

Contents

1	Introduction	7
2	Timetable Design Principles	9
2.1	The Purpose of Scheduling	9
2.2	Basic Terms of Railway Operation	9
2.3	Diagramming Traffic.....	14
2.4	Scheduled Running Time.....	16
2.5	Modelling Train Paths	17
2.5.1	Principles of Train Separation.....	17
2.5.2	Application of the Blocking Time Model.....	19
2.5.3	Modelling Specific Signalling Systems	23
2.5.4	Modelling Interlockings and Overlaps	26
2.5.5	An Alternative Approach: The Protected Zone Model	27
2.6	Headways and Buffer Times	29
2.7	Consumed Capacity.....	33
2.8	Scheduling Methods	35
2.8.1	Manual Scheduling	35
2.8.2	Computer-based Scheduling	36
2.9	Clockface Timetables	37
3	Infrastructure Modelling.....	43
3.1	Introduction.....	43
3.2	Graph Theory and its Application	44
3.3	Macroscopic Models.....	46
3.4	Microscopic Models.....	48
3.5	Differences between Infrastructure Models	51
3.6	Migration between Infrastructure Models	52
3.7	Application of Infrastructure Models.....	54
3.8	Outlook	56
4	Running Time Estimation.....	58
4.1	Introduction.....	58
4.1.1	Fundamentals.....	58
4.1.2	Speed Profile	59
4.2	Infrastructure and Train Data	61
4.2.1	Tractive Effort FT.....	61
4.2.2	Vehicle resistances	62
4.2.3	Line Resistances FRI	64
4.2.4	Combining Efforts and Resistances, Rotating Masses	64
4.3	Moving Sections	65
4.3.1	Characteristic Sections.....	66
4.3.2	Behaviour Sections.....	66
4.4	Modelling Running Time Calculations	67

Contents

4.4.1	Determination of Braking and Acceleration Sections.....	67
4.4.2	Modelling the Train as a Mass Point	69
4.4.3	Modelling the Train as a Homogeneous Strip.....	71
4.5	Solving the Differential Equations by a Difference Equation Approach	72
4.6	Solving the Differential Equations Analytically	74
4.6.1	Traction effort depends piecewise parabolically on speed.....	75
4.6.2	Traction depends hyperbolically on speed	76
4.6.3	Passing a section	78
4.7	Solving the Differential Equations by Gauss Quadrature	
	Integral Formulae	79
4.8	A Probabilistic Approach.....	80
4.9	Calculating Blocking Times.....	81
5	Energy-Efficient Train Operation.....	83
5.1	Minimisation of Mechanical Energy Consumption	83
5.1.1	Energy-Efficient Driving in Undisturbed Operation.....	83
5.1.2	Energy-Efficient Driving in Disturbed Operation.....	89
5.1.3	Operational Requirements for Energy-Efficient Driving	90
5.2	Optimisation under Practical Billing Systems	91
5.2.1	Energy Supply and Billing	91
5.2.2	Optimisation under Train-Based Billing Systems	94
5.2.3	Optimisation under Substation-Based Billing Systems.....	95
5.3	Measures to Introduce Energy-Efficient Driving.....	96
5.3.1	Driver Training	96
5.3.2	Driver Support Systems.....	97
5.3.3	Automatic Train Operation	104
5.4	Conclusions	104
6	Queueing.....	106
6.1	Introduction.....	106
6.2	Scheduled waiting times on railway lines.....	108
6.3	Set of tracks as multiple server queues	113
6.4	Estimating knock-on delays.....	113
6.5	Summary and future prospects	116
7	Timetable Stability Analysis.....	118
7.1	Introduction.....	118
7.2	Stability.....	119
7.3	Max-Plus Algebra	120
7.4	Max-Plus Modelling.....	122
7.4.1	The Higher-Order Max-Plus Model	122
7.4.2	The First-Order Max-Plus Model.....	124
7.5	Critical Circuit Analysis.....	126
7.6	Recovery Time Analysis.....	128
7.7	Delay Propagation	129
7.8	Conclusions	132

8	Optimisation Models for Railway Timetabling	135
8.1	Introduction.....	135
8.2	Cyclic Timetabling	136
8.2.1	A mathematical formulation	137
8.2.2	Example	138
8.2.3	Objectives	140
8.2.4	Solving PESP	140
8.2.5	Solution of the example.....	141
8.3	Robust timetabling	142
8.3.1	Notation	142
8.3.2	Timetabling part of the model.....	143
8.3.3	Simulation part of the model.....	144
8.3.4	Results and timetable experiment in practise.....	145
8.4	Routing Trains through Railway Stations.....	146
8.4.1	The routing problem	146
8.4.2	Platform assignment issues	147
8.4.3	Finding a feasible routing.....	148
8.4.4	Robust routing.....	148
8.5	Final remarks	151
9	Simulation.....	155
9.1	Basics of Railway Simulation.....	155
9.2	Methods of Simulation.....	156
9.2.1	Synchronous Simulation	156
9.2.2	Asynchronous Simulation and other Methods.....	159
9.3	Use of Simulation for Timetable construction	160
9.3.1	Further Aspects of Simulation	162
9.3.2	Simulation of Special Traffic	162
9.4	Simulation of Operation.....	163
9.5	Benefits of Simulation.....	165
9.6	Conclusion and Outlook	168
10	Statistical Analysis of Train Delays	170
10.1	Introduction.....	170
10.2	Train delays and punctuality	171
10.3	Data preparation.....	172
10.4	Selection of statistical distributions.....	173
10.5	Common approaches to parameter estimation.....	174
10.6	Testing the goodness-of-fit.....	175
10.7	Assessing distribution models by fine-tuning the parameters.....	176
10.8	Further remarks and future research	179

Contents

11	Rescheduling.....	182
11.1	The Purpose of Rescheduling.....	182
11.2	Current rescheduling practice.....	183
11.3	Conflict detection.....	184
11.4	Conflict resolution.....	184
11.4.1	Dispatching based on asynchronous simulation.....	184
11.4.2	Dispatching based on synchronous simulation.....	187
11.4.3	Outlook on simulation models.....	187
11.4.4	Optimisation methods.....	187
11.4.5	Rule based methods.....	188
11.4.6	Knowledge based methods.....	189
12	Performance Evaluation.....	192
12.1	Impact of Organisational Reforms.....	192
12.2	Aims of Performance Evaluation.....	192
12.3	Methods of Performance Evaluation.....	194
12.3.1	General Remarks.....	194
12.3.2	Applying Effectiveness and Efficiency as Indicators.....	194
12.3.3	Assessing Punctuality.....	195
12.3.4	Use of Capacity Research.....	199
12.3.5	Infrastructure Investments.....	203
12.4	Conclusion and Further Development.....	206
13	Conclusions.....	209
	The Authors.....	213
	Glossary.....	217
	Keywords.....	225