

Springer Complexity

Springer Complexity is a publication program, cutting across all traditional disciplines of sciences as well as engineering, economics, medicine, psychology and computer sciences, which is aimed at researchers, students and practitioners working in the field of complex systems. Complex Systems are systems that comprise many interacting parts with the ability to generate a new quality of macroscopic collective behavior through self-organization, e.g., the spontaneous formation of temporal, spatial or functional structures. This recognition, that the collective behavior of the whole system cannot be simply inferred from the understanding of the behavior of the individual components, has led to various new concepts and sophisticated tools of complexity. The main concepts and tools – with sometimes overlapping contents and methodologies – are the theories of self-organization, complex systems, synergetics, dynamical systems, turbulence, catastrophes, instabilities, nonlinearity, stochastic processes, chaos, neural networks, cellular automata, adaptive systems, and genetic algorithms.

The topics treated within Springer Complexity are as diverse as lasers or fluids in physics, machine cutting phenomena of workpieces or electric circuits with feedback in engineering, growth of crystals or pattern formation in chemistry, morphogenesis in biology, brain function in neurology, behavior of stock exchange rates in economics, or the formation of public opinion in sociology. All these seemingly quite different kinds of structure formation have a number of important features and underlying structures in common. These deep structural similarities can be exploited to transfer analytical methods and understanding from one field to another. The Springer Complexity program therefore seeks to foster cross-fertilization between the disciplines and a dialogue between theoreticians and experimentalists for a deeper understanding of the general structure and behavior of complex systems.

The program consists of individual books, books series such as “Springer Series in Synergetics”, “Institute of Nonlinear Science”, “Physics of Neural Networks”, and “Understanding Complex Systems”, as well as various journals.

Understanding Complex Systems

Series Editor

J.A. Scott Kelso

Florida Atlantic University
Center for Complex Systems
Glades Road 777
Boca Raton, FL 33431-0991, USA

Understanding Complex Systems

Future scientific and technological developments in many fields will necessarily depend upon coming to grips with complex systems. Such systems are complex in both their composition (typically many different kinds of components interacting with each other and their environments on multiple levels) and in the rich diversity of behavior of which they are capable. The Springer Series in Understanding Complex Systems series (UCS) promotes new strategies and paradigms for understanding and realizing applications of complex systems research in a wide variety of fields and endeavors. UCS is explicitly transdisciplinary. It has three main goals: First, to elaborate the concepts, methods and tools of self-organizing dynamical systems at all levels of description and in all scientific fields, especially newly emerging areas within the Life, Social, Behavioral, Economic, Neuro- and Cognitive Sciences (and derivatives thereof); second, to encourage novel applications of these ideas in various fields of Engineering and Computation such as robotics, nanotechnology and informatics, third, to provide a single forum within which commonalities and differences in the workings of complex systems may be discerned, hence leading to deeper insight and understanding. UCS will publish monographs and selected edited contributions from specialized conferences and workshops aimed at communicating new findings to a large multidisciplinary audience.

B. S. Kerner

The Physics of Traffic

Empirical Freeway Pattern Features,
Engineering Applications, and Theory

 Springer

Boris S. Kerner
DaimlerChrysler AG
70546 Stuttgart
Germany

ISBN 978-3-642-05850-9 ISBN 978-3-540-40986-1 (eBook)
DOI 10.1007/978-3-540-40986-1

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable to prosecution under the German Copyright Law.

springeronline.com

© Springer-Verlag Berlin Heidelberg 2004
Originally published by Springer-Verlag Berlin Heidelberg New York in 2004.
Softcover reprint of the hardcover 1st edition 2004

The use of general descriptive names, registered names, trademarks, 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.

Print data prepared by TechBooks
Cover design: Erich Kirchner, Heidelberg
Printed on acid-free paper 54/3141/XO - 5 4 3 2 1 0

Preface

This monograph is devoted to a new approach to an old field of scientific investigation, freeway traffic research. Freeway traffic is an extremely complex *spatiotemporal* nonlinear dynamic process. For this reason, it is not surprising that *empirical* traffic pattern features have only recently been sufficiently understood. Such empirical features are in serious conflict with almost all earlier theoretical and model results. Consequently, the author introduced a new traffic flow theory called “three-phase traffic theory,” which can explain these empirical spatiotemporal traffic patterns. The main focus of this book is a consideration of *empirical spatiotemporal* traffic pattern features, their engineering applications, and explanations based on the three-phase traffic theory.

