Railway Transportation Systems

Design, Construction and Operation

CHRISTOS N. PYRGIDIS
Aristotle University of Thessaloniki, Greece
## Contents

Preface xxi  
Acknowledgements xxiii  
Author xxv  
Symbols and Abbreviations xxvii  

1 The railway as a transport system 1  

1.1 Definition 1  
1.2 Constituents 1  
1.2.1 Railway infrastructure 1  
1.2.2 Rolling stock 5  
1.2.3 Railway operation 8  
1.3 The railway system technique 9  
1.3.1 Description of the system 9  
1.3.2 Fundamental functional principles 11  
1.3.2.1 Running on a straight path 13  
1.3.2.2 Running in curves 14  
1.3.3 Distinctive features of railway systems compared to road means of transport 14  
1.4 Classification of railway systems 15  
1.4.1 Speed in railway engineering: Design and operational considerations 15  
1.4.2 Classification of railway systems based on functionality 17  
1.4.3 Classification of railway systems based on track gauge 27  
1.4.4 Classification of railway systems based on traffic 28  
1.5 The capabilities of the railway system 29  
1.5.1 Advantages and disadvantages of the railway 29  
1.5.2 Comparison of the characteristics of railway systems 33  
1.5.3 Comparison of the capabilities of different transportation systems 33  
1.5.3.1 Comparison of air and high-speed train transport 37  
1.5.3.2 Comparison of urban systems 37  
1.6 Historical overview of the railway and future perspectives 37  

References 39
2 Loads on track

2.1 Classification of loads 41

2.2 Vertical loads on track 42

2.2.1 Static vertical loads 46

2.2.1.1 Axle load 46

2.2.1.2 Wheel weight 47

2.2.1.3 Daily traffic load 47

2.2.2 Quasi-static vertical loads 48

2.2.2.1 Vertical wheel load due to crosswinds 48

2.2.2.2 Vertical wheel load due to residual centrifugal force 49

2.2.3 Dynamic vertical loads 50

2.2.3.1 Dynamic vertical wheel load 50

2.2.3.2 Total vertical wheel load 51

2.2.3.3 Design vertical wheel load 52

2.2.3.4 Design loads of bridges 52

2.3 Transversal loads on track 54

2.3.1 Gravitational forces 55

2.3.2 Creep forces 57

2.3.2.1 Running on straight path 57

2.3.2.2 Running in curves 59

2.3.3 Crosswind forces 60

2.3.4 Residual centrifugal force 61

2.3.5 Guidance forces 63

2.3.6 Forces due to vehicle oscillations 64

2.3.7 Total transversal force 64

2.4 Longitudinal forces 65

2.4.1 Temperature forces 65

2.4.2 Rail creep forces 67

2.4.3 Braking forces: Acceleration forces 68

2.4.4 Traction forces: Adhesion forces 69

2.4.5 Fishplate forces 72

References 73

3 Behaviour of rolling stock on track

3.1 Behaviour of a single railway wheelset 77

3.1.1 Movement on straight path 77

3.1.2 Movement in curves 77

3.2 Behaviour of a whole vehicle 78

3.2.1 Operational and technical characteristics of bogies 78

3.2.1.1 Object and purposes of bogies 78

3.2.1.2 Conventional bogies 79

3.2.1.3 Bogies with self-steering wheelsets 83

3.2.1.4 Bogies with independently rotating wheels 84

3.2.1.5 Bogies with creep-controlled wheelsets 85

3.2.1.6 Bogies with wheels with mixed behaviour 86
3.2.2 Wheel rolling conditions and bogies inscription behaviour in curves 86
3.2.3 Lateral behaviour of a whole vehicle 89
  3.2.3.1 Vehicles with conventional bogies 90
  3.2.3.2 Vehicles with bogies with self-steering wheelsets 92
  3.2.3.3 Vehicles with independently rotating wheels 93
  3.2.3.4 Comparative assessment 94
3.2.4 Selection of bogie design characteristics based on operational aspects of networks 94
  3.2.4.1 High-speed networks 94
  3.2.4.2 Conventional speed networks 95
  3.2.4.3 Mountainous networks 95
  3.2.4.4 Metro networks 95
  3.2.4.5 Tramway networks 96

