacity expansions, dynamic traffic assignment problems, transportation demand analysis based on discrete choice models, and activity-based travel demand models.

Chapter 9 describes relationship between logistic systems and transportation. The chapter elaborates principles and techniques of city logistics (distribution of goods from warehouses to shops and supermarkets, emergency services, waste collection, street cleaning and sweeping in one city). This chapter covers basics of location theory, and vehicle routing and scheduling techniques.

Chapter 10 involves basic transportation economics concepts (fixed and variable costs in transportation, economies of scale, relationship between demand and supply, infrastructure costs, etc.). Transportation economics concepts and methods are described for every transportation mode.

Chapter 11 deals with the impacts of transportation systems on society and the environment. There is continuous construction, expansion, and maintenance of the transportation systems in the world. Different transportation systems have enormous impacts on energy use, air, water and soil quality, noise level, land use, and nature conservation. Chapter 11 analyzes the direct impacts of transportation systems on the society and environment, and their costs/externalities. The major impacts on the society taken into account include congestion, noise, and traffic incidents/accidents (ie, safety). The main impacts on the environment considered involve the energy/fuel consumption and related emissions of GHG (Green House Gases), land use, and waste. Considering the importance that transportation has on human society and environment, Chapter 11 contains material that exceeds the boundaries of university textbooks. The material given in Chapter 11 is related to the ideas of changing regulation and standards in the transportation sector, behavioral change of the participants in transportation (more pedestrian and bicycle transportation), as well as appearance of the new vehicle types and new fuel technologies.

The book is planned for use by students at the senior undergraduate level, and at the graduate level, interested in transportation engineering, civil engineering, city and regional planning, urban geography, economics, public administration, and management science. We believe that the book could also be useful for self-study, as well as for professionals working in the area of transportation.

The journey of writing this book was more than exciting. We tried, all the time, to find a balance between the explanation of the traffic phenomena, mathematical rigor, and real-world examples. We believe that the new generations of traffic engineers and planners will be more capable of reducing energy consumption and emissions from the transportation systems. We strongly believe that the future of transportation is the "green transportation." It is, in a way, the basic message of our book. The main motivation for writing this book is the desire to send this message to many young people in the world who are beginning to deal with complex transportation engineering problems.

Dušan Teodorović
Milan Janić

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