The book consists of four parts. In Part I, empirical studies of traffic flow patterns, earlier traffic flow theories, and mathematical models are briefly reviewed. Three-phase traffic theory is considered as well. This theory is a qualitative theory. Main ideas and results of the three-phase traffic flow theory will be introduced and explained without complex mathematical models. This should be suitable for a very broad audience of practical engineers, physicists, and other readers who may not necessarily be specialists in traffic flow problems, and who may not necessarily have worked in the field of spatiotemporal pattern formation.

In Part II, empirical spatiotemporal traffic pattern features are considered. A microscopic three-phase traffic theory of these patterns and results of an application of the pattern features to engineering applications are presented in Part III and Part IV, respectively.

I am very grateful to Herman Haken for the opportunity to write this book. I am also very grateful to my colleagues at DaimlerChrysler AG, Peter Häußermann, Harald Brunini, Ralf Guido Herrtwich, and Matthias Schulze for their support. I thank my colleagues and friends Hani Mahmassani, Dietrich Wolf, and Michael Schreckenbergr for their support in the first publications of my three-phase traffic theory. I would also like to thank the coauthors of our joint publications, Peter Konhäuser, Martin Schilke, Hubert Rehborn, Sergey Klenov, Dietrich Wolf, Matthias Herrmann, Malte Rödiger, Heribert Kirschfink, Mario Aleksić, and Andreas Haug for their very fruitful cooperation. In particular, I thank Sergey Klenov, Hubert Rehborn, Mario Aleksić,

Ines Maiwald-Hiller, Andreas Haug, and James Banks for their suggestions and help in the preparation of this book. I would like to thank the Hessen (Germany) Ministry of Roads and Traffic for help in the preparation of the empirical data. I acknowledge funding by the German Ministry of Education (BMBF) within projects SANDY and DAISY. I would like to thank Pravin Varaiya and his colleagues for access to traffic data of the PeMS (Freeway Performance Measurement System) database in the USA. I also thank my wife, Tatiana Kerner, for her help and understanding.

Stuttgart,
August 2004

Boris Kerner

Contents

1	Introduction	1
----------	---------------------------	----------

Part I Historical Overview and Three-Phase Traffic Theory

2	Spatiotemporal Pattern Formation in Freeway Traffic	13
2.1	Introduction	13
2.2	Traffic and Synergetics	14
2.3	Free and Congested Traffic	15
2.3.1	Local Measurements of Traffic Variables	15
2.3.2	Examples of Freeway Infrastructures and Detector Arrangements	17
2.3.3	Free Traffic Flow	18
2.3.4	Congested Traffic	21
2.3.5	Empirical Fundamental Diagram	22
2.3.6	Complex Local Dynamics of Congested Traffic	24
2.4	Main Empirical Features of Spatiotemporal Congested Patterns	27
2.4.1	Three Traffic Phases	27
2.4.2	Characteristic Parameters of Wide Moving Jams ...	28
2.4.3	Spontaneous Breakdown Phenomenon (Spontaneous F→S Transition).....	32
2.4.4	Induced Breakdown Phenomenon	34
2.4.5	Synchronized Flow Patterns	35
2.4.6	Catch Effect	37
2.4.7	Moving Jam Emergence in Synchronized Flow: General Pattern	41
2.4.8	Expanded Congested Patterns	46
2.4.9	Foreign Wide Moving Jams	51
2.4.10	Reproducible and Predictable Congested Patterns ..	53
2.4.11	Methodology for Empirical Congested Pattern Study	57
2.5	Conclusions. Fundamental Empirical Features of Spatiotemporal Congested Patterns.....	58

