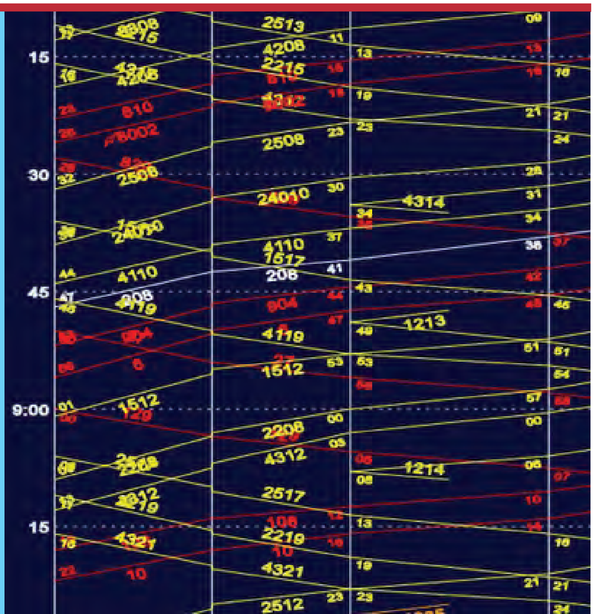
Quantitative Methods for Assessment of Railway Timetables

PhD Thesis



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February, 2013

DTU Transport
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February 2013

PhD-2013-02
Banedanmark / Rail Net Denmark &
Department of Transport, Technical University of Denmark

Published by: DTU Transport
Bygningstorvet 116B
DK-2800 Kongens Lyngby

Order at: http://www.transport.dtu.dk
Tel +45 45256500
transport@transport.dtu.dk

ISBN: 978-87-7327-257-2 (Electronic version)

ISBN: 978-87-7327-258-9 (Printed version)

Preface

This PhD thesis is the result of a PhD project entitled ”Quantitative Methods for Assessment of Railway Timetables”. The study is an industrial PhD and has been prepared as a collaboration between the Danish railway infrastructure manager Rail Net Denmark (in Danish: Banedanmark) and the Department of Transport, Technical University of Denmark. This collaboration further supported the establishment of the study line “Railway Technology” at the Technical University of Denmark sponsored by the Danish Railway Association (in Danish: BaneBranchen). The PhD study has been supervised by Professor Otto Anker Nielsen and associated Professor Alex Landex.

This PhD thesis provides a foundation for improving the attractiveness of future railway timetables. The thesis has conducted a process creating an agreement on the meaning of the term “timetable attractiveness” within the Danish railway sector. This resulted in a first common Danish list of six prioritized railway timetable evaluation and optimization criteria. Based on these criteria, the thesis has developed a set of 13 practical applicable key performance indicators for railway timetables in order to assess the timetable attractiveness level. The achieved results of this thesis are relevant for transport authorities, railway infrastructure managers, train operating companies and researchers studying the railway transportation system.

This thesis is submitted as a partial fulfillment of the requirements for the degree Doctor of Philosophy PhD in engineering science.

Kgs. Lyngby, Denmark,
February, 2013
Bernd Schittenhelm

Acknowledgements

First I would like to express my gratitude to Rail Net Denmark (in Danish: Banedanmark) for being open to my idea about this industrial PhD project. Special thanks go to former director for Traffic Operations Susan Münster, former assistant director for the Department of Traffic Planning, Kim Andersen and my team leader John Theede Nielsen for encouraging me to make the idea to reality. In the following time period with several organizational changes within Rail Net Denmark, I would like to thank the assistant directors for the Department of Traffic Planning Jens Hjul-Nielsen, Peter Sonne and Lars Faczinek-Beckmann for supporting the idea about this PhD project and ensuring its realization.

I would like to thank my supervisor Professor Otto Anker Nielsen for bringing his vast amount of experience into this PhD project and for supervising this PhD study. My biggest gratitude goes out to my co-supervisor, associated Professor Alex Landex. Without his help setting up this project, it might already have ended before it started. He was there to support me during phases in this PhD study when the motivation was not at its highest. In the final stage of this project, he set aside a big amount of time for extra supervisor meetings and for proof reading the PhD thesis. For his huge effort to helping realizing this PhD thesis I am very grateful.

This thesis would not have been possible without all the railway experts that accepted to participate in and contribute to this PhD project: For the timetable stakeholder interviews, the joined timetabling criteria workshop and meetings to map and describe timetabling processes. I wish to thank:

Arriva Danmark:	Kent Nielsen & Michael Selvig Hansen
Danish Ministry of Transport: (Transportministeriet)	Bastian Zibrandtsen
Danish Transport Authority: (Trafikstyrelsen)	Benny Mølgaard, Claus Jørgensen, Jacob Møldrup Petersen & Jens Brix
DB Schenker Rail Scandinavia:	Claus Jensen, Susanne Olling Nielsen & Thomas Vestergaard
DSB:	Emil Madsen, Lars Christian Krogsdam, Niklas Kohl & Per Elgaard
Hector Rail:	Hans-Åke Gustavsson
Lokalbanen:	Henrik Henriksen
Rail Net Denmark: (Banedanmark)	Ib Flod Johansson, Kim Andersen & Lasse Toylsbjerg-Petersen
Regionstog:	Michael Jensen

I would like to thank Fabrice Julien and Dr. Dennis Huisman for providing the graphical railway timetable examples from France and The Netherlands respectively.

In the final stages of this PhD project it was possible to draw on valuable support from the RobustRailS research program at the Technical University of Denmark. This was an important help improving the scientific level of this PhD thesis.

A big thank you goes out to the colleagues from the Department of Transport, Technical University of Denmark for making my stay there very joyful. I will miss our weekly football games. Special thanks go out to IT-supporter Kenneth Christensen for saving my computer a couple of times; to Michael Bruhn Barfod and Anders Vestergaard Jensen, from the Decision Management Group, for helping with planning and arranging the joined timetabling criteria workshop. They did a great job in taking on the roles of workshop facilitators. Thank you guys!

Finally, I want to thank my family for their never-ending support coming as far away as Southern Germany.

My sincerest gratitude,
Bernd

Summary

The aim of this PhD thesis is to improve the attractiveness of future railway timetables. To achieve this goal, the qualitative term “timetable attractiveness” needs to be made quantifiable. To establish what timetable attractiveness is, the thesis gives an introduction to railway timetables in the form of a timetable definition and an overview of commonly used timetable types and existing timetable classes. All major timetable stakeholders in a given railway sector must agree on the timetable aspects covered by the term “timetable attractiveness”. This research succeeded in creating such an agreement in the Danish railway sector, through a process that included individual stakeholder interviews followed by a joint timetabling criteria workshop. The agreement is a list of six prioritized timetable evaluation and optimization criteria.

To make the evaluation criteria quantifiable, a set of key performance indicators (KPIs) was developed for each criterion. A total of 13 KPIs are presented. Their practical applicability has been successfully tested on examples of real-life Danish timetables. The thesis recommends a revised timetabling process at railway infrastructure manager Rail Net Denmark (in Danish: Banedanmark) that will take the recommended KPIs into consideration. This new time-tabling process will create the necessary foundation for improving future railway timetable attractiveness in Denmark.

The aim and the structure of this PhD thesis are described in **Chapter 1**. The thesis shows how railway traffic and the railway timetable have been interlocked almost from the opening of the first public railway line in 1825. A timetable increases both the traffic safety and the attractiveness of railways. Timetables plan traffic, avoid train collisions, and announce train services to potential customers.

Chapter 2 gives an introduction to railway timetables. The thesis identifies a need for an improved European definition of a railway timetable. A two-part definition is introduced, with one part covering a liberalized railway sector and the other covering a state-owned or completely privately owned railway monopoly. The former is an agreement between an infrastructure manager and one or more train operating companies. The latter is an internal company agreement.

This is followed by the presentation of some basic facts that apply to all railway timetables. A railway timetable has a time period of validity. In the European Union this has been harmonized to one year and the timetable changes take place on the Sunday following the second Saturday in December.

The thesis distinguishes between timetables created as part of long or short-term planning. A short-term timetable tries to make the best of the available resources, such as railway infrastructure and rolling stock fleets, to accommodate as many railway customer preferences as possible. When preparing a long-term timetable, the starting point is to create an ideal timetable that fulfils the customer preferences on the assumption that the necessary infrastructure and rolling stock can be made available.

Moreover, the thesis identifies eight basic line structures for train services found in a railway timetable. These basic train service line structures are:

1. Point-to-point line (high speed trains)
2. Circle line (suburban trains or metro)
3. Centralized nodes (e.g. Paris or London)
4. Corridor / tree structure (e.g. the Danish railway network)
5. Star shape (e.g. the metro in Rome)
6. Universal star shape (e.g. the metro in Athens)

7. Railway network with a core route (suburban trains in Copenhagen and Munich)
8. Meshed railway network (German InterCity-Express trains).

Chapter 3 gives an overview of the six most commonly used timetable types in the railway sector. These timetable types are:

1. The public timetable (available to everybody, on paper and/or digitally)
2. The working timetable (primarily used by train staff)
3. The graphical timetable or train graph (used by timetable planners and traffic dispatchers)
4. The track occupation diagram (used by timetable planners and traffic dispatchers)
5. Rolling stock roster plan (used by employees of the train operating companies)
6. Train staff roster plan (used by employees of the train operating companies).

The thesis identifies seven existing basic railway timetable classes. At the beginning of **Chapter 4**, an extended timetable categorization model is presented. The categorization of timetables into classes is based on the level of structure in a given timetable. A set of basic structural characteristics determine the level of structure. These structural characteristics are:

- Timetable periodicity/the timetable is systematic (repeating traffic patterns)
- Timetable symmetry (same stopping pattern and travel times for both driving directions of a train service)
- Train meetings at selected station hubs (optimal transfer options)
- High frequency train services (train services run at least every 10 minutes)

The seven basic timetable classes identified by this thesis are:

- The periodic /systematic timetable
  - The symmetric periodic /systematic timetable
  - The integrated fixed interval timetable (IFIT)
- The high frequency timetable
- The non-periodic/non-systematic timetable
  - The symmetric non-periodic/non-systematic timetable
  - The integrated non-periodic/non-systematic timetable

Based on earlier British and Swiss approaches to measuring the level of structure in a railway timetable, the thesis proposes improvements to these existing methods and introduces two new timetable structure indexes based on the newly developed concept of timetable patterns. The two indexes are:

- Systematic timetable index – using the most used timetable pattern timewise
- Systematic timetable index – using the longest continuous timetable pattern timewise

Finally, the seven timetable classes are described and compared in detail with each other. This gives an overview of strengths and weaknesses based on selected, but generally accepted, timetable evaluation criteria.

Identifying the basic railway timetable classes in a timetable that covers an entire network is difficult and labour-intensive work. **Chapter 5** presents a series of examples of timetable analyses to illustrate the complexity of the task. It starts with the example of one railway line section served by one train service running according to one timetable class; goes on to the more complicated example of one railway line section served by several train services with different timetable classes, and ends with the most complicated example of an entire railway network served by several timetable classes.

The thesis recommends weighting the timetable classes identified with timetable statistical factors such as: the number of train runs, passenger numbers, freight tons, train-kilometres, and passenger or freight ton-kilometres.

Chapter 6 starts with a brief historical overview of the liberalization process in the European railway sector and of the liberalization of the Danish railway sector in particular. This is followed by a presentation of the overall Danish railway timetabling process. The process is one of collaboration between the infrastructure manager Rail Net Denmark (in Danish: Banedanmark), the train operating companies, and the Danish Transport Authority (in Danish: Trafikstyrelsen), which is the buyer of public railway service traffic.

Next comes a detailed description of the timetabling processes at the following railway timetable stakeholders:

- The Danish Transport Authority – buyer of public railway service traffic
- The train operating company DSB – the largest passenger train operator
- The state-owned infrastructure manager Rail Net Denmark – prepares the annual timetable

There is no formal timetabling process at the Danish Transport Authority. It changes from project to project. Since Rail Net Denmark is a member of the professional body of European infrastructure managers, Rail Net Europe, the basic timetable process steps and their deadlines are already given for the annual national timetable. Surprisingly, the basic Rail Net Europe timetabling process has no built-in formal learning loop.

Both DSB and Rail Net Denmark have informal learning loops in their existing timetabling processes, in the form of experience based input from employees at the beginning (Rail Net Denmark) and/or evaluation of the proposed timetable before the final approval (DSB and Rail Net Denmark).

The research for this thesis initiated a process to reach a consensus on timetable attractiveness in the form of timetable evaluation and optimization criteria in the Danish railway sector for the first time ever. **Chapter 7** describes the process in detail. First, the most important railway timetable stakeholders were identified. They are:

- DSB – the biggest Danish passenger train operating company
- Arriva Danmark –the winner of the first public passenger traffic tender in Denmark
- DB Schenker Rail Scandinavia – the biggest freight train operating company
- The Danish Transport Authority – the buyer of public railway service traffic
- Rail Net Denmark – the state-owned infrastructure manager

The process started with an individual interview with each stakeholder to establish a prioritized list of the five most important timetable evaluation criteria in the opinion of the interviewee. This was followed by a joint timetabling criteria workshop based on the five lists of prioritized criteria from the interviews. Arriva Danmark was not able to participate in the workshop. The participants of the workshop reduced the number of timetable evaluation criteria to six on their own initiative through discussion and dialogue. To achieve an individual ranking of the six criteria, each stakeholder was given three votes and was asked to give three different criteria one vote each. The result of the voting was three layers of priority with two criteria in each layer:

- High priority (3 votes): Systematic timetables and Capacity consumption on railway line sections
- Medium priority (2 votes): Robustness of the timetable and Societal acceptance of the timetable
- Low priority (1 vote): Attractive transfer options and Travel times

The workshop was unable to achieve consensus on an individual ranking of the six selected timetable evaluation and optimization criteria, so this is the result of the process initiated and conducted in the research for the thesis. It is the first version of a common list of prioritized railway timetable evaluation and optimization criteria in Denmark.

Since the Danish railway sector is highly affected by the ever-changing national political climate, this list is not necessarily very stable. The thesis therefore recommends that a similar (and perhaps improved) process should be carried out every two to five years to ensure an up-to-date common understanding of timetable attractiveness in the Danish railway sector.

A lack of focus on customer preferences was also identified through the results of the stakeholder interviews and the workshop. None of the parties set aside enough resources to perform large analyses within this important subject.

Chapter 8 analyses each criterion from the common Danish list of prioritized railway timetable evaluation and optimization criteria with regard to the most important influencing factors. This includes the societal aspect in the form of political decision makers and railway customers. Technical aspects are covered in the form of railway train operating companies and infrastructure managers. The most important influencing factors are shown to be “Political requirements”, “Customer requirements”, “Train operating company requirements” and “Infrastructure characteristics”.

This thesis recommends eight new steps of analysis in a future timetabling process to ensure an improved risk and attractiveness evaluation of a timetable. It also presents a proposal for a revised timetabling process at railway infrastructure manager Rail Net Denmark. The basic working steps remain the same, since they are given by European Union legislation and Rail Net Europe guidelines. The important changes are that timetable planners will work with several timetable variants simultaneously and that a real iterative capacity allocation process with the train operating companies will take place. This will require a much more intelligent and efficient timetable planning system than is available today.

A set of 13 key performance indicators for the Danish railway system is presented in **Chapter 9**. Seven of these are newly developed. Each key performance indicator is connected to one of the six timetable evaluation criteria. The key performance indicators are:

1. Systematic timetable index (Systematic timetable)
   - Based on the total time of the most used timetable pattern
2. UIC 406 methodology (Capacity consumption on railway line sections)

- Compressed timetables based on the blocking time theory

3. Degree of deviation from timetable planning rules (Robustness of the timetable)
   - Focus on agreed upon running times and timetable supplements
4. Conflict Risk Index (Robustness of the timetable)
   - The number of potential train path conflicts at a station and their estimated risk level
5. Timetable train path fix points (Robustness of the timetable)
   - Geographical and temporal distribution of potential train path conflicts
6. Proportion of train paths with shared rolling stock (Robustness of the timetable)
   - Number of train paths with shared rolling stock compared to the total number
7. Proportion of train paths with shared train staff (Robustness of the timetable)
   - Number of train paths with shared train staff compared to the total number
8. Proportion of buffer time in turnaround time and hand-over time for rolling stock (Robustness of the timetable)
   - Level of time supplements at terminus stations for rolling stock until next departure
9. Proportion of buffer time in turnaround time and hand-over time for train staff (Robustness of the timetable)
   - Level of time supplements at terminus station for train staff until next departure
10. Independent organization carrying out customer satisfaction surveys (Societal acceptance of the timetable)
    - Inspired by the British organization “Passenger Focus”
11. Proportion of timetable transfer time prolongation (Attractive transfer options)
    - Timetabled extra transfer time compared to physical minimum possible transfer time
12. Proportion of optimal transfer conditions (Attractive transfer options)
    - Number of transfers planned to take place on the same platform out of the total number
13. Proportion of timetable travel time prolongation (Travel time)
    - Timetabled extra travel time compared to travel time for theoretical non-stop train

These key performance indicators have proven themselves in practical applications on examples of real-life Danish timetables. All calculations were done manually, but they could be automated and integrated into future versions of timetabling software packages.

Summary in Danish (dansk resumé)

Formålet med denne ph.d. afhandling er at forbedre attraktiviteten af jernbanekøreplaner. For at opnå dette mål, må det kvalitative begreb ”Køreplansattraktivitet” gøres målbart. For at fastslå, hvad køreplansattraktivitet er, giver denne afhandling en introduktion til jernbanekøreplaner i form af en køreplansdefinition og et overblik over de mest anvendte køreplanstyper og eksisterende køreplansklasser. Alle de vigtigste interessenter i en given jernbanesektor skal enes om de aspekter der dækkes af begrebet ”køreplansattraktivitet”. Dette forskningsprojekt lykkedes med at skabe en sådan enighed i den danske jernbanesektor, igennem en proces, som indeholdt individuelle interviews med interessenter efterfulgt af en samlet køreplanlægningskriterie-workshop. Enigheden udmøntede sig i en liste af seks prioriterede køreplansevaluerings- og optimeringskriterier.

For at gøre evalueringskriterierne målbare, udvikledes et sæt af key performance indicators (KPIer) for hvert kriterie. I alt præsenteres 13 KPIer. Deres praktiske anvendelighed er blevet succesfuldt testet på danske køreplanseksempler fra det virkelige liv. Afhandlingen anbefaler en revideret køreplanlægningsproces hos infrastrukturforvalteren Banedanmark, som inddrager de anbefalede KPIer. Denne nye køreplanlægningsproces vil skabe den nødvendige forudsætning for at forbedre køreplansattraktiviteten for fremtidige danske jernbanekøreplaner.

Formålet med og strukturen af afhandlingen er beskrevet i **Kapitel 1**. Afhandlingen viser, hvorledes jernbanetrafik og køreplaner har været uløseligt forbundet med hinanden, næsten siden åbningen af den første offentlige jernbane i 1825. En køreplan højner både trafiksikkerheden på og attraktiviteten af jernbaner. Køreplaner planlægger trafikken og undgår togkollisioner og annoncerer togdrift til potentielle kunder.

Kapitel 2 giver en introduktion til jernbanekøreplaner. Afhandlingen identificerer et behov for en forbedret europæisk definition af en jernbanekøreplan. En to-delt definition bliver introduceret, hvor en del dækker en liberaliseret jernbanesektor og den anden del dækker en statsejet eller et komplet privatejet jernbanemonopol. I det første er køreplanen en aftale mellem en infrastrukturforvalter og en eller flere togoperatører. I det sidste er køreplanen en intern aftale i virksomheden.

Dette efterfølges af en præsentation af en række fakta som er gældende for alle jernbanekøreplaner. En køreplan har en gyldighedsperiode. I den Europæiske Union er dette blevet harmoniseret til at være et år og køreplansskiftet finder sted søndagen efter den anden lørdag i december.

Denne afhandling skelner mellem køreplaner der udarbejdes som en del af langtids- eller kortidsplanlægning. Ved korttidskøreplaner forsøges at få det bedste ud af de eksisterende ressourcer, såsom jernbaneinfrastruktur og flåden af rullende materiel, for at opfylde så mange jernbanekundeønsker som muligt. Ved udarbejdelse af en langtidskøreplan er udgangspunktet at skabe en ideal køreplan, som opfylder kunderens ønsker, baseret på den antagelse, at den nødvendige infrastruktur og det nødvendige rullende materiel er til rådighed.

Derudover identificerer afhandlingen otte grundlæggende linjestrukturer for togdrift, som kan findes i en jernbanekøreplan. Disse linjestrukturer er:

1. Punkt til punkt linje (dedikerede højhastighedsbaner)
2. Ringlinje (S-tog eller metrolinjer)
3. Centraliserede knudepunkter (Paris, London)

4. Korridor / træstruktur (det danske jernbanenetværk)
5. Stjerneformet (metroen i Rom)
6. Universel stjerneformet (metroen i Athen)
7. Jernbanenet med centralt strækningsafsnit (S-tog i København og München)
8. Tætmasket jernbanenet (de tyske InterCityExpress-tog)

Kapitel 3 giver et overblik over de seks mest brugte køreplanstyper i jernbanesektoren. Disse køreplanstyper er:

1. Publikumskøreplan (tilgængelig for alle, på papir og /eller digitalt)
2. Tjenestekøreplan (bruges primært af togpersonale)
3. Den grafiske køreplan eller toggraf (bruges af køreplanlæggere og trafikdisponenter)
4. Sporbenyttelsesplan (bruges af køreplanlæggere og trafikdisponenter)
5. Anvendelsesplan for rullende materiel (bruges af ansatte ved togoperatørerne)
6. Mandskabsplan for togpersonale (bruges af ansatte ved togoperatørerne)

Afhandlingen identificerer syv eksisterende køreplansklasser. I begyndelsen af **Kapitel 4** præsenteres en udbygget køreplankategoriseringsmodel. Kategoriseringen af køreplaner er baseret på niveauet af struktur i en given køreplan. Et sæt af strukturelle karakteristika er bestemmende for niveauet af struktur. Disse strukturelle karakteristika er:

- Køreplansperiodicitet / køreplanen er systematisk (gentagne trafikmønstre)
- Køreplanssymmetri (samme standsningsmønster og rejsetider for begge køreretninger af et togsystem)
- Togmøder på udvalgte knudepunktsstationer (optimale skifteforbindelser)
- Høj frekvente togsystemer (togsystemerne kører minimum hvert 10. minut)

De syv fundamentale jernbaneklasser er:

- Den periodiske køreplan / systematiske køreplan
    - Den symmetriske periodiske / systematiske køreplan
    - Den integrerede fast interval køreplan (IFIT)
- Den højfrekvente køreplan
- Den ikke-periodiske / ikke-systematiske køreplan
    - Den symmetriske ikke-periodiske / ikke-systematiske køreplan
    - Den integrerede ikke-periodiske / ikke-systematiske køreplan

Baseret på tidligere britiske og schweiziske fremgangsmåder for at måle niveauet af struktur i en jernbanekøreplan, foreslår denne afhandling forbedringer til disse eksisterende metoder og introducerer to nye køreplansstrukturindekser, byggende på det nyudviklede koncept ”køreplansmønstre”. De to indekser er:

- Systematisk køreplansindeks – benyttende det tidsmæssigt mest anvendte køreplansmønster
- Systematisk køreplansindeks – benyttende det længst kontinuerligt anvendte køreplansmønster

Til sidste beskrives de syv køreplansklasser og en detaljeret sammenligning foretages. Dette giver et overblik over styrker og svagheder, baseret på udvalgte, men almen anerkendte, køreplansevalueringskriterier.

Identificering af de syv fundamentale køreplansklasser i en køreplan der dækker et helt netværk er vanskeligt og arbejdsintensivt. **Kapitel 5** præsenterer en serie af eksempler på køreplansanalyser for at illustrere kompleksiteten af opgaven. Der begyndes med et simpelt eksempel af en jernbanedelstrækning betjent af et togsystem, som kører efter én køreplansklasse. Herefter fortsættes til et mere kompliceret eksempel af en jernbanedelstrækning betjent af flere togsystemer, som kører efter forskellige køreplansklasser. For endeligt at kigge på et helt jernbanenetværk betjent af flere jernbaneklasser.

Afhandlingen anbefaler at vægte de identificerede jernbaneklasser med statistiske faktorer, såsom antallet af afgange, antal passagerer, tons gods, togkilometre, passagerkilometre og gods ton-kilometre.

Kapitel 6 begynder med et kort historisk overblik over liberaliseringsprocessen i den europæiske jernbanesektor og specielt af den danske jernbanesektor. Dette er efterfulgt af en præsentation af den overordnede danske jernbanekøreplanlægningsproces. Processen er et samarbejde mellem infrastrukturforvalteren Banedanmark, togoperatørerne og Trafikstyrelsen, som er køber af offentlig service togtrafik.

Herefter kommer en detaljeret beskrivelse af køreplanlægningsprocesserne hos de følgende jernbanekøreplansinteressenter:

- Trafikstyrelsen – køber af offentlig service togtrafik
- Togoperatøren DSB – den største passagertogsoperatør
- Den statsejede infrastrukturforvalter Banedanmark – udarbejder den årlige køreplan

Der findes ingen formel køreplanlægningsproces hos Trafikstyrelsen. Processen tilpasses til hvert projekt. Siden Banedanmark er medlem af interesseforeningen for europæiske infrastrukturforvaltere, Rail Net Europe, er de basale køreplanlægningsprocestrin og deres deadline fastlagt for den årlige køreplan. Overaskende nok har den basale Rail Net Europe køreplanlægningsproces ingen formelle learning-loops indbygget.

Både DSB og Banedanmark har formelle learning-loops i deres eksisterende køreplanlægningsprocesser, i form af erfaringsmæssigt input fra de ansatte i startfasen (Banedanmark) og/eller evaluering af den foreslåede køreplan inden den endelige godkendelse (DSB og Banedanmark)

Forskningen bag denne afhandling iværksatte en proces for første gang nogensinde at opnå konsensus om begrebet køreplansattraktivitet, i form af køreplansevaluerings- og optimeringskriterier for den danske jernbane sektor. **Kapitel 7** beskriver denne proces i detaljer. Først blev de vigtigste køreplansinteressenter udpeget. De er:

- DSB – den største danske passagertogsoperatør
- Arriva Danmark – vinderen af det første offentlige jernbanetrafikudbud i Danmark
- DB Schenker Rail Scandinavia – den største godstogsoperatør
- Trafikstyrelsen – køber af offentlig service togtrafik
- Banedanmark – den statsejede infrastrukturforvalter som udarbejder den årlige køreplan

Processen startede med et individuelt interview med hver interessent for at etablere en prioriteret liste med de fem vigtigste køreplansevalueringskriterier jævnfør den interviewede. Dette blev fulgt af en samlet køreplanlægningskriterie-workshop baseret på de fem lister med prioriterede kriterier fra interviewsene. Arriva Danmark var ikke i stand til at deltage i workshoppen. Deltagerne af workshoppen reducerede på eget initiativ antallet af kriterier til seks ved diskussion og dialog. For at opnå en individuel ranking af de seks kriterier fik hver interessent tre stemmer og blev bedt om at give tre forskellige kriterier en stemme hver. Resultatet af afstemningen blev tre prioriteringslag med to kriterier i hvert lag:

- Høj prioritet (3 stemmer): Systematisk køreplan og Kapacitetsforbrug på jernbanedelstrækninger
- Mellem prioritet (2 stemmer): Robusthed af køreplanen og Samfundsmæssig acceptens af køreplanen
- Lav prioritet (1 stemme): Attraktive skifteforbindelser og Rejsetider

Workshoppen var ikke i stand til at opnå en konsensus om en individuel ranking af de seks udvalgte køreplansevaluerings- og optimeringskriterier, så dette er resultatet af den proces som blev iværksat og gennemført af forskningen for denne afhandling. Det er den første udgave af en fælles liste over prioriterede jernbanekøreplansevaluerings- og optimeringskriterier i Danmark.

Siden den danske jernbanesektor er meget påvirket af det evigt skiftende nationale politiske klima, er denne liste nødvendigvis ikke særlig stabil. Afhandlingen foreslår derfor at en lignende (eller måske en forbedret) proces skal gennemføres hver to til fem år, for at sikre en opdateret fælles forståelse af køreplansattraktivitet i den danske jernbanesektor.

