Simulation Foundations, Methods and Applications

Dietmar P.F. Möller

Introduction to Transportation Analysis, Modeling and Simulation

Computational Foundations and Multimodal Applications

Springer

Simulation Foundations, Methods and Applications

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Dietmar P.F. Möller
With a Chapter Contribution together
with Prof. Dr. Bernard Schroer

Introduction to Transportation Analysis, Modeling and Simulation

Computational Foundations and Multimodal Applications

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Foreword

Modeling and simulation are important to receive research results without the cost and time spent creating working prototypes. Thus, it seems to me a good reason for the NSF Blue Ribbon Panel to clearly constitute the advancement in modeling and simulation as critical for resolving multitude of scientific and technological problems in health, security, and technological competitiveness within the globalized world. Therefore, in our globalized world a variety of Simulation Centers have been established with an economic and scientific focus on modeling and simulation methodology and sophisticated tools and software. One of these centers is the recently founded Simulation Science Center Clausthal-Göttingen in Germany, a common interdisciplinary research facility in simulation science of Clausthal University of Technology and University of Göttingen. The core research areas are advanced methodologies in mathematical modeling and simulation techniques, and their application in real-world problems. The actual research areas the center is dealing with are: simulation and optimization of networks, computational materials science simulation, and distributed simulation, which will be expanded step by step by new hired staff. The available book, written by a member of the Simulation Science Center at Clausthal University of Technoöogy, is a showcase of creative ideas of ongoing research work at the Simulation Science Center with the focus "Introduction into Transportation Analysis, Modeling and Simulation" which belongs to the simulation and optimization of networks group of the center. The book shows how to analyze the complex transportation systems accurately and under varying operation conditions and/or scenarios to predict its behavior for engineering and planning purposes to provide adequate academic answers for today's emerging transportation technology management questions. The chapters are well written showing academic rigor and professionalism of the author. Therefore, the book can be stated as an important reading for new researchers entering this field of transportation research. It offers new perspectives and documents important progress in transportation analysis, modeling and simulation.

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Thomas Hanschke

Preface

The goal of this book is to provide a comprehensive, in-depth, and state-of-the-art summary of the important aspects of transportation analysis and modeling and simulation. The term modeling and simulation refers to computer simulation, with an emphasis on modeling real transportation systems and executing the models. A recent White House report identified computer modeling and simulation as one of the key enabling technologies of the twenty-first century. Its application is universal. For this reason, the book strives to motivate interest in transportation analysis and modeling and simulation as well as to present these topics in a technically correct yet clear manner. This required making some carefully considered choices in selecting the material for this book.

First the fundamentals of modeling are described, as they represent the largest portion of transportation analysis. In addition, the mathematical background describing real transportation systems is introduced on a basic level as well as on a more advanced one; and its correspondence to the respective modeling methodologies is described. Secondly, the most interesting simulation systems are presented at the language and logic level, and their use is described in several case studies. However, a textbook cannot describe all of the available simulation systems in detail. For this reason, the reader is referred to specific supplemental material, such as textbooks, reference guides, user manuals, etc., as well as Internet-based information which addresses several simulation languages. Thirdly, a variety of actual applications are presented which have been conducted during a long period of collaboration with Prof. Bernard Schroer, Ph.D., University of Alabama in Huntsville (UAH), USA.

This book was developed for use by senior and graduate level students in applied mathematics, operations research, computer science, and engineering and business informatics and to serve as the primary text for a course on Transportation Analysis, Modeling and Simulation, held annually at Clausthal University of Technology.

The material in the book can be difficult to comprehend if the reader is new to such an approach. This is also due to the fact that transportation analysis/modeling and simulation is a multidisciplinary domain, founded in computer science, engineering, mathematics, operations research, etc. The material may not be read and comprehended either quickly or easily. Therefore, specific case studies have been embedded with related topics to help the reader master the material.

It is assumed that the reader has some knowledge of basic calculus-based probability and statistics and some experience with computing.