3	Overview of Freeway Traffic Theories and Models: Fundamental Diagram Approach	63
3.1	Introduction:	
	Hypothesis About Theoretical Fundamental Diagram	63
3.2	Achievements of Fundamental Diagram Approach to Traffic Flow Modeling and Theory	64
3.2.1	Conservation of Vehicle Number on Road and Front Velocity	66
3.2.2	The Lighthill–Whitham–Richards Model and Shock Wave Theory	67
3.2.3	Collective Flow Concept and Probability of Passing	68
3.2.4	Scenarios for Moving Jam Emergence	69
3.2.5	Wide Moving Jam Characteristics	69
3.2.6	Flow Rate in Wide Moving Jam Outflow. The Line J	71
3.2.7	Metastable States of Free Flow with Respect to Moving Jam Emergence	73
3.3	Drawbacks of Fundamental Diagram Approach in Describing of Spatiotemporal Congested Freeway Patterns	78
3.3.1	Shock Wave Theory	78
3.3.2	Models and Theories of Moving Jam Emergence in Free Flow	80
3.3.3	Models and Theories with Variety of Vehicle and Driver Characteristics	83
3.3.4	Application of Classical Queuing Theories to Freeway Congested Traffic Patterns	84
3.4	Conclusions	85
4	Basis of Three-Phase Traffic Theory	87
4.1	Introduction and Remarks on Three-Phase Traffic Theory	87
4.2	Definition of Traffic Phases in Congested Traffic Based on Empirical Data	88
4.2.1	Objective Criteria for Traffic Phases in Congested Traffic	88
4.2.2	Explanation of Terms “Synchronized Flow” and “Wide Moving Jam”	90
4.2.3	Mean Vehicle Trajectories	91
4.2.4	Flow Rate in Synchronized Flow	91
4.2.5	Empirical Line J	93
4.2.6	Propagation of Two Wide Moving Jams	94
4.3	Fundamental Hypothesis of Three-Phase Traffic Theory	95

4.3.1	Three-Phase Traffic Theory as Driver Behavioral Theory	98
4.3.2	Synchronization Distance and Speed Adaptation Effect in Synchronized Flow	100
4.3.3	Random Transformations (“Wandering”) Within Synchronized Flow States	100
4.3.4	Dynamic Synchronized Flow States	101
4.4	Empirical Basis of Three-Phase Traffic Theory	102
4.5	Conclusions	103
5	Breakdown Phenomenon (F→S Transition) in Three-Phase Traffic Theory	105
5.1	Introduction	105
5.2	Breakdown Phenomenon on Homogeneous Road	106
5.2.1	Speed Breakdown at Limit Point of Free Flow	106
5.2.2	Critical Local Perturbation for Speed Breakdown	108
5.2.3	Probability for Breakdown Phenomenon	110
5.2.4	Threshold Flow Rate and Density, Metastability, and Nucleation Effects	111
5.2.5	Z-Shaped Speed–Density and Passing Probability Characteristics	114
5.2.6	Physics of Breakdown Phenomenon: Competition Between Over-Acceleration and Speed Adaptation	119
5.2.7	Physics of Threshold Point in Free Flow	120
5.2.8	Moving Synchronized Flow Pattern	122
5.3	Breakdown Phenomenon at Freeway Bottlenecks	123
5.3.1	Deterministic Local Perturbation	123
5.3.2	Deterministic F→S Transition	128
5.3.3	Physics of Deterministic Speed Breakdown at Bottleneck	133
5.3.4	Influence of Random Perturbations	133
5.3.5	Z-Characteristic for Speed Breakdown at Bottleneck	136
5.3.6	Physics of Speed Breakdown at Bottleneck	139
5.3.7	Time Delay of Speed Breakdown	140
5.4	Conclusions	142
6	Moving Jam Emergence in Three-Phase Traffic Theory ...	145
6.1	Introduction	145
6.2	Wide Moving Jam Emergence in Free Flow	147
6.3	Wide Moving Jam Emergence in Synchronized Flow	150
6.3.1	Hypothesis for Moving Jam Emergence in Synchronized Flow	150
6.3.2	Features of Metastable Synchronized Flow States	155
6.3.3	Stable High Density Synchronized Flow States	156

