

# Introduction

Science is made of facts just as a house is made of bricks, but a collection of facts is no more science than a pile of bricks is a house.

Henri Poincaré

The aim of the disciplines of praxis is not theoretical knowledge. . . . It is to change the forms of action. . . .

Aristotle

Transportation systems consist not only of the physical and organizational elements that interact with each other to produce transportation opportunities, but also of the demand that takes advantage of such opportunities to travel from one place to another. This travel demand, in turn, is the result of interactions among the various economic and social activities located in a given area. Mathematical models of transportation systems represent, for a real or hypothetical transportation system, the demand flows, the functioning of the physical and organizational elements, the interactions between them, and their effects on the external world. Mathematical models and the methods involved in their application to real, large-scale systems are thus fundamental tools for evaluating and/or designing actions affecting the physical elements (e.g., a new railway) and/or organizational components (e.g., a new timetable) of transportation systems.

This book discusses the mathematical models that are used to analyze transportation systems, presenting them as the result of a limited number of general assumptions (theory). It also deals with the methods needed to make these models operational, and with their application to transportation system project design and evaluation. This field of knowledge is known as transportation systems engineering.

The development of a transportation system project may involve functional design of new infrastructure facilities such as roads, railways, airports, and car parks; assessment of long-term investment programs; evaluation of project financing schemes; determination of schedules and pricing policies for transportation services; definition of circulation and regulation schemes for urban road networks; and design of strategies for new advanced traffic control and information systems. Physical elements of the system are designed and/or selected from among those available to provide the characteristics and performance that are required of the transportation services to be provided. A transportation system project must of course be technically feasible; but it is equally important that its definition reflects a quantitative assessment of its characteristics and impacts against the objectives and constraints that the project is intended to satisfy.

The difficulty, but also the fascination, of this field derives from the intrinsic complexity of transportation systems. They are, indeed, internally complex systems, made up of many elements influencing each other both directly and indirectly, often nonlinearly, and with many feedback cycles. Furthermore, only some elements in the system are “technical” in nature (vehicles, infrastructure, etc.), governed by the laws of physics and, as such, traditionally studied by engineers. In contrast, the number of travelers or quantity of goods that use these physical elements and,

through congestion, the performance of these elements and the impacts of their use, are strictly connected to travel demand and users’ behavior. Thus, the analysis of travel demand plays a key role in understanding and designing transportation systems. However, travel demand analysis requires a different kind of approach, one that draws on concepts traditionally used more in social and economic sciences than in engineering.

Apart from their internal complexity, transportation systems are closely interrelated with other systems that are external to them. Transportation projects may have implications for the economy, the location and intensity of the activities in a given area, the environment, the quality of life, and social cohesion. In short, they have a bearing on many, often conflicting, interests, as can easily be seen from the heated debates that accompany almost all decisions concerning transportation at all scales. Both the intensity of these impacts and our sensitivity to them have grown considerably in recent decades due to continued economic and social development, and they have to be addressed in the design and evaluation of transportation projects.

For all these reasons, the consequences of a project cannot be predicted using only experience and intuition. Although they are prerequisites for good design, experience and intuition do not allow quantitative evaluation of the effects of a project, and they may be seriously misleading for complex systems. Modeling supported by empirical evidence sometimes produces unexpected and seemingly paradoxical results: a capacity addition that increases congestion on existing facilities; local projects whose effects propagate to remote parts of the system; price increases that lead to revenue reductions; measures meant to reduce car usage that result in an overall increase in air pollution and energy consumption; and so on. Furthermore, due to the large number of design variables and the complexity of their interactions, modeling the effects of multiple variables requires powerful mathematical tools to help the designer find satisfactory combinations. Finally, social equity issues can only be objectively addressed using a quantitative approach.

The mathematical theory of transportation systems that is presented in this book has been developed over recent decades to develop solutions to these problems. This discipline is based on a systems engineering approach. It is concerned with the relationships among the elements making up a transportation system and with their performance. It possesses a theoretical core that is unique to transportation systems, and also draws on the theory and methods of many other disciplines, especially economics, econometrics, and operations research, in addition to those that are traditionally more directly relevant to transportation engineers, such as traffic engineering, transportation infrastructure engineering, and vehicle mechanics.

The discipline’s theoretical foundation is, in my opinion, a “topological–behavioral” paradigm consisting of a set of assumptions and a limited number of functional relationships. This paradigm is an abstract representation of transportation services and their functioning (supply or performance models), of travel demand and users’ behavior (demand models), and of the interactions of the two (demand/supply interaction or assignment models).

Over the years, these assumptions and relationships have been extended and formalized. The general mathematical properties of the resulting models have been

investigated, producing a wide and internally consistent system of results with a certain degree of formal elegance. This does not preclude the possibility of significant new theoretical and methodological developments in the future. Indeed, transportation systems engineering is probably one of the areas of applied systems engineering in which research is most active, most able to generate extensions and generalizations within the accepted assumptions, and most able to widen and even replace the assumptions on which it is based. Examples can be seen in research on the interactions of transportation with land-use and activity systems, in models of supply design and in the analysis of within-day dynamic systems.

