

Traffic Flow Dynamics

Martin Treiber · Arne Kesting

Traffic Flow Dynamics

Data, Models and Simulation

Translated by Martin Treiber and Christian Thiemann

 Springer

Martin Treiber
Institut für Wirtschaft und Verkehr
TU Dresden
Dresden
Germany

Arne Kesting
TomTom Development Germany GmbH
Berlin
Germany

ISBN 978-3-642-32459-8 ISBN 978-3-642-32460-4 (eBook)
DOI 10.1007/978-3-642-32460-4
Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2012944963

© Springer-Verlag Berlin Heidelberg 2013

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

In order to keep people moving in times of rising traffic and limited resources, science is challenged to find intelligent solutions. Over the past few years, contributions from engineers, physicists, mathematicians, and behavioral psychologists have led to a better understanding of driver behavior and vehicular traffic flow. This interdisciplinary field will surely produce further advances in the future. The focus is on new applications ranging from novel driver-assistance systems, to intelligent approaches to optimizing traffic flow, to the precise detection of traffic jams and the short-term forecasting of traffic for dynamic navigation aids.

This textbook offers a comprehensive and didactic account of the different aspects of vehicular traffic flow dynamics and how to describe and simulate them with mathematical models. We hope to make this fascinating field accessible to a broader readership; to date, it has only been documented in specialized scientific papers and monographs.

Part I describes how to obtain and interpret traffic flow data, the basis of any quantitative modeling. The second and main part is devoted to the different approaches and models used to mathematically describe traffic flow. The starting point of most models are the basic concepts of physics—many-particle systems, hydrodynamics, and classical Newtonian mechanics—augmented by behavioral aspects and traffic rules. At the website¹ accompanying this book, the reader can interactively run a selection of traffic models and reproduce some of the simulation results displayed in the figures. Part III gives an overview of major applications including traffic-state estimation, fuel consumption, and emission modeling, determining travel times (the basis of dynamic navigation), and how to optimize traffic flow.

The book is written for students, lecturers, and professionals of engineering and transportation sciences and for interested students in general. It also offers material for project work in programming, numerical methods, simulation, and mathematical modeling at college and university level. The reference implementations in the

¹ see: www.traffic-flow-dynamics.org

multi-model open-source vehicular traffic simulator *MovSim*² can be used as a starting point for the reader's own simulation experiments and model development.

This work originates from the lecture notes of courses in traffic flow dynamics and modeling at the Dresden University of Technology, Germany; these have been previously published, by the same publisher, in the German book “Verkehrsdynamik und Simulation”. The English edition has been updated and significantly extended to include new topics, e.g., on model calibration. To underline its textbook character, it contains many problems with elaborated solutions.

We thank all colleagues at our Department for Traffic Econometrics and Modeling at the Dresden University of Technology, particularly Dirk Helbing, for various scientific discussions and stimulations. We would also like to thank Marietta Seifert, Christian Thiemann, and Stefan Lämmer for suggestions and corrections. Special thanks go to Martin Budden for reviewing the manuscript as a native English speaker. He is also one of the main contributors to *MovSim*. Finally, we would like to thank Martina Seifert, Christine and Hanskarl Treiber, Ingrid, Bernd, and Dörte Kesting, Claudia Perlitius, and Ralph Germ who contributed to the book with valuable suggestions.

Dresden, June 2012

Martin Treiber
Arne Kesting

² see: www.movsim.org

Contents

1	Introduction	1
Part I Traffic Data		
2	Trajectory and Floating-Car Data	7
	2.1 Data Collection Methods	7
	2.2 Time-Space Diagrams	9
	Problems	10
3	Cross-Sectional Data	13
	3.1 Microscopic Measurement: Single-Vehicle Data	13
	3.2 Aggregated Data	15
	3.3 Estimating Spatial Quantities from Cross-Sectional Data	17
	3.3.1 Traffic Density	17
	3.3.2 Space Mean Speed	21
	3.4 Determining Speed from Single-Loop Detectors	22
	Problems	23
4	Representation of Cross-Sectional Data	25
	4.1 Time Series of Macroscopic Quantities	25
	4.2 Speed-Density Relation	27
	4.3 Distribution of Time Gaps	30
	4.4 Flow-Density Diagram	31
	4.5 Speed-Flow Diagram	35
	Problems	35
5	Spatiotemporal Reconstruction of the Traffic State	37
	5.1 Spatiotemporal Interpolation	37
	5.2 Adaptive Smoothing Method	40

5.2.1	Characteristic Propagation Velocities	41
5.2.2	Nonlinear Adaptive Speed Filter.	42
5.2.3	Parameters.	43
5.2.4	Testing the Predictive Power: Validation.	43
5.2.5	Testing the Robustness: Sensitivity Analysis	44
5.3	Data Fusion	45
5.3.1	Model-Based Validation of a Data Fusion Procedure	47
5.3.2	Weighting the Data Sources.	48
	Problems.	50