En mangel på kundefokus blev tydelig ved at studere resultatet fra interviewsene og workshoppen. Ingen af partnerne afsætter nok ressourcer til at udføre store analyser indenfor dette område.

Kapitel 8 analyserer hvert kriterie fra den fælles danske liste af prioriterede køreplansevaluerings- og optimeringskriterier i forhold til de mest betydningsfulde faktorer. Disse inkluderer det samfundsmæssige aspekt i form af politiske beslutningstagere og jernbanekunder. Tekniske aspekter dækkes i form af togoperatørerne og infrastrukturforvaltere. De mest betydningsfulde faktorer har vist sig som værende ”Politiske krav”, Kundekrav”, ”Togoperatørkrav” og ”Infrastrukturkarakteristika”.

Denne afhandling anbefaler otte nye analysearbejdstrin i en fremtidig køreplanlægningsproces, for at sikre en forbedret risiko- og attraktivitetsevaluering af en køreplan. Derudover præsenterer afhandlingen også en revideret køreplanlægningsproces hos infrastrukturforvalteren Banedanmark. De fundamentale arbejdstrin forbliver de samme, siden de er defineret af lovgivning fra den Europæiske Union og retningslinjer fra Rail Net Europe. De vigtige ændringer er, at køreplanslæggerne vil arbejde med flere køreplansvarianter simultant og at en reel iterativ kapacitetstildelingsproces med togoperatørerne vil finde sted. Dette kræver dog et langt mere intelligent køreplanlægningssystem end der haves i dag.

Et sæt af 13 key performance indicators (KPIer) for det danske jernbanesystem bliver præsenteret i **Kapitel 9**. Syv ad disse er nyudviklede. Hver KPI er tilknyttet til et af de seks køreplanevaluerings- og optimeringskriterier. KPIerne er:

1. Systematisk køreplansindeks (Systematisk køreplan)
   - Baseret på det tidsmæssigt mest brugte køreplansmønster
2. UIC 406 metoden (Kapacitetsudnyttelsen på jernbanedelstrækninger)
   - Komprimerede køreplaner baseret på ”blokering af infrastrukturelementer”-teorien
3. Graden af afvigelse fra køreplan-planlægningsregler (Robusthed af køreplanen)
   - Fokus på aftalte køretider og køretidstillæg
4. Konflikt Risiko Indeks (Robusthed af køreplan)
   - Antallet af potentielle konfliktende køreplanskanaler ved en station og det estimerede risiko niveau
5. Køreplans-fikspunkter (Robusted af køreplanen)
   - Geografisk og tidsmæssig fordeling af potentielle køreplanskanalkonflikter
6. Andel af køreplanskanaler med delt rullende materiel (Robusthed af køreplanen)
   - Antallet af kanaler med delt rullende materiel ift. det samlede antal kanaler
7. Andel af køreplanskanaler med delt togpersonale (Robusthed af køreplanen)
   - Antallet af kanaler med delt togpersonale ift. det samlede antal kanaler
8. Størrelsesorden af tidsreserve ved vendetider og overdragelsestider for rullende materiel (Robusted af køreplanen)
   - Niveau af tidstillæg ved endestationer for rullende materiel inden næste afgang
9. Størrelsesorden af tidsreserve ved vendetider og overdragelsestider for togpersonale (Robusted af køreplanen)
   - Niveau af tidstillæg ved endestationer for togpersonale inden næste afgang
10. Uafhængig organisation varetager kundetilfredshedsanalyser (Samfundsmæssig accept af køreplanen)
    - Inspireret af den britiske organisation ”Passenger Focus”
11. Størrelsesorden på skiftetidsforlængelse (Attraktive skifteforbindelser)
    - Køreplanslagt ekstra skiftetid ift. den fysisk mulige minimumstid
12. Andelen af optimale skifteforhold (Attraktive skifteforbindelser)
    - Antallet af togskift planlagt til at ske ved samme perron ift. det samlede antal togskift
13. Størrelsesorden af køreplanslagt rejsetidsforlængelse (Rejsetid)
    - Køreplanslagt ekstra rejsetid sammenlignet med rejsetiden for et teoretisk non-stop tog

Disse KPIer har bevidst deres praktiske anvendelse på danske køreplanseksempler fra det virkelige liv. Alle beregninger blev gennemført manuelt, men de kunne automatiseres og integreres i fremtidige versioner af køreplanlægningsprogrampakker.

Table of contents

Abbreviations

Abbreviation	**Full name**
CRI	Conflict Risk Index (key performance indicator)
DMT	Danish Ministry of Transport (in Danish: Transportministeriet)
DSB	Danish State Railways (in Danish: Danske Statsbaner)
DTA	Danish Transport Authority (in Danish: Trafikstyrelsen)
EC	European Commission
EU	European Union
IFIT	Integrated Fixed Interval Timetable (timetable class)
IM	Infrastructure Manager
KPI	Key Performance Indicator
RDS	Regularitets og Drifts Statistik (in English: Punctuality and Operation Statistics)
RND	Rail Net Denmark (in Danish: Banedanmark)
RNE	Rail Net Europe (professional body of European infrastructure managers)
RI	Regularity Index (Swiss timetable structure index)
SI	Structure Index (Swiss timetable structure index)
STI	Systematic Timetable Index (key performance indicator)
TMS	Traffic Management System
TOC	Train Operating Company
UIC	International Union of Railways / Union Internationale des Chemins de fer

1 Introduction

From its early beginnings, the railway was a public transport system, starting as an entertainment attraction called “Steam Circus” in 1808 and developing into the opening of the first public railway line: the Stockton – Darlington Railway Line in 1825 (Holland 2012). See Figure 1.1. To make a public means of transportation attractive to the public, it is necessary to announce the available services to attract as many customers as possible. This can be done by publishing a list of planned daily arrivals and departures of trains for each station: a timetable.

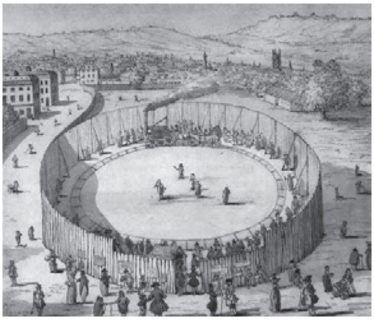


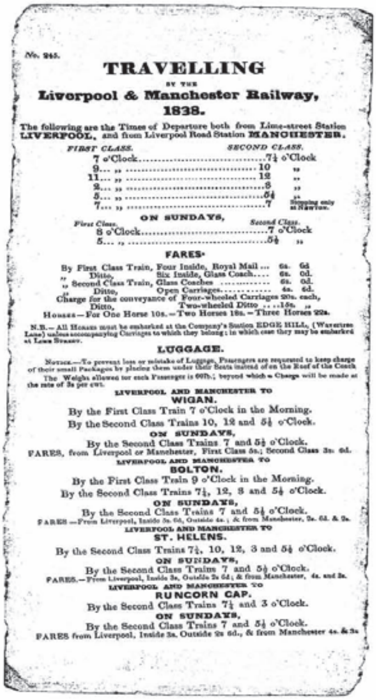
Figure 1.1: Steam Circus (left)(Holland 2012) and the opening of the Darlington-Stockton Railway (right)(Dobbin 1875)

The Liverpool and Manchester Railway in north-western England opened in 1830 and was the first railway line where all trains, both passenger and freight trains, ran according to a timetable. The published timetable for the railway line from the year 1838 can be seen on the left in Figure 1.2. This double tracked railway line was opened for train traffic on 15th September 1830 (Booth 1830). Note how departures from Liverpool and Manchester took place at the same time, so the timetable had some level of symmetry to it[1]. Departures consisted only of one carriage class, so departures were divided into first and second class departures. This informed passengers about fare levels for each train departure.

Railways and timetables are and have always been interlocked. Not many years passed from the opening of the first public railway line (1825) to the introduction of railway timetables during the 1830s. Since trains are guided by fixed rails, it was necessary from a safety perspective to plan the railway traffic as soon as there is more than one train running simultaneously on a single-tracked railway line; there are only limited opportunities to avoid other trains running on the same railway line/track. Crossings and overtaking can only take place at certain places: locations with more than one track available, e.g. stations with passing loops or sidings, and must therefore be planned in advance. For railway staff, the primary function of the timetable from the beginning was to ensure the safe handling of traffic, thereby avoiding train collision accidents (Hansen 2008).

On the right in Figure 1.2 is shown the cover of a timetable book from 1856 containing timetables for postal, railway and steamship routes in Denmark. This was published by N. Wichmann and T. Faber and printed in Copenhagen and is one of the oldest railway timetable documents in Denmark. Even then it was already clear that to make public transport attractive one must compile and publish timetables for the different means of public transport in one timetable book.

[1] Read more about symmetric timetables in section 4.5 and 4.6



No. 245.

TRAVELLING

BY THE

Liverpool & Manchester Railway,

1838.

The following are the Times of Departure both from Lime-street Station LIVERPOOL, and from Liverpool Road Station MANCHESTER.

FIRST CLASS.	SECOND CLASS.
7 o'Clock	7½ o'Clock
9 ,,	10 ,,
11 ,,	12 ,,
2 ,,	3 ,,
5 ,,	5¼ ,,
7 ,,	7 Stopping only at Newton.

ON SUNDAYS,

First Class.	Second Class.
8 o'Clock	7 o'Clock
5 ,,	5½ ,,

FARES.

By First Class Train, Four Inside, Royal Mail ... 6s. 6d.
,, Ditto, Six Inside, Glass Coach.... 6s. 0d.
,, Second Class Train, Glass Coaches .... 6s. 0d.
,, Ditto, Open Carriages............ 4s. 6d.
Charge for the conveyance of Four-wheeled Carriages 20s. each,
Ditto, Two-wheeled Ditto ......15s. ,,
Horses—For One Horse 10s.—Two Horses 18s.—Three Horses 22s.

N.B.—All Horses must be embarked at the Company's Station EDGE HILL, (Wavertree Lane) unless accompanying Carriages to which they belong; in which case they may be embarked at Lime Street.

LUGGAGE.

Notice.—To prevent loss or mistake of Luggage, Passengers are requested to keep charge of their small Packages by placing them under their Seats instead of on the Roof of the Coach.

The Weight allowed for each Passenger is 60lb.; beyond which a Charge will be made at the rate of 3s per cwt.

LIVERPOOL AND MANCHESTER TO

WIGAN.

By the First Class Train 7 o'Clock in the Morning.
By the Second Class Trains 10, 12 and 5¼ o'Clock.

ON SUNDAYS,

By the Second Class Trains 7 and 5½ o'Clock.
FARES, from Liverpool or Manchester, First Class 5s.; Second Class 3s. 6d.

LIVERPOOL AND MANCHESTER TO

BOLTON.

By the First Class Train 9 o'Clock in the Morning.
By the Second Class Trains 7½, 12, 3 and 5¼ o'Clock.

ON SUNDAYS,

By the Second Class Trains 7 and 5½ o'Clock.
FARES.—From Liverpool, Inside 5s. 6d., Outside 4s.; & from Manchester, 3s. 6d. & 2s.

LIVERPOOL AND MANCHESTER TO

ST. HELENS.

By the Second Class Trains 7½, 10, 12, 3 and 5¼ o'Clock.

ON SUNDAYS,

By the Second Class Trains 7 and 5½ o'Clock.
FARES.—From Liverpool, Inside 3s, Outside 2s 6d; & from Manchester, 4s. and 3s.

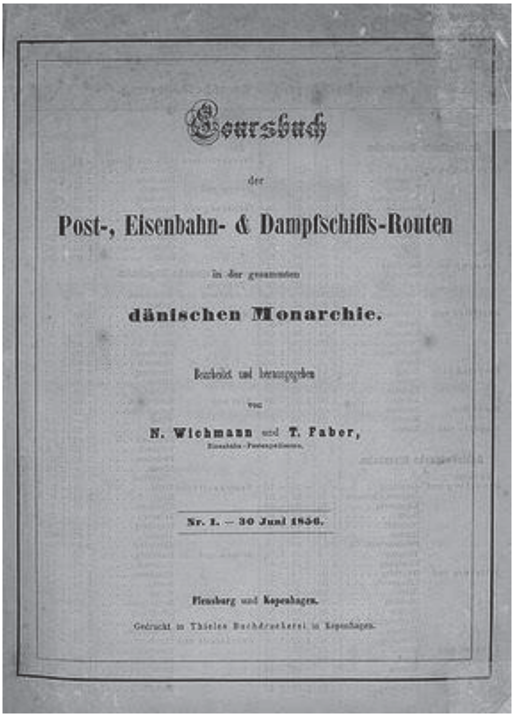
LIVERPOOL AND MANCHESTER TO

RUNCORN GAP.

By the Second Class Trains 7½ and 3 o'Clock.

ON SUNDAYS,

By the Second Class Trains 7 and 5½ o'Clock.
FARES from Liverpool, Inside 3s. Outside 2s 6d., & from Manchester 4s. & 3s.



Coursbuch

der

Post-, Eisenbahn- & Dampfschiffs-Routen

in der gesammten

dänischen Monarchie.

Bearbeitet und herausgegeben

von

N. Wichmann und T. Faber,

Eisenbahn-Postexpedienten.

Nr. 1. — 30 Juni 1856.

Flensburg und Kopenhagen.

Gedruckt in Thieles Buchdruckerei in Kopenhagen.

Figure 1.2: Timetable for the Liverpool and Manchester Railway from 1838 (http://www.pittdixon.go-plus.net/l+mr/timetable.htm (20.09.2012)) (left) and timetable book cover for postal, railway and steamship lines in Denmark from 1856 (http://www.statsbiblioteket.dk/forbiblioteker/specialsamlinger/koreplaner (20.09.2012)) (right)

1.1 Aim of the research

Competition between the various means of transport in Europe is intense at the present time. If the railway is to be an attractive alternative to road and aviation transport, it needs to run according to an attractive timetable. Making timetable attractiveness quantitatively measurable becomes an important issue for improving future timetables and the process that creates them. It also makes it possible to compare the timetable attractiveness of different organizations. To categorize a timetable as being attractive, a common perception of what makes a timetable attractive is needed.

The point of departure for the research for this thesis was the types of timetables and timetable classes currently used in Europe. Each timetable type gives insights into one or more aspects of timetabling, such as running times, dwell times, track occupation and roster plans for rolling stock and train staff. All timetable classes have individual structural characteristics that contribute to some degree to the timetable attractiveness criteria applied.

On this basis, the aim was to create an understanding of timetable attractiveness, using the Danish railway sector as a case, in the form of developing a common Danish list of prioritized timetable evaluation and optimization criteria. To make the presence of the timetabling criteria identified in a given timetable quantitatively measurable, a set of railway timetable key performance indicators (KPIs) had to be developed. The practical applicability of these KPIs needed be tested in a series of calculation examples based on real-life current Danish annual railway timetables. This could make it possible to adapt the timetabling process, taking the key performance indicators into consideration.

The research goals of this thesis are:

- Give an understanding of railway timetables by describing types and classes and their advantages and disadvantages
- Create a common understanding of timetable attractiveness – using the Danish railway sector as a case
- Develop a set of key performance indicators for railway timetables based on the achieved understanding of railway timetable attractiveness and give calculation examples of these key performance indicators. These recommended key performance indicators can be the basis for an adapted timetabling process.

1.2 Approach of the thesis

To create a common understanding of railway timetable attractiveness in the Danish railway sector this thesis applies an approach from the field of decision management: Decision conferencing. A workshop was organized on neutral grounds including all important stakeholders to identify and prioritize timetable attractiveness criteria. The workshop was facilitated by neutral outsiders – from the Decision Support Group from The Institute of Transport at the Technical University of Denmark. These were aware of the potential negative effects of groupthink and relay this back to the workshop participants.

This discursive approach was chosen over a mathematical/operations research approach due to the fact that the operations research approach needs to know which optimization criteria should be considered in its objective function and their given weight/priority. Without this input a mathematical approach must calculate many different optimal solutions according to different objective functions and in the end try to recommend one of the found solutions. The approach lacks credibility. Optimization criteria and their priority are provided by the chosen approach and therefore some of the results of this thesis can be the basis for a future mathematical approach.

Another alternative approach is to look at the (socio) economical side of railway timetables. This demands a very high level of detailed knowledge about factors that have influence on railway earnings and costs. The key factor is the used timetable class and the derived factors such as number of expected passengers per train, freight volumes per train, needed number of rolling stock + their costs and train staff + their costs etc. Factors vary from timetable class to timetable class and from timetable variant to timetable variant, hereby creating many scenarios that must be calculated. The needed detailed information is very difficult to attain and assumptions about the future have to be made. This gives this approach a very big work effort combined with a high level of uncertainty in regards to the made recommendations.

1.3 Structure of the thesis

The thesis is divided into four main parts, cf. Figure 1.3. The first part (chapters 1 to 3) gives an introduction to railway timetables. This is done by defining a railway timetable and describing some of the basic railway timetable features, such as its validity period and the possible structures of train service lines. An overview of the timetable types commonly used concludes the first part. The second part (chapters 4 to 6) presents existing timetable classes and how these can be found in real-life timetable examples. Closing the second part is a description of the timetabling process presently used in Denmark.

The beginning of the third part of the thesis (chapters 7 to 9) shows how a common understanding of railway timetable attractiveness was created by developing a common Danish list of prioritized railway timetable evaluation and optimization criteria. These laid the basis for a set of Danish railway timetable KPIs, which were tested on real-life timetable examples. Out of this research comes a recommendation for a revised timetabling process. Finally conclusions are drawn in the fourth and last part of the thesis (chapter 10).

Before work can be done on railway timetables, we need a precise definition of a railway timetable. This thesis presents its own railway timetable definition at the beginning of Chapter 2. All railway timetables share some basic features. The most important ones are described in the remaining part of the chapter.

There are several different types of railway timetables. Each is used for a specific aspect of planning. Chapter 3 gives an overview of the railway timetable types commonly used, describing their specific function in the world of railways. Each is illustrated with pictures or screenshots from real-life railway examples to give a better understanding of their use.

Railway timetables can be categorized according to their level of structure. Based on a timetable structure categorization model, all existing basic timetable classes are identified in Chapter 4. The thesis introduces new approaches to calculating the level of structure in railway timetables. Finally, the timetable classes identified are compared, describing their strengths and weaknesses with regard to commonly accepted timetable evaluation criteria.

It can be difficult to identify the timetable classes represented in a national timetable covering a large railway network. Chapter 5 presents a series of real-life railway timetable examples, going from the simple, one railway line section, to the very complicated, an entire network. The chapter recommends a set of statistical weighting factors for each timetable class identified, so as to achieve a differentiated overview of the timetable classes identified.

The liberalization of the Danish railway sector has resulted in several actors, including train operating companies and infrastructure managers, preparing their own timetables with their own internal timetabling process. Based on interviews with selected actors, Chapter 6 describes the timetabling processes in the train operating company DSB (Danish State Railways), the infrastructure manager Rail Net Denmark and the Danish Transport Authority.

To measure timetable attractiveness quantitatively, agreement must be reached between all important railway timetable stakeholders on what makes a timetable attractive, so that a set of evaluation criteria can result. Chapter 7 describes the process of finding a set of Danish timetable evaluation criteria as well as the criteria themselves. The agreement process includes individual stakeholder interviews and a joint timetabling criteria workshop.

	Chapter	Main features	Based on
Introduction	**Chapter 1** Introduction	• Aim of the thesis • Structure of the thesis	-
	Chapter 2 Introduction to railway timetables	• Definition of a railway timetable • Timetable validity period • Basic structures of train services	-
	Chapter 3 Railway timetable types	• Presentation of the timetable types commonly used	-
Present railway timetables: classes and timetabling processes	**Chapter 4** Railway timetable classes	• Presentation of existing timetable classes • Comparison of timetable classes – strengths and weaknesses • Measuring structure in timetables	Liebchen 2006, Schittenhelm 2008 Schittenhelm & Landex 2009, Tzieropoulos & Emery2009
	Chapter 5 Railway timetable class analysis	• Timetable class analysis for railways • Analysing railway timetables – from a single railway line to the entire network • Analysing railway network timetables – from a single timetable class to several classes	-
	Chapter 6 The Danish railway timetabling process	• The liberalization of the Danish railway sector • The overall structure of the Danish timetabling process • The railway timetabling process for train operating companies, infrastructure managers, and the Danish Transport Authority	Schittenhelm & Richter 2009, Schittenhelm & Landex 2012
Future railway timetables: Attractiveness, evaluation and the timetabling process	**Chapter 7** Creating a common list of Danish timetable evaluation and optimization criteria	• Individual interviews with Danish railway timetable stakeholders • Description of the joint timetable criteria workshop • Presentation of the first common Danish list of prioritized timetabling criteria	Schittenhelm 2011b, Schittenhelm & Landex 2012
	Chapter 8 Revising the timetabling process	• Recommendations for timetable process adaptations according to the prioritized timetabling criteria • Presentation of a revised timetabling process at infrastructure manager Rail Net Denmark	Schittenhelm & Landex 2012
	Chapter 9 Danish key performance indicators for railway timetables	• Presentation of a set of newly developed and already used railway timetable key performance indicators • Practical application of the recommended key performance indicators	Schittenhelm 2008, Schittenhelm & Landex 2009, Schittenhelm & Landex 2010, Schittenhelm 2011a, Schittenhelm 2011c, Schittenhelm & Landex 2013
Conclu-sion	**Chapter 10** Conclusion	• Main contributions • Conclusions • Recommendations for future research topics	-

Figure 1.3: Overview of the chapter structure of this PhD thesis and the main papers the chapters are based on

For each timetable evaluation and optimization criterion found, a set of KPIs can be developed. The KPIs recommended in this thesis are presented in Chapter 9. Most of these are newly developed, but some are already in use today. The calculation methods for each KPI are described and a practical application on a real-life timetable example is presented.

Chapter 10 presents the conclusions drawn in this thesis. Finally, a recommendation for future research topics in this field of research is given.

2 Introduction to railway timetables

When beginning to address the topic of railway timetables one must first define what a timetable and a railway timetable in particular is. This is done in section 2.1. Every timetable has a defined validity time period. This is described in Section 2.2. Preparing railway timetables can be done in a long or short term perspective. This has a big impact on what kind of timetable will be created. Section 2.3 describes the differences in the long and short term timetable planning processes. The basic structures of train services in a given timetable are presented in section 2.4. Finally a summary is given in section 2.5.

2.1 What is a timetable?

The word timetable is a combination of the words [time] and [table]. In general the word “timetable” gives associations to a table listing times when events are taking place.

In the following section a number of found definitions on the term “timetable” are presented. The list starts with the most general definitions and becomes more and more railway timetable specific:

- A schedule showing a planned order or sequence (http://www.merriam-webster.com/dictionary/timetable (20.09.2012) An Encyclopedia Britannica Company)

- A list or table of events arranged according to the time when they take place. (http://dictionary.reverso.net/english-definition/timetable (20.09.2012), Reverso)

- A plan that says how long you will take to do something and gives a time for finishing each stage of the process (http://www.macmillandictionary.com/dictionary/british/timetable (20.09.2012), online free dictionary)

- A schedule listing the times at which certain events, such as arrivals and departures at a transportation station, are expected to take place. (American Heritage Dictionary: http://ahdictionary.com/word/search.html?q=timetable (20.09.2012))

- Table of departure and arrival times of trains, buses, or airplanes (http://www.merriam-webster.com/dictionary/timetable (20.09.2012), An Encyclopaedia Britannica Company)

- The timetable fixes the time wise and geographical utilization of the railway network by the different trains in form of train paths. (Haldemann 2003 (translated from German))

- Forward looking determination of the train runs in regards to operational days, running times, speeds and used train routes (Pachl 2013 (translated from German))

- A program for the space and time wise running of railway passenger and/or freight traffic on a railway line, which is distributed among the involved stakeholders. A timetable for a railway line or railway network, minimum contains a list of stations per railway line with the arrival and departure times for trains. Operating economy wise the time table is the result of the traffic production planning for a given time period (the validity period for the timetable). (Prof. Dr. Winfried Krieger: http://.wirtschaftslexikon.gabler.de/Archiv/82269/fahrplan-v6.html (20.09.2012) (translated from German))

- A written document which establishes the authority for the movement of trains over designated lines of track, subject to the rules established for that track. Typically it describes maximum authorized train speeds for the entire rail line or a portion thereof. The timetable will also include the names and locations of control points for the rail line. (http://www.txdot.gov/project_information/projects/houston/railway/glossary.htm (20.09.2012), Texas Department of Transportation)

Most of the listed definitions above look at the timetable as being a public document available to railway customers, stating what basic information is necessary and therefore should be contained in a timetable document. Only the definition by Prof. Dr. W. Krieger mentions that there are different stakeholders, passenger and freight train operating companies, when it comes to railway timetables. The presented definitions do not adequately cover the present situation in the world's railway sectors. In today's world the national railway sectors are basically organized following two models. Both models can be more or less privatized and regulated by the state. (Gómez-Ibáñez & de Rus 2006):

1. Railway companies with their own infrastructure and train traffic operation, e.g. private railway companies such as North American "Union Pacific Railroad" (UP) and "Burlington Northern and Santa Fe Railway Company" (BNSF) or state monopoly's such as China Railways (CR)
2. Separating infrastructure from train operations – creating infrastructure managing companies and train operating companies, e.g. the Danish and Swedish railway sectors

This setup must be taken into account when defining a railway timetable. This thesis therefore proposes the following definition for European railway timetables:

European railway timetable definition of this thesis

a) For a railway sector with separated infrastructure management and train operation:

A railway timetable is an agreement between an infrastructure manager and one or more train operating companies on a safe and feasible schedule for the railway traffic. The timetable accommodates as many of the requested train paths from the train operating companies as possible.

b) A railway sector with railway companies:

A railway timetable is an internal agreement in a railway company on how to operate train traffic in a safe and feasible manner on the company's railway infrastructure.

A train path is the time-wise and geographical use of the infrastructure in the timetable for a single train run. Accommodation of as many train paths as possible can often only be achieved through negotiations between timetable stakeholders. It may demand adjustments of the requested train paths. If negotiations are fruitless a set of legal rules must determine which train operating companies (TOCs) get their requested train paths. Optimization of the timetable can be difficult due to the potential conflicting interests between stakeholders.

In a railway company there is a high potential for preparing a highly optimized timetable in regards to the company's internal goals. The management level will set these goals for the company and thereby reduce the risk for internal conflicting interests in regards to the timetable.

With the liberalization and thereby the division of the European railway sector into train operating companies (TOCs) and infrastructure managers (IMs) the railway timetable has been given a more versatile role. It has become the documentation for agreements made between the most important key stakeholders in railway traffic. See Figure 2.1. A TOC may win a public invitation to tender for railway traffic and thereby enter a contractual cooperation with a transport services organization. In Denmark the latter is called Trafikstyrelsen (in English: The Danish Transport Authority (DTA)) for the state owned railway lines. For the private Danish railway lines the respective transport service organizations are the administrative Danish regions.

A public invitation to tender for railway traffic can contain more or less detailed information about the future railway timetable. With a very high level of timetable detail the ownership of the timetable is with the transport services organization. With a low level of detail in the given timetable data, tendering TOCs have the flexibility to create their own timetable suggestions, which can become a very important competiveness parameter in the tendering process. The ownership of the future timetable is in this case, from the beginning handed over to the TOCs.
The TOCs that have won public traffic tenders and/or want to run competitive train services have to apply for use of railway capacity with the relevant IM. Presently DSB (Danish State Railways) is the biggest TOC in Denmark. The IM has the responsibility of preparing a feasible and safe timetable and thereby also allocates the network capacity to the different applying TOCs. In Denmark the biggest IM is the 100% state owned Banedanmark (in English Rail Net Denmark). Rail Net Denmark (RND) owns and operates 90% of the Danish railway infrastructure (Statistics Denmark 2012).

When the timetable is published the potential customers of the TOCs assume that the trains will run according to this timetable. Therefore, the timetable is also an agreement between TOCs and their customers. Customers can be passengers, shipping agents, haulers etc. This thesis presents Figure 2.1 which gives an overview of the relations a railway timetable covers in a liberalized railway sector with a state owned infrastructure as is the case in Denmark. TOCs can both be privately owned, e.g. Swedish freight train operator Hector Rail, and state owned, e.g. DSB.

