Contents

1 Introduction 1

Part I Traffic Data

2 Basic Quantities of Traffic Flow 9
2.1 Speed, Density, and Flow 9
2.1.1 Microscopic View 10
2.1.2 Basic Macroscopic Quantities 11
2.2 Time Mean, Space Mean, and Edie's Definitions 12
2.3 Leutzbach Relation Between Space and Time Mean 13
2.4 Estimating Space Mean Speed by Harmonic Averages 15
2.5 Two-Dimensional Macroscopic Quantities 15
Problems 19
Additional Reading 20

3 Trajectory Data 21
3.1 Data Collection Methods 21
3.2 Time-Space Diagrams 22
3.3 Errors in Trajectory Data and How to Correct Them 25
Problems 27
Additional Reading 30

4 Floating-Car Data 31
4.1 Data Collection 31
4.2 Data Characteristics 32
4.3 Floating-Car vs. Trajectory Data 33
4.4 Extended Floating-Car Data 34
4.5 Map Matching 36
4.6 Map-Matched Floating-Car Data 37
4.7 Estimation of Flow and Density 41
4.7.1 Penetration Level and Flow Estimation 41
4.7.2 Estimation from Extended Floating-Car Data 43

Problems 45
Additional Reading 47

5 Cross-Sectional Data 49
5.1 Microscopic Measurement: Single-Vehicle Data 49
5.2 Aggregated Data 51
5.3 Estimating Spatial Quantities from Cross-Sectional Data 54
5.3.1 Estimating Space Mean Speed 55
5.3.2 Traffic Density 56
5.3.3 Traffic Density for Non-Stationary Traffic 58
5.4 Determining Speed from Single-Loop Detectors 60
5.5 Analysis of Cross-Sectional Data 61
5.5.1 Desired Speed Distribution 61
5.5.2 Distribution of Time Gaps 63
5.5.3 Time Series of Macroscopic Quantities 64
5.5.4 Spatiotemporal Analysis 66
5.5.5 Speed-Density Relation 67
5.5.6 Flow-Density Diagram 70
5.5.7 Speed-Flow Diagram 74
Problems 74
Further Reading 77

6 Spatiotemporal Determination of the Traffic State 79
6.1 Spatiotemporal Interpolation 79
6.2 Adaptive Smoothing Method 82
6.2.1 Characteristic Propagation Velocities 83
6.2.2 Nonlinear Adaptive Speed Filter 84
6.2.3 Parameters 85
6.2.4 Testing the Predictive Power: Validation 85
6.2.5 Testing the Robustness: Sensitivity Analysis 87
6.3 Data Fusion 88
6.3.1 Model-Based Validation of a Data Fusion Procedure 90
6.3.2 Weighting the Data Sources 90
Problems 93
Further Reading 93

Part II Traffic Flow Modeling

7 General Aspects 97
7.1 History and Scope of Traffic Flow Theory 97
7.2 Model Classification 98
7.2.1 Aggregation Level 99
7.2.2 Mathematical Structure 102
7.2.3 Other Criteria 103
Problems 106
Further Reading 106

8 Continuity Equation 109
8.1 Traffic Density and Hydrodynamic Flow-Density Relation 109
8.2 Continuity Equations for Several Road Profiles 112
8.2.1 Homogeneous Road Section 112
8.2.2 Sections with On- and Off-Ramps 114
8.2.3 Changes in the Number of Lanes 115
8.2.4 Discussion 117
8.3 Continuity Equation from the Driver's Perspective 118
8.4 Lagrangian Description 121
Problems 124

9 The Lighthill-Whitham-Richards Model 127
9.1 Model Equations 127
9.2 Propagation of Density Variations 129
9.3 Shock Waves 130
9.3.1 Formation 130
9.3.2 Derivation of the Propagation Velocity 132
9.3.3 Vehicle Speed Versus Propagation Velocities 134
9.4 LWR Models with the Greenshields Fundamental Diagram 136
9.5 Numerical Solution of LWR Models 137
9.5.1 Cell-Transmission Model 138
9.6 LWR Models with Triangular Fundamental Diagram 142
9.6.1 Model Parameters 144
9.6.2 Characteristic Properties 144
9.6.3 Model Formulation with Measurable Quantities 148
9.6.4 Relation to Car-Following Models 149
9.6.5 Definition of Road Sections 151
9.6.6 Modeling Bottlenecks 152
9.6.7 Solving the Triangular LWR Model 158
9.6.8 Examples 163
9.7 Diffusion and Burgers' Equation 171
Problems 173
Further Reading 176