Part II Traffic Flow Modeling

6	General Aspects	55
6.1	History and Scope of Traffic Flow Theory	55
6.2	Model Classification	56
6.2.1	Aggregation Level	56
6.2.2	Mathematical Structure	59
6.2.3	Other Criteria.	61
6.3	Non-Motorized Traffic	63
	Problems.	65
7	Continuity Equation	67
7.1	Traffic Density and Hydrodynamic Flow-Density Relation	67
7.2	Continuity Equations for Several Road Profiles	69
7.2.1	Homogeneous Road Section.	70
7.2.2	Sections with On- and Off-Ramps	71
7.2.3	Changes in the Number of Lanes	72
7.2.4	Discussion	74
7.3	Continuity Equation from the Driver's Perspective.	75
7.4	Lagrangian Description	77
	Problems.	79
8	The Lighthill–Whitham–Richards Model.	81
8.1	Model Equations	81
8.2	Propagation of Density Variations	83
8.3	Shock Waves	84
8.3.1	Formation	84
8.3.2	Derivation of the Propagation Velocity	86
8.3.3	Vehicle Speed Versus Propagation Velocities	87
8.4	Numerical Solution.	90
8.5	LWR Models with Triangular Fundamental Diagram	91
8.5.1	Model Parameters.	92
8.5.2	Characteristic Properties	93

8.5.3	Model Formulation with Measurable Quantities	96
8.5.4	Relation to Car-Following Models	97
8.5.5	Definition of Road Sections	99
8.5.6	Modeling Bottlenecks	100
8.5.7	Numerical Solution of the Cell-Transmission Model	105
8.5.8	Solving the Section-Based Model	108
8.5.9	Examples	113
8.6	Diffusion and Burgers' Equation	121
	Problems	123
9	Macroscopic Models with Dynamic Velocity	127
9.1	Macroscopic Acceleration Function	127
9.2	Properties of the Acceleration Function	130
9.2.1	Steady-State Flow	130
9.2.2	Plausibility Conditions	130
9.3	General Form of the Model Equations	132
9.3.1	Local Speed Adaptation	132
9.3.2	Nonlocal Anticipation	133
9.3.3	Limiting Case of Zero Adaptation Time	133
9.3.4	Pressure Term	134
9.3.5	Diffusion Terms	136
9.3.6	On- and Off-Ramp Terms	137
9.4	Overview of Second-Order Models	137
9.4.1	Payne's Model	138
9.4.2	Kerner-Konhäuser Model	140
9.4.3	Gas-Kinetic-Based Traffic Model	142
9.5	Numerical Solution	145
9.5.1	Overview	145
9.5.2	Upwind and McCormack Scheme	147
9.5.3	Approximating Nonlocalities	148
9.5.4	Criteria for Selecting a Numerical Integration Scheme	148
9.5.5	Numerical Instabilities	150
9.5.6	Numerical Diffusion	153
	Problems	153
10	Elementary Car-Following Models	157
10.1	General Remarks	157
10.2	Mathematical Description	159
10.3	Steady State Equilibrium and the Fundamental Diagram	162
10.4	Heterogeneous Traffic	164
10.5	Fact Sheet of Dynamical Model Characteristics	165
10.5.1	Highway Scenario	165
10.5.2	City Scenario	168

10.6	Optimal Velocity Model	168
10.7	Full Velocity Difference Model	171
10.8	Newell's Car-Following Model	173
	Problems.	178
11	Car-Following Models Based on Driving Strategies	181
11.1	Model Criteria	181
11.2	Gipps' Model.	183
11.2.1	Safe Speed.	183
11.2.2	Model Equation	184
11.2.3	Steady-State Equilibrium	185
11.2.4	Model Characteristics	185
11.3	Intelligent Driver Model	187
11.3.1	Required Model Properties	188
11.3.2	Mathematical Description	188
11.3.3	Parameters	189
11.3.4	Intelligent Braking Strategy	191
11.3.5	Dynamical Properties	193
11.3.6	Steady-State Equilibrium	195
11.3.7	Improved Acceleration Function.	196
11.3.8	Model for Adaptive Cruise Control.	198
	Problems.	202
12	Modeling Human Aspects of Driving Behavior	205
12.1	Man Versus Machine	205
12.2	Reaction Times	207
12.3	Estimation Errors and Imperfect Driving Capabilities	210
12.3.1	Modeling Estimation Errors	210
12.3.2	Modeling Imperfect Driving	213
12.4	Temporal Anticipation	214
12.5	Multi-Vehicle Anticipation	215
12.6	Brake Lights and Further Exogenous Factors	218
12.7	Local Traffic Context	219
12.8	Action Points	220
12.9	The Wiedemann Car-Following Model	221
	Problems.	223
13	Cellular Automata	225
13.1	General Remarks	225
13.2	Nagel-Schreckenberg Model	229
13.3	Refined Models	232
13.3.1	Barlovic Model	232
13.3.2	KKW Model	233