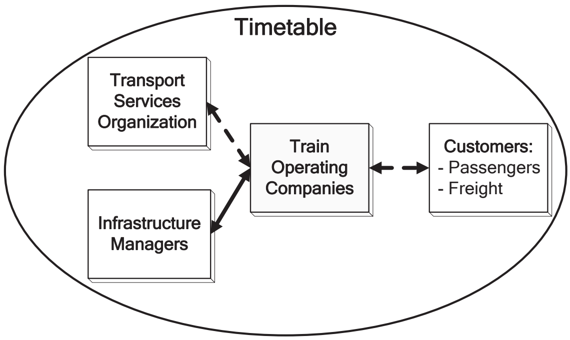


Figure 2.1: In a liberalized railway sector with state owned infrastructure a timetable is an agreement between important railway traffic stakeholders. The timetable is prepared in cooperation between TOCs and the IMs.

For a state owned railway sector e.g. Swiss Federal Railways (SBB) and China Railways (CR), or a privatized railway sector e.g. USA and Canada, the number of timetable stakeholders is reduced to a possible public transport services organization, the railway company and the customers of the railway company. Figure 2.2 gives an overview of this scenario. Here the railway company owns its own railway infrastructure and plans the train operation itself. This entails that the timetable as a whole is prepared by the railway company, based on possible contractual obligations with the public transport services organization, such as minimum service levels for train services. There are no or only few railway company competitors in “public transport” since these must own their own parallel infrastructure, pay more or less regulated access charges to the relevant railway company and own their own rolling stock or rent/lease this. Depending on the level of regulation from the state, this can make free competition difficult and potentially create regional or national monopolies.

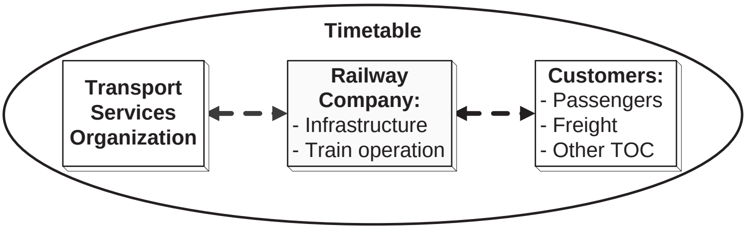


Figure 2.2: In a privatized or state owned railway sector a timetable is prepared internally in the railway company. There are fewer timetable stakeholders. Other TOCs can be customers.

2.2 Timetable validity time period

A timetable is valid for a given time period. The length of this time period has varied from country to country and also varied through history. From the beginning of the 20th century Germany changed the national railway timetable twice a year, having a summer and winter timetable. This procedure continued until the early 1990s. Hereafter a yearly timetable was reintroduced. Minor changes to a timetable could though still be implemented during June in the timetable validity time period (http://de.wikipedia.org/wiki/Fahrplan (20.09.2012)).

Until the year 2001 the timetable changed on a Sunday in the end of May or beginning of June in most European countries. Denmark changed its timetable during November or early December and this could create difficulties for border crossing train services between Denmark and Germany. Changed national train paths could cause long stopping times for trains at border stations reducing the attractiveness of the railway as an international transport system (Elgaard 2011). In 2002 the European Union (EU) decided to harmonize the yearly change of railway timetables and created the necessary legislation. It was decided that the timetable change takes place at 00:01 on the Sunday after the second Saturday in December within the area of the EU (RNE 2006). EU legislation still makes it possible to implement minor changes in June (EC 2002). As an exception to this, Switzerland only changes its railway timetable every two years, allowing only minor timetable changes in December of even years (http://www.admin.ch/ch/d/sr/745_13/a2.html (20.09.2012)). Switzerland is not a member of the EU and therefore does not need to comply with EU railway timetable legislation. To make cooperation easier with its EU railway neighbors, the Swiss timetable change takes place on the same day as in the EU.

2.3 Timetable planning – short and long term

Railway timetables can be created in a long or short term perspective. Long term planning is made on a strategic/tactical level (ca. 5+ years in the future), whereas short term planning covers the yearly timetabling process taking place at train operating companies (TOCs) and railway infrastructure managers (IMs). Figure 2.3 gives an overview of the overall long and short term planning process for railway traffic. Starting point for long term planning are the customers – both passengers and freight shippers. By providing customers with requested advantages in regards to the railway transport system, an improved perception of the accessibility of the railway as a mean of transportation can be achieved. The advantages must be made operational in an optimized railway timetable, focusing on achieving the requested improvements. The prepared timetable is not necessarily feasible when looking at needed infrastructure characteristics, such as number of available railway tracks (capacity), line speeds (travel time) and signaling system (headway times). Nor does the timetable have to be feasible in regards to rolling stock, e.g. size of vehicle fleets (train service frequency, seating capacity) and maximum allowed speed (travel times, tilting technology). The developed optimal timetable provides information about the potentially needed new infrastructure and rolling stock improvements to make it feasible. Necessary investments in railway infrastructure and rolling stock can then be estimated and planned (Laube 2011).

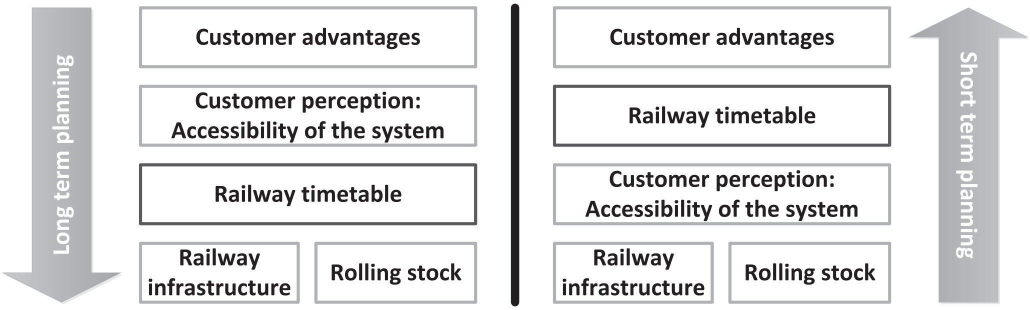


Figure 2.3: Process diagram for overall long and short term planning for railway traffic (based on Laube 2011)

Short term railway timetabling is based on the present available resources: The railway infrastructure and rolling stock. Limitations can arise due to cooperative agreements between TOCs and railway unions. Combined with available knowledge about customer perceptions, a feasible and attractive railway timetable is created. This timetable should provide railway customers with some advantages that make them choose the railway rather than other competitive means of transport (Laube 2011).

The recommended key performance indicators (KPIs) for railway timetables by this thesis in chapter 9, provide the necessary tools to evaluate the attractiveness of timetables made in a long and short term timetabling process.

2.4 Structure of timetabled train services

Topology characteristics of the railway network that is covered by a given timetable, will highly affect the basic structure of train services. A railway network's present topology characteristics are derived from:

- **Geographical features** - such as hills, mountains, swamps, rivers, lakes, fjords and oceans – limiting the possibilities for railway line alignments
- **Transport demand** - resources must be transported from one point to another e.g. passengers from one city to another or iron ore from a mine to a harbor or a steel plant
- **Removal of capacity bottlenecks** – building new parallel railway lines to create new capacity e.g. the new Danish railway between Copenhagen and Ringsted via Køge
- **Improving travel times** – Construction of dedicated high speed passenger and freight railway lines improve travel times of trains e.g. passenger high speed line Paris – Lyon and the dedicated freight train Betuwe route from Rotterdam harbor to the Dutch-German border
- **Military strategic motivation** – railways play an important role during wars, both for moving material and troops and keeping them supplied
- **Economic strategic motivation** – development of new land areas into urban and/or industrial zones, such as the new urban part of Copenhagen called "Ørestad"

Figure 2.4 gives an overview of the basic train service structures that can be found in a railway timetable. The first train service is a single point to point connection, e.g. connecting the cities of Copenhagen and

Roskilde with the first Danish railway line in 1847. Today this concept can be seen for new dedicated high speed railway lines. Some railway networks were built up around centralized nodes such as Paris in France and London in England. Station names like Gare du Nord (in English: Northern station), Gare de l'Est (in English: Eastern station) or Gare de Lyon (Lyon station, handling traffic to/from Lyon) are a continual reminders of this network topology. Train services will be planned accordingly. Similarly, to the centralized node a railway network can have a corridor/tree structure originating from the most important point. This is the overall case for the Danish railway system, where Copenhagen is the starting point of the tree structure. Some large cities have developed a circle line as a part of their suburban or metro networks. They normally surround the city center. Copenhagen is presently building a metro circle line servicing the central parts of the city.

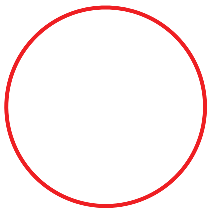
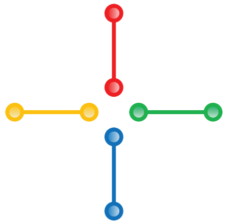
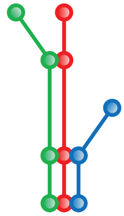
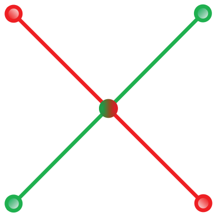
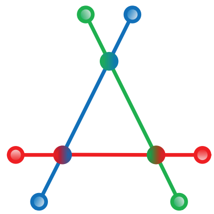
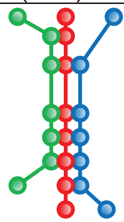
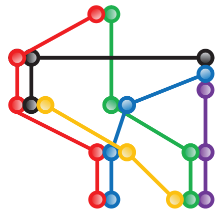
			
Point to point connection, e.g. a high speed line	Circle line, e.g. in Berlin, London and Tokyo (suburban trains)	Centralized nodes, e.g. the French railway network (Paris)	Corridor / tree, e.g. regional train traffic on the island of Zealand
			
Radial/star shaped network, e.g. the Rome metro system	Universal star shaped network, e.g. InterCity and metro networks	Network with core route, e.g. Copenhagen suburban trains (S-tog)	Mesh network, e.g. German InterCity-Express train network

Figure 2.4: Overview of basic train service structures in a railway timetable. Each color represents one train service running in both driving directions (based on EI 2012)

Star shaped or radial railway networks can be found for metro systems. Metro lines service the suburban areas of a city and meet at a transfer station situated in the center of the city. An extended version of the star shaped network is the universal star shaped network. Here the number of lines is increased and this also increases the number of transfer stations between the lines, if only two lines meet at one transfer station. An example of this train service line structure is the metro network in Athens (Greece). A network consisting of a core route that divides into several branch lines can often be found in large cities, where the core route goes through the city center; or in regions with a natural railway alignment bottleneck, such as a river or mountain crossing. A network layout like this can be found on the Copenhagen and Munich suburban train systems (S-tog and S-Bahn). Railway countries like Germany and Belgium have a meshed railway network, where one most often can go from A to B via C or D. The layout of train service lines will be determined by several important factors such as passenger flows, vehicle fleets and their numbers. As seen in the low right corner of Figure 2.4, there is not necessarily a transfer option between two meeting train services, see the green and black train line service. One reason for this can be that there are more attractive travel alternatives for

the given travel relation that could make use of the missing transfer option. An omission of a transfer option can also be caused by very low numbers of transferring passengers.
When train service lines are using the same infrastructure, a railway line section, it is possible to run the train services as one coupled train instead of running them as individual trains. Trains are then split up/coupled at the railway stations where the network divides. This can be the case for the corridor/tree shaped, core route and meshed train service line structures.

Each of the presented train service line structures can have an effect on the planning options in regards to rostering plans for rolling stock and train staff. If two train service lines share a terminus station it is easy for them to share rolling stock too. After arriving as one train service line, followed by the necessary minimum turn-around time or stopping time, the given rolling stock can depart as another train service line. This can minimize potential unproductive waiting time of rolling stock at terminus stations. A similar exchange can take place of train staff, with the same potential effects. If two train lines share an intermediate station, these options are available too, but in this case a transfer of train staff is by far easier to handle than transferring rolling stock.

When looking at the structure of train services for a given country, it will most often be a combination of several of the presented basic structures presented in Figure 2.4. The French railway network is centered on the node Paris but it has an overall meshed structure when looking at the overall railway network and its train services. Some national railway networks can be divided into regions/sections with different track gauge standards, electrical power supply systems (or none) and signaling systems e.g. the Swiss and Japanese railway network. This can be another reason for combining some of the basic train line service structures with each other.

Some train service lines structures will be more suitable for some of the described timetable classes described in section 4.1than others. See section 4.10 for a matching of the presented train service line structures and the existing basic timetable classes.

2.5 Summary

It is necessary to have two timetable definitions, one covering a liberalized railway sector consisting of TOCs and IMs, and one covering a state owned monopoly or a completely privatized railway business. This thesis has created its own set of definitions of a railway timetable and it is as follows:

Railway timetable definition of this thesis

a) For a railway sector with separated infrastructure management and train operation:

A railway timetable is an agreement between an infrastructure manager and one or more train operating companies on a safe and feasible schedule for the railway traffic. The timetable accommodates as many of the requested train paths from the train operating companies as possible.

b) A railway sector with railway companies:

A railway timetable is an internal agreement in a railway company on how to operate train traffic in a safe and feasible manner on the company's railway infrastructure.

Every timetable has a time period of validity. In Denmark the railway timetables are valid for one year and the yearly timetable change takes place on the Sunday after the second Saturday in December. This rule for the yearly date of timetable change has been implemented by the European Union and is in use throughout its member countries.

Timetables can be planned in a long and short term time perspective. Creating the yearly timetable is short term timetabling, being limited by the existing railway infrastructure characteristics, rolling stock characteristics and cooperative agreements applicable for the railway sector. A long term timetable can have an optimized structure according to customer preferences and does not have to be feasible with the current characteristics of the available infrastructure and rolling stock. It provides valuable information about necessary improvements before a given ideal long term timetable can be implemented.

Timetabled train service lines can follow eight basic line structures. These are based on the topology features of the railway network covered by the timetable. The basic train service structures are:

- Point to point connection (e.g. a dedicated high speed line)
- Circle line (e.g. suburban circle lines in great cities such as Berlin, London and Tokyo)
- Centralized nodes (e.g. Paris in the French railway network)
- Corridor / tree structure (e.g. the Danish railway network with Copenhagen as starting point)
- Star shape / radial network (e.g. metro network in Rome)
- Universal star shape network (e.g. metro system in Athens)
- Core route network (e.g. suburban train network in Copenhagen and Munich)
- Meshed network (e.g. German InterCity and InterCity-Express train service network)

If train line services share stations it is possible to transfer both rolling stock and train staff between them and thereby potentially achieving a higher utilization level of both those resources. Trains from train service lines that run on the same railway line section can be run as coupled trains rather than individual trains.

3 Railway timetable types

There exist several types of timetables. Each of them has been prepared with a specific purpose. In the following sections the most commonly used timetable types are presented and described in detail. Section 3.1 describes the timetable type that is made available to everybody: The public timetable. This is followed by the working timetable that is mainly used by train staff in section 3.2. In section 3.3 and 3.4 two graphical ways to show the timetable are presented: The basic graphical timetable, which is widely used by timetable planners and traffic dispatchers, and the netgraph, specifically made for presenting periodic timetables in a customer friendly way. To ensure a feasible plan for traffic handling at railway stations a track occupation diagram is used. This is shown in section 3.5. Finally the plans for rostering of rolling stock and train staff are presented in sections 3.6 and 3.7.

3.1 Public timetable

In today's information society the public timetable is made available to railway passengers in two ways:

1. An online travel planner that provides the passenger with information in regards to a specific journey that is to take place on a given day within a given time interval. See Figure 3.1. It is difficult for the passenger to see if the chosen train service is running according to a pattern e.g. every hour on week days or if it is a unique train service only running on e.g. Mondays.

Figure 3.1: Screenshot from the Danish online travel planner "Rejseplanen" (in English: Journey Planner). (http://www.rejseplanen.dk (05.09.2011))

2. A static document that gives an overview of all departure and arrival times at one or more stations. This can be done in the form of a book, which can be both in a digital version such as a portable document format (pdf) file, printed on paper, a black board or a poster. See Figure 3.2.

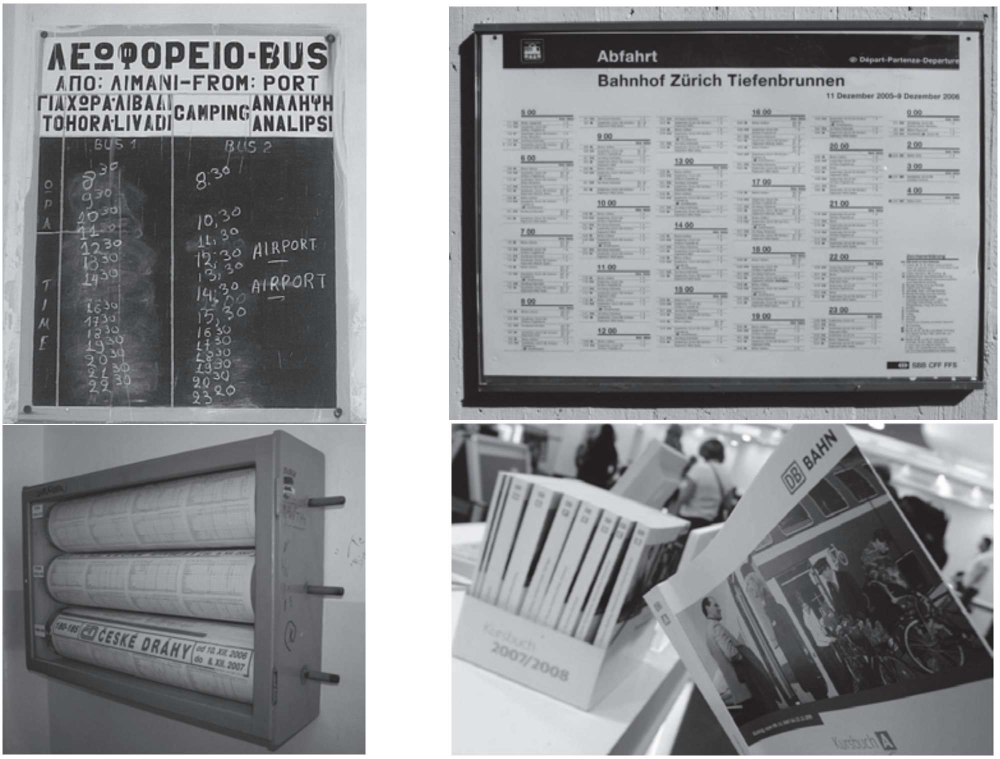


Figure 3.2: Public timetables - on black board (top left), poster (top right), roll (bottom left) and timetable book (bottom right) (http://de.wikipedia.org/wiki/Fahrplan (20.09.2012), http://www.n24.de/news/newsitem_3725627.html (20.09.2012))

Most public timetables are published with an accuracy of whole minutes. Times are rounded up or down to whole minutes according to national planning rules. Arrival and departure times are normally rounded down. This is to ensure that passengers and greeters are at the platform on time.

A blackboard or other forms of dynamic information e.g. monitors gives the option to easily update departure times if delays are occurring or departures are cancelled or added. This is not possible with the printed public timetable variants. The wish for real-time timetable information by railway passengers has prompted the development of new ways to present the public timetable information. A first improvement was the implementation of panel displays. With this technology it became possible to prepare a large number of standard messages regarding e.g. track changes, delays and cancellations of trains in advance. These messages improve the communication with passengers considerably. By introducing LCD and monitor displays a much higher degree of freedom in communication with passengers was achieved in regards to composing relevant messages for specific train passengers. See Figure 3.3.

Liberalization of the European railway sector has induced competition between different train operating companies (TOCs) on popular relations. This gives rise to a new category of necessary information for train passengers: The price to be paid for a ticket when using a specific TOC. Figure 3.4 shows a screen shot from the Swedish passenger TOC SJ (Statens Järnvägar) online journey planner showing varying ticket prices for train services between Gothenburg (Göteborg) and Stockholm. Prices can vary from week to week, from day to day and between time periods e.g. peak/off-peak hours during a day.

With the seemingly unstoppable increase in demand for railway capacity in Europe, it can become necessary to introduce differentiated access charges according to the time of day to use the railway infrastructure. On the network of Rail Net Denmark (RND), TOC pay an additional capacity fee between 450 and 1500 Danish kroner for running trains on a set of predefined railway line sections in the time interval from 07:00 to 18:59. This is an incitement for freight train operators to run trains outside daytime hours and thereby make capacity available for passenger trains (RND 2007, RND 2012a).

Figure 3.3: Public timetables presented with panel display (left) and monitors (right) (http://de.wikipedia.org/wiki/Abfahrtstafel (20.09.2012))

Best Buy Calendar – Find the lowest prices for SJ's most popular routes

From: Göteborg C | To: Stockholm C

Adult / Youth/Student
Single / Round trip
SJ High-speed train only

Prices and available seats are continuously updated. Deviations may occur, prices may be adjusted and tickets may be sold out.
More info

Show week 28-32	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Week 32	6 Aug 224:-	7 Aug 224:-	8 Aug 224:-	9 Aug 416:-	10 Aug 255:-	11 Aug 320:-	12 Aug 510:-
Week 33	13 Aug 330:-	14 Aug 236:-	15 Aug 236:-	16 Aug 236:-	17 Aug 297:-	18 Aug 297:-	19 Aug 297:-
Week 34	20 Aug 177:-	21 Aug 177:-	22 Aug 176:-	23 Aug 177:-	24 Aug 297:-	25 Aug 297:-	26 Aug 297:-
Week 35	27 Aug 145:-	28 Aug 145:-	29 Aug 145:-	30 Aug 145:-	31 Aug 233:-	1 Sep 210:-	2 Sep 248:-
Week 36	3 Sep	4 Sep	5 Sep	6 Sep	7 Sep	8 Sep	9 Sep
Morning 05:00 - 12:00	142:- 08:32	95:- 08:32	95:- 08:32	176:- 06:04	176:- 08:32	176:- 10:02	142:- 10:35
Day 12:00 - 18:00	95:- 15:12	95:- 15:12	95:- 15:12	210:- 12:02	286:- 15:12	176:- 12:02	307:- 16:32
Evening 18:00 - 05:00	145:- 20:42	145:- 20:42	145:- 20:42	145:- 20:42	146:- 20:42	159:- 18:42	314:- 18:02

Show week 36-40 — Lowest rate shown here: 95:-

Figure 3.4: Varying train ticket fares between Stockholm and Göteborg (Gothenburg). Variation depends on the yearly season, time of day (divided into morning hours (5-12), day hours (12-18) and evening (18-5)) and how far ahead you make your booking. (https://www.sj.se/start/startpage/index.form?l=en (20.09.2012))

Differentiated infrastructure access charges can also affect ticket prices for a journey – higher prices during rush hours and lower prices outside these time periods. This is already happening in e.g. London, United Kingdom (http://www.londontravelwatch.org.uk/consumer_advice/money_saving_transport_tips (20.09.2012)) and in Sweden (https://www.sj.se/start/startpage/index.form?l=en (20.09.2012)), where train fares depends on the yearly season, the time of day and how far ahead you have booked the train ticket. See Figure 3.4. If ticket prices are very dynamic, such as in the Swedish example, it is impossible to make ticket prices a part of the timetable information at stations. If ticket prices are fixed, this information can easily be integrated into the timetable information as seen in Figure 3.5.

Figure 3.5: Static public bus timetable board with added journey price information (http://en.wikipedia.org/wiki/Public_transport_timetable (20.09.2012))

Smartphones have taken the world by storm and improved possibilities to access and receive information of all kinds, also off line and real-time timetable information for public transport. Passengers demand more and better real-time information about train services. This includes navigation to the nearest station(s) and updated real-time departure and arrival times (including delays) of trains at the potential station(s). Figure 3.6 shows three screenshots from two public timetable applications for smartphones. Here the travel cost information would also be very useful for railway passengers, especially if you can choose between several TOCs (http://www.wired.com/autopia/2011//04/how-smartphones-can-improve-public-transit/ (06.09.2011)).

This stream of information can be divided into two categories: Push and pull. Pushing information takes place when an infrastructure manager (IM) or TOC takes initiative to deliver information to existing or potential customers. Push services are often based on information preferences expressed in advance. Information pull is when an existing or potential customer takes the initiative to get some timetable information. The most common category is the information pull; this has been known from the beginning of the internet. In the last 10 years more focus has been given to pushing information (Hermans 1998). TOCs and IMs can push information to customers to make their travel experience as good as possible. Examples of push information could real-time timetable data for customer-selected daily trains in case of train delays, planned timetable alterations due to e.g. maintenance work, for customer-selected railway line sections. On the other hand, customers can try to pull information from the data-systems of TOCs and IMs to get a better overview of the current travel options and their prices to get from point A to B. In this way customers get the best basis for making a considered and optimal journey choice from their point of view.

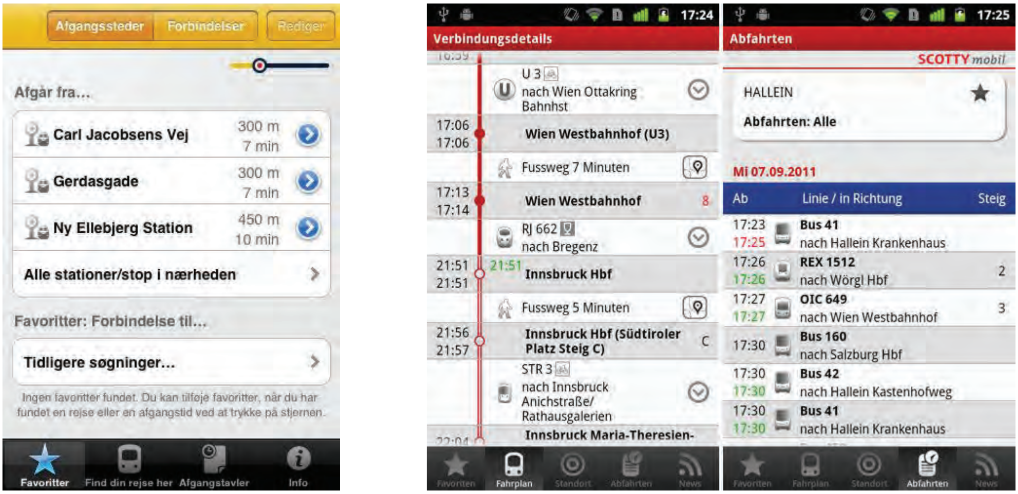


Figure 3.6: Examples showing public timetable applications on smartphones. The Danish "Rejseplanen" (in English Journey Planner) (left) (http://itunes.apple.com/us/app/rejseplanen/id317007942?mt=8 (06.09.2011)) and the Austrian "Scotty" with real-time timetable information (right) (http://itunes.apple.com/us/app/obb-scotty-mobil/id315497345?mt=8 (06.09.2011))

The demand for continuously updated real-time railway public timetable information will keep on growing and play a key role in making the railway a more attractive public transport system in the future.

Timetable times for freight trains and empty train runs are not made available in the public timetable. This information can be found in the working timetable used by the railway staff running these trains.

3.2 Working timetable

The accuracy of departure and arrival times in public timetables is in whole minutes. Calculated or measured running times between stations differ mostly from whole minutes. In most cases the running time consists of a number of minutes and a number of seconds. The precision of modern running time calculation and timetabling software tools is in seconds. To avoid possibly wasting time at all stations due to the rounding of times, a higher level of accuracy is needed in the detailed plan for train operations. Therefore a working timetable is introduced. The working timetable is more detailed in regards to railway locations. Both public stations and technical stations, such as junctions or overtaking tracks, are listed. In Denmark the accuracy of working timetables is in half minutes. Figure 3.7 shows the differences between a public timetable and the working timetable. Used as an example is a part of the train run of InterCity-train 141 from Copenhagen Airport to the city of Odense. The public timetable only shows arrival and departure times in whole minutes for stations at which the train is calling at. Please notice the differences between the two timetable types for the arrival and departure times at Ørestad station (marked in Figure 3.7), the first stop on the train run. In the public timetable both arrival and departure takes place at 11:45 while according to the working timetable the train arrives at 11:45 and departs at 11:45½ (=11:45:30).

The working timetable additionally shows passing through times for non-passenger railway locations on the train run. Between the stops Ørestad station and København H (Copenhagen central station), the InterCity-train 141 passes the location "Kalvebod" at 11:47:30. This is a junction, where a line braches of to bypass Copenhagen central station.

