## Contents

1 **Modeling Transportation Systems: Preliminary Concepts and Application Areas** .............................................. 1  
   1.1 Introduction ............................................................................. 1  
   1.2 Transportation Systems ......................................................... 1  
   1.3 Transportation System Identification ..................................... 5  
       1.3.1 Relevant Spatial Dimensions ......................................... 6  
       1.3.2 Relevant Temporal Dimensions ..................................... 9  
       1.3.3 Relevant Components of Travel Demand ...................... 13  
   1.4 Modeling Transportation Systems ......................................... 17  
   1.5 Model Applications and Transportation Systems Engineering 20  
       1.5.1 Transportation Systems Design and the Decision-Making  
            Process ........................................................................... 20  
       1.5.2 Some Areas of Application .......................................... 24  
   Reference Notes ........................................................................ 27

2 **Transportation Supply Models** ............................................ 29  
   2.1 Introduction ........................................................................... 29  
   2.2 Fundamentals of Traffic Flow Theory .................................... 29  
       2.2.1 Uninterrupted Flows ....................................................... 30  
           2.2.1.1 Fundamental Variables ........................................ 30  
           2.2.1.2 Model Formulation .............................................. 32  
       2.2.2 Queuing Models ............................................................. 36  
           2.2.2.1 Fundamental Variables ........................................ 37  
           2.2.2.2 Deterministic Models ......................................... 39  
           2.2.2.3 Stochastic Models .............................................. 43  
   2.3 Congested Network Models .................................................... 45  
       2.3.1 Network Structure ......................................................... 45  
       2.3.2 Flows ........................................................................... 46  
       2.3.3 Performance Variables and Transportation Costs .......... 48  
       2.3.4 Link Performance and Cost Functions ......................... 53  
       2.3.5 Impacts and Impact Functions ..................................... 54  
       2.3.6 General Formulation ..................................................... 55  
   2.4 Applications of Transportation Supply Models ...................... 56  
       2.4.1 Supply Models for Continuous Service Transportation  
            Systems ........................................................................... 59  
           2.4.1.1 Graph Models ....................................................... 59  
           2.4.1.2 Link Performance and Cost Functions .................. 61  
       2.4.2 Supply Models for Scheduled Service Transportation  
            Systems ........................................................................... 82  
           2.4.2.1 Line-based Graph Models .................................... 83  
           2.4.2.2 Link Performance and Cost Functions ................. 83  
   Reference Notes ........................................................................ 87
### 3 Random Utility Theory

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Introduction</td>
<td>89</td>
</tr>
<tr>
<td>3.2</td>
<td>Basic Assumptions</td>
<td>89</td>
</tr>
<tr>
<td>3.3</td>
<td>Some Random Utility Models</td>
<td>90</td>
</tr>
<tr>
<td>3.3.1</td>
<td>The Multinomial Logit Model</td>
<td>95</td>
</tr>
<tr>
<td>3.3.2</td>
<td>The Single-Level Hierarchical Logit Model</td>
<td>100</td>
</tr>
<tr>
<td>3.3.3</td>
<td>The Multilevel Hierarchical Logit Model*</td>
<td>107</td>
</tr>
<tr>
<td>3.3.4</td>
<td>The Cross-nested Logit Model*</td>
<td>115</td>
</tr>
<tr>
<td>3.3.5</td>
<td>The Generalized Extreme Value (GEV) Model*</td>
<td>118</td>
</tr>
<tr>
<td>3.3.6</td>
<td>The Probit Model</td>
<td>121</td>
</tr>
<tr>
<td>3.3.7</td>
<td>The Mixed Logit Model*</td>
<td>130</td>
</tr>
<tr>
<td>3.4</td>
<td>Expected Maximum Perceived Utility and Mathematical Properties of Random Utility Models</td>
<td>133</td>
</tr>
<tr>
<td>3.5</td>
<td>Choice Set Modeling</td>
<td>139</td>
</tr>
<tr>
<td>3.6</td>
<td>Direct and Cross-elasticities of Random Utility Models</td>
<td>143</td>
</tr>
<tr>
<td>3.7</td>
<td>Aggregation Methods for Random Utility Models</td>
<td>148</td>
</tr>
<tr>
<td>3.A</td>
<td>Derivation of Logit Models from the GEV Model</td>
<td>152</td>
</tr>
<tr>
<td>3.A.1</td>
<td>Derivation of the Multinomial Logit Model</td>
<td>153</td>
</tr>
<tr>
<td>3.A.2</td>
<td>Derivation of the Single-Level Hierarchical Logit Model</td>
<td>154</td>
</tr>
<tr>
<td>3.A.3</td>
<td>Derivation of the Multilevel Hierarchical Logit Model</td>
<td>156</td>
</tr>
<tr>
<td>3.A.4</td>
<td>Derivation of the Cross-nested Logit Model</td>
<td>159</td>
</tr>
<tr>
<td>3.B.1</td>
<td>The Gumbel Random Variable</td>
<td>161</td>
</tr>
<tr>
<td>3.B.2</td>
<td>The Multivariate Normal Random Variable</td>
<td>164</td>
</tr>
<tr>
<td></td>
<td>Reference Notes</td>
<td>166</td>
</tr>
</tbody>
</table>