- 13.4 Comparison of Cellular Automata and Car-Following Models 236
- Problems. 237
- 14 Lane-Changing and Other Discrete-Choice Situations 239**
- 14.1 Overview. 239
- 14.2 General Decision Model 240
- 14.3 Lane Changes 242
 - 14.3.1 Safety Criterion 242
 - 14.3.2 Incentive Criterion for Egoistic Drivers. 243
 - 14.3.3 Lane Changes with Courtesy: MOBIL Model 244
 - 14.3.4 Application to Car-Following Models 245
- 14.4 Approaching a Traffic Light 250
- 14.5 Entering a Priority Road 252
- Problems. 253
- 15 Stability Analysis 257**
- 15.1 Formation of Stop-and-Go Waves. 257
- 15.2 Mathematical Classification of Traffic Flow Instabilities. 259
- 15.3 Local Instability 267
- 15.4 String Instability. 272
 - 15.4.1 String Instability Conditions for Car-Following Models. 272
 - 15.4.2 Flow Stability of Macroscopic Models 279
 - 15.4.3 Application to Specific Models 283
- 15.5 Convective Instability and Signal Velocities 288
- 15.6 Nonlinear Instability and the Stability Diagram 294
- 15.7 Stability Classes 296
- 15.8 Short-Wavelength Collective Instabilities 298
- Problems. 299
- 16 Calibration and Validation 303**
- 16.1 General Aspects 304
 - 16.1.1 Mathematical Principles 304
 - 16.1.2 Nonlinear Optimization 307
 - 16.1.3 Assessing Models 311
 - 16.1.4 Implementing and Running a Calibration 313
- 16.2 Calibration to Microscopic Observations 314
 - 16.2.1 Data Preparation. 315
 - 16.2.2 Global Approach 318
 - 16.2.3 Local Approach 321
- 16.3 Calibration to Macroscopic Observations. 325
 - 16.3.1 Fitting Local Properties of Traffic Flow 326
 - 16.3.2 Calibration to Global Properties 328

- 16.4 Validation 333
- Problems. 337
- 17 The Phase Diagram of Congested Traffic States. 339**
 - 17.1 From Ring Roads to Open Systems 339
 - 17.2 Analysis of Traffic Patterns: Dynamic Phase Diagram 340
 - 17.2.1 Stability Class 1 342
 - 17.2.2 Stability Class 2 345
 - 17.2.3 Stability Class 3 346
 - 17.3 Simulating Congested Traffic Patterns
and the Phase Diagram 347
 - 17.4 Reality Check: Observed Patterns of Traffic Jams 350
 - Problems. 350

Part III Applications of Traffic Flow Theory

- 18 Traffic Flow Breakdown and Traffic-State Recognition 355**
 - 18.1 Traffic Flow Breakdown: Three Ingredients
to Make a Traffic Jam. 355
 - 18.2 Do Phantom Traffic Jams Exist? 360
 - 18.3 Stylized Facts of Congested Traffic 361
 - 18.4 Empirical Reality: Complex Patterns. 363
 - 18.5 Fundamentals of Traffic State Estimation 364
 - Problems. 365
- 19 Travel Time Estimation 367**
 - 19.1 Definitions of Travel Time 367
 - 19.2 The Method of Trajectories 368
 - 19.3 The Method of Accumulated Vehicle Counts. 369
 - 19.4 A Hybrid Method. 371
 - 19.5 Virtual Stationary Detectors. 373
 - 19.6 Virtual Trajectories. 373
 - 19.7 Instantaneous Travel Time. 375
 - Problems. 376
- 20 Fuel Consumption and Emissions 379**
 - 20.1 Overview. 379
 - 20.1.1 Macroscopic Models. 380
 - 20.1.2 Microscopic Models 382
 - 20.1.3 Relation Between Fuel Consumption
and CO₂ Emissions. 383

20.2	Speed-Profile Emission Models	383
20.3	Modal Emission Models	385
20.3.1	General Remarks	385
20.3.2	Phenomenological Models	386
20.3.3	Load-Based Models	387
20.4	Physics-Based Modal Consumption Model	388
20.4.1	Driving Resistance	388
20.4.2	Engine Power.	390
20.4.3	Consumption Rate	391
20.4.4	Characteristic Map for Engine Efficiency	392
20.4.5	Output Quantities	394
20.4.6	Aggregation to a Macroscopic Modal Consumption Model	397
	Problems.	397
21	Model-Based Traffic Flow Optimization	403
21.1	Basic Principles	403
21.2	Speed Limits	405
21.3	Ramp Metering	407
21.4	Dynamic Routing	411
21.5	Efficient Driving Behavior and Adaptive Cruise Control.	412
21.6	Further Local Traffic Regulations.	416
21.7	Objective Functions for Traffic Flow Optimization.	417
21.7.1	Setting up the Frame.	417
21.7.2	Constraining Conditions	418
21.7.3	Examples.	419
	Solutions to the Problems	423
	Index	495