To make it possible for the train driver to keep the planned schedule of the train run and thereby staying within the allocated train path of the train in the timetable, the listed passing through times at railway locations are necessary. If the timetable contains scheduled waiting time in form of reduced travel speeds between locations, the passing through times provide a guideline for the train driver for which speeds to apply.

TOC DSB (Danish State Railways) has implemented a new train driver support system called “GreenSpeed” which helps train drivers to minimize energy consumption while still running on time. To calculate useful recommended train speeds, the build in algorithm in the GreenSpeed-system is fed with the detailed data from working timetables (Bergendorff 2012, Edinger 2012).

Stop:	Ankomst:	Afgang:	Bus-/Tognummer:	Spor
Københavns Lufthavn, Kastrup st		Kl. 11:40	IC 141	2
Tårnby st				2
Ørestad st	Kl. 11:45	Kl. 11:45		2
København H	Kl. 11:53	Kl. 12:00		
Valby st				2
Glostrup st				2
Høje Taastrup st	Kl. 12:11	Kl. 12:12		3
Hedehusene st				3
Trekroner st				3
Roskilde st	Kl. 12:19	Kl. 12:21		3
Viby Sjælland st				2
Borup st				3
Ringsted st	Kl. 12:36	Kl. 12:37		1
Sorø st				1
Slagelse st	Kl. 12:50	Kl. 12:52		3
Korsør st	Kl. 13:00	Kl. 13:01		3
Nyborg st	Kl. 13:13	Kl. 13:14		3
Odense st	Kl. 13:28	Kl. 13:31		5

IC 141	Ank	Afg	
Kbh. Lufthavn	-	11:40	CPH
Tårnby	-	43	TÅT
Ørestad	11:45	45½	ØRE
Kalvebod	-	47½	KLV
København H	53	12:00	KH
Valby	-	03½	VAL
Hvidovre Fjern	-	05	HIF
Glostrup	-	07	GL
Høje Taastrup	12:11	12	HTÅ
Hedehusene	-	15	HH
Trekroner	-	17	TRK
Roskilde	19	21	RO
Viby Sj	-	26½	VY
Borup	-	29½	BO
Kværkeby	-	32½	KY
Ringsted	36	37	RG
Fjenneslev	-	41½	FJ
Sorø	-	43½	SO
Slagelse	50	52	SG
Forlev	-	56½	FO
Korsør	13:00	13:01	KØ
Sprogø	-	07½	SPR
Nyborg	13	14	NG
Hjulby	-	17½	JU
Ullerslev	-	19½	UV
Marslev	-	23½	MV
Odense	13:28	13:31	OD

Figure 3.7: Differences between the public timetable (left) (http://www.rejseplanen.dk (15.03.2011)) and the working timetable (right) in Denmark (RND 2010b)

Working timetables in other countries like e.g. England describe the entire train run from a possible depot/depot track to the first passenger station, the public train run until its terminus for passengers and finally the train run from the terminus to a potential depot/depot track. In Denmark this is handled differently. If the depot facilities are located within the starting station or terminus station area of a train run, the Danish working timetable does not cover the train movements between platform tracks and depot facilities. These train shunting movements are handled by traffic dispatchers responsible for the relevant stations. If the depot facilities are located at a different railway station, a separate empty train run between station and depot is planned and contained in the working timetable (Johansson 2011).

Within the next few years the train shunting movements between platform tracks and depot facilities at a station, will be included in the working timetable. Reason for this change is that these train movements take up valuable infrastructure capacity in station switch zones and can create conflicts with existing planned train paths. Therefore it is important that TOCs and IMs agree on the planning of these shunting movements to ensure a robust traffic management (Johansson 2011).

Figure 3.2 shows the last printed Deutsche Bahn (DB) public timetable book for the timetable year 2008/2009. It contains so much information that it has been divided into several volumes. The same has been done with the Danish working timetable. It contains the following four volumes:

1. “Passenger trains in East Denmark” (TKØ) (RND 2012c)
2. “Passenger trains in West Denmark” (TKV) (RND 2012d)
3. “Copenhagen suburban trains” (S-trains/S-tog) (TKS) (RND 2012e)
4. “Freight trains” (TKG) (RND 2012b, it is not made available to the public)

3.3 Graphical timetable

The preferred timetable type of the timetable planner and the train traffic dispatcher is the graphical timetable. Trains are displayed as lines in a two dimensional co-ordinate system, where time and location are on the two axes. In Denmark the progressing time is going downwards on the y-axis and location is on the x-axis – following the used mileage of the railway line. In most other European countries graphical timetables are displayed in the opposite way, location on the y-axis and time along the x-axis (Hansen & Pachl 2008).

An example of a graphical timetable from Denmark is shown in Figure 3.8. Red lines are fast passenger trains e.g. InterCity-trains, yellow lines are slow passenger trains e.g. regional trains, blue lines are long distance freight trains e.g. transit freight trains between Sweden and Germany and white lines are representing local freight trains servicing local customers. The number following a given line representing a train is the number of the train, a unique identification of trains in the timetable.

In Figure 3.9 an example of a graphical timetable from the Netherlands is presented. It shows the basic hourly timetable pattern for the railway line between the important cities of Rotterdam and Utrecht. The line has a few sections with four tracks and else two tracks. This can be seen to the left in Figure 3.9. Please notice that the location is along the y-axis and the time along the x-axis. In this example different train classes, such as InterCity and regional trains cannot be distinguished from each other simply by looking at the train lines. One must have knowledge about train numbers and stopping patterns to be able to do this.

These graphs are prepared for every day. Generally train numbers can be reused the following day since the specific date makes the train completely unique. For trains that cross midnight during their scheduled train run the start date becomes critical for their identification. In case of a delay that makes a train run take place on the following operational day, normally a new unique train number is given to that delayed train.

Please notice that both driving directions are presented in the same graph. This is particularly relevant for single track railway lines, where trains can only meet at crossing stations. The major advantage of this timetable type is that all running trains are displayed at the same time and thereby possible interactions between them become visible to the timetable planner and train traffic dispatcher.

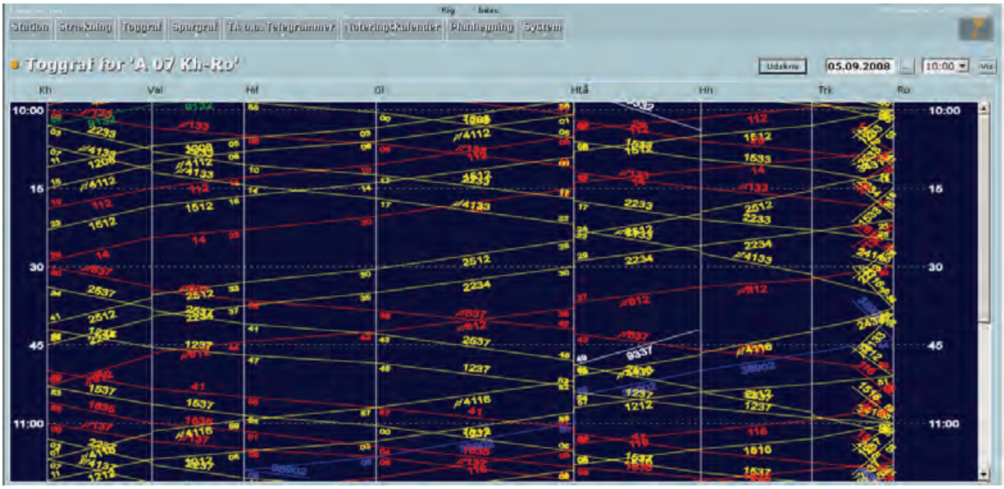


Figure 3.8: A Danish example of a graphical timetable for the railway line between Copenhagen (Kh) and Roskilde (Ro). Location is on the x-axis and time is on the y-axis (Rail Net Denmark software tool "P-base" (production database))

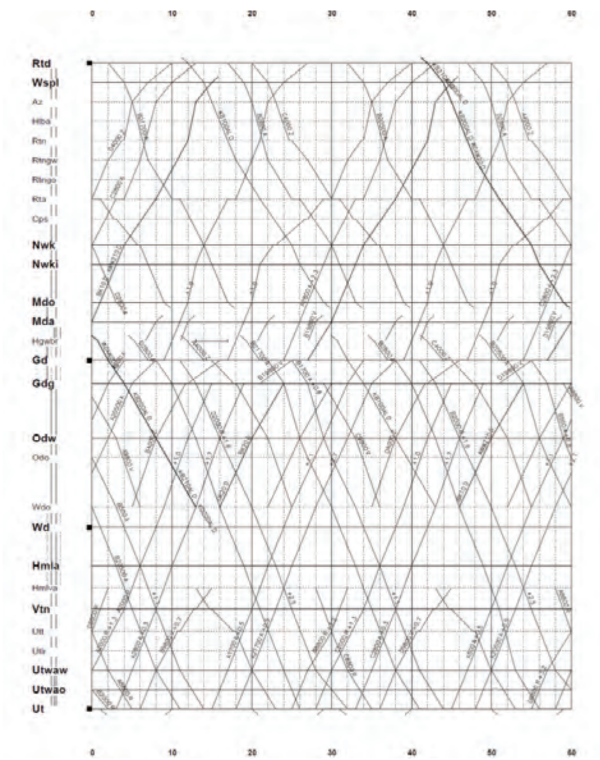


Figure 3.9: A Dutch example of a graphical timetable showing the basic hourly timetable pattern for the railway line between the cities of Rotterdam (Rtd) – Nieuwerkerk (Nwk) - Gouda (Gd) – Woerden (Wd) and Utrecht (Ut). Number of line tracks is visualized to the left. Location is on the y-axis and time on the x-axis (Huisman 2012)

The graphical timetable does not show which railway track is used between stations. If the railway line is single or double tracked, it is normally no problem for the timetable planner to overview. In case the railway line has three or more tracks it becomes more complicated. Same problem arises at stations. Halts and small stations make it easy to guess the utilization of platform tracks. For larger stations this becomes much more difficult and a need arises for creating an overview of the platform track utilization – a track occupation diagram.

3.4 Netgraph timetable

For periodic timetables it is possible to create the useful netgraph timetable. Figure 3.10 shows a small part of the national 2013 netgraph timetable for Switzerland. The railway network is represented in a schematic way. Major stations are marked with a grey rectangle and smaller stations, where a given train line stops are small circles. Train lines indicate railway lines between stations. A number above the circle indicates the number of total intermediate stops between two larger stations. Every colored line is a train per hour per direction. The line coloring indicates the train class and operating days. The digits at stations are the arrival and departure minutes for the train service. Minutes closest to the stations are arrivals, minutes furthest away are departures. This timetable type gives a quick overview of the timetable structure - departures, arrivals and frequencies of train lines - even for a complex railway network. But it also becomes clear for the reader that this concept of representing a timetable graphically is only suitable for a periodic timetable with only one basic traffic pattern.

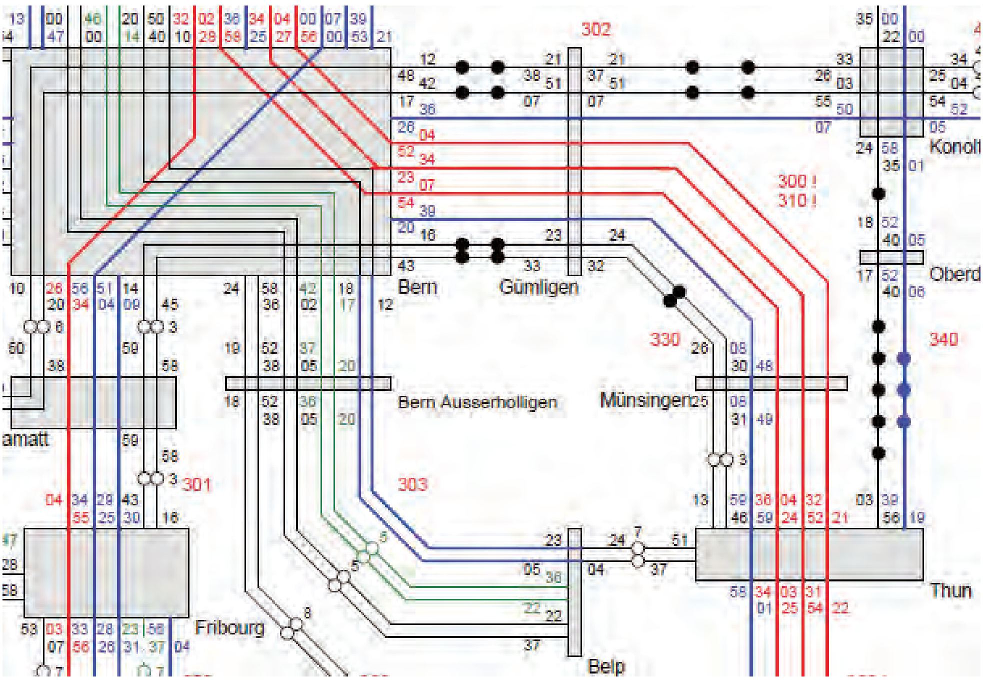


Figure 3.10: Part of the Swiss netgraph timetable valid for 2013. Red lines are InterCityExpress, TGV, InterCity or EuroCity trains. Blue lines are InterRegio, ICN, Regional Express and Suburban Express trains. Black lines are regional and suburban trains (S-Bahn). Green lines are regional and suburban trains only running on weekdays (http://www.sma-partner.ch/downloads/Netzgrafiken/Schweiz/NGCH_2013.pdf).

The netgraph timetable concept is being used in France, Switzerland, Austria, Germany, The Netherlands and Norway (only southern part). The concept was developed for the new periodic timetable 1970 for the Netherlands. It was used in the early 1970s by the Swiss timetable planners Berthouz, Meiner and Stähli for introducing the 1982 periodic timetable in Switzerland. In the year 2002 the Swiss railway magazine “Schweizer Eisenbahn Revue” published the complete Swiss netgraph timetable for the first time to celebrate the 20th anniversary of the periodic timetable in Switzerland (Berthouzoz et al 1972, Stohler 2002).

3.5 Track occupation diagram

In public timetables the planned use of platforms for trains is often published. See Figure 3.7 to the left. Big stations with a big amount of railway traffic often have a large number of platform tracks. It is necessary to plan the use of platform tracks to ensure that the traffic runs in a feasible way. One important available tool for this planning is the track occupation diagram. An example from Denmark can be seen in Figure 3.11. A track occupation diagram is built up similar to a co-ordinate system. Time is along the x-axis and on the y-axis are the platform tracks shown as horizontal lanes. Our example-station Roskilde has 7 main platform tracks. Trains are shown as short horizontal lines occupying a given platform track. Above the line is the train number (in blue), the beginning and end of the line is the arriving and departure minute respectively. If there is only one minute listed the train passes through the station. The hour of the day can be seen on the x-axis.

Track occupation diagrams can be improved by not only showing arrival, departure or passing through minutes given by the valid working timetable but also showing the block occupation times for the track circuits covering each platform track. This can be seen in most railway traffic planning and simulation tools such as TPS, RailSys and Open Track. See Figure 3.12.

Visualizing the utilization of station platform tracks in this manner gives the timetable planner and traffic dispatcher a quick and precise overview and it becomes clear if the degree of utilization is not equally distributed among the available platform tracks, thereby creating a potential increased risk for causing train delays (Landex 2008).

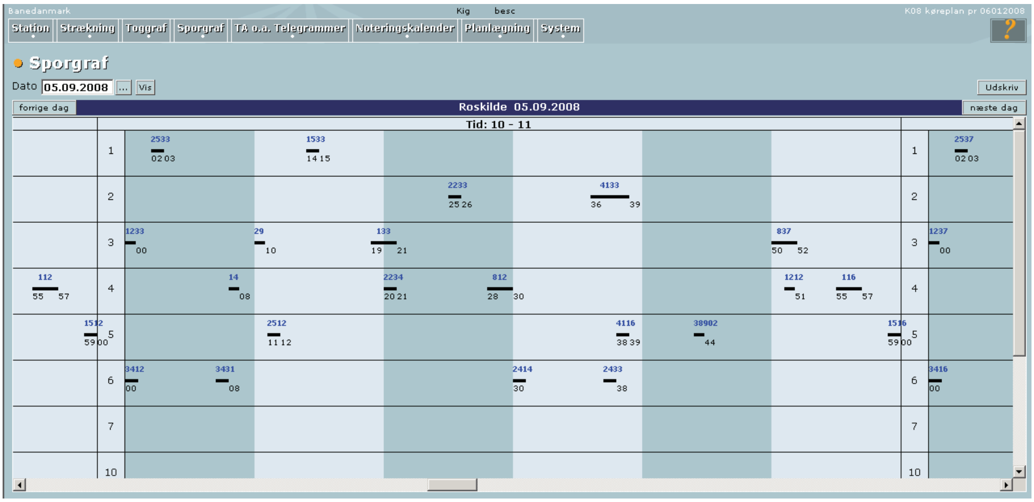


Figure 3.11: Track occupation diagram for Roskilde station in Denmark (screenshot from Rail Net Denmark software tool P-base)

These diagrams can also be seen displayed in the opposite fashion where the time is along the y-axis and the platform tracks are on the x-axis, which is the case in Figure 3.12, where a possible platform track block occupation for Esbjerg station is presented. The occupation level is calculated as a percentage based on block occupation minutes per hour. The percentage is listed in brackets below the platform track number on the y-axis at the top of Figure 3.12

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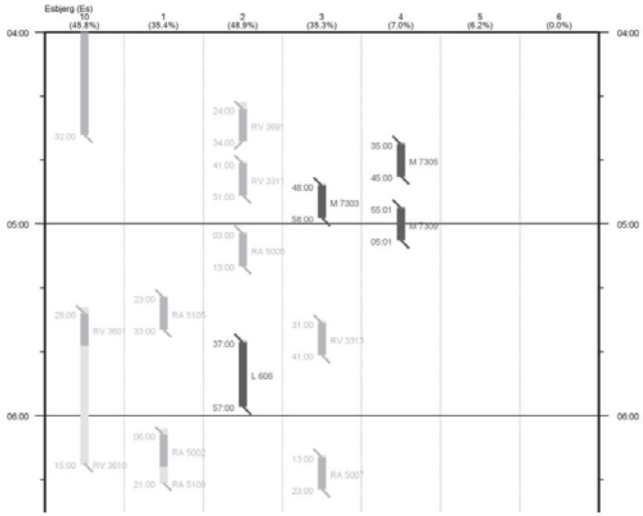


Figure 3.12: Example of platform track block occupation diagram for Esbjerg station from RailSys ver. 3

3.6 Rolling stock rostering plan

As soon as the railway capacity has been allocated by the IM among the applying TOCs and the yearly railway timetable has been fixed, the detailed planning of assigning rolling stock to timetabled train runs begins. This can be a very complicated optimization problem for each TOC and several software tools exist on the market to help TOCs preparing and optimizing their rolling stock rostering plans.

When preparing a rostering plan for rolling stock several things have to be taken into consideration:

1. **Assignment -** Enough rolling stock must be allocated to each train run to provide the required passenger seating or freight load capacity. With a locomotive hauled train it must be ensured that enough traction power is available so that the train run can follow its timetabled train path. With an increasing number of carriages it can become necessary to employ two locomotives instead of one, making the train more costly to operate for TOCs. The assignment of rolling stock is a compromise between minimizing the total number of needed rolling stock to reduce operational costs and not making the timetable too vulnerable towards secondary delays due to this optimization. Rolling stock that is assigned to several different train services during a day can potentially spread an initial delay to larger parts of the network. In the Netherlands an operations research approach has been taken by passenger TOC NS (Nederlandse Spoorwegen). Rolling stock can only be used within predefined train groups in order to reduce the risk of spreading delays in the network. Operations research methods are used to minimize the number of needed rolling stock (Peeters & Kroon 2003, Maróti 2006). The Copenhagen suburban passenger TOC, DSB S-tog, has and is still developing operations research methods

to handle the assignment of rolling stock and train drivers in situations with traffic disruptions. Focus has been given to the phase when going from reduced traffic caused by train cancellations, back to normal traffic operation (Jespersen Groth 2008, Rezanova 2009).

2. **Power supply** – There exist several electric power supply systems for railways in Europe. Direct current (DC) systems include the following voltages: 750V, 1500V and 3000V. It can both be delivered by overhead contact wire and a third rail. Alternating current (AC) systems include 25KV/50Hz and 15KV/16,66Hz and are delivered by overhead wire. Electric powered train sets or locomotives can only be employed on electrified lines for which they are equipped. To achieve a high degree of flexibility and thereby a higher competiveness, multi system locomotives or trains sets are necessary (Bakran et al 2004). Diesel powered rolling stock is more flexible in its use, since it can run on lines both with and without electric power supply.

3. **Track gauge** - In networks with different track gauges, the rolling stock can either be flexible, and be adapted to different gauges e.g. TALGO-trains in Spain, or must be dedicated to one track gauge thereby loosing flexibility. Flexible rolling stock makes the planning easier and reduces the need for rolling stock (Pourreza 2011).

4. **Train control system** - Railway networks containing different train control systems give a potential challenge to rolling stock planners. If rolling stock is only equipped to run under one train control system it can only be put to use on some parts of the network. This reduces the flexibility of its use and the optimization potential in the rolling stock rostering plan (Fan 2003).

5. **Axle load** - Some railway lines can handle higher axle loads than others. These are most often main lines and dedicated freight train lines for e.g. iron ore. Old bridges and regional railway lines are often not built to carry high axle loads and therefore some locomotives and/or carriages can be too heavy to run on them. This can reduce the options for rolling stock planners.

6. **Length** – Railway stations on railway lines are designed to handle a certain length of train. This becomes very important in case of crossing stations on single tracked railway lines and for stations that offer the possibility of overtaking trains.

7. **Clearance gauge** - If a railway network consists of lines with different clearance gauges, there is a risk of some classes of rolling stock not being able to run on parts of the network. This reduces the flexibility when preparing the rostering plan.

8. **Cleaning** – Both the exterior but mainly the interior of the rolling stock must be cleaned according to contractual obligations between the TOC and the transport services organization or internal TOC procedures if the train services are run on the company's own initiative. This must be planned into the daily schedule of every piece of rolling stock. This is a complicated task since cleaning facilities are only provided at certain depot facilities on the railway network and the necessary cleaning and train staff must be available at the given time (Lindner 2000).

9. **Depot facility** – Each railway network has a number of rolling stock depots and these are normally spread across the network. A depot facility may only be able to handle certain classes of rolling stock and also be limited to holding a given number of rolling stock. Furthermore,

some depots may only be equipped to handle certain maintenance tasks. Such factors reduce the flexibility in creating an optimal rolling stock rostering plan minimizing the needed numbers of rolling stock (Maróti 2006).

10. **Maintenance** - Each piece of rolling stock has to comply with strict maintenance regulations for each class of rolling stock. Regulation demands follow mostly the number of run train-kilometers e.g. 10.000trainkm and 100.000trainkm. These regulations must be accepted by the national railway authority and will also be overseen by the same authorities. If trains are not maintained according to the given regulations, rolling stock can be grounded and is not available to the TOC before the needed maintenance has been carried out and documented (EC 2004/49). This happened to TOC DB S-Bahn in Berlin in 2009 and caused reduced service levels on large parts of the Berlin suburban railway network. S-Bahn Berlin has not yet been able to return to the normal timetable (IFB 2011).

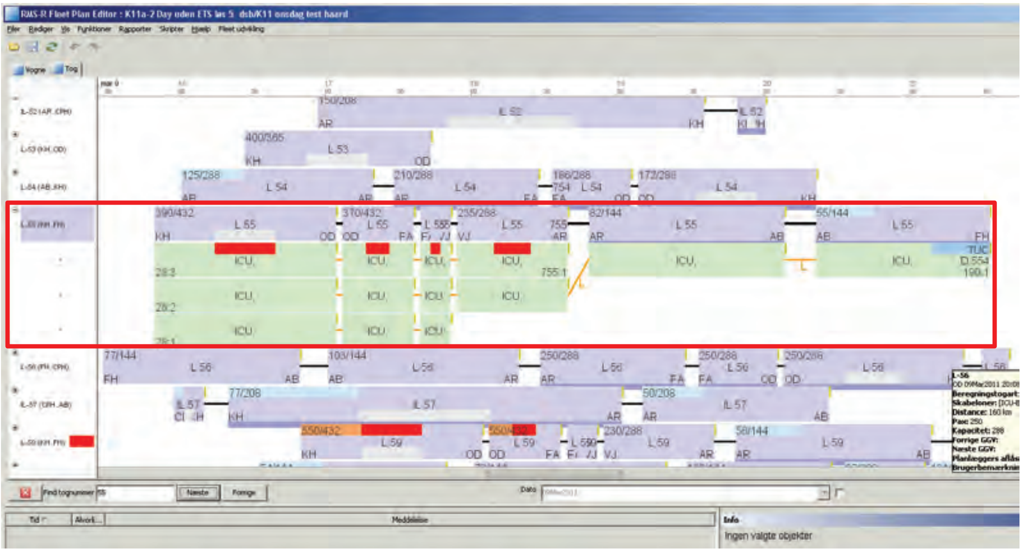


Figure 3.13: Screenshot from DSB's OMPLS2 software tool for preparing rolling stock rostering plans (Madsen 2010)

Figure 3.13 shows a “train view” -screenshot from the DSB planning tool called “OMPLS2” (rolling stock rostering planning system 2). This software tool has been developed specific for DSB in cooperation with the Boeing owned company Jeppesen. The InterCityExpress-train L55 is used as an example; it is marked by the red rectangle in Figure 3.13. Train L55 runs from Copenhagen central station (KH) via Odense (OD), Fredericia (FA), Vejle (VJ), Aarhus (Ar) and Aalborg (Ab) to Frederikshavn (FH). See the purple top row in the red rectangle. It consists of three multiple units. This is shown with the three green rows in the red rectangle. The multiple units are taken over from train number 28. See left (28:1 (train number 28, train unit 1), 28:2 and 28:3). The used multiple units are of the class ICU, this means that they are diesel multiple units equipped for driving in Germany (InterCityUdland). Until Vejle (VJ) the train consists of three multiple units. In Vejle (VJ) the rear multiple unit is uncoupled (bottom green row) and does not go any further. It is not shown to which next train number it is dedicated. This uncoupling of a train set is done to adapt the seating capacity of the train to the passenger demand. Demand estimation is based on frequently performed passenger counts by train staff, yearly national public traffic flow registrations and information from ticket sales (Madsen 2010).

The rest of the train continues on to Aarhus (AR) with the remaining two train sets. At Aarhus station the train is divided into two trains: Train number L55 with one multiple unit, continues on towards Frederikshavn (FH) via Aalborg (AB) (see middle green row and follow the orange links between green boxes). This multiple unit is dedicated to train number 190 after arriving at Frederikshavn (see far right). The last train set becomes train number 755 (see top green row in the middle) and continues on towards Struer via Langå and Viborg. It is not shown if the multiple unit is dedicated to another train number after arriving in Struer. This can be seen in the software tool when changing the view to train number 755 (Madsen 2010).

This software tool optimizes the use of rolling stock according to DSB rostering planning rules. These planning rules do not include the use of dedicated rolling stock for certain train services and thereby give a high levelof flexibility in the planning process. There are two goals with the introduction of OPLS2 (Madsen 2010):

1. Minimize costs for empty train runs, changing the composition of trains during a train run and train staff. Cost reduction is expected to be in the order of a two-digit Danish kroner million amount per year
2. Reduce the present manual workload when preparing rolling stock rostering plans.

OPLS2 does not show which specific multiple units are going to be used for which train runs. An overall daily plan is created for the run of multiple units. The allocation of specific multiple units is until now done manually in the software tool called "MADS2" (MAterielDisponeringsSystem); this is due to the fact that constrains such as upcoming technical inspections/revisions of multiple units are not yet considered in OPLS2 and must therefore be taken care of manually in MADS2 (Madsen 2010).

3.7 Train staff rostering plan

After rolling stock has been allocated to all train runs, it is possible to assign the needed train staff to train runs. This is again a complicated optimization problem for the TOC and software tools that help with creating attractive solutions for this problem are available.

When allocating staff to timetabled train runs the following issues must be considered:

1. **Assignment** – Each scheduled train run must be assigned the necessary train staff, e.g. a train driver and a conductor. The allocated train staff must be allowed to work with the class of rolling stock they have been assigned to. This often requires some specific education and training. Train staff must be able to handle situations such as correcting minor failures of technical installations e.g. the air condition system and carrying out specific emergency evacuation procedures.