6.4	Double Z-Shaped Traffic Flow Characteristics	158
6.4.1	Z-Characteristic for S→J Transition	158
6.4.2	Cascade of Two Phase Transitions (F→S→J Transitions)	161
6.4.3	Wide Moving Jam Emergence Within Initial Moving Synchronized Flow Pattern . . .	167
6.5	Moving Jam Emergence in Synchronized Flow at Bottlenecks	169
6.5.1	Why Moving Jams Do not Emerge in Free Flow at Bottlenecks	169
6.5.2	Z-Characteristic for S→J Transition at Bottlenecks . .	171
6.5.3	Physics of Moving Jam Emergence in Synchronized Flow	172
6.5.4	Double Z-Characteristic and F→S→J Transitions at Bottlenecks	176
6.6	Conclusions	178
7	Congested Patterns at Freeway Bottlenecks in Three-Phase Traffic Theory	179
7.1	Introduction	179
7.2	Two Main Types of Spatiotemporal Congested Patterns	179
7.3	Simplified Diagram of Congested Patterns at Isolated Bottlenecks	180
7.4	Synchronized Flow Patterns	183
7.4.1	Influence of Fluctuations on Limit Point for Free Flow at Bottlenecks	183
7.4.2	Moving Synchronized Flow Pattern Emergence at Bottlenecks	185
7.4.3	Pinning of Downstream Front of Synchronized Flow at Bottlenecks	189
7.4.4	Transformation Between Widening and Localized Synchronized Flow Patterns	192
7.5	General Patterns	194
7.5.1	Spatiotemporal Structure of General Patterns	194
7.5.2	Dissolving General Pattern and Pattern Transformation	198
7.6	Physics of General Patterns	200
7.6.1	Region of Wide Moving Jams	200
7.6.2	Narrow Moving Jam Emergence in Pinch Region . . .	204
7.6.3	Moving Jam Suppression Effect	209
7.6.4	Width of Pinch Region	210
7.6.5	Wide Moving Jam Propagation Through Bottlenecks	211
7.7	Conclusions	213