3.3 Derailment of railway vehicles 96
  3.3.1 Definition 96
  3.3.2 Derailment through displacement of track 98
  3.3.3 Derailment as a result of vehicle overturning 98
  3.3.4 Derailment with wheel climb 99
    3.3.4.1 Description of the phenomenon 99
    3.3.4.2 Derailment criteria 99
    3.3.4.3 Factors affecting derailment 100

References 101

4 Tramway 103

  4.1 Definition and description of the system 103
  4.2 Classification of tramway systems 103
    4.2.1 Physical characteristics of the corridor 103
    4.2.2 Functional/operational criteria 107
    4.2.3 Floor height of the vehicles 109
      4.2.3.1 Low floor 109
      4.2.3.2 Very low floor 110
      4.2.3.3 Moderately high floor 110
      4.2.3.4 High floor 111
    4.2.4 Power supply system 111
    4.2.5 Other classifications 111
  4.3 Constructional and operational characteristics of the system 112
    4.3.1 Data related to track alignment and track superstructure 112
    4.3.2 Rolling stock data 115
    4.3.3 Tramway signalling system and traffic control 115
    4.3.4 Transport capacity of the system 116
    4.3.5 Travel time and commercial speeds 116
    4.3.6 Cost of implementing a tramway 118
  4.4 Integration of tramway corridors across the road arteries 119
    4.4.1 Types of integration of tramway corridors 119
      4.4.1.1 A single track per direction at two
                      opposite sides of the road 120
4.4.1.2 Double track on one side of the road 120
4.4.1.3 Central alignment 120
4.4.2 Geometric features of the integration of tramway corridors 122
4.4.2.1 Technical and total tramway infrastructure right-of-way 122
4.4.2.2 Geometric integration of tramway corridors at curved sections of roads in the horizontal alignment 124

4.5 Integration of stops 125
4.5.1 Types of stops integration 125
4.5.2 Geometric and operational features of tramway stop integration 131
4.5.2.1 Geometric criteria 131
4.5.2.2 Operational criteria 133

4.6 Tramway depot facilities 133
4.6.1 General description and operational activities 133
4.6.1.1 Parking area/yard 134
4.6.1.2 Maintenance hall/workshop 134
4.6.1.3 Vehicle cleaning/washing area 135
4.6.2 Classification of tramway depots 135
4.6.3 Main design principles and selection of a ground plan area 135

4.7 Requirements for implementing the system 138
4.8 Applicability verification of alternative alignments 140
4.8.1 Verification of track alignment and geometric integration 141
4.8.2 Verification of impact on other transport modes 145
4.8.2.1 Roadside land uses 145
4.8.2.2 Pedestrians 145
4.8.2.3 Operation of other public transport modes 146
4.8.2.4 Road traffic 146
4.8.3 Verification of environmental impacts 147
4.8.3.1 Noise pollution 147
4.8.3.2 Visual annoyance 148
4.8.3.3 Impact on the urban space 148
4.8.3.4 Impact on safety 149
4.8.3.5 Impact during construction 149
4.8.4 Applicability verification of operational efficiency 149
4.8.4.1 Verification of commercial speed 149
4.8.4.2 Verification of passenger transport volume 151
4.8.4.3 Verification of operating cost ($K_{op}$) 153
4.8.5 Applicability verification of a tramway depot 153
4.8.6 Verification of implementation cost 155

4.9 Historical overview and present situation 155
4.9.1 Historical overview 155
4.9.1.1 The first horse-drawn tram 155
4.9.1.2 The transition period from the horse-drawn tram to electrification 156
4.9.1.3 The development of electric trams 156
4.9.1.4 The period of dismantling of tram networks 156
4.9.1.5 Restoration and reintegration of tramway systems 156
4.9.2 Present situation 157

