

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	36
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	46
5.3.2	Weighting the Data Sources	49
	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	57
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	69
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	88
8.4	Numerical Solution	90
8.5	LWR Models with Triangular Fundamental Diagram	91
8.5.1	Model Parameters	93
8.5.2	Characteristic Properties	94
8.5.3	Model Formulation with Measurable Quantities	97
8.5.4	Relation to Car-Following Models	98
8.5.5	Definition of Road Sections	100
8.5.6	Modeling Bottlenecks	101
8.5.7	Numerical Solution of the Cell-Transmission Model	106
8.5.8	Solving the Section-Based Model	109

8.5.9	Examples	114
8.6	Diffusion and Burgers' Equation	122
	Problems	124
9	Macroscopic Models with Dynamic Velocity	127
9.1	Macroscopic Acceleration Function	127
9.2	Properties of the Acceleration Function	129
9.2.1	Steady-State Flow	129
9.2.2	Plausibility Conditions	130
9.3	General Form of the Model Equations	131
9.3.1	Local Speed Adaptation	132
9.3.2	Nonlocal Anticipation	132
9.3.3	Limiting Case of Zero Adaptation Time	134
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	138
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	144
9.5.1	Overview	144
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	149
9.5.6	Numerical Diffusion	152
	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	164
10.5.1	Highway Scenario	166
10.5.2	City scenario	167
10.6	Optimal Velocity Model	168
10.7	Full Velocity Difference Model	171
10.8	Newell's Car-Following Model	173
	Problems	177

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	184
11.2.4	Model Characteristics	185
11.3	Intelligent Driver Model	187
11.3.1	Required Model Properties	187
11.3.2	Mathematical Description	188
11.3.3	Parameters	189
11.3.4	Intelligent Braking Strategy	190
11.3.5	Dynamical Properties	192
11.3.6	Steady-State Equilibrium	195
11.3.7	Improved Acceleration Function	195
11.3.8	Model for Adaptive Cruise Control	198
	Problems	201
12	Modeling Human Aspects of Driving Behavior	205
12.1	Man vs. 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	224
13	Cellular Automata	227
13.1	General Remarks	227
13.2	Nagel-Schreckenberg Model	231
13.3	Refined Models	234
13.3.1	Barlovic Model	234
13.3.2	KKW Model	235
13.4	Comparison of Cellular Automata and Car-Following Models	238
	Problems	239
14	Lane-Changing and other Discrete-Choice Situations	241
14.1	Overview	241
14.2	General Decision Model	242
14.3	Lane Changes	244

14.3.1	Safety Criterion	244
14.3.2	Incentive Criterion for Egoistic Drivers	245
14.3.3	Lane Changes with Courtesy: MOBIL Model	246
14.3.4	Application to Car-Following Models	247
14.4	Approaching a Traffic Light	252
14.5	Entering a Priority Road	254
	Problems	255
15	Stability Analysis	259
15.1	Formation of Stop-and-Go Waves	259
15.2	Mathematical Classification of Traffic Flow Instabilities	261
15.3	Local Instability	269
15.4	String Instability	273
15.4.1	String Instability Conditions for Car-Following Models	274
15.4.2	Flow Stability of Macroscopic Models	280
15.4.3	Application to Specific Models	285
15.5	Convective Instability and Signal Velocities	290
15.6	Nonlinear Instability and the Stability Diagram	295
15.7	Stability Classes	297
15.8	Short-Wavelength Collective Instabilities	299
	Problems	300
16	Calibration and Validation	305
16.1	General Aspects	306
16.1.1	Mathematical Principles	306
16.1.2	Nonlinear Optimization	309
16.1.3	Assessing Models	313
16.1.4	Implementing and Running a Calibration	315
16.2	Calibration to Microscopic Observations	316
16.2.1	Data Preparation	317
16.2.2	Global Approach	319
16.2.3	Local Approach	323
16.3	Calibration to Macroscopic Observations	327
16.3.1	Fitting Local Properties of Traffic Flow	327
16.3.2	Calibration to Global Properties	330
16.4	Validation	335
	Problems	339
17	The Phase Diagram of Congested Traffic States	341
17.1	From Ring Roads to Open Systems	341
17.2	Analysis of Traffic Patterns: Dynamic Phase Diagram	342
17.2.1	Stability Class 1	344
17.2.2	Stability Class 2	347
17.2.3	Stability Class 3	348
17.3	Simulating Congested Traffic Patterns and the Phase Diagram	349

17.4 Reality Check: Observed Patterns of Traffic Jams	352
Problems	353

Part III Applications of Traffic Flow Theory

18 Traffic Flow Breakdown and Traffic-State Recognition	357
18.1 Traffic Flow Breakdown: Three Ingredients to Make a Traffic Jam ..	357
18.2 Do Phantom Traffic Jams exist?	362
18.3 Stylized Facts of Congested Traffic	364
18.4 Empirical Reality: Complex Patterns	365
18.5 Fundamentals of Traffic State Estimation	366
Problems	368
19 Travel Time Estimation	369
19.1 Definitions of Travel Time	369
19.2 The Method of Trajectories	370
19.3 The Method of Accumulated Vehicle Counts	371
19.4 A Hybrid Method	373
19.5 Virtual Stationary Detectors	375
19.6 Virtual Trajectories	375
19.7 Instantaneous Travel Time	377
Problems	378
20 Fuel Consumption and Emissions	381
20.1 Overview	381
20.1.1 Macroscopic Models	382
20.1.2 Microscopic Models	384
20.1.3 Relation Between Fuel Consumption and CO ₂ Emissions ..	385
20.2 Speed-Profile Emission Models	385
20.3 Modal Emission Models	387
20.3.1 General Remarks	387
20.3.2 Phenomenological Models	388
20.3.3 Load-Based Models	389
20.4 Physics-Based Modal Consumption Model	390
20.4.1 Driving Resistance	390
20.4.2 Engine Power	392
20.4.3 Consumption Rate	393
20.4.4 Characteristic Map for Engine Efficiency	394
20.4.5 Output Quantities	395
20.4.6 Aggregation to a Macroscopic Modal Consumption Model ..	398
Problems	399

21 Model-Based Traffic Flow Optimization	405
21.1 Basic Principles	405
21.2 Speed Limits	407
21.3 Ramp Metering	409
21.4 Dynamic Routing	413
21.5 Efficient Driving Behavior and Adaptive Cruise Control	414
21.6 Further Local Traffic Regulations	417
21.7 Objective Functions for Traffic Flow Optimization	419
21.7.1 Setting up the Frame	419
21.7.2 Constraining Conditions	420
21.7.3 Examples	421
Solutions to the Problems	425
Index	491