### 4 Travel-Demand Models

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Introduction</td>
<td>169</td>
</tr>
<tr>
<td>4.2</td>
<td>Trip-based Demand Model Systems</td>
<td>172</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Random Utility Models for Trip Demand</td>
<td>176</td>
</tr>
<tr>
<td>4.3</td>
<td>Examples of Trip-based Demand Models</td>
<td>181</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Models of Spatial and Temporal Characteristics</td>
<td>181</td>
</tr>
<tr>
<td>4.3.1.1</td>
<td>Trip Production or Trip Frequency Models</td>
<td>181</td>
</tr>
<tr>
<td>4.3.1.2</td>
<td>Distribution Models</td>
<td>185</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Mode Choice Models</td>
<td>192</td>
</tr>
<tr>
<td>4.3.3</td>
<td>Path Choice Models</td>
<td>195</td>
</tr>
<tr>
<td>4.3.3.1</td>
<td>Path Choice Models for Road Networks</td>
<td>197</td>
</tr>
<tr>
<td>4.3.3.2</td>
<td>Path Choice Models for Transit Systems</td>
<td>207</td>
</tr>
<tr>
<td>4.3.4</td>
<td>A System of Demand Models</td>
<td>215</td>
</tr>
<tr>
<td>4.4</td>
<td>Trip-Chaining Demand Models</td>
<td>219</td>
</tr>
<tr>
<td>4.5</td>
<td>Activity-Based Demand Models</td>
<td>228</td>
</tr>
<tr>
<td>4.5.1</td>
<td>A Theoretical Reference Framework</td>
<td>231</td>
</tr>
<tr>
<td>4.5.1.1</td>
<td>Weekly Household Activity Model</td>
<td>232</td>
</tr>
<tr>
<td>4.5.1.2</td>
<td>Daily Household Activity Model</td>
<td>233</td>
</tr>
<tr>
<td>4.5.1.3</td>
<td>Daily Individual Activity List Model</td>
<td>234</td>
</tr>
<tr>
<td>4.5.1.4</td>
<td>Activity Pattern and Trip-Chain Models</td>
<td>234</td>
</tr>
</tbody>
</table>
4.6 Applications of Demand Models .............................................. 235
4.7 Freight Transportation Demand Models ................................. 238
  4.7.1 Multiregional Input–Output (MRIO) models ....................... 240
  4.7.2 Freight Mode Choice Models ........................................... 253
Reference Notes ................................................................. 255

5 Basic Static Assignment to Transportation Networks .................. 259
  5.1 Introduction ........................................................................ 259
  5.1.1 Classification of Assignment Models ................................. 259
  5.1.2 Fields of Application of Assignment Models ...................... 263
  5.2 Definitions, Assumptions, and Basic Equations ...................... 265
  5.2.1 Supply Model .................................................................. 266
  5.2.2 Demand Model .................................................................. 269
  5.2.3 Feasible Path and Link Flow Sets ..................................... 274
  5.2.4 Network Performance Indicators ...................................... 275
  5.3 Uncongested Networks ......................................................... 278
  5.3.1 Models for Stochastic Assignment ..................................... 280
  5.3.2 Models for Deterministic Assignment ............................... 283
  5.3.3 Algorithms Without Explicit Path Enumeration .................. 286
  5.4 Congested Networks: Equilibrium Assignment ........................ 304
  5.4.1 Models for Stochastic User Equilibrium ............................ 307
  5.4.2 Algorithms for Stochastic User Equilibrium ....................... 313
  5.4.3 Models for Deterministic User Equilibrium ....................... 318
  5.4.4 Algorithms for Deterministic User Equilibrium .................. 324
  5.4.5 Relationship Between Stochastic and Deterministic Equilibrium . 329
  5.4.6 System Optimum Assignment ........................................... 331
  5.5 Result Interpretation and Parameter Calibration ..................... 338
  5.5.1 Specification and Calibration of Assignment Models ............. 341
  5.A Optimization Models for Stochastic Assignment .................... 341
  5.A.1 Uncongested Network: Stochastic Assignment .................... 342
  5.A.2 Congested Network: Stochastic User Equilibrium ................. 342
Reference Notes ...................................................................... 344
  Assignment Models ............................................................... 344
  Assignment Algorithms .......................................................... 346