References 159

5 Metro 161

5.1 Definition and description of the system 161
5.2 Classification of metro systems 161
  5.2.1 Transport capacity 161
  5.2.2 Grade of automation of their operation 162
  5.2.3 Guidance system 164
  5.2.4 Other classification categories 165
5.3 Constructional and operational characteristics of a metro system 165
  5.3.1 Track layout 166
  5.3.2 Track superstructure 166
  5.3.3 Tunnels 171
  5.3.4 Rolling stock 173
  5.3.5 Operation 173
    5.3.5.1 Commercial speeds, service frequency and service reliability 174
    5.3.5.2 Fare collection and ticket supply 175
    5.3.5.3 Revenues for the system operator 176
  5.3.6 Implementation cost 176
5.4 Metro stations 177
  5.4.1 Location selection for metro stations 178
  5.4.2 Construction depth of metro stations 179
  5.4.3 Construction methods 180
    5.4.3.1 Construction of the station's shell 180
    5.4.3.2 Surface construction 181
    5.4.3.3 Number of station levels 182
    5.4.3.4 Station architecture 183
  5.4.4 Platforms 184
    5.4.4.1 Layout of platforms 184
    5.4.4.2 Platform dimensions 185
5.5 Depot facilities 187
5.6 Requirements for implementing the system 190
5.7 Historical overview and present situation 191
  5.7.1 Historical overview 191
  5.7.2 Present situation 191

References 194

6 Monorail 197

6.1 Definition and description of the system 197
6.2 Classification of the monorails and techniques of the system 197
  6.2.1 Train placement on the guidebeam 197
  6.2.2 Transport capacity 198
  6.2.3 System techniques 200
6.3 Constructional and operational characteristics of the system 200
   6.3.1 Permanent way 200
   6.3.2 Rolling stock 202
   6.3.3 Operation 203
6.4 Advantages and disadvantages of monorail systems 204
   6.4.1 Advantages 204
   6.4.2 Disadvantages 204
6.5 Requirements for implementing the system 204
6.6 Historical overview and present situation 205
   6.6.1 Historical overview 205
   6.6.2 Present situation 205
References 207

7 Automatic passenger transport railway systems of low- and medium-transport capacity 209
   7.1 Definition 209
   7.2 Cable-propelled railway systems 209
      7.2.1 General description and classification 209
      7.2.2 Constructional and operational features of the systems 211
         7.2.2.1 System 'principles' and superstructure configurations 211
         7.2.2.2 Guideway 215
      7.2.3 Advantages and disadvantages 215
      7.2.4 Requirements for implementing the system 217
   7.3 Self-propelled electric systems 218
      7.3.1 General description and classification 218
      7.3.2 Battery-powered systems 221
      7.3.3 Outside power feeding systems 223
References 225

8 Suburban railway 227
   8.1 Definition and classification of suburban railway systems 227
   8.2 Constructional and operational characteristics of the system 227
   8.3 Advantages and disadvantages of the suburban railway 230
      8.3.1 Advantages 230
      8.3.2 Disadvantages 230
   8.4 Requirements for implementing the system 230
   8.5 Applicability verification of the system 231
      8.5.1 Operation of suburban trains on existing infrastructure 232
         8.5.1.1 Constructional features of the railway infrastructure 232
         8.5.1.2 Passenger transport volume 233
         8.5.1.3 System operability 233
         8.5.1.4 The station service level 234
         8.5.1.5 Availability of the depot facilities 235
         8.5.1.6 Environmental impacts 235
         8.5.1.7 Implementation cost 235
8.5.2 Operation of suburban trains on new infrastructure 235
8.5.2.1 Constructional features of the railway infrastructure 235
8.5.2.2 Passenger transport volume 236
8.5.2.3 Location, construction and operation of the depot facilities 236
8.5.2.4 Environmental impacts 236
8.5.2.5 Implementation cost 236

