

Martin Treiber • Arne Kesting

Traffic Flow Dynamics

Data, Models and Simulation

Second Edition

 Springer

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

10.3.6	On- and Off-Ramp Terms	187
10.3.7	Lane Closings and Openings	188
10.4	Overview of Second-Order Models	188
10.4.1	Payne's Model	189
10.4.2	Kerner-Konhäuser Model	191
10.4.3	Gas-Kinetic Based Traffic Model	193
10.5	Numerical Solution	197
10.5.1	Overview	197
10.5.2	Upwind and McCormack Scheme	199
10.5.3	Approximating Nonlocalities	200
10.5.4	Boundary Conditions	200
10.5.5	Criteria for Selecting a Numerical Integration Scheme	202
10.5.6	Numerical Instabilities	203
10.5.7	Numerical Diffusion	207
	Problems	208
	Further Reading	210
11	Elementary Car-Following Models	211
11.1	General Remarks	211
11.2	Mathematical Description	213
11.3	Numerical Integration	216
11.4	Steady State Equilibrium and the Fundamental Diagram	218
11.5	Heterogeneous Traffic	219
11.6	Fact Sheet of Dynamical Model Characteristics	220
11.6.1	Highway Scenario	220
11.6.2	City Scenario	223
11.7	Optimal Velocity Model	224
11.8	Full Velocity Difference Model	227
11.9	Newell's Car-Following Model	229
11.10	Linear Control Model	234
	Problems	236
	Further Reading	238
12	Car-Following Models Based on Driving Strategies	239
12.1	Model Criteria	239
12.2	Gipps' Model	241
12.2.1	Original Formulation	243
12.2.2	A Simplified Version	248
12.2.3	Steady-State Equilibrium	249
12.2.4	Model Characteristics	251
12.3	Intelligent Driver Model	252
12.3.1	Required Model Properties	253
12.3.2	Mathematical Description	254
12.3.3	Parameters	254
12.3.4	Intelligent Braking Strategy	257

12.3.5	Dynamical Properties	259
12.3.6	Steady-State Equilibrium	261
12.4	Variants of the Intelligent Driver Model	262
12.4.1	Improved Acceleration Function	262
12.4.2	IDM Plus	265
12.5	Models for Adaptive Cruise Control	266
12.5.1	Controlling Overreactions to Discontinuous Input	266
12.5.2	Jerk Control	269
12.5.3	Upper-Level and Lower-Level Control	271
12.6	Stochastic Models and Indifference Regions	273
12.6.1	Stochastic Processes for Acceleration and Parameter Noise	274
12.6.2	Numerical Implementation of the Stochastic Processes	276
12.6.3	Indifference Regions and the IDM-2d	277
12.6.4	Simulations of Platoon Experiments	279
	Problems	281
	Further Reading	284
13	Modeling Human Aspects of Driving Behavior	285
13.1	Man vs. Machine	285
13.2	Reaction Times	287
13.3	Estimation Errors and Imperfect Driving Capabilities	290
13.3.1	Modeling Estimation Errors	290
13.3.2	Modeling Imperfect Driving	292
13.4	Temporal Anticipation	293
13.5	Multi-Vehicle Anticipation	294
13.6	Brake Lights and Further Exogenous Factors	297
13.7	Local Traffic Context	298
13.8	Action Points	300
13.9	Wiedemann Car-Following Model	301
13.9.1	Wiedemann-74 Model Equations	303
13.9.2	Wiedemann-99 Model Equations	305
13.9.3	Simulations and Discussion	307
	Problems	309
	Further Reading	309
14	Cellular Automata	311
14.1	General Remarks	311
14.2	Nagel-Schreckenberg Model	316
14.3	Refined Models	319
14.3.1	Barlovic Model	319
14.3.2	KKW Model	320
14.4	Comparison of Cellular Automata and Car-Following Models	323
	Problems	324
	Further Reading	325

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