

# Fundamentals of Transportation and Traffic Operations

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*by*

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INVESTOR IN PEOPLE

*To Jenifer and Sally*

# Preface

This book is an attempt to present in a self-contained way those basic concepts in the transportation and traffic operations field that should be well understood by every transportation professional. This includes graduate students planning to pursue more advanced studies, as well as newcomers to the field who may be readying themselves for an in depth review of the literature. It is also hoped that academics will find parts of this book suitable for teaching material and/or reading assignments.

The book has evolved from a set of course notes that were prepared for an introductory graduate course in transportation operations currently taught in the transportation engineering division at U.C. Berkeley. The goal of this course is to introduce the basics of transportation operations to a wide crosssection of graduate students entering our interdisciplinary program, with backgrounds in civil engineering, city planning, operations research, economics, etc.

The structure and level of the book, as that of the course, is dictated by the necessity to reach such a wide audience in a pedagogically sensible manner. For example, probabilistic concepts are avoided to the extent possible until chapter 6 in order to allow some students to take a concurrent course on probability theory. Elementary calculus concepts, however, are used from the beginning. It is also assumed that the reader has the basic modeling skills that one would develop in an introductory physics course. An effort has been made to represent different things by different symbols within each chapter, and to use a unique symbol for the most important variables used throughout the book. Notational inconsistencies across chapters could not be totally avoided, however, due to the variety of subjects.

The book has chapters on tools (1, 2, 3, and the first part of 6) and others on applications (4, 5, 2nd part of 6, and 7). Very brief introductions to graphical methods, optimization, probability, stochastic processes, statistics and simulation are provided as part of the “tool” chapters. Somewhat unorthodox, these discussions have been made as self-contained as possible, emphasizing the most useful aspects of each tool. This is not the emphasis one usually finds in more specialized books. Readers already familiar with these subjects may skip chapter 3 and the first two sections of chapter 6, although they may find some portions of the discussion entertaining. Chapters 1 and 2 should not be skipped, however.

The book covers some of the application topics in more depth than

would be necessary for an introduction in order to fill gaps in the existing literature. Most notably, “Fundamentals” includes a fairly detailed treatment of “traffic flow theory” in Chaps. 1, 2 and 4. The second half of Chap. 4, covering “traffic dynamics”, is more demanding than the rest of the book, but this was necessary for the sake of completeness. A more detailed treatment of this subtle topic is included because certain aspects of it are repeatedly missinterpreted in the published literature. The presentation of this topic stresses the simple traffic theories introduced in the fifties, whose successes and drawbacks are well understood, and ignores modern refinements which have not stood serious scrutiny.

The remaining application topics, “control” (Chap. 5), “observation” (2nd part of Chap. 6) and “scheduled modes” (Chap. 7), use a “building block” approach. Basic ideas involving simple systems (e.g., the timing of a simple traffic signal, the estimation of a bottleneck’s “capacity”, and the evaluation of passenger delay at a bus stop) are presented in detail and more complicated ones (e.g., networks, estimation of an origin-destination table, and coordination of transit schedules) more qualitatively. An objective was to present the issues clearly, more than a list of specific techniques. As with the material on traffic flow theory, an effort has been made to point out various pitfalls so that they can be avoided. Here too, only that material which is definitely known and correct has been presented in the hope that a newcomer to the transportation field will find in this book a useful source of basic culture.

The application subjects included do not represent a complete survey of those topics one could characterize as “transportation operations” because the book deemphasizes the description of facts (which change as technology changes) in favor of logic. Furthermore, only logical ideas which in my opinion have a solid grounding in physical reality have been included because those are the ones that have the best chance of standing the test of time. This seems appropriate for an introductory book (course) that attempts to prepare the reader for a critical understanding of the field. Of course, many excluded topics deserve treatment in journals and in more specialized books/courses. The reader should turn to these for proper coverage of the current literature.