References 236

9 Rack railway 237

9.1 Definition and description of the system 237
9.2 Classification of rack railway systems 237
9.2.1 Type of cog rail 237
9.2.2 Type of adhesion along the line 242
9.3 Evolution of the system and application examples 243
9.4 Constructional and operational features of rack railway systems 243
9.4.1 Track alignment 243
9.4.2 Track superstructure 244
9.4.3 Rolling stock 246
9.4.4 Operation 247
9.5 Advantages and disadvantages of rack railway systems 248
9.6 Requirements for implementing the system 249
References 250

10 Cable railway systems for steep gradients 251

10.1 Definition and description of the system 251
10.2 The funicular 252
10.2.1 Evolution of funiculars and application examples 252
10.2.2 Constructional and operational features of funiculars 253
10.2.2.1 Infrastructure 253
10.2.2.2 Rolling stock 258
10.2.2.3 Operation 259
10.3 The inclined elevator 259
10.4 Advantages and disadvantages of cable railway systems for steep gradients 261
10.5 Requirements for implementing the system 261
References 262

11 Organisation and management of passenger interurban railway transport 263

11.1 Services and basic design principles 263
11.2 Service level of interurban passenger railway transport: Quality parameters 264
11.3 Scheduling of passenger train services 265
11.4 Selection and purchase of rolling stock 266
11.4.1 Step 1: Assessment of the existing situation 267
11.4.2 Step 2: Determination of the target year 267
11.4.3 Step 3: Assessment of the situation in the target year 269
11.4.4 Step 4: Determination of the transport volume target 271
11.4.5 Step 5: Determination of the service frequency target 273
11.4.6 Step 6: New train timetable scheme 273
11.4.7 Step 7: Checks on corridor track capacity and transport volume 274
11.4.8 Step 8: In theory: Required rolling stock for the performance of scheduled services 274
11.4.9 Step 9: Practically required rolling stock 275
11.4.10 Step 10: Required rolling stock 277

References 277

12 High-speed trains 279

12.1 Distinction between high speeds and conventional speeds 279
12.2 High-speed train issues 280
12.3 Specifications and technical solutions for the achievement of high speeds 284
12.3.1 Track geometry alignment characteristics 284
12.3.1.1 Selection of horizontal alignment radii 284
12.3.1.2 Distance between track centres 285
12.3.1.3 Longitudinal slopes 287
12.3.2 Track superstructure components 287
12.3.3 Civil engineering structures 287
12.3.3.1 Tunnel traffic 287
12.3.3.2 Passage under bridges 289
12.3.3.3 Track fencing 291
12.3.3.4 Noise barriers 291
12.3.3.5 Handling aerodynamic effects in an 'open' track and on platforms 293
12.3.4 Track systems 293
12.3.5 Rolling stock 293
12.3.5.1 Aerodynamic design of vehicles 293
12.3.5.2 Design of bogies 294
12.3.5.3 Braking system 295
12.3.5.4 Vehicle design: Construction 295
12.3.5.5 Implementation cost 295
12.4 Historical review and current situation of high-speed networks and trains 295
12.5 Interoperability issues 301

References 307

13 Tilting trains 309

13.1 Definition and function principle of tilting technology 309
13.2 Tilting techniques and systems 312
13.2.1 Passive tilting 312
13.2.2 Active tilting 312
13.3 Main constructional and operational characteristics of tilting trains 314
13.3.1 Performances in terms of speed 314
13.3.2 Tilting angle 316
13.3.3 Track gauge 316
13.3.4 Axle load 316
13.3.5 Track superstructure 316
13.3.6 Bogies technology 316
13.3.7 Train formation 316
13.3.8 Signalling 316
13.3.9 Traction 316
13.3.10 Cost of rolling stock supply 317
13.4 Requirements for implementing the system 317
13.4.1 Existing conventional-speed infrastructure 317
13.4.2 New conventional-speed infrastructure 319
13.4.3 New high-speed infrastructure 319
13.5 Historic overview and present situation 319
References 322