The book can be used as the primary text in a course in various ways. It contains more material than can be covered in detail in a quarter-long (30-h) or semester-long (45-h) course. Instructors may elect to choose their own topics and add their own case studies. The book can also be used for self-study; as a reference for graduate engineers, scientists, and computer scientists for training on the job or in graduate school; and as a reference for transportation analysis and modeling and simulation practitioners and researchers.

For instructors who have adopted the book for use in a course, a variety of teaching support materials are available for download from http://www.springer.com/978-1-4471-5636-9. These include a comprehensive set of Microsoft PowerPoint slides to be used for lectures and all video-recorded classes.

The book is divided into six chapters which can be read independently or consecutively.

Chapter 1, Computational Foundation in Transportation and Transportation Systems Modeling, covers the classification of models used for multimodal transportation systems and introduces transportation and transportation systems for the movement of passengers or freight and how to analyze their behavior. A transportation case study planning a seagate harbor expansion by a dry port is introduced.

Chapter 2, Transportation Models, contains a brief overview of the use of models in the transportation sector, the several types of models used in transportation planning, the specific evaluation methods used, queuing theory to predict queuing lengths and waiting times, and the methodological background of congestion, graph theory, and bottlenecks. Finally a ProModel-based case study for a four-arm road intersection is introduced.

Chapter 3, Traffic Assignments to Transportation Networks, introduces traffic assignment to uncongested and congested road networks; the equilibrium assignment, which can be expressed by so-called fixed point models where origin-to-destination demands are fixed, representing systems of nonlinear equations or variational inequalities; and the multiclass assignment based on the assumption that travel demand can be allocated as a number of distinct classes which share behavioral characteristics. The case study involves a diverging diamond interchange (DDI), an interchange in which the two directions of traffic on a nonfreeway road cross to the opposite side on both sides of a freeway overpass (or underpass).

Chapter 4, Integration Framework and Empirical Evaluation, is an introduction to computer simulation integration platforms and their use in the transportation systems sector. It provides, in addition to an overview of the framework architectures, an introduction into ontology-based modeling and its integration into transportation; the workflow-based application integration in transportation; and detailed case studies for a marine terminal traffic network simulation, an airport operation simulation, a highway ramp control simulation, and vehicle tracking using the Internet of Things paradigm.

Chapter 5, Simulation Tools in Transportation, gives an overview of transportation simulation tools including continuous systems simulation tools, such as block-oriented and equation-oriented simulation tools, and discrete-event simulation tools. Some of the many available simulation software packages are described with a focus on those used for the case studies in this book. Finally, a ProModel-based case study for a maritime transportation analysis is introduced.

Chapter 6, Transportation Use Cases, introduces, from a general perspective, critical issues in the design, development, and use of simulation models of transportation systems. Case studies in Chap. 6 include real transportation projects such as the McDuffie Coal Terminal at the Alabama State Docks in Mobile, the Container Terminal at the Port of Mobile and its intermodal container handling facilities, and an analysis of the operation of an intermodal terminal center before the design of any planned expansion is finalized. A case study on port security inspection is included due to the increased security requirements for the operation of seaports. The objective of the simulation is to evaluate the impact of various inspection protocols on the operation of the container terminal at the Port of Mobile. The objective of the Interstate Traffic Congestion case study is to determine the congestion point as traffic increases and to evaluate adding additional lanes at congestion points. Tunnels are an important solution for the transportation infrastructure, e.g., for crossing a river such as the Mobile River in downtown Mobile, Alabama. Besides the maritime transportation sector, the aviation domain also calls for innovative solutions to optimize their operational needs. Thus the first of the two aviation case studies focuses on passenger and freight operations at Hamburg Airport to estimate the maximum numbers of passengers and freight that can be dispatched to identify potential opportunities in process optimization with regard to the expected growth in passenger and freight numbers. In the second aviation case study, an Italian airport transportation operation conducted by an international student team is introduced to demonstrate how an international group of students can be motivated to conduct an innovative, advanced project in a very complex area of concentration in modeling and simulation.

