Public Transit Planning and Operation
Public Transit Planning and Operation
Theory, modelling and practice

Avishai (Avi) Ceder
Civil and Environmental Faculty, Transportation Research Institute, Technion-Israel Institute of Technology, Haifa, Israel

Cartoons: Avishai (Avi) Ceder
# Contents

Preface xiii

## Chapter 1 Introduction to Transit Service Planning 1
1.1 Motivation 2
1.2 The operational planning decomposition process 4
1.3 Service and evaluation standards and their derivatives 9
1.4 Viability perspectives 13
1.5 Outline of other chapters 16
References 18

## Chapter 2 Data Requirements and Collection 21
2.1 Introduction 23
2.2 Data-collection techniques 24
2.3 Data requirements 27
2.4 Basic statistical tools 30
2.5 Literature review and further reading 37
References 41

## Chapter 3 Frequency and Headway Determination 49
3.1 Introduction 51
3.2 Max load (point check) methods 52
3.3 Load profile (ride check) methods 56
3.4 Criterion for selecting point check or ride check 60
3.5 Conclusion (two examples) 64
3.6 Literature review and further reading 73
Exercises 79
References 80

## Chapter 4 Timetable Development 81
4.1 Introduction 83
4.2 Objectives, optional timetables and comparison measures 84
4.3 Even headways with smooth transitions 90
4.4 Headways with even average loads 94
4.5 Automation, test runs and conclusion 98
4.6 Literature review and further reading 113
<table>
<thead>
<tr>
<th>Chapter 5</th>
<th>Advanced Timetables I: Maximum Passenger Load</th>
<th>119</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>Introduction</td>
<td>121</td>
</tr>
<tr>
<td>5.2</td>
<td>Even max load on individual vehicles</td>
<td>121</td>
</tr>
<tr>
<td>5.3</td>
<td>Optimization, operations research and complexity</td>
<td>127</td>
</tr>
<tr>
<td>5.4</td>
<td>Minimum passenger-crowding timetables for a fixed vehicle fleet</td>
<td>130</td>
</tr>
<tr>
<td>Exercise</td>
<td></td>
<td>137</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td>137</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 6</th>
<th>Advanced Timetables II: Maximum Synchronization</th>
<th>139</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>Introduction</td>
<td>141</td>
</tr>
<tr>
<td>6.2</td>
<td>Formulating an OR model for synchronization</td>
<td>142</td>
</tr>
<tr>
<td>6.3</td>
<td>The Synchro-1 Procedure</td>
<td>145</td>
</tr>
<tr>
<td>6.4</td>
<td>The Synchro-2 Procedure</td>
<td>146</td>
</tr>
<tr>
<td>6.5</td>
<td>Examples</td>
<td>148</td>
</tr>
<tr>
<td>6.6</td>
<td>Literature review and further reading</td>
<td>154</td>
</tr>
<tr>
<td>Exercises</td>
<td></td>
<td>159</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td>161</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 7</th>
<th>Vehicle Scheduling I: Fixed Schedules</th>
<th>163</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1</td>
<td>Introduction</td>
<td>165</td>
</tr>
<tr>
<td>7.2</td>
<td>Fleet size required for a single route</td>
<td>168</td>
</tr>
<tr>
<td>7.3</td>
<td>Example of an exact solution for multi-route vehicle scheduling</td>
<td>170</td>
</tr>
<tr>
<td>7.4</td>
<td>Max-flow technique for fixed vehicle scheduling</td>
<td>172</td>
</tr>
<tr>
<td>7.5</td>
<td>Deficit-function model with deadheading trip insertion</td>
<td>176</td>
</tr>
<tr>
<td>7.6</td>
<td>Depot-constrained vehicle scheduling</td>
<td>188</td>
</tr>
<tr>
<td>7.7</td>
<td>Literature review and further reading</td>
<td>193</td>
</tr>
<tr>
<td>Exercises</td>
<td></td>
<td>196</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td>198</td>
</tr>
<tr>
<td>Appendix 7.A: The maximum-flow (max-flow) problem</td>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 8</th>
<th>Vehicle Scheduling II: Variable Schedules</th>
<th>207</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1</td>
<td>Introduction</td>
<td>209</td>
</tr>
<tr>
<td>8.2</td>
<td>Fleet-size lower bound for fixed schedules</td>
<td>210</td>
</tr>
<tr>
<td>8.3</td>
<td>Variable trip-departure times</td>
<td>214</td>
</tr>
<tr>
<td>8.4</td>
<td>Fleet-size lower bound for variable schedules</td>
<td>220</td>
</tr>
<tr>
<td>8.5</td>
<td>Fleet-reduction procedures</td>
<td>223</td>
</tr>
<tr>
<td>8.6</td>
<td>Experiences with bus schedules</td>
<td>229</td>
</tr>
<tr>
<td>8.7</td>
<td>Examination and consideration of even-load timetables</td>
<td>233</td>
</tr>
<tr>
<td>Exercises</td>
<td></td>
<td>237</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td>240</td>
</tr>
<tr>
<td>Appendix 8.A: Deficit-function software</td>
<td>241</td>
<td></td>
</tr>
</tbody>
</table>
### Chapter 9  Vehicle-type and Size Considerations in Vehicle Scheduling 249