14 Metric track gauge interurban railway networks 323
14.1 Definition and description of the system 323
14.2 General overview of metric gauge interurban railway networks 324
14.3 Main constructional characteristics of interurban metric track gauge lines 326
14.3.1 Track alignment: Differences between tracks of metric and normal gauge 326
14.3.2 Track superstructure 328
14.4 Advantages and disadvantages of interurban metric gauge lines 330
14.5 Requirements for implementing the system 330
References 332

15 Organisation and management of freight railway transport 335
15.1 Services and cargo movement 335
15.2 Service level of freight railway transport: Quality parameters 336
15.3 Scheduling of freight train services 337
15.4 Combined transport 337
15.5 Mass transport 341
15.6 Transportation of dangerous goods 344
15.6.1 Differentiation from the rest of freight transport services 344
15.6.2 Creation of safe transport conditions 344
15.6.3 Special measures to protect the environment 345
References 345

16 Heavy haul rail transport 347
16.1 Definition and general description of the system 347
16.2 The international market in heavy haul rail transport 347
16.3 Differences between conventional and heavy haul freight railway networks 348
16.4 Impacts of heavy haul rail operations and main design principles 348
   16.4.1 Selection of track infrastructure components 351
      16.4.1.1 Selection of the track's alignment geometric characteristics 351
      16.4.1.2 Selection of rails 351
      16.4.1.3 Selection of the type of sleepers and the distances between them 352
      16.4.1.4 Selection and dimensioning of track bed layer features 352
      16.4.1.5 Construction principles of the formation layer 353
      16.4.1.6 Dimensioning of bridges 354
      16.4.1.7 Dimensioning of the signalling system 354
   16.4.2 Effects on the rolling stock 354
   16.4.3 Effects on the operation 354
16.5 Economic efficiency of heavy haul rail transport 355
References 359

17 Impact of traffic composition on the economic profitability of a railway system 361
   17.1 Traffic composition and classification of railway networks/corridors 361
   17.2 Economic profitability and classification of railway networks/corridors 362
   17.3 The problem of mixed traffic operation 365
   17.4 Investigation of the impact of traffic composition on the economic profitability of a railway system 368
      17.4.1 Data published by the railway networks 368
      17.4.2 Mathematical simulation 369
         17.4.2.1 Selection of the operational framework for a new railway corridor 369
         17.4.2.2 Selection of the operating framework for an existing railway corridor 372
   References 374

18 Railway safety 377
   18.1 Types of railway incidents and definition of railway safety 377
      18.1.1 Types of railway incidents 377
      18.1.2 Definition of railway safety 377
         18.1.2.1 Risk level 377
         18.1.2.2 Incident 'indicators' 379
      18.2 Significance of safety in railway systems and differences in road safety 380
         18.2.1 Significance of safety in railway systems 380
         18.2.2 Distinctions between railway and road safety 380
      18.3 Classification of railway incidents 381
      18.4 Causes of railway incidents 381
      18.5 Safety in civil engineering structures 385
         18.5.1 Railway civil engineering structures and related incidents 385
         18.5.2 Safety at railway bridges 385
18.5.3 Safety in railway tunnels 387
18.5.4 Safety at road overpasses 387
18.5.5 Safety on embankments 389
18.5.6 Safety in cuttings 390
18.6 Safety at railway stations 390
18.7 Safety on the 'open' track 391
   18.7.1 Potential risks 391
   18.7.2 Safety measures 391
18.8 Safety at RLCs 393
18.9 Correlation between the cost of interventions and the safety level improvement 397
   18.9.1 General approach 397
   18.9.2 The change in the value of accident indicators 398
   18.9.3 The change in the risk level 400
       18.9.3.1 Characterisation of the frequency of a particular incident 401
       18.9.3.2 Characterisation of the severity of a particular incident 402