Besides the methodological and technical content, all chapters of the book contain comprehensive questions from the chapter-specific area to help students determine if they have gained the required knowledge, identifying possible knowledge gaps and conquering them. Moreover, all chapters include references and suggestions for further reading.

I would like to express my special thanks to Prof. Bernard Schroer, Ph.D., University of Alabama in Huntsville, USA, for our long collaboration on research-oriented projects in transportation analysis and modeling and simulation; to Prof. Jerry Hudgins, Ph.D., University of Nebraska-Lincoln, USA, for his great support in working at the University of Nebraska-Lincoln on computer modeling and simulation; to Prof. Dr. Thomas Hanschke, Chairman of the Simulation Science Center at Clausthal-Göttingen (SWZ), Germany, for electing me as a member of the Simulation Science Center Clausthal-Göttingen; to Prof. Louis G. Birta, Ph.D., University of Ottawa, Canada, for inviting me to contribute this book to the series, *Simulation Foundations, Methods and Applications*, he is editing; to Patricia Worster, University of Nebraska-Lincoln, for her excellent assistance in proofreading; and to Simon Rees, Springer Publ., for his help with the organizational procedures between the publishing house and the author.

For developing sample models and exercise problems and for executing prototype simulation models which appear in the book, I would like to thank my graduate students at Clausthal University of Technology (TUC), Germany, and University of Hamburg (UHH), Germany.

Finally, I would like to deeply thank my wife, Angelika, for her encouragement, patience, and understanding during the writing of this book.

This book is dedicated to my parents, Wilhelm and Hildegard Möller, whose hard work and belief in me made my dreams a reality.

Clausthal-Zellerfeld, Germany　　　　Dietmar P.F. Möller

Contents

Computational Foundation in Transportation and Transportation Systems Modeling

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This chapter begins with a brief overview of transportation systems. Section 1.1 covers the classification of models used for multimodal transportation systems. Section 1.2 introduces transportation and transportation systems for the movement of passengers or freight. Thereafter, Sect. 1.3 introduces model building in transportation by describing the main types of models and their representation through mathematical notation. Section 1.4 covers the important topic of modeling formalism in transportation systems to analyze their behavior and/or composite structure. Simulation models in the transportation sector are approximate imitations of the real-world phenomena which never exactly imitate the real-world phenomena. Therefore, models have to be verified and validated to the degree required for the models' intended purpose or application which is introduced in Sect. 1.5. Section 1.6 describes a transportation case study for planning a Seagate harbor expansion by a dry port. Section 1.7 contains comprehensive questions from the transportation system area, and a final section includes references and suggestions for further reading.

1.1 Introduction

The transportation systems sector—comprised of all modes of transportation, each with different operational structures and approaches to security—is a vast, open, interdependent network moving millions of tons of freight and millions of passengers. Every day, the transportation systems network connects cities, manufacturers, and retailers by moving large volumes of freight and passengers through a complex network of roads and highways, railways and train stations, sea ports and dry ports, and airports and hubs (Sammon and Caverly 2007). Thus, the transportation systems sector is the most important component of any modern economy's infrastructure in the globalized world. It is also a core component of daily human life with all of its essential interdependencies, such as demands for

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travel within a given area and freight transportation in metropolitan areas, which require a comprehensive framework in which to integrate all aspects of the target system. The transportation systems sector also has significant interdependencies with other important infrastructure sectors (e.g., the energy sector). Transportation and energy are directly dependent on each other for the movement of vast quantities of fuel to a broad range of customers, thereby supplying fuel for all types of transportation. Moreover, cross-sector interdependencies and supply chain implications are among the various sectors and modalities in transportation that must be considered (Sammon and Caverly 2007).

The transportation system sector consists of physical and organizational objects interacting with each other to enable intelligent transportation. These objects include information and communication technology (ICT), the required infrastructure, vehicles and drivers, interfaces for the multiple modes of transportation, and more (Torin 2007). Advanced transportation systems are essential to the provision of innovative services via multiple modes of transportation interacting and affecting each other in a complex manner, which cannot be captured by a single existing model of transportation systems traffic and mobility management.