10 Macroscopic Models with Dynamic Velocity 177
10.1 Macroscopic Acceleration Function 177
10.2 Properties of the Acceleration Function 179
10.2.1 Steady-State Flow 179
10.2.2 Plausibility Conditions 180
10.3 General Form of the Model Equations 182
10.3.1 Local Speed Adaptation 182
10.3.2 Nonlocal Anticipation 183
10.3.3 Limiting Case of Zero Adaptation Time 184
10.3.4 Pressure Term 184
10.3.5 Diffusion Terms 186

15 Lane-Changing and Discrete-Choice Situations 327
15.1 Overview 327
15.2 General Decision Model 329
15.3 Lane Changes 331
15.3.1 Safety Criterion 331
15.3.2 Incentive Criterion for Egoistic Drivers 332
15.3.3 Lane Changes with Courtesy: MOBIL Model 334
15.3.4 Tactical Aspects: Mandatory Lane Changes and Cooperation 335
15.3.5 Continuous Lane Changing: Trajectory Planning 336
15.4 Application to Car-Following Models 338
15.5 Approaching a Traffic Light 343
15.6 Intersections 346
15.7 Overtaking on a Lane for Opposite Traffic 351
15.8 Considerations on Numerical Implementation 353
15.8.1 Race Condition 353
15.8.2 Summary of Numerical Update Steps 354
Problems 355
Further Reading 357

16 Stability Analysis 359
16.1 Formation of Stop-and-Go Waves 359
16.2 Mathematical Classification of Traffic Flow Instabilities 361
16.3 Local Stability 370
16.3.1 Single Leader-Follower Pair 372
16.3.2 More Than One Follower 375
16.3.3 Models with Delay 376
16.4 String Stability of Car-Following Models 376
16.4.1 String Stability Criteria 377
16.4.2 Extension to Multi-Anticipation 385
16.4.3 String Stability for Open Systems: Transfer Function 387
16.4.4 Application to Specific Car-Following Models 391
16.5 Flow Stability of Macroscopic Models 400
16.5.1 Generalized Linear Formulation of Second-Order Models 400
16.5.2 Linear Stability Analysis 401
16.5.3 Application to Specific Macroscopic Models 405
16.6 Convective Instability and Signal Velocities 408
16.7 Nonlinear Instability and the Stability Diagram 413
16.8 Stability Classes 415
16.9 Short-Wavelength Collective Instabilities 418
Problems 419
Further Reading 421

17 Calibration and Validation 423
17.1 Introduction 423
17.2 General Aspects 425
17.2.1 Mathematical Principles 425
17.2.2 Objective Function 431
17.2.3 Nonlinear Optimization 434
17.2.4 Data 438
17.2.5 Intra-Driver and Inter-Driver Variations 442
17.2.6 Assessing Models 443
17.2.7 Implementing and Running a Calibration 445
17.3 Calibration to Microscopic Observations 445
17.3.1 Data Preparation 446
17.3.2 Local Approach 449
17.3.3 Global or Indirect Approach 455
17.3.4 Platoon Calibration 456
17.3.5 Estimation Errors 459
17.3.6 Calibrating Stochastic Car-Following Models 460
17.3.7 Calibrating Lane Changes 462
17.4 Calibration to Macroscopic Observations 463
17.4.1 Time Series of Stationary Detector Data 464
17.4.2 Global Macroscopic Observations 469
17.5 Validation 474
Problems 479
Further Reading 480

18 The Phase Diagram of Congested Traffic States 481
18.1 From Ring Roads to Open Systems 481
18.2 Analysis of Traffic Patterns: Dynamic Phase Diagram 483
18.2.1 Stability Class 1 484
18.2.2 Stability Class 2 487
18.2.3 Stability Class 3 489
18.3 Simulating Congested Traffic Patterns and the Phase Diagram 489
18.4 Reality Check: Observed Patterns of Traffic Jams 493
Problems 494
Further Reading 494

19 Pedestrian Traffic Flow 495
19.1 General Remarks 495
19.2 Macroscopic Models for Unidirectional Flow 496
19.2.1 First-Order LWR-Type Models 497
19.2.2 Fundamental Diagram and Directed Flows 499
19.3 The Social Force Model 500
19.3.1 Self-Driving Force and Destination Floor Field 501
19.3.2 Interaction Forces 503
19.3.3 Directionality 513