9.1 Introduction 251
9.2 Optimization framework 251
9.3 Procedure for vehicle scheduling by vehicle type 253
9.4 Examples 257
9.5 Vehicle-size determination 266
9.6 Optimal transit-vehicle size: literature review 268
Exercises 276
References 278

### Chapter 10  Crew Scheduling 279

10.1 Introduction 281
10.2 Vehicle-chain construction using a minimum crew-cost approach 282
10.3 Mathematical solutions 290
10.4 A case study: NJ commuter rail 294
10.5 Crew rostering 300
10.6 Literature review and further reading 305
Exercises 309
References 312
Appendix 10.A: The Shortest-path problem 315

### Chapter 11  Passenger Demand 319

11.1 Introduction 321
11.2 Transit demand, its factors and elasticity 322
11.3 Example of a demand forecasting method and process 330
11.4 Multinomial logit (MNL) model 336
11.5 Literature review and further reading (O-D estimation) 338
Exercises 341
References 341

### Chapter 12  Route Choice and Assignment 343

12.1 Introduction 345
12.2 Route choice using waiting-time strategy 345
12.3 Proportion of passengers boarding each route 349
12.4 Proportions derived for regular vehicle arrivals 352
12.5 Passenger assignment based on route choice 354
12.6 Literature review and further reading 358
Exercise 362
References 363

### Chapter 13  Service Design and Connectivity 365

13.1 Introduction 367
13.2 Service-design elements 368
13.3 Scheduling-based solution for operational parking conflicts 374
13.4 Optimum stop location: theoretical approach 381
13.5 Connectivity measures and analysis 388
13.6 Literature review and further reading 399
Exercises 400
References 404

Chapter 14 Network (Routes) Design 407
14.1 Introduction 409
14.2 Objective functions 410
14.3 Methodology and example 419
14.4 Construction of a complete set of routes 428
14.5 Multi-objective technique 438
14.6 Literature review and further reading 445
Exercises 449
References 452

Chapter 15 Designing Short-turn Trips 455
15.1 Introduction 457
15.2 Methodology 458
15.3 Candidate points and example 458
15.4 Excluding departure times 462
15.5 Maximum extensions of short-turn trips 467
15.6 Literature review and further reading 476
Exercise 478
References 480

Chapter 16 Smart Shuttle and Feeder Service 481
16.1 Introduction 483
16.2 Minimum fleet size required for a circular (shuttle) route 485
16.3 Routing strategies 487
16.4 Simulation 490
16.5 Case study 494
16.6 Customer survey 498
16.7 Optimal routing design: base network 503
16.8 Optimal routing design: algorithm 507
16.9 Implementation stages 509
16.10 Literature review and further reading 513
Exercise 516
References 519

Chapter 17 Service Reliability and Control 521
17.1 Introduction 523
17.2 Measures of reliability and sources of unreliable service 525
17.3 Modelling of reliability variables 530
17.4 Passenger waiting time at a stop 537
17.5 Advanced reliability-based data and control 542
17.6 Techniques to resolve reliability problems 546
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.7 Literature review and further reading</td>
<td>555</td>
</tr>
<tr>
<td>Exercises</td>
<td>563</td>
</tr>
<tr>
<td>References</td>
<td>566</td>
</tr>
<tr>
<td>Chapter 18 Future Developments in Transit Operations</td>
<td>569</td>
</tr>
<tr>
<td>18.1 Introduction</td>
<td>571</td>
</tr>
<tr>
<td>18.2 Multi-Agent Transit System (MATS)</td>
<td>575</td>
</tr>
<tr>
<td>18.3 Vehicle encounters on road segments</td>
<td>578</td>
</tr>
<tr>
<td>18.4 Developments in transit automation</td>
<td>584</td>
</tr>
<tr>
<td>18.5 Literature review and further reading</td>
<td>586</td>
</tr>
<tr>
<td>18.6 Concluding remark</td>
<td>591</td>
</tr>
<tr>
<td>References</td>
<td>591</td>
</tr>
<tr>
<td>Answers to Exercises</td>
<td>595</td>
</tr>
<tr>
<td>Author Index</td>
<td>607</td>
</tr>
<tr>
<td>Subject Index</td>
<td>615</td>
</tr>
</tbody>
</table>
This page intentionally left blank
To my late Dad, Samuel (who worked for a large bus agency as a driver and treasurer for over 30 years), to my Mom, Anna, with wishes for many good years, and to my triumvirate, Roy, Ohad and Dror
Preface
Preface