2. **Route knowledge** - A train driver must have a certain level of local knowledge about the railway line he or she is assigned to be driving on. This includes particular alignment features, local speed restrictions, functionality of used interlocking systems, signal positions etc. If a train is running on an unknown line to the train driver, it can result in a general reduced maximum speed (RND 2013b). Throughout their career train drivers can increase their local knowledge to include large parts of a railway network. This increases the flexibility of their assignment to scheduled train runs.

3. **Schedule** - The working day schedule of the train staff must comply with the collective agreement made between the TOC and the relevant (railway) unions. This is in regards to breaks, rest hours, longest period of continuous work for e.g. train drivers, and variation in work during the day e.g. driving on different railway lines. This is taken very seriously by TOCs (Rezanova 2009).

4. **Base station/depot** - Railway staff is normally based at a given station/depot equipped with the adequate facilities e.g. rest rooms and canteen. The daily working schedule of train staff should preferably begin and end at their base station/depot. This limits the flexibility in preparing an optimal plan for rostering of train staff (Rezanova 2009).

Figure 3.14 shows a screenshot from the software tool “LTD” (train staff planning system) used by TOC DSB to prepare the rostering plan of train staff. Again we are using InterCity-Express train L55/755 as an example. To the far left, the chosen planning period can be seen. In our example it is March 25th 2011 (marked with the blue box in the calendar view). To the right of the calendar view, a list of DSB employees can be seen. Each employee has a unique ID, which consists of 3 digits + a letter + 1 or 2 digits. Every DSB employee on this list is assigned to be a part of the train staff on train run “Lyn 55” (see tab above the list) from Copenhagen central station (Kh) to Frederikshavn (Fh) (L55) and Struer (Str) (755) via Fredericia (Fa) and Aarhus (Ar). Inside the brown rectangles in Figure 3.14, we can see the start and end time, as well as the length of the duty of each allocated employee. In the window below we can see the duty details. They are marked with red rectangles. In this example train drivers are assigned to the train run. Starting from the top, the train driver with ID 352F3 is part of the train staff from Aarhus (Ar) to Frederikshavn (Fh). Please remember that our example train is divided in Aarhus into two trains: One going to Frederikshavn (Fh) via Aalborg (Ab) (train number L55) and one going to Struer (Str) via Langå (Lg) (train number 755). The duty of this employee started in Frederikshavn (Fh) with the train number 3250 to Aalborg (Ab) and then from there to Aarhus (Ar) with train number 50 (Madsen 2012).

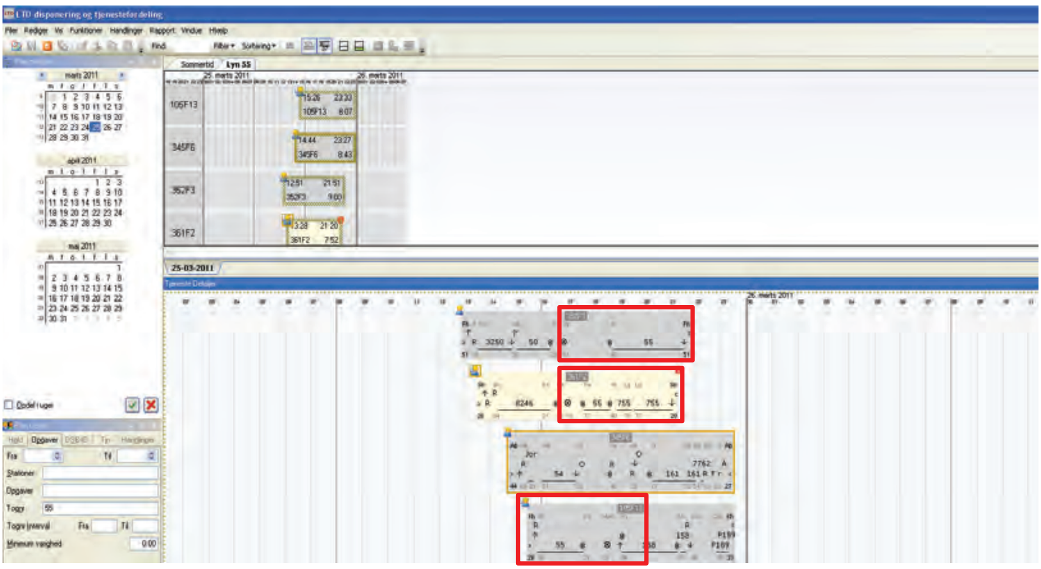


Figure 3.14: Screenshot from DSB's train staff rostering plan tool “LTD” (Madsen 2010)

Below can be seen train driver 361F2 who joins train L55/755 in Fredericia (Fa) and continues on the train all the way to Struer (Str). The duty of this train driver started in Struer (Str) with train number 8246. At the bottom can be seen employee 105F13. He starts his shift on Copenhagen central station (Kh) with train L55/755 to Fredericia (Fa), then returns to Copenhagen by driving train number 158. It becomes evident that the train staffs return to their base stations/depots at the end of their duty. In earlier days it was not uncommon for train staff to stay overnight in other parts of the country, only to return to their base station the following day. This is an inefficient and expensive feature for the TOCs and unattractive for the train staff and therefore avoided in present time rostering plans for train staff (Madsen 2012).

3.8 Overview of the presented timetable types

Table 3.1 gives an overview of the presented commonly used timetable types. Their purpose and strength(s) are briefly described.

Timetable type	Purpose	Strength(s)
Public timetable	• Informing current and potential train passengers about available train services	• Easy accessible for the public. It is available in many formats e.g. paper, board and digital (on-line)
Working timetable	• Giving detailed timetable information about a timetabled train run to the train staff	• Train drivers have the necessary detailed arrival, departure and passing through times for all locations to keep the train punctual
Graphical timetable	• Timetable planners and traffic dispatchers get a detailed overview of planned train traffic • Conflicting train paths become visible	• Conflicting train paths can quickly be recognized, especially for single tracked railway lines • Scheduled short headway times between trains become visible
Netgraph timetable	• Timetable planners and railway customers can get a quick overview of planned train traffic	• Gives a quick overview of the timetable structure, departures, arrivals and frequencies of train lines even for a complex railway network
Track occupation diagram	• Giving the timetable planner and traffic dispatcher an overview of which track is allocated to which train • Conflicting train paths become visible	• Easy to overview the utilization level of different station tracks • Makes the re-scheduling of trains at stations easier
Rolling stock rostering plan	• Allocating rolling stock to each scheduled train run	• It gives an overview of the complexity level of rolling stock circulation • It gives important input to the possible re-scheduling plans for train runs
Train staff rostering plan	• Allocating the needed train staff to each scheduled train run	• It gives an overview of the complexity level of train staff circulation • It gives important input to the possible re-scheduling plans of train runs

Table 3.1: Overview of the presented commonly used timetable types

3.9 Summary

This chapter presents the most common used timetable types. Ranging from the timetable type available to everybody, the public timetable, going on to the more detailed working timetable used primarily by train staff. The public timetable only lists arrival and departure times for passenger trains whereas the working timetable contains a higher level of detail for the entire train run. This is followed by the favored timetable type by timetable planners and train traffic dispatchers: The graphical timetable. Here timetabled train paths are shown as lines in a time-space coordinate system. Periodic timetables can be visualized with the netgraph timetable. This gives both timetable planners and the public a quick overview of the timetable structure.

Track occupation diagrams are useful when planning the detailed running of train traffic at larger stations. Trains are allocated to platform tracks and their arrival and departure or passing through times are listed in lanes, representing the tracks. This is a very useful tool for traffic dispatchers controlling larger stations.

Finally the thesis presents rostering plans for rolling stock and train staff. When the yearly timetable has been created, TOCs must assign rolling stock to each of their timetabled train paths. On one hand TOCs will try to minimize the need for rolling stock to reduce operational costs, but on the other hand they do not want to create a timetable vulnerable to secondary delays caused by complex rostering plans. This is a difficult optimization problem since many aspects such as differences in train control systems and allowed axle loads per railway line must be taken into consideration. Today TOCs use software tools to help prepare rolling stock rostering plans. The tool OPLS2 developed by DSB and Jeppesen is briefly presented as an example.

After the allocation of rolling stock the train staff must be assigned to each scheduled train run. Again TOCs will try to minimize the needed number of train staff to reduce operational costs and thereby increase competiveness. This is again a complicated optimization problem since issues such as necessary qualification of staff and route knowledge of the travelled railway lines must be respected. TOC DSB uses its own software tool “LTD” to produce rostering plans for train staff. This is shortly presented at the end of this chapter.

Finally an overview of the presented timetable types is given, briefly describing their purpose and strength(s).

4 Railway timetable classes

When looking at railway timetables around the world several timetable classes can be identified; each has its own specific structural features. In section 4.1 seven basic timetable classes are presented. Section 9.1.1 describes the concept of structure in timetables and how it can be quantitatively measured. In the following sections the identified timetable classes are described in more detail and compared with each other. Non-periodic timetables are discussed in section 4.2, periodic timetables in section 4.3. A comparison between these two basic timetable classes is made in section 4.4. High frequency timetables are described in section 4.5. In section 4.9 and 4.7 a description of symmetric periodic timetables and integrated fixed interval timetables is given respectively. Section 4.11contains a comparison between the seven presented basic railway timetable classes. Finally a summary of chapter 4 is given in section 4.12.

4.1 Basic railway timetable classes

A timetable can be more or less structured. Weits states that timetables containing periodic repeating patterns have structure, whereas non-periodic timetables have no structure (Weits 2000). This is not entirely correct. This thesis presents two new non-periodic timetable classes that contain some level of structure but must still be characterized as being non-periodic. A systematic approach to a classification of railway timetables is given by Liebchen (Liebchen 2006). Figure 4.1 shows Liebchen's classification of railway timetables. Every railway timetable can be part of the set of non-periodic timetables. If a timetable is based on repeating patterns it can be part of the set of periodic timetables. Liebchen uses two structural characteristics: Symmetry and Integrated Fixed Intervals, to further refine the classification of periodic timetables. Since integrated fixed interval timetables (IFIT) are symmetric, they are included in the set of symmetric timetables. In his approach, Liebchen therefore identifies four basic railway timetable classes (Liebchen 2006).

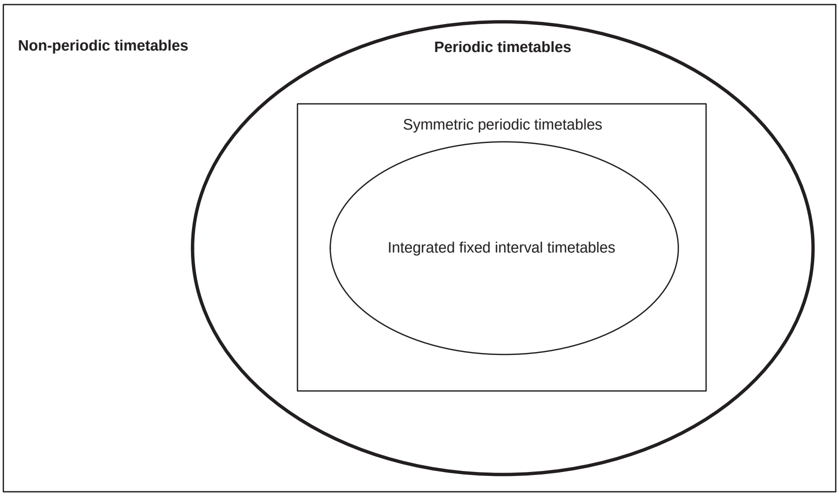


Figure 4.1: Systematic overview of timetable classes (Liebchen 2006)

In mathematical terms, Liebchen considers railway timetabling primarily to be a periodic event scheduling problem (PESP) (Liebchen et al 2004, Liebchen & Möhring 2004). Since most European railway timetables are periodic, this assumption can be justified. This focus on periodic timetables is reflected in Liebchen's approach to a classification of railway timetables, where the classification of periodic timetables is much more detailed than non-periodic timetables.

This thesis has identified three more basic railway timetable classes, besides the four previous identified by Liebchen. In Figure 4.2 this thesis presents a revised version of Liebchen's timetable classification approach. Newly added basic timetable classes are: Non-periodic symmetric timetable, non-periodic integrated interval timetable and the high frequency timetable.

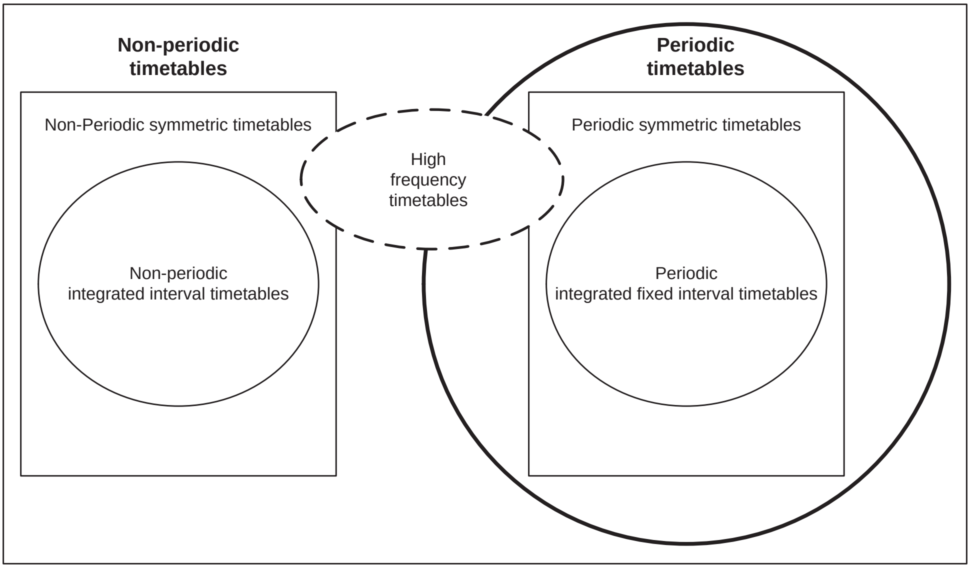


Figure 4.2: Revised systematic overview of timetable classes of this thesis

The two presented classification approaches have two things in common:

1. There are two fundamental railway timetable classes: Non-periodic and periodic timetables
2. Periodic timetables can be divided into sub sets according to the presence of specific structural features: Symmetry and integrated intervals

This thesis has found that non-periodic timetables theoretically also can be divided into the same sub sets of timetable classes as periodic timetables. An example of a non-periodic symmetric timetable can be seen in Figure 1.2. Departures take place at the same time in Liverpool and Manchester but they do not follow a pattern, such as e.g. an hourly departure.

Furthermore this thesis has identified a new basic timetable class: High frequency timetables. Such timetables are most often used for metro or suburban train services. The frequency of trains is so high that passengers have no need for timetable information, since potential waiting times at stations are very short. High frequency timetables are a cross between non-periodic and periodic timetables. An average train passenger may consider high frequency timetables to be very structured because of the high number of departures and arrivals per hour. Theoretically there has to be no structure in this timetable class but the frequencies of train services are so high, that passengers do not demand a high level of timetable structure. For high frequency timetables a public timetable with specific arrival and departure times is often not produced.

Timetables can be more or less periodic. This goes for when looking at a single train service, a single railway line or an entire railway network. On a railway network, some railway lines might be operated using a periodic timetable, other railway lines may be serviced with a non-periodic timetable, individual scheduled trips. This can be caused by infrastructure characteristics or big differences in travel demands on different parts of the selected railway network.

The applied timetable class can change during an operational day. This can again be for a single train service, railway line or for an entire railway network. During rush hours a non-symmetric periodic timetable can be used to meet the differences in travel demands for each travel direction. Outside rush hours a symmetric periodic timetable can be applied if travel demands are more even between travel directions.

Periodic timetables can have different periodicity characteristics. This occurs if a timetable goes through several different timetable patterns during a day e.g. one pattern for the morning rush hour, a different pattern for the afternoon rush hour and a pattern for the rest of the daytime hours between e.g. 06:00 and 19:00 o'clock. There arises a need for further differentiation of the periodic timetable classes according to their different periodicity characteristics. This thesis has added three new periodicity classification steps for a refined classification of periodic timetables. In
Figure 4.3: this thesis has refined the variety of railway timetable classes accordingly and in total 25 timetable classes, marked **T1-T5-7**, can be identified. The three periodicity classification steps are:

Step 1
The periodicity characteristics of a periodic timetable are based on the characteristics of the patterns in the timetable. Periodic timetables can work with the same timetable pattern all day or they can change their operational pattern a few or numerous times during a day. This includes returning to an earlier used pattern.

Step 2
Two succeeding timetable patterns can be entirely the same, partly identical or completely different. Being partly alike can cover containing all the train services of the previous pattern and have additional new train services e.g. rush hour services or lengthened existing train services. The introduction or removal of entire train services is seen as a basic change between two patterns. Changing timetable pattern can also result in new arrival, departure and travel times but also changed frequencies of train services. These are also seen as basic changes. Going from one timetable pattern to another can entail both basic and non-basic changes.

Step 3
Final characteristic is the number of shifts between different timetable patterns during a day. The number of shifts can be seen as high or low. Examples are presented in Table 4.1. A non-periodic timetable could in this way be regarded as a periodic timetable with a unique pattern every hour.

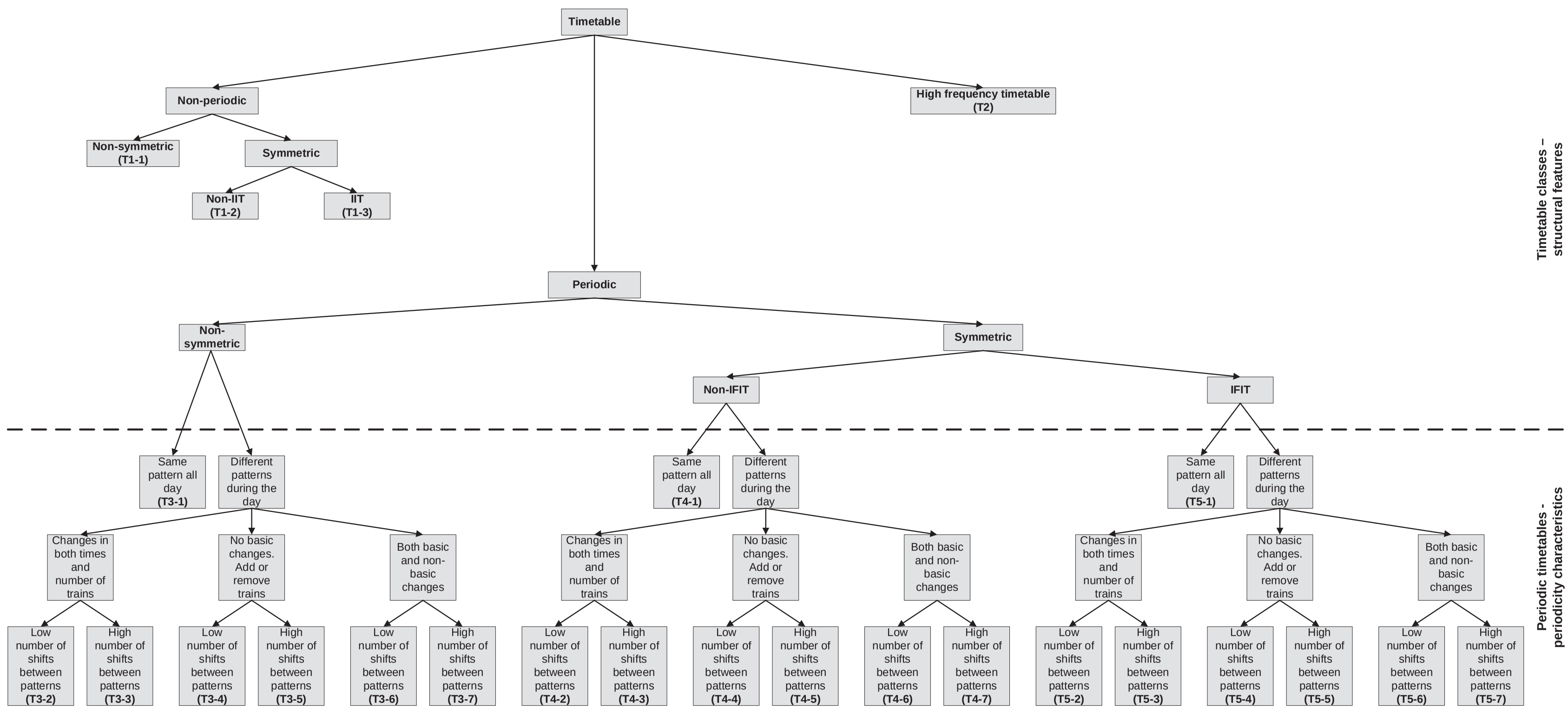


Figure 4.3: Systematic overview of timetable classes identified by this thesis. The classification developed by this thesis is based on specific structural features and general structural characteristics

It can be difficult to classify the number of shifts between timetable patterns as low or high. It depends highly on the investigated railway system and on the person(s) doing the investigation. The definitions of high and low numbers of this thesis are presented in Table 4.1. Here examples are given on low and high number of shifts between patterns depending on the category of the railway system. A metro system may have as few as two timetable patterns during an operational day e.g. daytime and evening + night hours. This gives a need for only changing pattern twice. For long distance railway traffic the minimum number of timetable patterns is normally higher since numbers of trains are more finely adjusted to the variations in travel demand during the day.

<table>
<tr><th rowspan="2">Number of timetable patterns</th><th colspan="2">Railway system</th></tr>
<tr><th>Metro / Suburban</th><th>Regional / Long distance</th></tr>
<tr><td>Low</td><td>1. Daytime
2. Evening + night + early morning</td><td>1. Early morning+ night
2. Rush hours
3. Daytime
4. Evening</td></tr>
<tr><td>High</td><td>1. Early morning
2. Rush hours
3. Daytime
4. Evening
5. Night</td><td>1. Early morning
2. Morning rush hour
3. Daytime
4. Afternoon rush hour
5. Evening
6. Night</td></tr>
</table>

Table 4.1: Examples of low and high number of timetable patterns according to the railway system – for passenger train services

A high level of shifts between patterns can be driven by optimizing operational costs of the railway traffic, e.g. only providing the requested seating capacity per hour. Operational cost drivers are amongst others staff wages, wear and tear on the rolling stock and infrastructure, and fuel or electric power consumption.

4.2 Non-periodic timetables

A non-periodic timetable contains no structure. It consists of individual scheduled trips that are based on travel demand. Figure 4.4 shows an example of a non-periodic timetable between the cities of Bordeaux and Marseille in France and a schematic graphical timetable for a non-periodic timetable. Every departure time during a day is unique. Travel times for trains have the same characteristic; only 2 out of 9 train departures have the same travel time: 6 hours and 10 minutes. This indicates that train runs often have different stopping patterns and different levels of scheduled waiting times in the timetable.

This timetable class was the most commonly used for long distance railway traffic in Europe when looking back in history. Only in the 1970s and early 80s did the national railway companies introduce periodic timetables in large scale for their train services. Some countries like France still use non-periodic timetables for the larger part of their travel relations. The French IM Réseau Ferré de France (RFF) announced that the number of periodic departures had gone up from 8 to 16% with the introduction of the timetable for 2012 (Klee 1996, Ministère de l'Écologie 2011, Mitzlaff et al 1994, http://de.wikipedia.org/wiki/Taktfahrplan (10.10.2012)).

Station/Stop	Date	Time		Duration	Chg.	Products
Bordeaux-St-Jean	Fr, 01.04.11	dep	06:03	5:44	0	
Marseille-St-Charles	Fr, 01.04.11	arr	11:47			
Bordeaux-St-Jean	Fr, 01.04.11	dep	07:25	9:22	2	RE, TGV
Marseille-St-Charles	Fr, 01.04.11	arr	16:47			
Bordeaux-St-Jean	Fr, 01.04.11	dep	11:46	6:57	0	
Marseille-St-Charles	Fr, 01.04.11	arr	18:43			
Bordeaux-St-Jean	Fr, 01.04.11	dep	14:50	5:52	0	
Marseille-St-Charles	Fr, 01.04.11	arr	20:42			
Bordeaux-St-Jean	Fr, 01.04.11	dep	16:28	6:31	0	
Marseille-St-Charles	Fr, 01.04.11	arr	22:59			
Bordeaux-St-Jean	Fr, 01.04.11	dep	17:22	6:20	1	TGV
Marseille-St-Charles	Fr, 01.04.11	arr	23:42			
Bordeaux-St-Jean	Fr, 01.04.11	dep	20:11	14:06	4	RE, NZ, BUS,
Marseille-St-Charles	Sa, 02.04.11	arr	10:17			TGV
Bordeaux-St-Jean	Fr, 01.04.11	dep	20:11	14:27	3	RE, NZ
Marseille-St-Charles	Sa, 02.04.11	arr	10:38			
Bordeaux-St-Jean	Fr, 01.04.11	dep	22:39	12:03	1	TGV
Marseille-St-Charles	Sa, 02.04.11	arr	10:42			

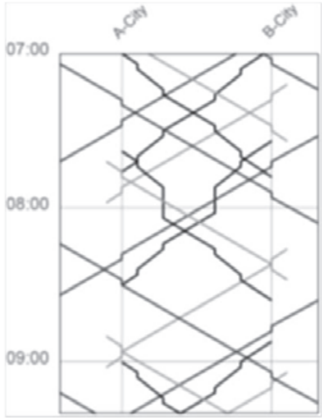


Figure 4.4: Example for a non-periodic timetable – Public departure and arrival times for train services between Bordeaux and Marseille in France (left) and a schematic example of a graphical timetable for a non-periodic timetable (right) (www.bahn.de (29.03.2011), Liebchen 2006)

If the planning of railway traffic is done using a market oriented approach, this timetable class would be preferable to the other identified timetable classes. When there is a high demand for running a train at a given time on a travel relation, a train fulfilling this demand will be added to the timetable.

A classic passenger demand is short travel times. This can be achieved by implementing direct train connections on travel relations. Non-periodic timetables are therefore primarily based on direct connections rather than providing good transfer options. This generally induces shorter travel times.

Prioritization between two conflicting trains in the timetabling process will primarily be based on the planned travel speed: Faster trains are run first and secondly on the profit potential per train: The train that generates the greater profit will get the highest priority.

This timetable class can provide the TOCs with a high level of flexibility in their planning phase. There are no restrictions in regards to fixed train service frequencies. It creates a potential for optimizing the utilization level of rolling stock, including the use of empty train runs and consequently using minimum turnaround times at the terminuses, if there is available infrastructure capacity. The same potential exists for optimizing the utilization level for train staff. In this way the TOCs are potentially able to reduce the number of necessary rolling stock and train staff to transport a given amount of passengers and can hereby achieve greatly reduced operational costs. In contrast to this, experience from real-life railway operations shows that the utilization level of rolling stock and train staff is increased when running trains services in a repeating pattern – a periodic timetable. The main reason for this paradox must be the reduced complexity level when preparing rostering plans (Brünger 2000, Tyler 2003, Graffagnino 2012).

4.3 Periodic timetables

On the 10th of January 1863 the first underground railway opened in London, The Metropolitan Railway. The train service was running with an off-peak hour train service frequency of 15 minutes, which increased to 10 minutes during morning peak hours and was reduced to 20 minutes in the early morning hours and after 8 pm (Simpson 2003). This timetable showed structure since trains were running according to repeating different timetable patterns during the day. The London Underground introduced the periodic timetable.

Other underground railway lines in Budapest, Paris and Berlin also operated their train services according to periodic timetables (Kinder 2008).

With the implementation of the new timetable on the 15th of May 1934 the Copenhagen suburban trains, the S-trains, began their operation. The first train service had a basic service frequency of a train every 20 minutes. The S-trains have ever since been operated according to a periodic timetable (Larsen & Poulsen 2009).

In 1938 the periodic timetable class was introduced for the first time for long distance train services. This happened in the national railway timetable for the Netherlands. Train services ran every 30 or 60 minutes and there was a clear separation between fast and slow trains. Germany followed by introducing a periodic timetable for InterCity-trains in 1971. These trains ran every two hours and consisted of only first class coaches. In 1979 the timetable was improved, so that the InterCity-trains ran every hour and had both second and first class service. Switzerland implemented a national periodic timetable in the year 1982. Austria and Belgium railways followed in 1991 (Avelino 2006, Kinder 2008, Rey 2007).