6 Advanced Models for Traffic Assignment to Transportation Networks .......................................................... 349
  6.1 Introduction ........................................................................ 349
  6.2 Assignment with Pre-trip/En-route Path Choice ...................... 349
    6.2.1 Definitions, Assumptions, and Basic Equations ................. 349
    6.2.2 Uncongested Networks .................................................. 357
    6.2.3 Congested Networks: Equilibrium Assignment .................. 363
  6.3 Equilibrium Assignment with Variable Demand ..................... 367
    6.3.1 Single-Mode Assignment ................................................ 368
| 6.3.1.1 Models for Stochastic User Equilibrium | 372 |
| 6.3.1.2 Models for Deterministic User Equilibrium | 375 |
| 6.3.1.3 Algorithms | 379 |
| 6.3.2 Multimode Equilibrium Assignment | 385 |
| 6.4 Multiclass Assignment | 389 |
| 6.4.1 Undifferentiated Congestion Multiclass Assignment | 392 |
| 6.4.2 Differentiated Congestion Multiclass Assignment | 394 |
| 6.5 Interperiod Dynamic Process Assignment | 396 |
| 6.5.1 Definitions, Assumptions, and Basic Equations | 398 |
| 6.5.2 Deterministic Process Models | 403 |
| 6.5.3 Stochastic Process Models | 410 |
| 6.6 Synthesis and Application Issues | 419 |
| Reference Notes | 419 |

7 Intraperiod (Within-Day) Dynamic Models* 421

7.1 Introduction 421
7.2 Supply Models for Transport Systems with Continuous Service 423
7.2.1 Space-Discrete Macroscopic Models 426
7.2.1.1 Variables and Consistency Conditions 426
7.2.1.2 Network Flow Propagation Model 435
7.2.1.3 Link Performance and Travel Time Functions 438
7.2.1.4 Dynamic Network Loading 439
7.2.1.5 Path Performance and Travel Time Functions 440
7.2.1.6 Formalization of the Whole Supply Model 442
7.2.2 Mesoscopic Models 443
7.2.2.1 Variables and Consistency Conditions 444
7.2.2.2 Link Performance and Travel Time Functions 447
7.2.2.3 Path Performance and Travel Time Functions 448
7.2.2.4 Dynamic Network Loading 449
7.2.2.5 Formalization of the Whole Supply Model 450
7.3 Demand Models for Continuous Service Systems 451
7.4 Demand–Supply Interaction Models for Continuous Service Systems 455
7.4.1 Uncongested Network Assignment Models 455
7.4.2 User Equilibrium Assignment Models 458
7.4.3 Dynamic Process Assignment Models 461
7.5 Dynamic Traffic Assignment with Nonseparable Link Cost Functions and Queue Spillovers 464
7.5.1 Network Performance Model 467
7.5.1.1 Exit Capacity Model 472
7.5.1.2 Exit Flow and Travel Time Model 473
7.5.1.3 Entry Capacity Model 475
7.5.1.4 Fixed-Point Formulation of the NPM ............... 477
7.5.2 Network Loading Map and Fixed-Point Formulation of the
Equilibrium Model ..................................... 477
7.6 Models for Transport Systems with Scheduled Services .......... 480
  7.6.1 Models for Regular Low-Frequency Services ........... 482
    7.6.1.1 Supply Models ............................... 482
    7.6.1.2 Demand Models ................................. 487
    7.6.1.3 Demand–Supply Interaction Models ........... 489
  7.6.2 Models for Irregular High-Frequency Services .......... 489
    7.6.2.1 Supply Models ................................. 489
    7.6.2.2 Demand Models ................................. 490
    7.6.2.3 Demand–Supply Interaction Models ........... 495
7.A The Simplified Theory of Kinematic Waves Based on Cumulative
Flows: Application to Macroscopic Link Performance Models .... 497
  7.A.1 Bottlenecks ...................................... 499
  7.A.2 Segments .......................................... 501
Reference Notes .............................................. 510