Chapter outline

- Personal motivation
- Purpose and intended audience
- Organization
- Website and remarks
- Acknowledgments

Personal motivation

The following story may serve to help understand the stimulus behind this book: A ship is sailing through a stormy ocean, and a little girl, who happens to be the captain’s daughter, is playing on the deck when all of a sudden a large wave carries her overboard into the sea. The captain, who sees this from his post, immediately orders his sailors to jump into the ocean and save the girl, but no one dares for fear of risking his life. In desperation, the captain turns to the passengers and asks them for help while promising that whoever saves his daughter will get anything he or she wants as a reward. Again, no one reacts. But then suddenly a man with a long beard, who had been standing by the railing, lurches overboard into the sea. The sailors throw him a life preserver, and fortunately he manages to lift the little girl safely back on deck and into the arms of her father. The captain then hugs the man, who is thoroughly drenched, and says he will give him anything he wants, just name it. The hero’s response: “I don’t want anything. I just want to know who pushed me. . . .”

What pushed me, actually started some time between 1967 and 1971, when I was a bus driver for EGGED (the National Bus Company of Israel), whose 4000 buses make it one of the largest bus companies in the world. Before gaining a bus driver’s licence, I had a theory about the way one should drive a bus; now I have a bus driver’s licence – and no theory. The second motivation for writing this book came from my consulting work at EGGED from 1975–1985, when I was exposed daily to planning and operational problems in the public transit field. The third motivation came in 1981. I was at Massachusetts Institute of Technology (MIT) in Boston where, together with Professor Nigel Wilson, I was to give a new summer session course on Transit Operations Planning. This course became an annual offering until 2003.

From all these foregoing activities, I internalized the following realization: experience is what you get when you are expecting something else. My teaching of transit operations planning has taken place at universities in Adelaide, Boston, California, Hong Kong, Israel, Melbourne, Rome, and Sydney. Indeed, it has been my more than 30 years of teaching, research, and hands-on experience that has pushed me to write this book and to construct it in such a way that it will help not only teachers, researchers, and students in the area, but also practitioners in the field.

Purpose and intended audience

This book uses the concise term ‘transit’ to refer to public transit or public transportation or public transport; all three expressions are commonly used.
A major goal of this book is to establish a bridge between the world of practitioners and the world of research and academia for the purpose of narrowing the gap between these two worlds. I hope that such a bridge will also lead to opportunities for collaboration and interaction in order to improve public transit service and, no less important, its image. Henry Ford once said: “Failure is only the opportunity to start all over again more intelligently.” With this in mind, the book intends to introduce a few new ways of thinking about: (a) already implemented and investigated transit themes, while combining retro-perspective thoughts and cumulative experience; and (b) new concepts and ideas.

One of the main features of the book is its stand-alone (self-contained) capability, obviating the need to look back and forth at other publications for comprehending the text. At the same time, every chapter contains a literature review and a further reading list. Practitioners may have some difficulty in comprehending the sections with mathematical notation, but hopefully they can grasp the substance of the material and its practical implications. Researchers and academic professionals may find some of the sections unnecessarily detailed, but they should be aware that the book is also aimed at practitioners and undergraduate students, thus requiring more explanation. In summary, this work follows the notion that: (1) it is better to ask twice than to lose your way once; and (2) clarity is no less important than certainty.

**Organization**

Each chapter opens with a section containing information and remarks for practitioners, called ‘Practitioner’s Corner’. In fact, one can never tell which way the train went by looking at the track: for a practical decision, one needs more information. The purpose of these Corners is to impart guidance about sections of the chapter that are appropriate and sections that are perhaps too difficult for practitioners, thus allowing the less academically inclined to flow with the book and capture its substance.