References 404

19 Railway and the natural environment 407
19.1 Natural environment of the railway 407
19.2 Energy consumption 408
   19.2.1 Definition: Units expressing energy consumption 408
   19.2.2 Energy-consuming railway activities 408
   19.2.3 Special features of each railway system category 409
   19.2.4 Measures for energy consumption reduction 410
19.3 Air pollution 411
   19.3.1 Definition: Expression units of air pollution 411
   19.3.2 Railway activities causing air pollution 411
   19.3.3 Special features of each railway system category 412
   19.3.4 Measures for air pollution reduction 413
19.4 Soil and water pollution 414
   19.4.1 Definition: Measurement methods of soil and water pollution 414
   19.4.2 Railway activities causing soil pollution 415
   19.4.3 Special features of each railway system category 415
   19.4.4 Countermeasures against the pollution of soil due to the presence of the railway 415
19.5 Visual annoyance 416
   19.5.1 Definition: Measurement methods of visual annoyance 416
   19.5.2 Railway activities causing visual annoyance 416
   19.5.3 Special features of each railway system category 417
   19.5.4 Countermeasures against visual annoyance caused by the presence of the railway 417
19.6 Integration of the track into the landscape 418
   19.6.1 Definition: Measurement indices of integration 418
19.6.2 Railway activities causing a change of landscape 418
19.6.3 Special features of each railway system category 419
19.6.4 Measures for smooth integration of the railway into the landscape 419

19.7 Ecosystem disturbance 420
19.7.1 Definition: Indices of expression of ecosystem disturbance 420
19.7.2 Railway activities causing ecosystem disturbance 420
19.7.3 Special features of each railway system category 420
19.7.4 Reduction measures of ecosystem disturbance 420

19.8 Disturbance of local resident activities: Access restriction and disruption of urban space 422
19.8.1 Definition: Measurement indices of disturbance on local resident activities 422
19.8.2 Railway activities causing disturbance on local resident activities 422
19.8.3 Special features of each railway system category 422
19.8.4 Measures for the reduction of disturbance caused to local residential activities due to the presence of railway infrastructure 423

19.9 Acoustic annoyance 424
19.9.1 Definition: Units of expression of acoustic annoyance 424
19.9.2 Railway activities causing acoustic annoyance 425
19.9.3 Special features of each category of railway systems 425
19.9.4 Countermeasures against acoustic annoyance 427
19.9.4.1 The path of noise transmission 427
19.9.4.2 The source of noise 428

19.10 Ground-borne noise and vibrations 429
19.10.1 Definition: Measurement units of ground-borne noise and vibrations 429
19.10.2 Railway activities causing and affecting ground-borne noise and vibrations 432
19.10.3 Special features of each category of railway systems 434
19.10.4 Countermeasures against vibrations and ground-borne noise 434

19.11 Impacts on land use 436
19.12 Comparative assessment of the impacts of various means of transport to the natural environment 436
19.12.1 Methodology approach 436
19.12.2 Long distances: Comparison between the aeroplane and the high-speed train 436
19.12.3 Urban transport: Comparing the metro, tram, urban bus and private car 438
19.12.4 High-speed transport modes: Comparisons of the aeroplane, the high-speed train and the magnetic levitation train 439
19.12.5 Freight transport: Comparison of freight trains and road trucks 440

References 440

20 Cutting-edge technologies in railways 443
20.1 Definition and classification of cutting-edge technologies 443
20.2 Smart windows 443
20.3 Carbon and glass fibres 446
20.4 Laser railhead cleaner system 447
20.5 Catenary-free power supply of tramway systems 447
  20.5.1 Ground power supply systems 449
    20.5.1.1 The APS system 449
    20.5.1.2 The TramWave system 453
    20.5.1.3 The PRIMOVE system 454
  20.5.2 Power supply systems with energy storage devices 456
    20.5.2.1 Supercapacitor charging/ESS
        (supercapacitors or ultracapacitors) 457
    20.5.2.2 Charging/ESS with batteries 459

References 460

Index 463