8 Estimation of Travel Demand Flows .......................... 513
  8.1 Introduction .......................................... 513
  8.2 Direct Estimation of Present Demand ....................... 514
    8.2.1 Sampling Surveys ................................ 514
    8.2.2 Sampling Estimators .............................. 516
  8.3 Disaggregate Estimation of Demand Models .................. 520
    8.3.1 Model Specification ................................ 521
    8.3.2 Model Calibration .................................. 522
    8.3.3 Model Validation .................................. 530
  8.4 Disaggregate Estimation of Demand Models with Stated
Preference Surveys* ....................................... 536
    8.4.1 Definitions and Types of Survey .................. 537
    8.4.2 Survey Design ..................................... 538
    8.4.3 Model Calibration .................................. 545
  8.5 Estimation of O-D Demand Flows Using Traffic Counts ........ 549
    8.5.1 Maximum Likelihood and GLS Estimators ........... 555
    8.5.2 Bayesian Estimators ................................ 560
    8.5.3 Application Issues ................................ 562
    8.5.4 Solution Methods .................................. 564
  8.6 Aggregate Calibration of Demand Models Using Traffic Counts ... 569
  8.7 Estimation of Within-Period Dynamic Demand Flows Using
Traffic Counts ........................................... 574
    8.7.1 Simultaneous Estimators ............................ 578
    8.7.2 Sequential Estimators .............................. 579
  8.8 Real-Time Estimation and Prediction of Within-Period Dynamic
Demand Flows Using Traffic Counts .......................... 580
  8.9 Applications of Demand Estimation Methods .................. 582
9 Transportation Supply Design Models ........................................... 589
  9.1 Introduction ................................................................. 589
  9.2 General Formulations of the Supply Design Problem .............. 592
  9.3 Applications of Supply Design Models .............................. 595
    9.3.1 Models for Road Network Layout Design ....................... 596
    9.3.2 Models for Road Network Capacity Design ...................... 598
    9.3.3 Models for Transit Network Design .............................. 602
    9.3.4 Models for Pricing Design ....................................... 604
    9.3.5 Models for Mixed Design ...................................... 606
  9.4 Some Algorithms for Supply Design Models ....................... 607
    9.4.1 Algorithms for the Discrete SDP ............................... 607
    9.4.2 Algorithms for the Continuous SDP ............................. 614
  Reference Notes ............................................................. 619

10 Methods for the Evaluation and Comparison of Transportation
  System Projects ........................................................................ 621
  10.1 Introduction .................................................................. 621
  10.2 Evaluation of Transportation System Projects .................. 622
    10.2.1 Identification of Relevant Impacts ............................ 623
    10.2.2 Identification and Estimation of Impact Indicators ........ 626
    10.2.3 Computation of Users’ Surplus Changes ...................... 628
  10.3 Methods for the Comparison of Alternative Projects ........... 641
    10.3.1 Benefit-Cost Analysis ............................................ 641
    10.3.2 Revenue-Cost Analysis ........................................... 647
    10.3.3 Multi-criteria Analysis .......................................... 648
      10.3.3.1 Noncompensatory Methods* ................................ 658
      10.3.3.2 Multiattribute Utility Theory Method (MAUT)* ........ 660
      10.3.3.3 Linear Additive Methods* .................................. 665
      10.3.3.4 The Analytical Hierarchy Process (AHP)* ............... 667
      10.3.3.5 Outranking Methods* ........................................ 673
      10.3.3.6 Constrained Optimization Method* ....................... 677
  Reference Notes ................................................................. 680

Appendix A Review of Numerical Analysis ....................................... 683
  A.1 Sets and Functions ....................................................... 683
    A.1.1 Elements of Set Topology ....................................... 683
    A.1.2 Continuous and Differentiable Functions .................... 685
    A.1.3 Convex Functions ................................................. 689
  A.2 Solution Algorithms ..................................................... 690
  A.3 Fixed-Point Problems ................................................... 691
    A.3.1 Properties of Fixed-Points ..................................... 693
    A.3.2 Solution Algorithms for Fixed-Point Problems ............. 695
Contents

A.4 Optimization Problems .................................................. 697
  A.4.1 Properties of Minimum Points ........................................ 697
    A.4.1.1 Properties of Minimum Points on Open Sets .............. 697
    A.4.1.2 Properties of Minimum Points on Closed Sets .......... 698
  A.4.2 Solution Algorithms for Optimization Problems ............... 699
    A.4.2.1 Monodimensional Optimization Algorithms .............. 699
    A.4.2.2 Unconstrained Multidimensional Optimization
      Algorithms ..................................................... 703
    A.4.2.3 Bounded Variables Multidimensional
      Optimization Algorithms .................................. 706
    A.4.2.4 Linearly Constrained Multidimensional
      Optimization Algorithms ................................. 707
A.5 Variational Inequality Problems ...................................... 709
  A.5.1 Properties of Variational Inequalities ........................... 711
  A.5.2 Solution Algorithms for Variational Inequality Problems ... 712

Index ...................................................................................... 715

References .............................................................................. 725
Transportation Systems Analysis
Models and Applications
Cascetta, E.
2009, XVIII, 742 p. 100 illus., Hardcover