In Denmark the first periodic timetable was introduced in 1974 with an hourly InterCity-train service between the cities of Copenhagen and Aarhus via the railway ferry crossing over the Great Belt between Korsør and Nyborg. In the following years a periodic timetable was introduced for all train services on the Kystbane (the Coastal Line) between the cities of Copenhagen and Elsinore. The year 1982 gave birth to a periodic timetable for DSB (Danish State Railways) owned lines on the Danish island of Zealand, on which the capitol Copenhagen is situated (Elgaard 2011).

Figure 4.5 gives a time line overview of the presented high lights from the history of the periodic railway timetable class. Text boxes marked with red indicate Danish events.

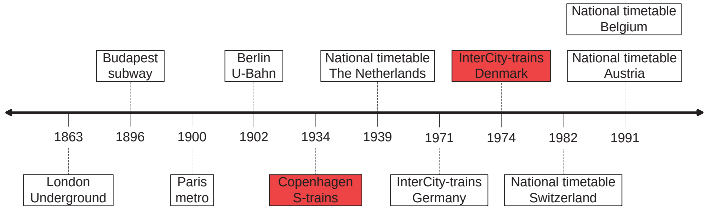


Figure 4.5: Time line for the development of the periodic timetable class. Danish events are marked with red (based on Avelino 2006, Kinder 2008, Rey 2007)

The present Danish timetable for long distance and regional trains is as far as possible a periodic timetable. See Figure 4.6. The time interval of periodicity is one hour. There are different timetable patterns for the early morning hours, morning peak hour, daytime hours, afternoon peak hour, evening hours and night hours. In the peak hours more trains are running in the primary travel direction than in the secondary driving direction. This makes the timetable a non-symmetric periodic timetable during these time periods. During evening and night hours the number of trains per driving direction can also vary do to the need for allocating rolling stock to selected stations in time for the morning peak hour.

Figure 4.6 shows both a public timetable and a schematic graphical timetable as examples for a periodic timetable. Easy noticeably are the hourly repeating departure times for InterCity-trains from Copenhagen Central Station (København H) to the left. They depart on the hour and half hour.

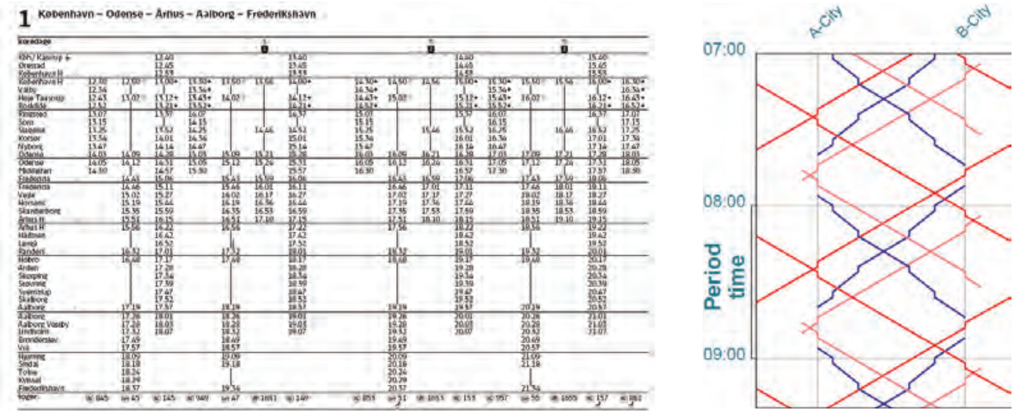


Figure 4.6: Example for a periodic timetable – Public timetable for long distance trains in the yearly Danish timetable (left) and a schematic example of a graphical timetable for a periodic timetable (right) (DSB 2011c, Liebchen 2006)

4.4 Non-periodic vs. periodic timetables

In this section the two basic timetable classes, non-periodic and periodic timetables are being compared. Table 4.2 gives an overview of the advantages these two timetable classes each possess. An advantage for a non-periodic timetable could most often be listed as a disadvantage for a periodic timetable and vice versa. There have been identified noticeably more advantages for periodic timetables, making this timetable class attractive to the railway sector.

Non-periodic timetables make it easy to adjust the number of departures to time sensitive markets or groups of customers. The non-existing structure of the timetable will not always give the possibility to run extra trains during specific hours of the day, but the possibilities will in general be better than compared with periodic timetables with dense traffic, especially the IFIT-class (Schittenhelm 2008, Schittenhelm & Landex 2009). With periodic timetables, a possibility can be to adjust the length of trains according to the passenger demand.

The departure and arrival times for trains are not easy to remember for passengers, when faced with the non-periodic timetable class, since they do not follow a specific pattern. This makes the timetable less attractive to passengers. Since detailed timetable information has become easily available to passengers through online railway traffic information services, the severity of this drawback of the timetable class has been reduced within the last years.

An existing high demand for a series of direct connections between two stations can often easily be implemented in a non-periodic timetable. Direct connections give shorter travel times and can thereby make railway travels on a given relation more attractive and give rise to the implementation of more direct connections on other travel relations in the timetable (Schittenhelm 2008, Schittenhelm & Landex 2009).

When applying a market oriented timetable there will be a big difference in numbers of running trains per driving direction during rush hours. There will be a primary driving direction that is serviced very intensely and a secondary driving direction with a lower service level. Between rush hours the numbers of running trains will be low. Such characteristics will in general make it difficult to achieve an optimal utilization of rolling stock and train staff. This increases the expenses for the TOC and thereby in the end the ticket price for the passengers. A periodic timetable creates a more even utilization demand for rolling stock and train staff and therefore a better basis to achieve a more optimized use of rolling stock and train staff by the TOCs. The preparation of rostering plans for periodic timetables is simpler than for non-periodic timetables - due to the use of timetable patterns - and this makes it in practice easier to focus more on the optimization of utilization levels of rolling stock and train staff (Schittenhelm & Landex 2009, Graffagnino 2012). A non-periodic timetable holds a potential for optimal utilization levels of rolling stock and train staff because of less restrictions when applying operations research tools in the timetabling and rostering process.

Non-periodic timetables **Advantages**	**Periodic timetables** **Advantages**
- Easily adaptable to market demands - High level of flexibility in the planning process - High number of direct connections - Short travel times - Attractive transfer times for the most used transfer connections - Potential for optimal utilization levels of rolling stock due to a higher degree of freedom in timetable planning – less restrictions when applying operational research methodology - Potential for optimal utilization levels of train staff due to a higher degree of freedom in timetable planning – less restrictions when applying operational research methodology - Potential for reduced operational costs due to a higher degree of freedom in timetable planning	- Easy to market to passengers - Easy to memorize for passengers - In practice a more optimal utilization of rolling stock due to simpler planning (patterns) - In practice more optimal utilization of train staff due to simpler planning (patterns) - Logic and coherent timetable for the entire network - Minimizing waiting time for randomly arriving passengers at stations - Reducing risk for passengers concerning train to train transfers - Focus on attractive transfer times - Well defined hierarchy of train services - Less work for the timetable planner (producing one timetable hour for each timetable pattern) - Less complex to generate with operational research methodologies, e.g. PESP-approach

Table 4.2: Overview of advantages of the non-periodic (left) and periodic (right) timetable classes based on (Brünger 2000, Schittenhelm & Landex 2009, Tyler 2003)

A timetable planner will find more degrees of freedom when preparing a timetable based on individual scheduled trips than when preparing a periodic timetable. There exist no predefined timetable structures that must be followed. This freedom contains the potential to achieve very high levels of rolling stock and train staff utilization levels. Furthermore, this precondition makes solving conflicts between trains easy by simply translating the train run of one of the involved trains by a few minutes. On the other hand, does the lack of structure in the timetable create more manual work for the timetable planner, since it is not possible to simply copy a timetable pattern and reuse it a number of times. This increases the working time to create a timetable (Schittenhelm & Landex 2009).

The preparation of a periodic timetable can become more difficult since all TOCs that want to run trains on the given railway network have to agree on implementing this timetable class. Some TOCs may base their train services on market demands, e.g. freight TOCs and are therefore not interested in running trains according to a predefined pattern. A political decision or a passenger demand may be necessary for implementation of a periodic timetable (Schittenhelm & Landex 2009).

If a periodic timetable is implemented on an entire railway network, the high level of structure in the timetable makes it logical and coherent. This applies for both railway customers and timetable planners (Schittenhelm & Landex 2009).

When creating a pattern it is necessary to have a well-defined hierarchy of train services. The structural skeleton of a timetable pattern is normally based on one or two passenger train categories with the highest priority e.g. InterCity Express or InterCity-trains. These are followed by passenger trains with lower priority such as regional and local trains. Freight trains have historically had the lowest priority and thereby often been given unattractive timetable train paths. In recent years this has changed and more effort has been put into creating attractive freight train timetable train paths by increasing the priority level of freight trains. At Rail Net Denmark they are now considered in the same planning stages in the timetabling process as the fast high priority passenger trains since scheduled overtakings most often occur between these train categories. Figure 4.7 shows the ranked order of train services in a timetable.

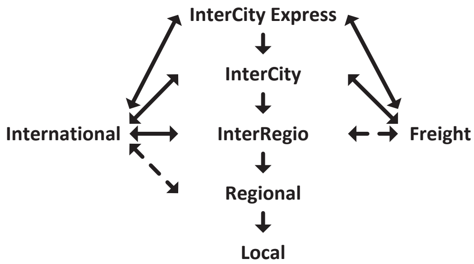


Figure 4.7: Ranked order of train services in the timetable. Based on (Landex 2008)

Depending on the geographical location of the country, international passenger trains, such as EuroCity-trains, can be a more or less important part of the national timetable. In countries like Switzerland and Austria, international trains play an important part as national fast passenger train services in the timetable. In Denmark the EuroCity-trains between Copenhagen and Hamburg follow the timetable train path of a fast regional train.

Working with timetable patterns makes the timetable more rigid and can in the worst case be cause for losing customers. It can be very difficult to add direct train services between two stations to accommodate sensitive market demands in a periodic timetable. The structure of the timetable pattern may not allow for new direct trains because of the existing train services. This is specially the case with dense traffic. Changing the stopping pattern of an existing train service is also rarely possible since it was planned to fit a specific traffic pattern (Schittenhelm & Landex 2009).

In a periodic timetable attention is given to attractive transfer options at selected stations. This ensures attractive train to train transfers for the majority of train passengers. Non-periodic timetables will focus on a few train to train transfers, the most used train transfers. When trains are delayed it can occur that transfer options are lost. For transferring passengers the risk of very long waiting times for the next train service to the requested destination is reduced with periodic timetables. Maximum waiting time can be the periodicity time interval (Schittenhelm & Landex 2009).

Patterns are easier to memorize for train passengers and therefore the timetable as a whole is more marketable towards customers. If passengers cannot recall the train departure times at a given train station and therefore arrive randomly, a periodic timetable will ensure that the maximal average waiting time is half the train service frequency (Schittenhelm & Landex 2009).

4.5 Periodic Symmetric timetables

Both periodic and non-periodic timetables can be symmetric. If the same stopping pattern and running times are used for train services in both driving directions, an axis of symmetry will exist in the timetable. If train services follow a pattern it is a symmetric periodic timetable. An axis of symmetry is easily recognized if train services for both driving directions cross at a given station. However, this is often not the case as axis of symmetry can be located anywhere on the railway network. On the right side in Figure 4.8, an example of a schematic graphical timetable for a periodic symmetric timetable is presented. A symmetric train service can be recognized by looking at the arrival and departure times of the two driving directions. If the sum of the number of minutes equals the service frequency or a whole multiple of this, then the timetable is symmetric (Liebchen 2003). In the left side of Figure 4.8 an example of this is shown: A return trip between the German capitol Berlin and the Dutch city of Delft. Departure minute at Berlin central station is 51 and arrival minute is 8. The sum is approximately 60 minutes, which is also the service frequency of the ICE-train service between Berlin and Duisburg. The same pattern can be seen at Duisburg and Amsterdam stations.

Berlin Hbf	08:51	ICE 642	21:08	
Duisburg Hbf	12:47		17:10	ICE 643
Duisburg Hbf	13:28	ICE 126	16:32	
Amsterdam Centraal	15:25		14:34	ICE 127
Amsterdam Centraal	15:40	2263	14:22	
Delft	16:38		13:24	2238

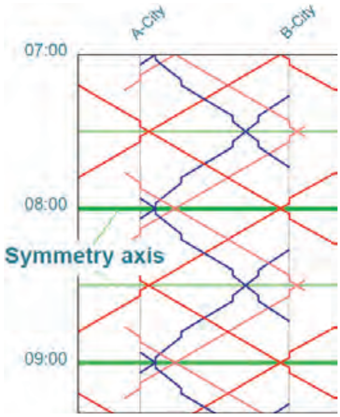


Figure 4.8: Example for a symmetric periodic timetable – public timetable for train service (left) and schematic graphical timetable (right) (Liebchen 2006)

This thesis gives an overview of specific advantages and disadvantages for symmetric periodic timetables, additionally to the advantages/disadvantages of the periodic timetable in Table 4.3. When train services are identical for both driving directions it becomes easier for the timetable planner to build up the basic timetable structure since the skeleton of the timetable is even more fixed than in a periodic timetable. This on the other hand reduces the degrees of freedom in the planning process and creating a satisfactory feasible timetable can become more difficult.

Symmetric periodic timetables	
Advantages	**Disadvantages**
- Easier to plan train services - Easier to plan attractive transfer options - Transfer times are identical for both driving directions	- Service levels per driving direction are not optimized according to market demands - Fewer degrees of freedom in the timetable development

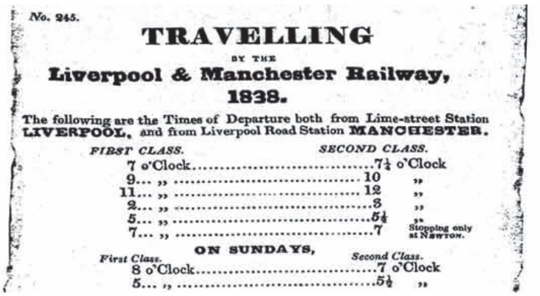
Table 4.3: Overview of advantages (left) and disadvantages (right) of symmetric periodic timetables

Close to the axis of symmetry in the timetable, it is possible to achieve attractive transfer options to a given train service in both driving directions. This concept can become powerful if the symmetry axis is placed at a big station with several transfer possibilities to other trains and/or bus services. Transfer times are identical for both driving directions ensuring that a passenger will experience an attractive journey in both travelling directions.

With a symmetric periodic timetable it is difficult to take big differences in travel demand for different driving directions during rush hours into consideration. An optimized utilization of rolling stock and thereby also train staff is therefore not likely. It is a possibility to apply the concept of symmetry to a set of selected basic train services in a timetable and handle the differences in travel demand during rush hours by e.g. adding or removing additional non symmetric rush hour train services. This concept is used in Denmark for long distance and regional trains.

4.6 Non-periodic symmetric timetables

A new timetable class has been identified by this thesis and been added to the group of basic timetable classes: The non-periodic symmetric timetable. Symmetry in non-periodic timetables is no hindrance. An example of a non-periodic symmetric timetable can be seen in Figure 4.9 to the left. An example of a schematic graphical timetable of a non-periodic symmetric timetable is shown to the right in Figure 4.9.


No. 245.

TRAVELLING

BY THE

Liverpool & Manchester Railway,

1838.

The following are the Times of Departure both from Lime-street Station LIVERPOOL, and from Liverpool Road Station MANCHESTER.

FIRST CLASS.	SECOND CLASS.	
7 o'Clock	7¼ o'Clock	
9... ,,	10	,,
11... ,,	12	,,
2... ,,	3	,,
5... ,,	5¼	,,
7... ,,	7	Stopping only at Newton.

ON SUNDAYS,

First Class.	Second Class.	
8 o'Clock	7 o'Clock	
5... ,,	5½	,,

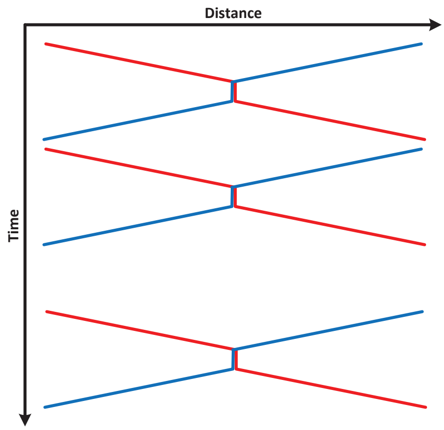


Figure 4.9: Timetable for the Liverpool and Manchester Railway from 1838 (http://www.pittdixon.go-plus.net/l+mr/timetable.htm (20.09.2012)) (left). Example of a schematic graphical timetable for a non-periodic symmetric timetable (right)

Adding symmetry to periodic or non-periodic timetables entails the same advantages and disadvantages from a railway customer or timetable planner point of view. See Table 4.3. Adding a minimum level of structure to a non-periodic timetable with symmetric train services reduces the potential for creating an extreme non-periodic timetable.

4.7 Integrated fixed interval timetables

An Integrated Fixed Interval Timetable (IFIT), or also called regular and integrated timetable (R&I), is characterized by using a number of predefined selected stations, called hubs, where trains from all driving directions meet at a certain planned time to provide attractive transfer conditions. These meetings of trains can take place once or several times during the periodicity interval of the given timetable. IFIT is also a symmetric periodic timetable. The symmetry axis of the IFIT timetable will be situated in the hubs (Avelino2006).

German publicist August Scherl proposed as early as 1909 the concept of IFIT. In his book “Ein neues Schnellbahnsystem – Vorschläge zur Verbesserung des Personenverkehrs” (in English: A new high-speed railway system – Proposals to improve passenger transport) he envisaged a railway system with trains running between major cities with speeds up to 200 km/h and having station hubs in these cities where attractive transfers to both bus and other train services existed. This traffic concept would ensure a minimal stop to stop travel time (Ebinger 2009, Scherl 1909).

In the year 1940, John Frederick Pownall presented a proposal for an IFIT for southern England. In his work, he was already considering train travel times between hub stations to be just under one hour and proposing improvements of the railway infrastructure where necessary to achieve these travel times. This proposal was never implemented (Pownall 1940).

The Netherlands introduced a timetable in 1970 (Spoorslag '70) which was a symmetric periodic timetable with focus on attractive train to train transfers, thereby introducing the concept of having selected stations as hubs. This timetable was never developed into a national IFIT (Avelino 2006, Rey 2007).

Switzerland introduced the first national periodic timetable in the year 1982. This was improved continuously and resulted in the present Bahn2000 IFIT. This is the most famous present example of this timetable class. The IFIT concept is still being extended, most recently to the southern cities of Interlaken and Visp with the opening of the Lötschberg basis tunnel in 2007. This timetable class focuses on the overall travel times through the railway network for passengers. A focus on attractive transfer options, an integration of train services, becomes necessary. Integration is achieved by having trains meet once or twice per hour at selected larger stations, also called hubs, in minutes 00/30 or 15/45. Trains will arrive a few minutes before and depart shortly after the “hub minute”, hereby creating optimal transfer conditions for passengers. Slow regional and local trains will arrive first followed by fast passenger trains such as InterCity or EuroCity-trains. The fast passenger trains will depart first followed by the slower trains. An overview of hubs and the meeting times is given in Figure 4.10 (Avelino 2006, DTA 2013, http://de.wikipedia.org/wiki/Taktfahrplan (21.09.2012), http://de.wikipedia.org/wiki/bahn2000 (21.09.2012)).

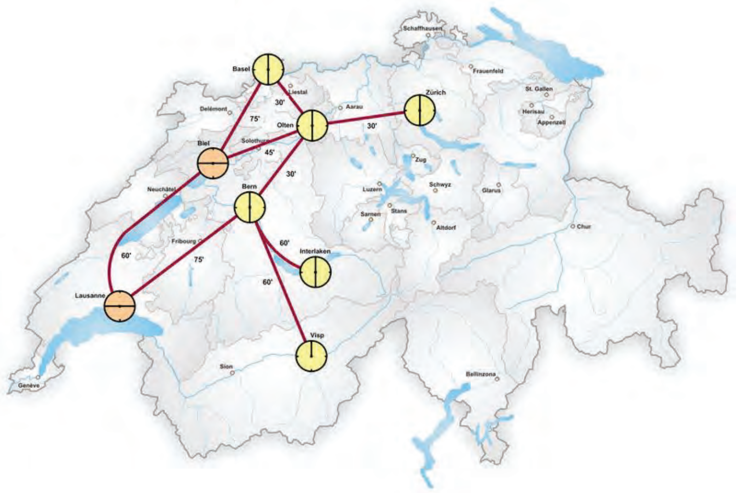


Figure 4.10: Swiss Bahn 2000 timetable concept (DTA 2013)

It must be emphasized that it is only the fast passenger trains that have travel times between hubs that make it possible for trains to run from train meeting to train meeting. Slower regional trains are either dedicated to train meetings at one selected station hub or their scheduled travel time between two hubs makes it possible to be part of a train meeting at the next station hub as well. The difference in travel time between a fast and slow passenger train between two hubs must then be the periodicity time interval of train meetings or a whole multiple of this (Graffagnino 2012).

Ankunftstabelle

Bhf./Haltest.: Zürich HB
Fahrplan: Ankunft 14:30-15:28 05.03.07 » aktuelle Zeit

Zeit	Fahrt	Aus Richtung
14:30	ICN 2125	**Biel/Bienne** Biel/Bienne 13:15 - Grenchen Süd 13:24 - Solothurn 13:33 - HB 14:30
14:47	IR 774	**Chur** Chur 13:16 - Landquart 13:26 - Bad Ragaz 13:32 - Sargans SZ 14:19 - Wädenswil 14:28 - Thalwil 14:38 - Zürich HB 14:4
14:48	ICE 185	**Stuttgart Hbf** Stuttgart Hbf 12:04 - Horb 12:42 - Rottweil 13:09 - Tuttlingen Schaffhausen 14:09 - Bülach 14:30 - Zürich HB 14:48
14:49	IC 828	**Romanshorn** Romanshorn 13:41 - Amriswil 13:47 - Weinfelden 13:59 - Fra Flughafen 14:39 - Zürich HB 14:49
14:51	CIS 154 CISALPINO	**Trieste Centrale** Trieste Centrale 06:30 - Venezia Mestre 08:34 - Padova 08: Brescia 10:17 - Milano Centrale 11:18 • Bellinzona 12:34 - A HB 14:51
14:53	ICN 1528	**St. Gallen** St. Gallen 13:48 - Gossau SG 13:56 - Wil 14:10 - Winterthur HB 14:53
14:54	IR 1927	**Bern** Bern 13:32 - Olten 14:03 - Aarau 14:14 - Brugg AG 14:30 - B
14:56	ICN 527	**Genève-Aéroport** Genève-Aéroport 12:05 - Genève 12:14 - Nyon 12:27 - Morg Biel/Bienne 13:47 • Solothurn 14:02 - Olten 14:22 - Aarau 14
14:56	IR 2346	**Luzern** Luzern 14:10 - Zug 14:31 - Thalwil 14:46 - Zürich HB 14:56
14:58	EC 7	**Hamburg-Altona** Hamburg-Altona 04:28 - Hamburg Hbf 04:42 - Dortmund Hbf Hbf 08:26 - Köln Hbf 08:53 • Freiburg im Breisgau (D) 12:55 Zürich HB 14:58
14:59	IR 2347	**Zürich Flughafen** Zürich Flughafen 14:47 - Zürich Oerlikon 14:52 - Zürich HB 1
15:00	IC 927	**Interlaken Ost** Interlaken Ost 12:56 - Interlaken West 13:02 - Spiez 13:21 -
15:02	IR 2027	**Bern** Bern 13:38 - Burgdorf 13:52 - Herzogenbuchsee 14:04 - Lan HB 15:02
15:20	ICN 2128	**Konstanz** Konstanz 14:03 - Kreuzlingen 14:07 - Weinfelden 14:29 - Fra Flughafen 15:09 - Zürich HB 15:20

Abfahrtstabelle

Bhf./Haltest.: Zürich HB
Fahrplan: Abfahrt 14:38-15:36 05.03.07 » aktuelle Zeit

Zeit	Fahrt	In Richtung Gleis/Haltestelle
14:39	IC 725	**St. Gallen** Zürich HB 14:39 - Zürich Flughafen 14:50 - Winterthur 15:05 - Wil 15:24 - Gossau SG 15:43 - St. Gallen 15:53
14:58	IR 2028	**Bern** Zürich HB 14:58 - Olten 15:27 - Langenthal 15:47 - Herzogenbuchsee 15: Bern 16:22
15:00	IC 828	**Brig** Zürich HB 15:00 - Bern 15:58 - Thun 16:24 - Spiez 16:36 - Frutigen 16:48 Goppenstein 17:18 - Brig 17:42
15:01	IR 2346	**Zürich Flughafen** Zürich HB 15:01 - Zürich Oerlikon 15:07 - Zürich Flughafen 15:13
15:02	IC 776	**Basel SBB** Zürich HB 15:02 - Basel SBB 15:54
15:04	ICN 1528	**Lausanne** Zürich HB 15:04 - Aarau 15:27 - Olten 15:38 - Solothurn 15:57 - Biel/Bienn Yverdon-les-Bains 16:52 - Lausanne 17:15
15:04	IR 2347	**Luzern** Zürich HB 15:04 - Thalwil 15:13 - Zug 15:28 - Luzern 15:49
15:05	CIS 154 CISALPINO	**Schaffhausen** Zürich HB 15:05 - Bülach 15:22 - Schaffhausen 15:47
15:06	IR 1928	**Bern** Zürich HB 15:06 - Baden 15:21 - Brugg AG 15:30 - Aarau 15:45 - Olten 15
15:07	IC 927	**Romanshorn** Zürich HB 15:07 - Zürich Flughafen 15:16 - Winterthur 15:33 - Frauenfeld Amriswil 16:10 - Romanshorn 16:18
15:09	EC 177	**Chiasso** Zürich HB 15:09 - Zug 15:31 - Arth-Goldau 15:48 - Bellinzona 17:36 - Lug
15:09	EC 177 CISALPINO	**Milano Centrale** Zürich HB 15:09 - Zug 15:31 - Arth-Goldau 15:48 - Bellinzona 17:36 - Lug Como S. Giovanni 18:52 - Milano Centrale 19:35
15:10	ICN 527	**St. Gallen** Zürich HB 15:10 - Zürich Flughafen 15:20 - Winterthur 15:35 - Wil 15:52 - Gallen 16:15
15:12	EC 7	**Chur** Zürich HB 15:12 - Thalwil 15:21 - Wädenswil 15:31 - Pfäffikon SZ 15:39 - Sargans 16:19 - Bad Ragaz 16:26 - Landquart 16:32 - Chur 16:43
15:14	ICE 184	**Stuttgart Hbf** Zürich HB 15:14 - Bülach 15:30 - Schaffhausen 15:50 - Singen (Hohentwi Rottweil 16:46 - Horb 17:17 - Stuttgart Hbf 17:56
15:30	ICN 2128	**Biel/Bienne** Zürich HB 15:30 - Olten 15:59 - Oensingen 16:12 - Solothurn 16:25 - Gren Biel/Bienne 16:44

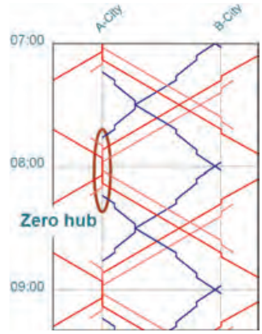


Figure 4.11: Example for an IFIT - the Swiss Bahn 2000 timetable (Liebchen 2008) (left) and a schematic view of a graphical timetable for an IFIT (Liebchen 2006) (right)

Figure 4.11 shows departure and arrival times for trains at Zurich central station to the left and a schematic graphical timetable for an IFIT to the right. The shown arrival times of trains are concentrated just before minute 00 - the full hour - and the departure times shortly after. This makes it clear that Zurich is one the central hubs in the Bahn2000 timetable structure where trains meet in minute 00/30.

After having experienced a huge success by implementing this overall timetable class in Switzerland it has been exported to other European countries. It can e.g. be found in Germany on regional railway networks with one major hub. Here regional trains get optimal transfer conditions to long distance passenger trains that are only stopping at this hub e.g. at Lübeck main station.

Table 4.4 gives an overview of specific advantages and disadvantages for the IFIT. In contrast to the symmetric periodic timetable class, the number of identified possible disadvantages is much higher than the number of advantages. Since this overall timetable class has become so successful the fewer advantages must have a very high priority with railway customers.