“Fundamentals of transportation and traffic operations” may be used as a textbook if complemented with problems. A set of solved problems jointly developed with U.C. Berkeley colleagues will be available in the near future and can be ordered by writing to “Institute of Transportation Studies, Publications Office, 109 McLaughlin Hall, University of California, Berkeley, CA 94720” or by sending e-mail to “its@its.berke-

ley.edu". The book can also be used as background reading in graduate and undergraduate courses on transportation and traffic operations. "Fundamentals" also describes a number of computer spreadsheets that can be used for various purposes, including class demonstrations. These can be downloaded from the INTERNET by looking up the book title at "[www.ce.berkeley.edu/~daganzo](http://www.ce.berkeley.edu/~daganzo)" and following instructions. The problems, but not the solutions can also be downloaded from the INTERNET.

I would be interested in learning of any errors, and plan to issue an errata sheet in conjunction with the set of problems when/if significant ones are found; the errata will also be posted on the INTERNET. Comments may be sent by e-mail to "[daganzo@ce.berkeley.edu](mailto:daganzo@ce.berkeley.edu)".

I wish to thank my mentor and colleague Gordon F. Newell for his valued comments, both on the course and on the book. Professor Rod Troutbeck of Queensland University of Technology, Brisbane, Australia, hosted me graciously during a sabbatical leave which made possible preparation of a first draft. His comments and encouragement are also deeply appreciated; the title of the book was suggested by him. Thanks are also due to Prof. Mike Cassidy of U.C. Berkeley for furnishing valuable feedback on those portions of the book he has used in the classroom, to Mrs. Ping Hale for patiently putting up with me while preparing a first draft of the manuscript and to Ms. Esther Kerkmann for doing the graphics. A grant from the University of California Transportation Center made it all possible. Most of all, however, I want to thank my wife, friend and companion, Valery, for her support and understanding.

Carlos F. Daganzo  
Berkeley, California  
December 29, 1996

## CHAPTER ONE

# The time-space diagram

Because the transportation field has not been developed to the point where many of the existing problems can be addressed with well established recipes, transportation professionals are often required to use basic modeling skills and think on their own. This, of course, can only be done effectively if one ‘owns’ a complete set of thinking tools. Since a basic set of tools is also necessary for a meaningful discussion of transportation operations, this book starts with brief introductions to those ‘deterministic’ tools that are not always covered in an undergraduate engineering curriculum: first the time-space diagram (Chapter 1), then cumulative plots (Chapter 2) and finally optimization (Chapter 3).

The material in chapters 1 and 2 is necessary to describe and think about the collective motion of items over guideways. The diagrams presented in these chapters are ‘fundamental’ in that they shed much light on time and motion problems that one may be trying to understand. Chapters 4 (traffic flow theory) and 7 (scheduled systems) rely on these diagrams extensively. The material in chapter 3 is often useful for the design and/or control of systems that are already well understood.

The present chapter introduces the time-space diagram and its application to the study of vehicular motion. It is organized in three sections. Section 1.1 discusses the motion of a single item, Sec. 1.2 that of many items sharing a guideway, and Sec. 1.3 some applications to more specific scheduled and unscheduled transportation problems.

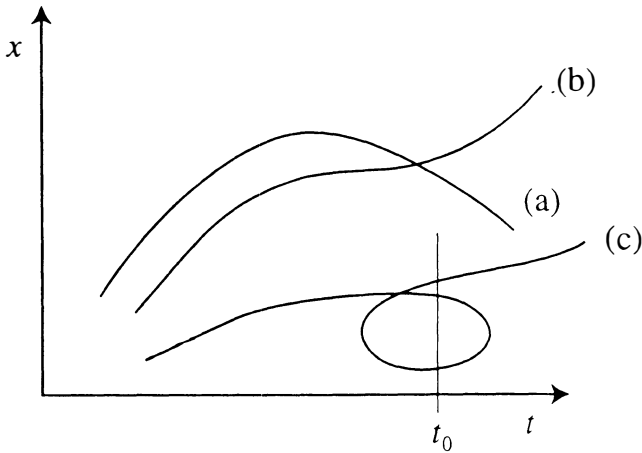
### 1.1 Trajectories for a single vehicle

Very often in the analysis of a particular transportation operation one has to track the position of a vehicle over time along a 1-dimensional guideway as a function of time, and then summarize the relevant information in an understandable way. This can be done by means of mathematics if one uses a variable  $x$  to denote the distance traveled along the guideway from some arbitrary reference point, and another variable  $t$  to denote the time elapsed from an arbitrary instant. Then, the desired information can be provided by a function  $x(t)$  that returns an  $x$  for every  $t$  in the relevant range for our application.<sup>1</sup>