8 Freeway Capacity in Three-Phase Traffic Theory 217

8.1 Introduction 217

8.2 Homogeneous Road 217

8.3 Freeway Capacity in Free Flow at Bottlenecks 218

8.3.1 Definition of Freeway Capacity 218

8.3.2 Probability for Speed Breakdown at Bottlenecks 220

8.3.3 Threshold Boundary for Speed Breakdown 223

8.3.4 Features of Freeway Capacity at Bottlenecks 226

8.4 Z-Characteristic and Probability for Speed Breakdown 228

8.5 Congested Pattern Capacity at Bottlenecks 232

8.6 Main Behavioral Assumptions of Three-Phase Traffic Theory 234

8.7 Conclusions 237

Part II Empirical Spatiotemporal Congested Traffic Patterns

9 Empirical Congested Patterns at Isolated Bottlenecks 241

9.1 Introduction 241

9.2 Effectual Bottlenecks and Effective Locations of Bottlenecks 242

9.2.1 Effectual Bottlenecks on Freeway A5-South 244

9.2.2 Effectual Bottlenecks on Freeway A5-North 247

9.2.3 Isolated Effectual Bottleneck 247

9.3 Empirical Synchronized Flow Patterns 250

9.3.1 Widening Synchronized Flow Pattern 250

9.3.2 Localized Synchronized Flow Pattern 255

9.3.3 Moving Synchronized Flow Pattern 256

9.4 Empirical General Patterns 259

9.4.1 Empirical General Pattern of Type (1) 259

9.4.2 Empirical General Pattern of Type (2) 262

9.4.3 Dependence of Effective Location of Bottleneck on Time 264

9.5 Conclusions 268

10 Empirical Breakdown Phenomenon: Phase Transition from Free Flow to Synchronized Flow 269

10.1 Introduction 269

10.2 Spontaneous Breakdown Phenomenon (Spontaneous $F \rightarrow S$ Transition) at On-Ramp Bottlenecks 270

10.3	Probability for F→S Transition	274
10.3.1	Empirical and Theoretical Definitions of Freeway Capacities at Bottlenecks	275
10.3.2	Pre-Discharge Flow Rate	278
10.4	Induced Speed Breakdown at On-Ramp Bottlenecks	281
10.4.1	F→S Transition Induced by Wide Moving Jam Propagation Through Effectual Bottleneck	282
10.4.2	Induced Speed Breakdown at Bottlenecks Caused by Synchronized Flow Propagation	282
10.5	Breakdown Phenomenon at Off-Ramp Bottlenecks	285
10.6	Breakdown Phenomenon Away from Bottlenecks	289
10.7	Some Empirical Features of Synchronized Flow	294
10.7.1	Complex Behavior in Flow–Density Plane	294
10.7.2	Three Types of Synchronized Flow	296
10.7.3	Overlapping States of Free Flow and Synchronized Flow in Density	299
10.7.4	Analysis of Individual Vehicle Speeds	302
10.8	Conclusions	302
11	Empirical Features of Wide Moving Jam Propagation	305
11.1	Introduction	305
11.2	Characteristic Parameters of Wide Moving Jams	305
11.2.1	Empirical Determination of Line J	306
11.2.2	Dependence of Characteristic Jam Parameters on Traffic Conditions	310
11.2.3	Propagation of Wide Moving Jams Through Synchronized Flow	311
11.2.4	Moving Blanks Within Wide Moving Jams	314
11.3	Features of Foreign Wide Moving Jams	316
11.4	Conclusions	318
12	Empirical Features of Moving Jam Emergence	321
12.1	Introduction	321
12.2	Pinch Effect in Synchronized Flow	321
12.2.1	Narrow Moving Jam Emergence	323
12.2.2	Wide Moving Jam Emergence (S→J Transition)	328
12.2.3	Correlation of Characteristics for Pinch Region and Wide Moving Jams	332
12.2.4	Frequency of Narrow Moving Jam Emergence	332
12.2.5	Saturation and Dynamic Features of Pinch Effect	334
12.2.6	Spatial Dependence of Speed Correlation Function	335

12.2.7	Effect of Wide Moving Jam Emergence in Pinch Region of General Pattern	337
12.3	Strong and Weak Congestion	337
12.4	Moving Jam Emergence in Synchronized Flow Away from Bottlenecks	340
12.5	Pattern Formation at Off-Ramp Bottlenecks	343
12.6	Induced F→J Transition	344
12.7	Conclusions	348
13	Empirical Pattern Evolution and Transformation at Isolated Bottlenecks	349
13.1	Introduction	349
13.2	Evolution of General Patterns at On-Ramp Bottlenecks	350
13.2.1	Transformation of General Pattern into Synchronized Flow Pattern	350
13.2.2	Alternation of Free Flow and Synchronized Flow in Congested Patterns	350
13.2.3	Hysteresis Effects Due to Pattern Formation and Dissolution	352
13.3	Transformations of Congested Patterns Under Weak Congestion	354
13.4	Discharge Flow Rate and Capacity Drop	357
13.5	Conclusions	363
14	Empirical Complex Pattern Formation Caused by Peculiarities of Freeway Infrastructure	365
14.1	Introduction	365
14.2	Expanded Congested Pattern	366
14.2.1	Common Features	366
14.2.2	Example of Expanded Congested Pattern	367
14.3	Dissolution of Moving Jams at Bottlenecks	369
14.3.1	Dynamics of Wide Moving Jam Outflow	369
14.3.2	Localized Synchronized Flow Patterns Resulting from Moving Jam Dissolution	371
14.4	Conclusions	372
15	Dependence of Empirical Fundamental Diagram on Congested Pattern Features	373
15.1	Introduction	373
15.1.1	Empirical Fundamental Diagram and Steady State Model Solutions	373
15.1.2	Two Branches of Empirical Fundamental Diagram	374
15.1.3	Line <i>J</i> and Wide Moving Jam Outflow	375

- 15.2 Empirical Fundamental Diagram and Line J 378
 - 15.2.1 Asymptotic Behavior of Empirical Fundamental Diagrams 378
 - 15.2.2 Influence of Different Vehicle Characteristics on Fundamental Diagrams 383
- 15.3 Dependence of Empirical Fundamental Diagram on Congested Pattern Type 385
- 15.4 Explanation of Reversed- λ , Inverted-V, and Inverted-U Empirical Fundamental Diagrams 392
- 15.5 Conclusions 394

Part III Microscopic Three-Phase Traffic Theory

- 16 Microscopic Traffic Flow Models for Spatiotemporal Congested Patterns** 399
 - 16.1 Introduction 399
 - 16.2 Cellular Automata Approach to Three-Phase Traffic Theory . 401
 - 16.2.1 General Rules of Vehicle Motion 401
 - 16.2.2 Synchronization Distance 402
 - 16.2.3 Steady States 403
 - 16.2.4 Fluctuations of Acceleration and Deceleration in Cellular Automata Models 405
 - 16.2.5 Boundary Conditions and Model of On-Ramp 407
 - 16.2.6 Summary of Model Equations and Parameters 408
 - 16.3 Continuum in Space Model Approach to Three-Phase Traffic Theory 408
 - 16.3.1 Vehicle Motion Rules 408
 - 16.3.2 Speed Adaptation Effect Within Synchronization Distance 409
 - 16.3.3 Motion State Model for Random Acceleration and Deceleration 411
 - 16.3.4 Safe Speed 413
 - 16.3.5 2D Region of Steady States 414
 - 16.3.6 Physics of Driver Time Delays 415
 - 16.3.7 Over-Acceleration and Over-Deceleration Effects ... 419
 - 16.3.8 Lane Changing Rules 420
 - 16.3.9 Boundary Conditions and Models of Bottlenecks ... 421
 - 16.3.10 Summary of Model Equations and Parameters 425
 - 16.4 Conclusions 431
- 17 Microscopic Theory of Phase Transitions in Freeway Traffic** 433
 - 17.1 Introduction 433