19.3.4 Forces by Obstacles and Boundaries 516
19.3.5 Extension of the SFM: Physical Forces 518
19.3.6 Fundamental Diagram 519
19.3.7 Numerical Integration 523
19.4 An Alternative, Energy-Minimizing Approach 524
19.4.1 Free Flow 524
19.4.2 Constraints by Other Pedestrians and Obstacles 525
19.4.3 Advantages and Disadvantages of the PLE Model 526
19.5 Two-Dimensional Cellular Automata 527
19.5.1 Free-Flow Dynamics 528
19.5.2 Dynamics with Interactions 529
Problems 530
Further Reading 532

20 Disordered Traffic Flow 533
20.1 General Remarks 533
20.2 Macroscopic Models for Disordered Flows 536
20.2.1 An Effectively One-Dimensional First-Order Model 537
20.2.2 Application to Mass-Sports Events: Vasaloppet 538
20.3 Intelligent Agent Model 541
20.3.1 Self-Driving Forces 542
20.3.2 Interaction Forces 543
20.3.3 Boundary Forces and Floor Fields 546
20.3.4 Model Parameters and Driving Style 547
20.3.5 Numerical Integration 548
20.4 Simulation Examples 549
20.4.1 Lane-Based City Traffic 549
20.4.2 Lane-Free Bicycle Traffic 553
Problems 556
Further Reading 556

Part III Applications of Traffic Flow Theory

21 Traffic Flow Breakdown and Traffic-State Recognition 561
21.1 Traffic Flow Breakdown: Three Ingredients to Make a Traffic Jam 561
21.2 Do Phantom Traffic Jams Exist? 567
21.3 Stylized Facts of Congested Traffic 569
21.4 Empirical Reality: Complex Patterns 571
21.5 Fundamentals of Traffic State Estimation 572
Problems 574
Further Reading 575

22 Travel Time Estimation 577
22.1 Definitions of Travel Time 577
22.2 The Method of Trajectories 578

22.3 Method of Accumulated Vehicle Counts 579
22.4 A Hybrid Method 581
22.5 Virtual Stationary Detectors 583
22.6 Virtual Trajectories 583
22.7 Instantaneous Travel Time 585
Problems 586
Further Reading 588

23 Fuel Consumption, Energy Demand, and Emissions 589
23.1 Overview 589
23.1.1 Macroscopic Models 591
23.1.2 Microscopic Models 592
23.1.3 Relation Between Fuel Consumption and CO_2 Emissions 593
23.2 Speed-Profile Emission Models 593
23.3 Modal Emission Models 595
23.3.1 General Remarks 595
23.3.2 Phenomenological Models 596
23.3.3 Load-Based/Physics-Based Models 597
23.3.4 A Physics-Based Modal Consumption Model in Detail 598
23.3.5 Output Quantities of Modal Emission Models 606
23.4 Electric Vehicles 609
23.4.1 Characteristic Map of Electrical Motors and Generators 611
23.4.2 Driving the Vehicle 613
23.4.3 Charging the Battery 613
23.4.4 Power Demand and Range for Typical Driving Patterns 614
Problems 619
Further Reading 623

24 Dynamic Routing 625
24.1 Load Balancing 625
24.2 Dynamic Route Choice Modeling 627
24.2.1 Network of Two Alternatives 627
24.2.2 User Equilibrium and System Optimum 628
24.2.3 Logit Model for Route Choice 629
24.3 Macroscopic Approach 631
24.3.1 Model Specification 631
24.3.2 Simulating Routing Oscillations 633
24.4 Microscopic Approach 640
24.4.1 Model Specification 641
24.4.2 Microscopic Simulation Results 641
Problems 643
Further Reading 644

25 Model-Based Traffic Flow Optimization 645
25.1 Basic Principles 645
25.2 Speed Limits 647
25.3 Ramp Metering 650
25.4 Efficient Driving Behavior and Adaptive Cruise Control 653
25.5 Traffic-Light Assistance Systems 657
25.5.1 Suitable Models and Calibration 658
25.5.2 Early Braking 659
25.5.3 Early Start 660
25.5.4 Flying Start 661
25.5.5 Assessing the Performance 663
25.6 Further Local Traffic Regulations 664
25.7 Objective Functions for Traffic Flow Optimization 665
25.7.1 Setting up the Frame 665
25.7.2 Constraining Conditions 666
25.7.3 Examples 667
Further Reading 670

Solutions to the Problems 671

Index 771