The organization of the book is described in Chapter 1. Generally speaking, five groups of themes are addressed:

1. Overview of transit planning and data collection needs (Chapters 1 and 2).
2. Design and optimization of transit timetables, and of vehicle and crew scheduling (Chapters 3–10).
3. Passenger demand and assignment analysis (Chapters 11 and 12).
4. Transit service, network and route design, encompassing scheduling elements (Chapters 13–16).
5. Transit reliability and future operations planning developments (Chapters 17 and 18).

All the quantitative chapters offer exercises for practising the methods covered; of the book’s 18 chapters, only Chapters 1, 2 and 18 are without exercises. The answers to these exercises appear at the end of the book.

The literature review of papers relevant to the topic(s) covered in a chapter appears as the last numbered section of each chapter, except for Chapters 1 and 8 (the review for which actually precedes it, in Chapter 7). The reason for this order – instead of the traditional pattern of
starting a scientific article with a literature review, is to focus on each chapter’s essence from
the beginning, and only at the end to give the reader who may wish to broaden his or her knowl-
edge of the particular topic, a kind of annotated reference list and an extended bibliography.

Website and remarks

The success of a professional book can be evaluated by the extent to which it succeeds in
introducing new and improved ideas and methods. It is not only a matter of learning the
book’s content; it has to do, as well, with how much the volume can inspire the reader’s
imagination to think further. This concept has served as the guideline for the development
of this book.

Indeed, the process of writing this book motivated the formulation of an interactive-software
program, which may be found at this website: www.altdoit.com. This site (instead of the
publisher attaching a CD) provides a highly informative graphical technique with which it
is simple to interact. The user can interject practical suggestions, whose effects on the vehicle’s
schedule are immediately described. This useful tool, which relates more specifically to
Chapters 7–9 and Chapters 12–15, will also assist the reader in solving some of the exercises
and practical problems outlined in those chapters.

Finally, when lecturing this transit course, I tended to use humour at times because I
believe in the insight captured by the English playwright George Bernard Shaw, who once
said: “When a thing is funny, search it carefully for a hidden truth.” More than once I have
been asked to employ some of this humour (including the cartoons that I have also drawn) if
I ever wrote a book. I have done this to some extent, especially in the Practitioner’s Corners.

Acknowledgements

Many people have contributed to this book through their constructive feedback and encour-
gagement. My views and understanding of the importance of public transit planning, service,
and operations greatly benefited from my discussions with Professor Nigel Wilson of the
MIT, with whom I annually shared the teaching of a summer course on the subject at MIT
for 22 years.

I would like to acknowledge and thank Professor Hai Yang of the Hong Kong University of
Science and Technology for his course material, including exercises on demand modelling in
public transit (from which some of the exercises in Chapter 11 were drawn); Professors Yoram
Shiftan and Shlomo Bekhor of the Technion-Israel Institute of Technology for their comments
on demand modelling and transit assignment; Dr Yechezkel (Hezi) Israeli, who was my PhD
student, for his contribution and remarks on transit-route modelling; the majority of Chapter
14 and part of Chapter 12 are based on his dissertation; and Moshe Flam for his contribution to
future transit developments in Chapter 18. My appreciation to Yaron Hollander, a doctoral stu-
dent at the University of Leeds, who contributed to the literature review of this book; and to my
PhD student, Yuval Hadas of the Technion, whose thesis supported part of the last chapter of
the book. Many thanks are also due to my Master’s degree students, Shirin Azzam, Gali Israel
and Shai Jerby, for their useful work and comments on the subjects of Chapters 9, 13 and 16,
respectively; and Yana Shnirman, an undergraduate student, for her practical comments on Chapter 10. Let me express my gratitude to Asher Goldstein, who provided me with editorial support. In this stream of acknowledgements, it will be only fair to thank the inventor of the treadmill, which has helped me stay in shape throughout the writing of this book.

Lastly, I offer my heartfelt thanks to my wife, Patricia (Shira) Tolentino Ceder, for her great encouragement, love and understanding. But also, and not least, for making dedicated use of her talent as an architect in doing the artwork for the figures in this work. Finally, a bouquet of affections goes to my three sons and daughter-in-law, Roy and Roni, Ohad, and Dror, as well as to my Mom, Anna, and my brothers, Tuli and Hagai and their families, all of whom helped me get through the difficult periods when writing this book.

I retain, of course, sole responsibility for any errors. I would be very pleased to gain feedback.

Avishai (Avi) Ceder
Haifa, Israel