17.2	Microscopic Theory of Breakdown Phenomenon (F→S Transition)	434
17.2.1	Homogeneous Road	434
17.2.2	Breakdown Phenomenon at On-Ramp Bottlenecks ...	438
17.3	Moving Jam Emergence and Double Z-Shaped Characteristics of Traffic Flow	442
17.3.1	F→J Transition on Homogeneous Road	442
17.3.2	S→J Transition on Homogeneous Road	443
17.3.3	Moving Jam Emergence in Synchronized Flow Upstream of Bottlenecks	445
17.4	Conclusions	448
18	Congested Patterns at Isolated Bottlenecks	449
18.1	Introduction	449
18.2	Diagram of Congested Patterns at Isolated On-Ramp Bottlenecks	450
18.2.1	Synchronized Flow Patterns	450
18.2.2	Single Vehicle Characteristics in Synchronized Flow .	454
18.2.3	Maximum Freeway Capacities and Limit Point in Diagram	458
18.2.4	Pinch Effect in General Patterns	458
18.2.5	Peculiarities of General Patterns	462
18.3	Weak and Strong Congestion in General Patterns	464
18.3.1	Criteria for Strong and Weak Congestion	464
18.3.2	Strong Congestion Features	467
18.4	Evolution of Congested Patterns at On-Ramp Bottlenecks	469
18.5	Hysteresis and Nucleation Effects by Pattern Formation at On-Ramp Bottlenecks	471
18.5.1	Threshold Boundary for Synchronized Flow Patterns	471
18.5.2	Threshold Boundary for General Patterns	475
18.5.3	Overlap of Different Metastable Regions and Multiple Pattern Excitation	476
18.6	Strong Congestion at Merge Bottlenecks	477
18.6.1	Comparison of General Patterns at Merge Bottleneck and at On-Ramp Bottleneck	477
18.6.2	Diagram of Congested Patterns	478
18.7	Weak Congestion at Off-Ramp Bottlenecks	480
18.7.1	Diagram of Congested Patterns	480
18.7.2	Comparison of Pattern Features at Various Bottlenecks	480
18.8	Congested Pattern Capacity at On-Ramp Bottlenecks	483

- 18.8.1 Transformations of Congested Patterns
at On-Ramp Bottlenecks 483
- 18.8.2 Temporal Evolution of Discharge Flow Rate 486
- 18.8.3 Dependence of Congested Pattern Capacity
on On-Ramp Inflow 490
- 18.9 Conclusions 492
- 19 Complex Congested Pattern Interaction
and Transformation 495**
- 19.1 Introduction 495
- 19.2 Catch Effect and Induced Congested
Pattern Formation 496
- 19.2.1 Induced Pattern Emergence 496
- 19.3 Complex Congested Patterns
and Pattern Interaction 498
- 19.3.1 Foreign Wide Moving Jams 498
- 19.3.2 Expanded Congested Patterns 501
- 19.4 Intensification of Downstream Congestion
Due to Upstream Congestion 504
- 19.5 Conclusions 507
- 20 Spatiotemporal Patterns in Heterogeneous Traffic Flow ... 509**
- 20.1 Introduction 509
- 20.2 Microscopic Two-Lane Model for Heterogeneous Traffic
Flow with Various Driver Behavioral Characteristics
and Vehicle Parameters 510
- 20.2.1 Single-Lane Model 510
- 20.2.2 Two-Lane Model 512
- 20.2.3 Boundary, Initial Conditions, and Model
of Bottleneck 514
- 20.2.4 Simulation Parameters 515
- 20.3 Patterns in Heterogeneous Traffic Flow
with Different Driver Behavioral Characteristics 515
- 20.3.1 Vehicle Separation Effect in Free Flow 515
- 20.3.2 Onset of Congestion in Free Flow
on Homogeneous Road 516
- 20.3.3 Lane Asymmetric Emergence
of Moving Synchronized Flow Patterns 519
- 20.3.4 Congested Patterns at On-Ramp Bottlenecks 519
- 20.3.5 Wide Moving Jam Propagation 525
- 20.4 Patterns in Heterogeneous Traffic Flow
with Different Vehicle Parameters 528
- 20.4.1 Peculiarity of Wide Moving Jam Propagation 530
- 20.4.2 Partial Destroying of Speed Synchronization 533