Integrated Fixed Interval Timetable (IFIT)	
Advantages	**Disadvantages**
- Optimal transfer options - User friendly timetable with few patterns and few shifts between patterns (easy to remember) - Attractive origin to destination travel time for users of the public transport	- Long dwell times at hubs for slower trains - Transfer times are too short for elderly or physically disabled passengers - Either a transfer is offered regularly or not at all. There is no in between solution - Risk of delays (both initial and consecutive) - Peaks and gaps in track utilization - Inflexible during operation - Costs of secondary investments (adaption of running times between hubs) - Inflexible at the strategic level (e.g. introduction of new high speed lines) - Obstructs marginal improvements (e.g. tilting trains) - Need for transfers to get through the railway network causing longer train travel times - Inexperienced train passengers do not have the necessary overview to make short time transfers at station hubs (changing platform) - High demand for station capacity at hubs - Running times between hubs must be a whole multiple of the frequency of train meetings

Table 4.4: Overview of advantages (left) and disadvantages (right) of integrated fixed interval timetables (Liebchen 2008, Schittenhelm & Landex 2009, Tyler 2003, Wardman et al 2004)

The planned meeting of trains at selected stations creates optimal transfer options for passengers. Having these excellent transfer possibilities can increase the need for transfers to get through the network. This could cause longer travel times through the railway network (Schittenhelm & Landex 2009).

Trains arrive and depart in a specific order to and from the hubs. In general the order is as follows: The slowest trains arrive first and the fastest trains arrive last. First to leave the hub, are the fastest trains whereas the slowest trains depart last. If a hub station is not the terminus for the slow train services, they will experience long dwell times, while fast passenger trains services will get the optimal transfer conditions (Schittenhelm & Landex 2009).

When transfers between trains is one of the most important features of a timetable class, the risk of transferring delays from one train to another increases. If one train in the planned train meeting at a hub is arriving delayed, the delay can be transferred to all other trains taking part in the train meeting and thereby resulting in consecutive delays spreading to a big part of the railway network (Schittenhelm & Landex 2009).

It can be difficult for elderly or physically disabled persons to make a wanted train to train transfer at a train meeting because the scheduled transfer time is not long enough. This will cause a long waiting time, almost the train service frequency. Furthermore, it can be difficult for inexperienced train travelers to have the needed overview to make a quick train transfer at station hub. Especially if a change of platforms is required (http://de.wikipedia.org/wiki/Taktfahrplan (09.21.2012)).

Station capacity utilization is kept to extremities: Either all or most platform tracks are in use or the station is practically empty. A very high level of station capacity is demanded to handle the number of arrivals and departures within small time spans. The number of platform tracks has minimum to be equal to the number of train connections that can be made at the hub. Creating the needed station capacity can give rise to large investment costs which could be avoided with a more evenly spread out traffic arrival and departure pattern (Schittenhelm & Landex 2009).

It can likewise be very costly to achieve the required travel times for trains between hubs, so that the planned train meetings can take place. Upgrading existing infrastructure with e.g. higher line speeds and shorter headway times can be very costly. Building completely new railway lines to achieve reduced running times demands high a level of investment. Furthermore it can be necessary to buy new rolling stock that can utilize the infrastructure improvements (Schittenhelm & Landex 2009).

Once the timetable is implemented it obstructs both marginal improvements, such as minor travel time reductions with tilting trains and large scale improvements e.g. introduction of high speed lines. Travel time reduction between two station hubs must be equal to or a whole multiple of the periodicity of train meetings. Smaller or larger running time reductions will cause trains to arrive/depart in the time intervals between train meetings, thereby not being part of the basic timetable concept and therefore making the timetable less attractive (Schittenhelm & Landex 2009).

The overall timetable class as a whole shows a high level of inflexibility during operation. This is caused by the extreme capacity utilization of the hubs and the very high degree of structure in the timetable which does not leave much room for running additional passenger trains during rush hours or extra freight trains due to increased demand (Schittenhelm & Landex 2009).

Running times between all combinations of station hubs must be a whole multiple of the frequency of train meetings or else trains will not be able to participate in train meetings and thereby not offer optimal transfer conditions. Figure 4.12 gives an example of this potential problem. Trains from A to B via either C or D will participate in all train meetings. All trains running via C and D, and vice versa, will not be able to make it to station B in time for the train meeting in minute 00.

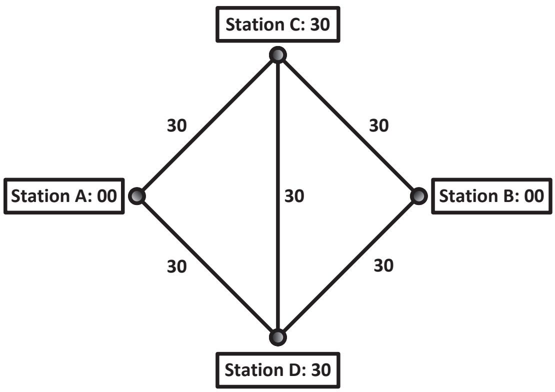


Figure 4.12: Running times between station hubs and train meetings in an IFIT. Train meeting minutes are listed next to the station nodes. Travel times between stations are listed next to the edges (Liebchen 2008)

4.8 Non-periodic integrated interval timetables

Symmetry is no hindrance in a non-periodic timetable and the same applies to integrated intervals. This thesis has identified a new timetable class: The non-periodic integrated interval timetable. Since the timetable belongs to the basic class of non-periodic timetables, there are no fixed intervals between train meetings. Train meetings do not have to take place every 30 or 60 minutes, as is the case in most IFIT. Train meetings can occur according to an overall non-periodic symmetric timetable. Figure 4.13 shows an example of a schematic graphical timetable of this timetable class.

It has not been possible to find an implemented example of this timetable class for a set of passenger train services. When looking at freight train services, there is a potential for that this timetable class exists today to some degree. Freight train traffic to/from large shunting yards often arrives and departs in large bundles. Large groups of trains arrive in the morning hours and depart again in the evening hours. This is due to the fact that it is easier to get freight traffic through a congested railway network during night hours than daytime hours. During the day time hours, arrived trains are split up and divided according to the destination of the freight carriages. In this way a long freight train meeting takes place at shunting yards. Due to the highly demand driven timetables for freight trains these freight train meetings do most likely not have a strictly periodic pattern to them.

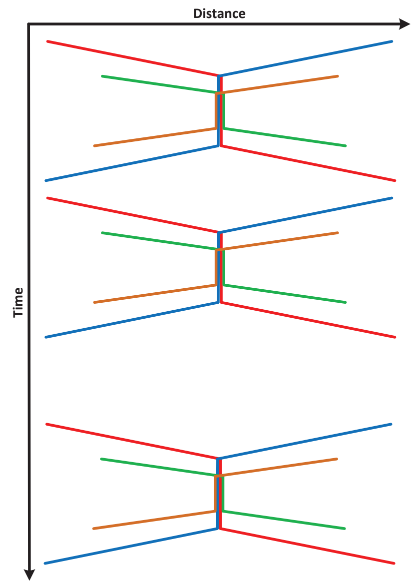


Figure 4.13: A schematic graphical timetable example for a non-periodic integrated interval timetable

The advantages and disadvantages of this timetable class are equal to those of the IFIT, see Table 4.4, with one exception: A non-periodic timetable is not easy memorable and therefore one of the advantages from the IFIT is not valid in this case. However, the level of structure in this timetable class will reduce the potential of creating an extreme non-periodic timetable.

4.9 High frequency timetables

This thesis has identified a new basic timetable class: High frequency timetables. A high frequent timetable is a cross between non-periodic and periodic timetables. A timetable of this class must provide such a high frequency of trains that a periodic pattern of arrival and departures is not necessary for customers. It is generally accepted that a service frequency of maximum 10 minutes makes passengers arrive randomly or following a Poisson-distribution at stations. By doing so, one assumes that passengers are not planning their arrival time at a given station (Coor 1997).

Figure 4.14 and Figure 4.15 show a map of the London underground metro system and an example of a high frequency train timetable for the Central Line which is a part of the London Underground metro system. The central line was opened in the year 1900 and is today the longest underground line with a length of 76 km. It crosses London on an east-west axis. During operational hours the headway between trains is 2 to 5 minutes. Operational hours are slightly reduced on Sundays (http://journeyplanner.tfl.gov.uk/user/XSLT_SEL_STT_REQUEST (13.11.2013), http://www.tfl.gov.uk/corporate/modesoftransport/londonunderground/keyfacts/13164.aspx (13.11.2013)).

Figure 4.14: Map of the London metro system. The Central Line is marked with the color red (http://www.tfl.gov.uk/gettingaround/14091.aspx (09.21.2012))

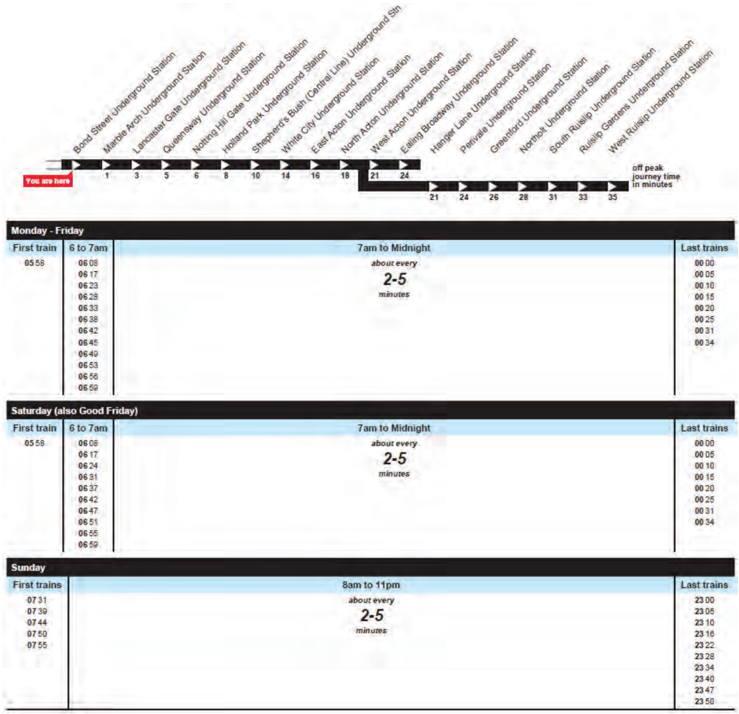


Figure 4.15: Timetable for the Central Line in London (http://journeyplanner.tfl.gov.uk/user/XSLT_SEL_STT_REQUEST?language=en&sessionID=TLJJP15P1_1988195739&requestID=1&mode=line&lineSelIndex=0&itdLPxx_motCode=1 (28.07.2011))

These time intervals in headways between trains reduce the amount of structure in the timetable and it must be classified as a non-periodic timetable. If these time intervals in service frequency indicate that trains are planned to run every 3½ minutes, leaving room for smaller deviations, then the timetable can be classified as periodic. A degree of "flexible" structure is provided. The perceived possible variations are so small that passengers properly regard the timetable as belonging to the periodic timetable class even though numbers of departures on the central line per hour theoretically can vary between 12 and 30, which is actually up to 60%.

When having a build in flexibility in the timetable, as is the case here, it becomes possible for the TOC to optimize the number of hourly departures to the passenger travel demand. The TOC has the opportunity to reduce operational costs and increase profits and/or reduce ticket prices.

In addition this flexibility in frequency provides the TOC with the possibility to plan with headways of 2 minutes and thereby be able to run with delays up to 3 minutes without passengers noticing and reacting towards it.

Since 2002 Copenhagen has a modern fully automated driverless metro system. This mean of public transport is also using a high frequency timetable. The network and maximum number of seconds between trains are presented in Figure 4.16 and Table 4.5 respectively.

Figure 4.16: Copenhagen metro network (DSB 2011d)

The metro network is serviced by two metro lines, M1 and M2. M1 runs between Vanløse and Vestamager and M2 between Vanløse and Lufthavnen (Copenhagen Airport). Between Vanløse and Christianshavn they share the same tracks. Both lines are fully automatic and driverless.

Headway times between metro trains depend on time of the day and part of the network. Table 4.5 shows the maximum headways in seconds between two following trains on each section of the network. It becomes clear that the Copenhagen metro is a highly optimized transport system that provides the necessary capacity for changing passenger demands during a week. The service frequency, and hereby the timetable pattern, is in theory changed up to nine times during a day. This is a high number of timetable pattern changes. Thick horizontal borders indicate a change in maximum headways in Table 4.5.

When planning a journey using the Copenhagen metro via the online Danish journey planner www.rejseplanen.dk, specific arrival and departures times are presented to the passengers. This proves that the metro operation is based on detailed working timetables but these are not published, even though headways between trains go up to 15 and 20 minutes during night operations (Schultz 2012).

Time interval	Vanløse – Christianshavn (M1+M2)				Christianshavn - Vestamager (M1) / Lufthavnen (M2)			
	Mon-Thu	Fri	Sat	Sun	Mon-Thu	Fri	Sat	Sun
00:00-01:00	1200	1200	300	300	1200	1200	600	600
01:00-05:00	1200	1200	450	450	1200	1200	900	900
05:00-06:00	300	300	450	450	600	600	900	900
06:00-07:00	180	180	450	450	360	360	900	900
07:00-09:15	120	120	180	180	240	240	360	360
09:15-10:00	150	150	180	180	300	300	360	360
10:00-12:00	180	180	180	180	360	360	360	360
12:00-13:00	180	180	150	180	360	360	300	360
13:00-14:00	180	150	150	180	360	300	300	360
14:00-17:00	120	120	150	180	240	240	300	360
17:00-18:00	120	120	180	180	240	240	360	360
18:00-19:00	180	150	180	180	360	300	360	360
19:00-00:00	180	180	180	180	360	360	360	360

Table 4.5: Maximum number of seconds between trains on the Copenhagen metro network. Thick horizontal borders indicate a change in the maximum headway (Schmidt Schultz 2012)

Most high frequent railway transport systems are operated with train services calling at all stations. This is also the case for the two earlier presented examples: London Underground and Copenhagen Metro. Small headway times between trains make other operational concepts difficult to implement. Calling at all stations maximizes the travel time through the transport system. During rush hours the metro systems in Santiago de Chile and Philadelphia in USA are operating with skip-stop train services on double tracked metro lines. The latter has done this since 1956. Train departures on a metro line are in both cases divided into two train services. In Philadelphia they are called “A” and “B” trains. Santiago uses a color code. Stations are either served by only one or both train services. Stations with low passenger volumes are only served by one train service. All trains call at stations with high passenger volumes and transfer stations. Skipped stations must be allocated to the train services in an alternating fashion to avoid that trains catch up with each other. Figure 4.17 shows a schematic graphical timetable for a skip-stop service. By implementing skip-stop services travel times can be reduced but the need for transfers increases (Lee 2012).

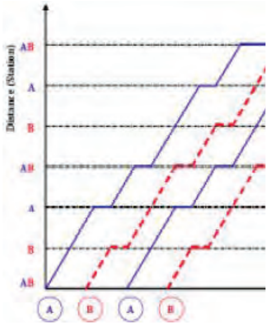


Figure 4.17: Schematic graphical timetable for skip-stop train service (Lee 2012)

This thesis presents an overview of found advantages and disadvantages for high frequency timetables in Table 4.6. Even though the number of disadvantages is higher than advantages, this timetable class has an increasing popularity. The fewer advantages must be given more weight than the disadvantages.

High frequency timetables	
Advantages	**Disadvantages**
- No specific public timetable is necessary for time intervals with headways lower than 10 minutes	- Need to change to other timetable classes in time intervals with lower demand
- Customers experience a high degree of availability of the transport system	- Train services are most often operated with stops at all stations, which leads to longer travel times
- Transfers to a system with a high frequency timetable give minimal waiting times and must not be planned in detail	- Planned transfers to systems with lower frequency must contain buffer times to assure their feasibility
	- Difficult to measure achieved punctuality and reliability levels in operation
	- High degree of uncertainty in making plans for rolling stock and crew rostering
	- High level of complexity when preparing contingency plans

Table 4.6: Advantages (left) and disadvantages (right) of high frequency timetables

It is not necessary to publish a specific timetable for a train service running according to a high frequency timetable. Average waiting times are so low that customers accept this level of uncertainty. Customers will not be aware of minor delays and a single cancellation in the same way as if having a detailed timetable to refer to.

A system with a high frequency will create a feeling of high availability and freedom to the passengers. Passengers do not have to plan their arrival time at a given station. Same applies when transferring to a train service with a high frequency timetable since minimal transfer waiting times are ensured. Planning transfers to traffic systems using high frequency timetables is much easier or not necessary at all, this reduces the workload for timetable planners.

It is rarely that travel demand justifies the use of a high frequency timetable during all operational hours. Therefore shifts to other timetable classes are needed during operational hours. Shifts from a high frequency timetable to other timetable classes can be more drastic than shifts between two periodic timetables since you move from a timetable class that does not need the publishing of specific timetables to one that does.

Transfers from a train service using a high frequency timetable to a system with a lower frequency and running according to a different timetable class requires a buffer time to be feasible. This need arises since the high frequency timetable is not specific in regards to departure and arrival times.

For passengers but also the transport services organization it can be difficult to measure and control the achieved punctuality and reliability levels of a given train service when using a high frequency timetable, since specific arrival and departure times and required number of departures per given time span are not published (van Oort 2011, Landex 2012).

If using a high frequency timetable with time intervals for headways between trains it becomes more difficult to prepare rostering plans for both rolling stock and any train crew. This is especially important in regards to optimization of utilization levels of rolling stock and staff.

It is more difficult to prepare detailed contingency plans for train services operated with high frequency timetables since the operational conditions such as headways between trains can change very often. Contingency plans can therefore not be as detailed as for e.g. periodic timetables where train services have lower headways, and must be prepared on a strategically level.

High frequent timetables most often entail that all train services call at all stations. The very short headways between trains make this the obvious choice when creating the timetable. This unfortunately increases the travel time for passengers that have to travel a longer distance. Implementing skip-stop operation on a high frequent train service requires either infrastructure improvements like extra line tracks, overtaking tracks at stations or a train service stopping pattern like presented in Figure 4.17.

4.10 Timetable classes and basic train line service structures

The presented basic train service line structures in section 2.4 can be combined with the seven identified basic timetable classes by this thesis. Some basic line structures are more reasonable for some timetable classes than others. Table 4.7 gives an overview of reasonable combinations of basic train service line structures and basic timetable classes.

For a point to point connection, there is not much focus on train to train connections. Therefore the non-periodic integrated interval timetables are not listed. Symmetric timetables can ensure potential good transfer options to other means of transport. A point to point metro line can be operated with a high frequency timetable.

The same arguments mentioned for a point to point connection are valid for a circle line. Train to train transfer are not the most important issue. Therefore the same timetable classes apply for a circle line as a point to point connection.

A centralized node makes train to train transfers between different lines difficult and therefore all other timetable classes than the transfer-focused integrated interval timetables are reasonable to apply to this basic train service line structure.

For a tree shaped/corridor line structure the main transport flows are between the important starting point and several locations using a shorter or longer part of the railway corridor before branching of to the final destination. Focus is again not on good train to train transfers since these can involve long detours for passengers and can be made smarter with radial bus connections between railway lines. Again the transfer focused integrated interval timetables are not reasonable. A basic train service line structure of a metro system can be a corridor, e.g. the Copenhagen metro system, and therefore the high frequency timetable is also reasonable. The core route based train service line structure is similar to the tree shaped/corridor line basic structure. The same arguments for using the same selected timetable classes can be applied.

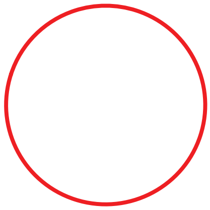
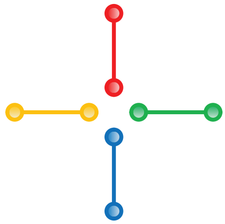
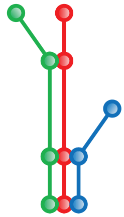
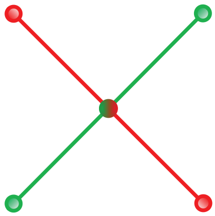
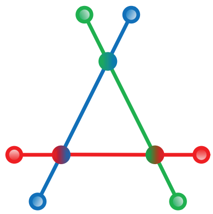
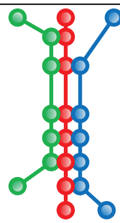
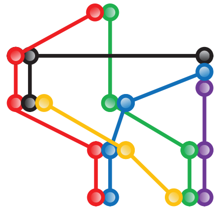
Point to point	Circle line	Centralized node	Tree shape/corridor
			
• Non-periodic • Symmetric non-periodic • High frequency • Periodic • Symmetric periodic	• Non-periodic • Symmetric non-periodic • High frequency • Periodic • Symmetric periodic	• Non-periodic • Symmetric non-periodic • High frequency • Periodic • Symmetric periodic	• Non-periodic • Symmetric non-periodic • High frequency • Periodic • Symmetric periodic
Radial & Star shape	Universal star shape	Core route	Meshed network
			
• Symmetric non-periodic • Integrated interval non-periodic • High frequency • Symmetric periodic • IFIT	• Symmetric non-periodic • Integrated interval non-periodic • High frequency • Symmetric periodic • IFIT	• Non-periodic • Symmetric non-periodic • High frequency • Periodic • Symmetric periodic	• Non-periodic • Symmetric non-periodic • Integrated interval non-periodic • High frequency • Periodic • Symmetric periodic • IFIT

Table 4.7: Overview of reasonable combinations of basic train service line structures and basic timetable classes

Both the radial/star shaped and the universal star shaped train service line structures focus on good train to train transfer options in nodes with crossing/meeting train service lines. Therefore the timetable classes that help to provide good transfer options are preferable. These are covering both the non-periodic symmetric and periodic timetable and the symmetric and non-symmetric integrated interval timetables, which primary focus is on providing optimal transfer options in selected stations. The basic layout of a metro system can be star shaped and consequently the high frequency timetable is also plausible.

When working with a meshed railway network, all timetable classes can be implemented. If periodic/systematic timetables are generally preferred it limits the number of available timetable classes. A high level of focus on providing attractive train to train transfers will limit the applicable timetable classes to symmetric and integrated timetables.

4.11 Comparison of identified timetable classes

In Table 4.8, this thesis compares the 25 found timetable class variants in regards to commonly used timetable evaluation criteria. The criteria have been grouped into four overall topics: Timetable structure, travel time, demand and marketing. It is listed if a given timetable criteria has been evaluated to be a small (+/÷), medium (++/÷÷) or big (+++/÷÷÷) advantage or disadvantage.

Figure 4.18 visualizes some of the key characteristics of five selected timetable classes. Five basic timetable classes are represented. Each axis represents a chosen timetabling criterion from the 14 used criteria in this timetable class analysis. From Figure 4.18 it can be seen that the high frequency timetable class (T2) and the non-periodic non-symmetric timetable class (T1-1) have opposite advantages and disadvantages. Whereas the IFIT timetable class (T5-4) and the high frequency timetable class (T2) have similar characteristics. The chosen periodic symmetric timetable class (T4-3) has a unique pattern of advantages and disadvantages compared to the other timetable classes.

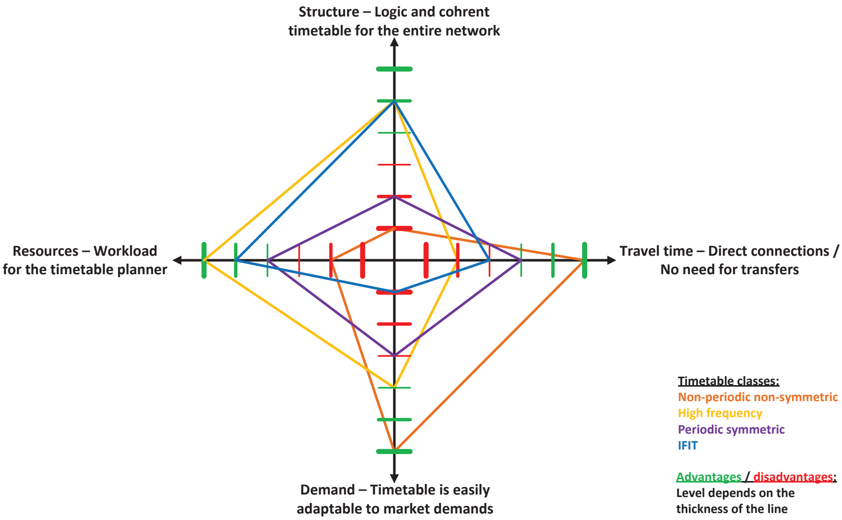


Figure 4.18: Timetable class characteristics based on four timetabling criteria (the four axes).

In the following sections the made evaluations in this thesis, of the 19 found timetable classes, are explained in more detail.

Timetable criteria		Non- periodic timetables			High frequency timetable	Periodic timetables																				
		Non-symmetric	Sym-metric	Inte-grated interval		Non symmetric timetables							Symmetric timetables							Integrated Fixed Interval Timetables						
		T1-1	T1-2	T1-3	T2	T3-1	T3-2	T3-3	T3-4	T3-5	T3-6	T3-7	T4-1	T4-2	T4-3	T4-4	T4-5	T4-6	T4-7	T5-1	T5-2	T5-3	T5-4	T5-5	T5-6	T5-7
Structure	Logic and coherent timetable for the entire network	÷÷÷	÷÷	÷	++	++	÷÷	÷÷÷	÷÷	÷÷	÷÷	÷÷÷	++	÷	÷÷	÷	÷	÷	÷÷	+++	++	÷/ (+)	++	÷/ (+)	++	÷/ (+)
	Well defined hierarchy of services	÷÷÷	÷÷	÷	++	+++	+	÷÷	+	+	+	÷÷	+++	++	÷	÷/ (++)	÷/ (++)	÷/ (++)	÷/ (++)	+++	++	÷/ (+)	++	÷/ (++)	++	÷/ (+)
	Symmetric services in all driving directions	÷÷÷	+++	+++	++	÷	÷	÷	÷	÷	÷	÷	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++
	Rigidity of the timetable	+++	++	+	÷	÷	÷	+	+	+	÷	+	÷÷	÷÷	÷	÷	÷	÷÷	÷	÷÷÷	÷÷÷	÷÷	÷÷÷	÷÷	÷÷÷	÷÷
Travel time	Short transfer times at selected hubs	÷÷÷	+	+++	++	÷	÷	÷	÷	÷	÷	÷	+	+	+	+	+	+	+	+++	+++	+++	+++	+++	+++	+++
	Risk for waiting times for passengers concerning train transfers at a given station	÷÷÷	÷÷	÷	++	++	++	+	+	+	+	+	++	++	+	+	+	+	+	++	++	++	++	++	++	++
	Waiting time for randomly arriving passengers	÷÷÷	÷÷	÷÷	+++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++
	Direct connections / No need for transfers	+++	++	÷	÷÷	+	+	+	+	+	+	+	+	+	+	+	+	+	+	÷	÷	÷	÷	÷	÷	÷
Demand	Marketing and memorization for passengers	÷÷/(++)	÷÷/(++)	÷÷/(++)	+++	+	+	÷÷	÷	÷	÷	÷÷	++	+	÷	÷	÷	÷	÷	+++	++	+	++	+	++	+
	Timetable is easily adaptable to market demands	+++	÷÷	÷÷	+	+	+	+++	++	++	+	++	÷÷	÷÷	÷	÷	÷	÷÷	÷	÷÷÷	÷÷÷	÷÷	÷÷÷	÷÷	÷÷÷	÷÷

Resources	Timetable planning process – agreement between all TOCs	++	+	÷÷	++	÷	÷÷	÷	÷	÷	÷÷	÷	÷÷	÷÷	÷÷÷	÷÷÷	÷÷÷	÷÷÷	÷÷÷	÷÷÷	÷÷÷	÷÷÷	÷÷÷	÷÷÷	÷÷÷	÷÷÷
	Optimal utilization of rolling stock	+++	÷	÷÷	÷÷	++	+	++	++	++	+	++	÷	÷	÷	÷	÷	÷	÷	÷÷	÷÷	÷÷	÷÷	÷÷	÷÷	÷÷
	Optimal utilization of train staff	+++	++	+	++	+	+	++	++	++	+	++	÷	÷	+	+	+	÷	+	÷/ (+)	÷/ (+)	÷/ (+)	÷/ (+)	÷/ (+)	÷/ (+)	÷/ (+)
	Workload for the timetable planner	÷÷	÷	+	+++	++	+	+	+	+	+	+	++	+	+	+	+	+	+	++	++	++	++	++	++	++
Total score (sum of ÷/+)		22÷/17+	14÷/11+	14÷/9+	5÷/24+	4÷/17+	7÷/11+	10÷/13+	20÷/15+	20÷/13+	8÷/9+	10÷/12+	8÷/18+	9÷/13+	10÷/10+	8÷/17+	8÷/10+	12÷/9+	10÷/10+	13÷/21+	13÷/18+	13÷/13+	13÷/18+	13÷/13+	13÷/13+	13÷/13+

Table 4.8: Thesis comparison of timetable classes – advantages (+, ++, +++)/disadvantages (÷, ÷÷, ÷÷÷), + = small, ++ = medium, +++ = big, () = a potential exists but it may not be possible to utilize. TX-1 = Same pattern all day, TX-2 = Low number of shifts between timetable patterns + basic differences between patterns, TX-3 = High number of shifts between timetable patterns + basic differences between patterns, TX-4 = Low number of shifts between timetable patterns + no basic differences between patterns, TX-5 = High number of shifts between timetable patterns + no basic differences between patterns, TX-6 = Low number of shifts between timetable patterns + both basic and no basic differences between patterns, TX-7 = High number of shifts between timetable patterns + both basic and no basic differences between patterns

4.11.1 Structure - Logic and coherent timetable for the entire network

Since there is no structure in a non-periodic non-symmetric timetable, this evaluation criterion is a big disadvantage for this timetable class. With no existing timetable patterns the logic in the timetable can be hard to find for passengers. With possible large variations in attractive transfer options during a day the coherency of the timetable can be difficult to see for customers.