## 2 Fundamentals of transportation and traffic operations

A graphical representation of  $x(t)$  in the  $(t,x)$  plane is a curve which we call a *trajectory*. As illustrated by two of the curves in Fig. 1.1, trajectories provide an intuitive, clear and complete summary of vehicular motion in one dimension. Curve 'a', for example, represents a vehicle that is proceeding in the positive direction, slows down and finally reverses direction. Curve 'b' represents a vehicle that resumes travel in the positive direction after nearly stopping. Curve 'c', however, is not a representation of a trajectory because there is more than one position given for certain  $t$ 's (e.g.  $t_0$ ); such a curve is not the representation of a (single-valued) function  $x(t)$ . Valid vehicle trajectories must exhibit one and only one  $x$  for every  $t$ . For problems requiring a level of resolution comparable or finer than the vehicular length, e.g., when tracking the position of a mile-long train over a vertical curve, the curve  $x(t)$  should refer to a particular point of the vehicle such as the vehicle's front, rear or center of gravity. Any point is valid, provided the diagram is interpreted in accordance with the choice.

In some practical applications a vehicle's trajectory must be developed analytically from knowledge about the operating characteristics of the vehicle and the guideway such as: the vehicle mass, resistive forces, engine horsepower, guideway elevation profile, etc. Examples of such applications are: (1) determination of the minimum travel time between stations for a transit train when one is given the maximum operating speed, the maximum acceleration and the maximum allowable 'jerk'<sup>2</sup>, as well as the distance between stations; (2) determination of a vehicle's



**Figure 1.1** Time-space curves: (a) and (b) are vehicle trajectories; (c) is not.

initial speed from its skid marks and its estimated collision speed, given the vehicle's coefficient of friction and the road geometry; (3) studies of runway length and taxiway exit location, which use as inputs airplane deceleration characteristics and an initial speed to predict the distance traveled to achieve a target speed; (4) similar studies for the length of acceleration and deceleration lanes of freeway on-ramps and off-ramps, (5) calculation of high-speed rail travel times over rugged terrain as a function of the engine power and the vertical profile of a proposed alignment.

In other applications the trajectory of a vehicle can be recorded, e.g. with a video-camera, and the objective is to convert the raw data into a curve  $x(t)$  that can then be studied mathematically. Sometimes, as may happen for transit systems using an automated vehicle monitoring system, no conversion may be necessary at all. In other cases, however, data may only be available in the form of observed vehicle positions at discrete times, as happens for example in elevator and public transportation studies when only the times at which each vehicle arrives and leaves each stop are recorded. Then the full set of vehicle trajectories may be approximated by interpolation.

Later in this chapter we will see how representing multiple vehicle trajectories on the same time-space diagram, whether analytically or experimentally obtained, can help solve many problems. Before this can be done a more detailed look at single vehicle trajectories is in order, although it is with multiple vehicles that the technique really shines.

We recall from elementary physics that the first and second time-derivatives of a vehicle trajectory (e.g. curve 'a' of Fig. 1.1) represent the velocity,  $v$ , and acceleration,  $a$ , of the vehicle; i.e., that  $v(t) = dx(t)/dt$  and  $a(t) = d^2x(t)/dt^2$ , or in abbreviated form:

$$v = dx/dt \text{ and } a = d^2x/dt^2. \quad (1.1)$$

Although Eq. (1.1) is widely known and its qualitative graphical consequences are rather obvious, it is worth emphasizing that steeply increasing (decreasing) sections of  $x(t)$  denote a rapidly advancing (receding) vehicle; horizontal portions of  $x(t)$  denote a stopped vehicle and shallow sections a slow-moving vehicle. Straight line segments depict constant speed motion (with no acceleration) and curving sections denote accelerated motion; here, the higher the curvature, the higher the absolute value of the acceleration. Concave downwards curves (such as curve 'a') denote deceleration and concave upwards (convex) sections denote accelerated motion.

The reader is encouraged not just to understand rationally these properties, but also to draw and study a large number of examples in an