20.4.3	Extension of Free Flow Recovering and Vehicle Separation	533
20.5	Weak Heterogeneous Flow	535
20.5.1	Spontaneous Onset of Congestion Away from Bottlenecks	535
20.5.2	Lane Asymmetric Free Flow Distributions	537
20.6	Characteristics of Congested Pattern Propagation in Heterogeneous Traffic Flow	538
20.6.1	Velocity of Downstream Jam Front	538
20.6.2	Flow Rate in Jam Outflow	540
20.6.3	Velocity of Downstream Front of Moving Synchronized Flow Patterns	541
20.7	Conclusions	542

Part IV Engineering Applications

21	ASDA and FOTO Models of Spatiotemporal Pattern Dynamics based on Local Traffic Flow Measurements	547
21.1	Introduction	547
21.2	Identification of Traffic Phases	548
21.3	Determination of Traffic Phases with FOTO Model	550
21.3.1	Fuzzy Rules for FOTO Model	551
21.4	Tracking Moving Jams with ASDA: Simplified Discussion	554
21.4.1	Tracking Synchronized Flow with FOTO Model	557
21.4.2	ASDA-Like Approach to Tracking Synchronized Flow	559
21.4.3	Cumulative Flow Rate Approach to Tracking Synchronized Flow	560
21.5	Conclusions	561
22	Spatiotemporal Pattern Recognition, Tracking, and Prediction	563
22.1	Introduction	563
22.2	FOTO and ASDA Application for Congested Pattern Recognition and Tracking	563
22.2.1	Validation of FOTO and ASDA Models at Traffic Control Center of German Federal State of Hessen	563
22.2.2	Application of FOTO and ASDA Models on Other Freeways in Germany and USA	565
22.3	Spatiotemporal Pattern Prediction	568
22.3.1	Historical Time Series	568

22.3.2	Database of Reproducible and Predictable Spatiotemporal Pattern Features	575
22.3.3	Vehicle Onboard Autonomous Spatiotemporal Congested Pattern Prediction	580
22.4	Traffic Analysis and Prediction in Urban Areas.....	582
22.4.1	Model for Traffic Prediction in City Networks.....	582
22.5	Conclusions.....	589
23	Control of Spatiotemporal	
	Congested Patterns	591
23.1	Introduction	591
23.2	Scenarios for Traffic Management and Control	592
23.3	Spatiotemporal Pattern Control	
	Through Ramp Metering	593
23.3.1	Free Flow Control Approach	595
23.3.2	Congested Pattern Control Approach	606
23.3.3	Comparison of Free Flow and Congested Pattern Control Approaches.....	610
23.3.4	Comparison of Different Control Rules in Congested Pattern Control Approach.....	614
23.4	Dissolution of Congested Patterns	617
23.5	Prevention of Induced Congestion	620
23.6	Influence of Automatic Cruise Control on Congested Patterns	624
23.6.1	Model of Automatic Cruise Control.....	624
23.6.2	Automatic Cruise Control with Quick Dynamic Adaptation	626
23.6.3	Automatic Cruise Control with Slow Dynamic Adaptation	628
23.7	Conclusions.....	629
24	Conclusion	631
A	Terms and Definitions	633
A.1	Traffic States, Parameters, and Variables	633
A.2	Traffic Phases	633
A.3	Phase Transitions	634
A.4	Bottleneck Characteristics	635
A.5	Congested Patterns at Bottlenecks.....	636
A.6	Local Perturbations.....	637
A.7	Critical and Threshold Traffic Variables	637
A.8	Some Features of Phase Transitions and Traffic State Stability	638