Transportation systems models enable transportation managers to run their daily businesses safely and more effectively through a smarter use of transportation networks. But the transportation systems sector in today's open, interdependent network encompassing urban and metropolitan areas requires optimization of all operating conditions. This can be successfully achieved if the interactions between transportation modes, the economy, land use, and the impact on natural resources are included in transportation systems planning strategies.

The proposed future of multimodal transportation systems cannot be measured through planning alone. Mathematical models of transportation systems and mobility management, incorporating both real and hypothetical scenarios, should be embedded in transportation systems analysis, including the evaluation and/or design of the traffic flows, determining the most reliable mode of operation of physical (e.g., a new road) and organizational (e.g., a new destination) objects, and the interaction between the objects and their impact on the environment. These mathematical models are fundamental to the analysis, planning, and evaluation of small-, medium-, and large-scale multimodal transportation systems (Cascetta 2009). The success of model-based scenario analysis can be evaluated by the resulting forecast or prediction of the transportation system response. An ideal design or operational methodology for a transportation system can be achieved using model-based analysis in conjunction with backcasting or backtracking. Thus, modeling and simulation can play a central role in planning, developing, and evaluating multimodal transportation systems, improving transportation efficiency, and keeping pace with the rising demands for optimizing multimodal transportation systems.

Various simulation models capture different aspects of a transportation system enabling evaluation of complex simulation scenarios where each one represents a certain aspect of a transportation system or a certain operational strategy. Multimodal transportation system models can be classified as:

- *Supply models*: representing the multimodal transportation systems sector services used to travel between different operating points within a given area
- *Demand models*: predicting the relevant aspects of travel demand as a function of system activity and level of service provided by the transportation system
- *Assignment models*: using the objects of the multimodal transportation system assignments

1.2 Transportation and Transportation Systems Sector

The importance of understanding and determining dynamic behavior in multimodal transportation in the transportation systems sector has been recognized for a long time, because without adequate modes of transportation, the globalized economy can neither grow nor survive. However, multimodal transportation of freight and passengers contributes to congestion, environmental pollution, and traffic accidents and has a tremendous impact, especially in metropolitan areas. Therefore, a prerequisite for any solution proposing to make the existing transportation systems sector with its multiple modalities more effective is a precise analysis and understanding of the traffic demands. This should take economic forecasts into account to keep pace with the growing demand. Thus, modeling and simulation-based analysis, along with holistic optimization, can help in studying complex transportation scenarios and identifying solutions without committing expensive and time-consuming resources to the implementation of various alternative strategies.

A holistic evaluation of the impact of different transportation policies in a complex transportation scenario requires a comprehensive simulation environment which integrates all aspects of the target transportation system. However, transportation systems analysis is a multidisciplinary field which draws on economics, engineering, logistics, management, operations research, political science, psychology, traffic engineering, transportation planning, and other disciplines (Manheim 1979). Therefore, numerous details must be considered in determining how major concepts can be applied in practice to particular modes and problems of the transportation systems sector.

Transportation modes include:

- *Air transportation sector*: involves modeling and simulation of airport terminal operations, such as baggage handling, gate handling, security check handling, ramp operations (such as vehicle management on the apron), freight handling, and taxiway and runway operations.
- *Maritime transportation sector*: involves modeling and simulation of container terminal operations, including the logistics of efficient container handling, intermodal transport to and from dry ports which expands the sea port container yard capacity, as well as ferry and cruise ship operations.

- *Rail transportation sector*: involves modeling and simulation of freight movement to determine operational efficiency and rationalize planning decisions. Freight simulation can include aspects such as commodity flow, corridor and system capacity, traffic assignment/network flow, and freight plans that involve travel demand forecasting. Rail transportation models also integrate passenger travel.
- *Roadway or ground transportation sector*: widely uses modeling and simulation for both passenger and freight movement. Simulation can be carried out at a corridor level or at a more complex roadway grid network level to analyze planning, design, and operations with regard to congestion, delay, and pollution. Ground transportation models are based mostly on all options of roadway travel, including bicycles, buses, cars, pedestrians, and trucks. In traditional road traffic models, an aggregate representation of traffic is typically used where all vehicles of a particular group obey the same rules of behavior; in microsimulation, driver behavior and network performance are included so that complete traffic problems can be examined (URL 1).