Transportation systems theory would, however, be of little use for addressing practical problems without a set of methods to make it operational. This allows us to specify systems of mathematical models that are consistent with the theory and able to represent the relevant aspects of different transportation systems in the real world. Such methods range from rules for defining a network model to techniques for estimating travel demand and algorithms for solving large-scale computational problems. These methods use the results of a variety of disciplines and, taken as a whole, make up the technical tools and resources of transportation system engineers and analysts.

This book extends and generalizes the contents of my previous book *Transportation Systems Engineering: Theory and Methods* published in 2001, updating both the theory and the application methods. In its attempt to address both general theory and practical methods, the book should be useful to readers with different needs and backgrounds. The various topics are presented, wherever possible, with a gradually increasing level of detail and complexity. Some sections can be used as the basis for beginning and advanced courses in transportation systems engineering and other disciplines, such as economics and regional science. Some sections deal with topics that are mainly of interest for specific applications or are still subjects of research; exclusion of such sections, which are marked with an asterisk, should not limit the understanding of later sections and chapters. The book is made up of ten chapters and an appendix.

Chapter 1 defines a transportation system, and identifies its components and the assumptions on which the theory described in later chapters is developed. It also introduces some application areas of transportation systems engineering, as well as the decision-making process and the role of quantitative methods in this process.

Chapters 2 to 6 explore the theory of transportation systems under the traditional assumption of intraperiod stationarity of the relevant variables. More specifically, Chap. 2 deals with mathematical models that represent transportation supply systems. These models combine traffic flow theory and network flow theory models. The chapter introduces an abstract model that links network flow theory models with the mathematical relationships between transportation costs and flows. The chapter then presents general guidelines concerning the applications of network models and specific models for transportation systems for both continuous and scheduled service. Chapter 3 describes the theoretical basis and mathematical properties of random utility models; these are the general tools most widely adopted to model the travel behavior of transportation system users. Chapter 4 then describes specific

mathematical models that represent different aspects of passenger and freight travel demand, introducing their theoretical formulations and providing several examples.

Chapters 5, 6, and 7 describe and analyze assignment models, which predict the outcome of transportation demand/supply interactions; these outcomes include user flows and travel conditions (times, costs, etc.) on the different components of the supply system. Some solution methods are also presented.

Chapter 5 concerns models (and simple algorithms) for within-day static network equilibrium, assuming (fully) pre-trip path choice (either deterministic or stochastic), fixed demand, one transportation mode, a single user class. Shortest path computation as well as assignment to uncongested networks are also addressed.

Chapter 6 extends the results of Chap. 5 to within-day static network equilibrium with combined pre-trip en-route path choice (such as hyperpath assignment), variable demand, several user classes, several transportation modes. Some references are also made to recent inter-period (day-to-day) dynamic models, including both deterministic and stochastic process approaches.

Chapter 7 extends the results of the previous chapters to intra-period (within-day) dynamic systems. In particular, it describes supply, demand and supply/demand interaction (assignment) models for within-day dynamic systems, considering both continuous and scheduled service systems.

Chapter 8 explores methods for estimating travel demand. Methods derived from statistics and econometrics are applied to survey data to estimate existing travel demand in a given area, and to specify and calibrate travel demand models. The chapter also discusses techniques for estimating existing demand flows and model parameters from aggregate data, specifically traffic counts.

Chapter 9 briefly describes several supply design models and algorithms. It considers design problems for road and transit networks that relate to network topology, performance characteristics, and pricing. The design models and algorithms can be used to determine the values of variables that define the design problem at hand by optimizing different types of objective functions under various constraints.

Finally, Chap. 10 describes methods for evaluating and comparing alternative transportation projects. Cost-benefit analysis is presented as an example of economic analysis, cost-revenue analysis as an example of financial analysis, and different multicriteria analysis approaches as examples of quantitative methods for comparing different projects.

For full appreciation and understanding of the book, the reader should have a basic knowledge of calculus, mathematical analysis, optimization techniques, graph and network theory, probability theory, and statistics. Appendix A provides an overview of additional relevant mathematics.

Different reading paths can be followed according to the reader's interests. For example, a path focusing on demand analysis could consist of Chaps. 3, 4, and 8, whereas one focusing on transportation systems design and planning could consist of Chaps. 2, 5, 6, 7, 9, and 10.

A book of this scope and magnitude cannot be completed without the help and the assistance of several individuals. Giulio Erberto Cantarella took part in the entire decision process that underlies the structure of the book and the choice of its

contents. He also contributed directly to it, co-authoring Sect. 2.2 of Chap. 2 and Chaps. 5 and 6.

Francesca Pagliara contributed to Chaps. 1 and 10, Vincenzo Punzo contributed to Chaps. 2 and 7, Andrea Papola and Vittorio Marzano to Chaps. 3, 4, and 8, Armando Cartenì to Chaps. 5 and 6, and Mariano Gallo to Chap. 9. Natale Papola and Guido Gentile are the authors of Sect. 7.5 and Appendix 7.A. I would also like to thank Paolo Ferrari and Pietro Rostirolla for their advice and contributions to the preparation of Chap. 10. Almost all topics covered in this book were discussed over the years with Agostino Nuzzolo, who also co-authored Sect. 7.6 of Chap. 7 on scheduled service transportation systems.

I would like also to thank Jon Bottom for revising the English of the whole book as well as for several comments and suggestions.

Despite such extensive contributions and input from others, I take sole responsibility for any mistakes.