B ASDA and FOTO Models for Practical Applications 641

B.1 ASDA Model for Several Road Detectors 641

 B.1.1 Extensions of ASDA for On-Ramps, Off-Ramps, and Changing of Number of Freeway Lanes Upstream of Moving Jam 643

 B.1.2 Extensions of ASDA for On-Ramps, Off-Ramps, and Changing of Number of Freeway Lanes Downstream of Moving Jam 645

 B.1.3 FOTO Model for Several Road Detectors 646

 B.1.4 Extended Rules for FOTO Model 646

B.2 Statistical Evaluation of Different Reduced Detector Configurations 651

References 655

Index 679

Acronyms and Conventions

SP	synchronized flow pattern
MSP	moving SP
WSP	widening SP
LSP	localized SP
ASP	alternating SP
GP	general pattern
DGP	dissolving GP
AGP	alternating GP
EP	expanded congested pattern
FCD	floating car data
TCC	traffic control center
UTA	model for traffic prediction in city networks
ASDA	model for automatic tracking of moving jams
FOTO	model for automatic identification of traffic phases and tracking of synchronized flow
CA model	cellular automata traffic flow model
ALINEA	model for automatic feedback on-ramp metering
ANCONA	model for automatic on-ramp control of congested patterns at freeway bottleneck
ACC	automatic cruise control
x	spatial coordinate in direction of traffic flow
t	time
q	flow rate
ρ	vehicle density
v	vehicle speed
d	vehicle length
v_g	velocity of downstream front of wide moving jam
$q_{out}^{(J)}$	flow rate in traffic flow formed by wide moving jam outflow
q_{out}	flow rate in free flow formed by wide moving jam outflow
ρ_{min}	density in free flow formed by wide moving jam outflow

XXII Acronyms and Conventions

v_{\max}	average speed in free flow formed by wide moving jam outflow
ρ_{\max}	density within wide moving jam (jam density)
v_{\min}	average speed within wide moving jam
L_J	width (in longitudinal direction) of wide moving jam
F→S transition	phase transition from free flow to synchronized flow
F→J transition	phase transition from free flow to wide moving jam
S→J transition	phase transition from synchronized flow to wide moving jam
S→F transition	phase transition from synchronized flow to free flow
J→S transition	phase transition from wide moving jam to synchronized flow
J→F transition	phase transition from wide moving jam to free flow
F→S→J transitions	F→S transition followed by S→J transition
P_{FS}	probability for F→S transition on hypothetical homogeneous road for given observation time T_{ob} and given road length
$P_{FS}^{(B)}$	probability for F→S transition at freeway bottleneck for given observation time T_{ob}
$q_C^{(B)}$	freeway capacity in free flow at freeway bottleneck
$q_{\max}^{(free\ B)}$	maximum freeway capacity in free flow at freeway bottleneck relative to $P_{FS}^{(B)} = 1$
$q_{th}^{(B)}$	minimum freeway capacity in free flow at freeway bottleneck
$q_{FS}^{(B)}$	pre-discharge flow rate
$q_{out}^{(bottle)}$	discharge flow rate from congested pattern at freeway bottleneck
$q^{(pinch)}$	average flow rate in pinch region of GP or EP
$q_{lim}^{(pinch)}$	limiting (minimum) flow rate in pinch region of GP or EP
L_{syn}	width of synchronized flow region (in longitudinal direction) in congested pattern
q_{on}	flow rate to on-ramp
q_{in}	flow rate in free flow on main road upstream of on-ramp bottleneck
q_{sum}	flow rate downstream under free flow condition at on-ramp bottleneck
η	percentage of vehicles which want to leave main road via off-ramp
$\rho_{\max}^{(free, emp)}$	maximum density relative to empirical limit point for free flow
$q_{\max}^{(free, emp)}$	maximum flow rate relative to empirical limit point for free flow

$\rho_{\max}^{(\text{free})}$	maximum density relative to hypothetical limit point for free flow on homogeneous road
$q_{\max}^{(\text{free})}$	maximum flow rate relative to hypothetical limit point for free flow on homogeneous road
T_{av}	averaging time interval for traffic variables
T_{ob}	time interval for observing traffic flow
$T_{\text{J}}^{(\text{wide})}$	mean time between downstream fronts of wide moving jams
τ_{J}	mean duration of wide moving jams
T_{J}	mean time between narrow moving jams