In this book, we study the presence of multiple modes of transportation with regard to transportation systems analysis, modeling, and simulation use cases, developed as part of independent grant projects. In addition to simulating individual modes, it is often more important to simulate a multimodal network, since in reality modes are integrated and represent more complexities that can be overlooked when simulating modes. Intermodal network simulation can also help in gaining a more comprehensive understanding of the impact of a certain network and its policy implications. Transportation simulations can also be integrated with urban environmental simulations, where a large urban area, including roadway networks, is simulated to better understand land use and other planning implications of the traffic network on the urban environment (Ioannou et al. 2007). Hence, manifold transportation applications can be analyzed by modeling and simulation to holistically evaluate the impact of different policies in complex scenarios, such as freight transportation in metropolitan areas, congestion problems in transportation systems traffic, and mobility management. In general, these types of analyses are too complicated or difficult for traditional analytical or numerical methods, which means they require a comprehensive simulation model which consider all aspects of the target system.

Simulation in the transportation systems sector, based on comprehensive simulation models of transportation systems and using specific simulation software, enables better planning, design, and operation of transportation systems. This new approach helps to solve transportation problems (e.g., evaluating the impact of terminal handling strategies on local traffic conditions and terminal throughput) (Ioannou et al. 2007), through real-world demonstrations of present and/or future scenarios (e.g., in traffic engineering and transportation planning). It also assists with difficult obstacles, such as cost requirements in planning and building new infrastructure.

1.3 Models and Their Mathematical Notation

Depending on the nature of the problems in the transportation systems sector, activity-based models, demand-based models, discrete choice analysis, dynamic traffic assignment, and public transportation models as well as traffic flow models, and their different representative forms as macroscopic, microscopic, and mesoscopic models, are used for in-depth, state-of-the-art study in the transportation systems sector.

The advantage of macroscopic traffic models is that they simply capture the general relationships between flow, density, and speed. Thus, macroscopic models abstract traffic to traffic streams that pass along traffic pipes which can be represented as continuous flow, often using formulations based on hydrodynamic flow theories, and by network theory, described as voltage and current in an electrical network. Hence, for segments of the network, the edges in the traffic graph, indicating traffic densities, can be calculated. The advantages of the macroscopic approach are its simplicity and the possibility of solving the traffic model equations in accordance with the rules of network theory, even analytically. Numerical solutions are necessary if a dynamic adaptation of the segment element's resistance and capacity is required. It is obvious that macroscopic models can be easily parameterized, because the level of information required can be compared with the information provided by measurements from traffic censuses. The main disadvantage to using the macroscopic approach is its lack of information, because the traffic streams in macroscopic models are based on statistical information. This means that there is no information about individual traffic events, because the model cannot predict information about departure points and destinations of traffic events passing a certain segment in the traffic graph. However, in most transportation applications, this information is essential to interpret changes (e.g., in the road net or the traffic load) and their implications for individual vehicle driving time and/or the distribution of individual traffic within the traffic network.

Microscopic traffic models are used to capture the behavior of individual objects (vehicles and drivers) in great detail, including interactions among vehicles, lane changing, and behavior at merge points. Therefore, they provide information that macroscopic models are not able to reproduce. Microscopic models generate information at the individual object level, describing acceleration and deceleration at the process level, separately for each object, and can also include sophisticated strategies for routing individual objects. The main disadvantage to using the microscopic approach is the simulation time required, caused by the large number of objects and the resulting interactions which must be handled by the model. However, the difficulty in properly parameterizing microscopic models by defining attributes of individual model objects adequately, completely, and consistently is another main disadvantage.

Mesoscopic traffic models incorporate objects such as the microscopic modeling paradigm, but at an aggregate level, usually by speed-density relationships and queuing theory approaches. These models require more effort in specification and interpretation, because the mesoscopic approach does not give any constructive