By introducing symmetry to the non-periodic timetable some level of structure is added but the lack of an operational pattern still gives this timetable class the same weaknesses as the non-symmetric version. The structure can still be difficult to overview for customers and no coherency is guaranteed. However, the symmetry reduces the level of disadvantage.

Integrated non periodic intervals ensure good transfer options at selected station hubs and thereby greatly improving the coherency of this timetable class. The intervals between train services are not fixed and therefore the railway customer must check up on departure and arrival times, which makes this timetable class less logic.

Train services running according to a high frequency timetable give the impression of a logic and coherent service. All trains most often stop at all stations on their train run and the service is very easy to transfer to because of the high frequency. One single drawback in regards to logic and coherency is the non-existing public timetable and the frequent changes in headway times between trains.

Periodic timetables generally provide a logic and coherent service of the railway network because they consist of repeating service patterns. Non symmetric periodic timetables have a larger potential for big differences between timetable patterns since the service level does not have to be the same for both driving directions e.g. during rush hours. What can reduce the perceived logic and coherency in a non-symmetric periodic timetable is a high number of shifts between timetable patterns and if there are big differences between patterns. The worst combination in regards to experienced logic and coherency is a high number of shifts between very different service patterns.

For symmetric periodic timetables the potential for differences between timetable patterns is lower since the service level for a train service is the same for both driving directions. This reduces the level of disadvantages compared to non-symmetric periodic timetables, which is also reflected in Table 4.8. Adapting this timetable class to varying customer demand throughout a day can be difficult due to the high level of timetable structure.

The basic concept of IFIT, working with hubs where all trains meet once or more per hour, makes this timetable class very rigid and it is therefore unlikely to have a high number of shifts between patterns during an operational day and the differences between patterns are likely to be small or easy to overview. A big difference between two timetable patterns could be to reduce the frequency of train services from 30 minutes to 1 hour in the evening and/or night hours. In Table 4.8 the level of advantage reflects this. The brackets indicate that there is a potential for only a low level of advantage with this timetable class but this is very unlikely to take place in reality.

4.11.2 Structure - Well defined hierarchy of services

The lack of structure in non-periodic non-symmetric timetables makes this criterion a big disadvantage for this timetable class. Every train service is adapted to travel demand and therefore no focus is given to a clear hierarchy of train services during the construction of the timetable.

Symmetric timetables require a minimum level of structure but still entail enough flexibility to not necessarily having a well-defined hierarchy of train services. Planning with train meetings at station hubs in integrated interval timetables requires a level of hierarchy amongst train services. Slower trains arrive first and depart last.

High frequency timetables are normally used for train services with only one service offer: All trains on a given line section stop at all stations. Trains can though have different terminuses as is the case for the Copenhagen metro. See Figure 4.16. A hierarchy is on one hand given from the beginning since all trains have the same travel characteristics and on the other hand a specific hierarchy is not needed for train services following a high frequency timetable. The first approach has been used in Table 4.8.

When working with timetable patterns a hierarchy of train services will be developed by the timetable planners for each pattern that exists in the relevant timetable. If the same train hierarchy is kept during an operational day it makes it easier for train passengers to overview the timetable. If there are big changes between timetable patterns, including the train hierarchy, this timetable evaluation criterion becomes a disadvantage for the timetable. The disadvantage increases with the number of shifts between patterns with big differences. This could be shifts between a day time and a rush hour pattern where the service level per driving direction can differ greatly.

For symmetric timetables, the potential differences between timetable patterns are smaller and therefore the disadvantage regarding this evaluation criterion is reduced.

In IFIT the hierarchy of train services is very important since trains arrive and depart from the hubs in a specific and necessary order: The slowest trains arrive first and the fastest trains arrive last, when departing the fastest trains leave first and the slowest trains leave last. This is to ensure the optimal train order on the railway lines to/from the hubs. This concept reduces the possibilities to perform changes in the train hierarchy and therefore this timetable class is not prone to having disadvantages based on this timetable evaluation criterion.

4.11.3 Structure - Symmetric train services in all driving directions

The two groups of symmetric timetable classes: Non-periodic symmetric timetable + non-periodic integrated interval timetable and periodic symmetric timetable + IFIT contain symmetric train services; and therefore obviously have a very big advantage in regards to this timetable evaluation criterion. Periodic timetables can be very close to having symmetric train services and therefore potentially only have a very little disadvantage.

The concept of symmetry for both driving directions is not that relevant for high frequency train services. With very small headway times between train departures/arrivals attractive transfer options will most often be available to passengers. A high frequency timetable can easily be planned as being symmetric as shown earlier with the maximum headway between trains example from the Copenhagen metro, see Table 4.5. This timetable class is therefore not considered to have any disadvantage in regards to symmetric train services.

It becomes clear that both the non-periodic and periodic non-symmetric timetable classes have a very big disadvantage in regards to symmetric train services. It can be discussed how much difference in scheduled running times and dwell times is allowed to call a train service symmetric. Time differences between travelling directions can be caused by e.g., scheduled waiting time and scheduled coupling maneuvers at stations.

4.11.4 Structure - Rigidity of the timetable

When timetable patterns are introduced, the timetable gains rigidity. Train services have to run at a certain frequency based on the periodicity time span of the given timetable. New train runs must fit into a given timetable pattern and this reduces the flexibility of planning new trains. A non-periodic non-symmetric timetable has the lowest level of rigidity since no timetable patterns are used. During rush hours, where the number of trains is at its highest in non-periodic timetables, a certain level of rigidity is unavoidable. The order of train runs must be coordinated to get a high utilization of the available infrastructure capacity of a given railway network.

The second most flexible timetable class is the non-periodic symmetric timetable. Adding symmetry increases the level of structure and hereby the rigidity of the timetable but the non-periodicity maintains a high level of flexibility.

A timetable class with scheduled train meetings at hubs has a high level of rigidity. Integrated interval timetables are the most rigid of the non-periodic timetables but still have a minimum level of flexibility to them. This thesis estimates their advantage to be on the same level as some of the non-symmetric periodic timetable classes.

If a periodic timetable contains several timetable patterns it is considered to be less rigid than a periodic timetable with few patterns. A high number of timetable patterns can be necessary to fulfill all or most wishes from TOCs in the preparation phase of the timetable. Adding new trains to the timetable after its implementation can be equally difficult with few or several timetable patterns. Few patterns reduce the variety of possible new train runs in a timetable, but make it potentially easier to plan for both IMs and TOCs, since the train run can be reused during long time intervals. Several patterns can provide the TOC with a better possibility to add new train runs in a potentially optimal way, but these train runs can possibly only be used in shorter time intervals with a specific timetable pattern.

With symmetric periodic timetables the rigidity of the timetable increases since both driving directions for a train service must have similar dwell and running times. This results in one less degree of planning freedom when creating the timetable. In regards to the number of used timetable patterns and the possibilities to add new train runs to the timetable, the symmetric timetable class must be seen in the same way as the periodic timetable class.

Rigidity of timetables reaches its maximum with the IFIT-timetable class. When introducing train meetings at selected stations with a fixed frequency and therefore requiring specific maximum running times between hubs, reduces the degree of freedom in the timetable planning process to a minimum. An IFIT-timetable normally features only a small number of timetable patterns and the differences between them are also small. Adding new train runs to the timetable is very difficult and if at all possible, can only take place in very restricted ways limiting the variety of new train runs.

4.11.5 Travel time - Short transfer times at selected hubs

In non-periodic non-symmetric timetables the train services are based on travel demand and therefore focus is on providing direct connections to train passengers and not on attractive transfer options. This timetable evaluation criterion is a big disadvantage for this timetable class.

Symmetric non periodic timetables hold a higher potential for achieving attractive transfer options with short transfer times. But it is only a potential since the non-periodicity element of this timetable class opens up for scheduling with unattractive transfer options with long transfer times.

Integrated interval timetables contain the same big advantage as IFIT. Planning with train meetings at selected station hubs makes it possible to achieve shortest possible transfer times between all trains. Therefore this timetable class has a big advantage.

It is very easy to transfer between two train services with high frequencies, e.g. two metro lines. Transferring to a train service that is scheduled with a high frequency is attractive. Going from a high frequency train service to a train service with a much lower frequency is more problematic. It demands a minimum of buffer time when planning the transfer, since there often is no public timetable available for the high frequency train service. Generally it is easy to plan with short transfer times at transfer stations when high frequency timetables are used.

Non symmetric periodic timetables do not necessarily focus on providing attractive transfer possibilities at selected hubs. Train services are planned according to repeating timetable patterns for travel relations, thereby making the timetable more attractive to passengers. Repeating patterns reduce the risk of long waiting times in connection with train transfers but the missing symmetry in the timetable does not promote the planning principle with hubs. Therefore, this evaluation criterion becomes a minor disadvantage for this timetable class.

When adding symmetry to a periodic timetable a potential is created for planning with short transfer times at selected stations. This potential exists if the axis of symmetry is located at or very close to a larger railway station serviced by several train services. If the two driving directions of train services cross each other at a given station it is possible to plan with attractive transfer options between train services for all travel directions. Therefore this timetable class is considered to have a minor advantage in regards to the timetable evaluation criterion.

The very core of the IFIT timetable is to provide optimal transfer possibilities at selected hubs in the railway network. Therefore this timetable class is given a big advantage when considering the evaluation criterion.

4.11.6 Travel time - Risk for long waiting times for passengers concerning train transfers at a given station

Transfers between train services have no high priority in a non-periodic non-symmetric timetable and therefore there is a high risk of long waiting times for passengers with this timetable class. Attractive interchange options at a given station arise often more by sheer luck/coincidence than intention. Therefore, this timetable class has a big disadvantage.

Symmetric non-periodic timetables have a similar disadvantage towards the risk of waiting times for passengers when making a transfer at a given station as the non-periodic non-symmetric timetables. But the symmetry in the timetable can reduce the disadvantage to a medium level.

Integrated interval timetables have due to their higher level of timetable structure a small disadvantage in regards to this timetable criterion. It is the non-periodicity element of the timetable class that keeps it a disadvantage.

Transfers to and between high frequency train services will not cause long waiting times for passengers. When transferring from train services running with high frequencies to train services with periodic headways of 30 or 60 minutes there is a risk for longer waiting times. This risk increases if the train services run according to a non-periodic timetable. This timetable evaluation criterion is considered to be a big advantage for high frequency timetables.

The repeating timetable patterns in periodic non-symmetric timetables reduce the risk of very long waiting times in connection with train transfers. Waiting times cannot be longer than the periodicity interval of the connecting train service, if the train is running on time. Therefore, the evaluation criterion is considered to be an advantage for periodic timetables. If there are many different timetable patterns during a day the risk of prolonging transfer waiting times goes up. This is further increased if there are big differences between timetable patterns.

Symmetric periodic timetables share the same basic characteristics as non-symmetric periodic timetables. The concept of symmetry holds both a potential to improve and prolong waiting times concerning train transfers. If the transfer station is located on or very close to an axis of symmetry in the timetable and the train runs for the two driving directions for a train service meet each other on this axis, it gives the possibility to create attractive transfer options to both driving directions. If the transfer station is situated far from a timetable axis of symmetry it can become difficult to create more than one attractive transfer option at a time. This increases the risk of long transfer waiting times for passengers. Therefore, this thesis evaluates this timetable class to have the same advantage as the periodic non-symmetric timetable class.

The IFIT timetable class focuses on providing very attractive transfer options at selected station hubs. This reduces the degree of freedom when creating the timetable. The train order on the different railway lines and thereby also in some extend the departure and arrival times of trains is fixed from the beginning. If there is a transfer possibility between two hubs to e.g. a completely separate narrow gauge railway line, it can become difficult to create attractive transfer options for both driving directions on the main line. It depends very much on the location of the transfer station. If it is situated close to or halfway between two hubs it is possible to create attractive transfers if this is not the case it becomes more difficult. The IFIT timetable class has been evaluated to have a slightly bigger advantage than periodic and symmetric periodic timetables.

4.11.7 Travel time - Waiting time for randomly arriving passengers

The non-periodic timetable classes have the highest risk for giving long waiting times to randomly arriving passengers at stations. This is due to their lack of structure. Therefore, the non-periodic non-symmetric timetable class has a very big disadvantage in regards to this evaluation criterion. Since non-periodic symmetric and non-periodic integrated interval timetables have some levels of structure they have been evaluated by this thesis to have a medium disadvantage in regards to waiting time for randomly arriving passengers.

With periodic timetables the risk of long waiting times is reduced. The average waiting time for passengers is half the frequency of a given train service. If it is possible to use more than one train service on a given travel relation the average waiting times are further reduced. If there a several changes in timetable patterns and/or the differences between patterns are big the average waiting time for randomly arriving passengers can both increase and decrease. In the evaluation no differences have been made concerning this issue. The periodic timetable classes have been given a medium advantage.

The most attractive timetable class in regards to this timetable evaluation criterion is the high frequency timetable. Here passengers do not consider timetable times of a train service because headway times between trains are so small. This timetable class has a big advantage.

4.11.8 Travel time - Direct connections / No need for transfers

One of the classical public transport passenger requests is direct connections between the origin and destination of a journey. Hereby there is no hassle with transfers and the travel time is or is close to the possible minimum. Non symmetric timetables are based on travel demand and therefore focus on providing direct connections if feasible. Having no transfers is not identical with a nonstop train; travel times are as attractive as possible or needed. Non-periodic non-symmetric timetables give the passengers generally the best chance of getting a direct train connection and therefore have been given a big advantage by this thesis.

As the structure level increases in a timetable, it becomes easier to schedule with attractive transfer options and the risk for needed transfers to get through the network grows. Non-periodic symmetric timetables are evaluated to have a medium advantage with this timetable criterion.

Integrated interval timetables focus on train meetings at selected hubs and therefore provide optimal transfer options. The risk for necessary transfers to get through the network rises drastically. This timetable class has been given a small disadvantage similar to the IFIT.

Railway networks operated with high frequency timetables, e.g. metro or suburban systems provide minimum prolongation of travel times when making a transfer. The unattractiveness of transfers is hereby reduced and transfers become a common part of a journey with those systems. It is very complicated to operate a complex long distance railway system, with a high number of different train services providing direct connections throughout the network, with a high frequency timetable. If the timetable class should be implemented, a reduction in number of train services would be necessary and this would in general increase the need for transfers. This thesis has evaluated the high frequency timetables to have a big disadvantage.

A non-symmetric periodic timetable can have as many direct connections as a non-periodic non-symmetric timetable. They simply follow an attractive and feasible pattern and are therefore more evenly distributed. Periodic timetables make it easier to plan with attractive transfers during an entire operational day and therefore transfers will be more likely to be found in this timetable class.
The non-symmetric periodic timetable has the highest degree of planning freedom and therefore has the greatest potential for direct connections.

Symmetry in timetables reduces the degree of freedom in the planning process and therefore the potential for direct connections is reduced compared to the non-symmetric periodic timetable. If an axis of symmetry is based at an important railway station or junction it becomes possible to provide good transfers for all driving directions. This is an incentive to plan with transfers.

When the Swiss railways introduced the IFIT-timetable “Bahn2000”, focus was on door to door travel times for passengers and not the travel time between two given stations in the railway network. Providing passengers with optimal transfer conditions at selected hubs, both to other trains and busses, could in the end often give shorter travel times than with other timetable classes. This focus on optimal transfers increases the risk for passengers to have to make transfers to get through the railway network.

4.11.9 Demand - Marketing and memorization for passengers

Periodic timetables are easy to market towards passengers because they are easy to memorize for passengers. This makes this timetable class attractive and can increase ridership on train services using periodic timetables (Tyler 2003, Wardman et al 2004, Liebchen 2006). Periodic timetables therefore have an advantage in regards to this criterion. The level of advantage depends on the number of shifts between timetable patterns and how big the differences are between the individual timetable patterns. A high number of shifts between patterns combined with big differences between patterns is the worst combination.

High frequency timetables take this philosophy a step further when passengers do not have to memorize a timetable because trains run very often and therefore the marketing of such a train service is also made easier for the TOC. A high frequency train service is considered to have a very high level of availability and accessibility by passengers. This timetable class therefore has a big advantage when evaluated with this criterion.

The starting point for non-periodic timetables in this perspective looks very poor. A timetable without a repeating pattern is very difficult to remember for passengers and therefore also more difficult to market for the TOC. In recent years the development within the area of information technology has been going very fast. This has resulted in new possibilities for passengers to get access to timetable data, even real-time timetable data. Timetable data can be obtained by using a computer or a smartphone with access to the internet. The latter is becoming more and more popular and therefore more and more passengers have an easy access to real-time timetable data, and do not need to memorize departure and arrival times of trains. If a non-periodic timetable has been optimized in regards to passenger travel demand it can suddenly become much more attractive for passengers with access to the right information at the right time. This timetable class has been evaluated based on earlier research and on its new potential connected with the development in information technology.

4.11.10 Demand - Timetable is easily adaptable to market demands

The non-periodic non-symmetric timetable class is a pure market oriented timetable and therefore is the best suited to adapt to changing market demands during an operational day. Depending on requested seating capacity on different travel relations the timetable will be put together. There are no restrictions in regards to fixed train services, frequencies, running times or stopping patterns.

During rush hours a symmetric timetable will feature excess seating capacity in the secondary travel direction. This is the case for both the non-periodic symmetric and non-periodic integrated interval timetable classes. Their adaptability to market demands is reduced and this thesis has evaluated them to have a medium disadvantage.

High frequency timetables must provide a minimum frequency throughout the day to get the label “high frequency timetable” (Coor 1997). This reduces the adaptability to market demands in case of time intervals with low travel demand. In peak hours it is no problem to increase the frequency to a higher level, but this timetable class faces the same problem with excess capacity for the secondary travel direction. Normally a high frequency timetable is introduced in systems where the minimum travel demand during a day is high enough for the demand of a minimum frequency. Therefore this timetable class has a small advantage.

Amongst the periodic timetables, the non-symmetric periodic timetable class is the most flexible to accommodate changes in travel demand during a day. A basic pattern of train services can be kept during an entire operational day. This pattern can be extended with train services that run during day time hours and again further extended with peak hour services in the primary travel directions since there is no requirement for symmetry in the timetable. When increasing the number of timetable patterns and/or shifts between timetable patterns, the flexibility of the timetable class improves to accommodate variations in travel demand during a day. This timetable class can have a big advantage.

When adding symmetry to the periodic timetable it can become more difficult to adapt the service level to the requested travel demand. Additional services have to run in both driving directions in fixed intervals and this can be more difficult to implement than just adding extra rush hour trains in the primary travel direction. Furthermore the additional trains will most likely run with a low occupancy rate in the secondary travel direction of the rush hour.

With IFIT-timetables the flexibility to adapt to travel demand is even further reduced. Additional trains have to fit into the pattern with train meetings at specified hubs at given times. This can be a capacity challenge for both the station hubs and the railway lines running to/from them. In this case it could be preferable to increase the length of trains during rush hours to provide the needed seating capacity. This timetable class has the potential for a big disadvantage.

4.11.11 Resources - Timetable planning process – agreement between all train operating companies

The non-periodic timetable classes have no reoccurring pattern in the timetable and an agreement on one or several timetable patterns during an operational day makes no sense and is therefore not needed. Since these classes of timetables are based on travel demand, the number of trains will increase dramatically during rush hour time periods and this normally demands a higher level of coordination between TOCs. Basic planning rules, such as letting the train order be determined by travel speeds of trains, should make this coordination between TOCs a manageable issue. Non-symmetric timetables give the highest level of flexibility in the planning process and therefore should have the greatest advantage in regards to this evaluation criterion.

Non-periodic symmetric timetables have a lower degree of flexibility due to the added symmetry. This thesis still considers this timetable class to have a small advantage.

When introducing train meetings at selected hubs in a timetable class, such as integrated interval timetables, the level of flexibility in the planning process is drastically reduced. A very high level of coordination between TOCs is needed to make these train meetings happen in a feasible manner. Therefore this timetable class has a medium disadvantage, similar to the IFIT.

A railway line that is served by a train service running according to a high frequency timetable is rarely served by more than one train service. Therefore no high level of coordination between train services and no agreement between potential several TOCs is needed. If more than one train service is using a railway line where a high frequency timetable is applied it demands a very high level of coordination between train services and therefore also an agreement between all involved TOCs.

As soon as timetable patterns are introduced with periodic non-symmetric timetables, an agreement between involved TOCs is needed. The level of needed agreement between TOCs depends on the complexity of the single timetable pattern, on the number of timetable patterns and on the number of shifts between timetable patterns during a day. A periodic timetable with a low number of timetable patterns and also a low number of shifts between timetable patterns requires the lowest level of coordination and agreement between TOCs. Periodic timetables with several different timetable patterns and frequent shifts between timetable patterns demand a very high level of coordination and agreements between relevant TOCs.

For a symmetric periodic timetable the picture is identical with the periodic timetable. Adding symmetry to the periodic timetable increases the need for coordination between train services and therefore also the level of agreement between TOCs.

The complexity of timetable patterns in an IFIT-timetable is very high. The degree of freedom when creating the timetable is very low and the needed level of coordination between train services is very high. This demands the highest level of agreement between all TOCs and can be a challenge to achieve. Often a political decision is needed as a basis for introducing this timetable class.

4.11.12 Resources - Optimal utilization of rolling stock

The non-periodic non-symmetric timetable gives the highest degree of freedom in the timetable planning process and therefore focus can be pointed at optimizing the utilization of rolling stock. This can be done in several ways, e.g. during rush hours it is possible to plan with fast non-stop train runs in the secondary travel direction. In this way it may become possible to utilize the rolling stock more than once during a rush hour period. Going one step further is to plan with empty train runs in the secondary travel direction. These initiatives are only possible if the necessary infrastructure capacity is available.

Symmetric timetables will most often provide excess seating capacity in the secondary travel direction during rush hours. This reduces the possibility to have an optimal utilization of rolling stock and gives the non-periodic symmetric timetable class a small disadvantage.

Integrated interval timetables are less flexible than non-periodic symmetric timetables due to the necessary train meetings at hubs. Therefore this timetable class is evaluated by this thesis to have a medium disadvantage, similar to the IFIT.

For a high frequency train service it is almost impossible to further optimize the utilization of rolling stock. Headways between trains in both driving directions are very small. The introduction of skip-stop services during rush hours, such as done by the metro systems in Santiago de Chile and Philadelphia in the USA, could be a possibility to improve utilization levels.

Amongst the periodic timetable classes the non-symmetric timetable provides the best opportunities to optimize the utilization of rolling stock. It is possible to run extra trains during rush hours in the primary travel directions and if the timetable and infrastructure allows it, let them return as non-stop or even empty trains, to be used in the primary travel direction again. The potential of rolling stock utilization increases in general with the flexibility of using several timetable patterns and shifting between them. Experience from real-life train operation has shown that periodic timetables improve the utilization levels of rolling stock. Repeating patterns make the planning of rostering plans easier and this can be used to put more effort into refining the utilization levels of rolling stock.

Similar to high frequency timetables it is almost impossible to achieve an optimal utilization of rolling stock in a symmetric timetable. Extra rush hour trains must run both in the primary and secondary travel direction, using the same running times and stopping pattern. The only possibility to optimize the use of rolling stock is to apply a high number of timetable patterns and shifting between them.

In IFIT-timetables, the possibility to apply a high number of timetable patterns is generally reduced dramatically. This timetable class has a very fixed basic structure, operating with train meetings at selected stations at given times, makes it almost impossible to have several larger changes during a day. This timetable feature makes it very difficult to achieve an optimal utilization of rolling stock.

4.11.13 Resources - Optimal utilization of train staff

As with the optimal utilization of rolling stock, the non-periodic non-symmetric timetable class provides the possibilities to focus on high utilization levels of train staff in the planning process. The high degree of freedom in the timetabling process allows this. Potentially train runs can be planned in such a way that makes it possible to utilize train staff in an optimal way according to the collective agreements between the labor unions and the TOC.

The non-periodic symmetric timetable class has less degree of freedom in the timetable planning process and therefore limits the possibilities for an optimal utilization of the train staff. When looking at the non-periodic integrated interval timetable class the flexibility in the planning process is further reduced and so is the potential for an optimal utilization of train staff.

High frequency train services should provide the TOC with a big chance to achieve a high level of utilization of train staff, since there are so many train runs. When creating the rostering plan for train staff, a high number of train runs, gives the needed flexibility to reach a high level of train staff utilization.

Non symmetric periodic timetables have the highest degree of freedom in the planning process amongst the periodic timetable classes and therefore hold the biggest potential to realize a high utilization level of train staff. This is specially the case when working with several timetable patterns and frequent shifts between them. Repeating traffic patterns simplify the preparation of rostering plans for train staff. This can lead to an overall improved level of train staff utilization.

The symmetric periodic timetable class is less flexible than the non-symmetric timetable class and therefore generally has a lower potential to achieve a high level of train staff utilization. Flexibility can be increased with the application of several timetable pattern and numerous shifts between these patterns.

Train meetings at station hubs at given times is the distinctive feature of the IFIT-timetable class. This very fixed timetable class does not offer many possibilities to optimize the utilization of train staff. On the other hand, these train meetings provide a unique opportunity to easily shift train crews between train runs and this could create a potential possibility to increase the utilization level of train staff.

4.11.14 Resources - Workload for the timetable planner

The timetable class with the lowest level of structure is the non-periodic non-symmetric timetable. This lack of structure increases the workload for the timetable planner since there are no timetable patterns that can be copied to other hours of the operational day. Unique train runs can cause potential conflicts between trains in many different places on the railway infrastructure. The timetable planner is aware of this and must spend much time on checking the timetable for conflicting train paths.

Non-periodic symmetric timetables entail a reduced workload for the timetable planner, since the use of symmetric train services makes it easier to create the timetable. The non-periodicity element ensures that timetable class still has a small disadvantage in regards to this timetable criterion.

Integrated interval timetables have such a high level of structure that they have a small advantage when evaluating the workload of the timetable planner. It is still a non-periodic timetable class but the major part of the timetable structure will be repeated.

With modern timetabling software tools, such as TPS from HACon (Barber et al 2007, Kaas & Goossmann 2004, http://hacon.de/tps-en?set_language=en (21.09.2012)), Viriato from SMA und Partner AG (Barber et al 2007, http://www.sma-partner.ch/index.php?option=com_content&view=article&id=368&Itemid=210&lang=en (21.09.2012)), RailSys from RMCon (Barber et al 2007, Sewcyk 2007, http://www.rmcon.de/en/products/railsys-product-family.html (21.09.2012)) and OpenTrack from OpenTrack Railway Technology Ltd. (Barber et al 2007, Nash & Hürlimann 2004, http://www.opentrack.ch/opentrack/opentrack_e/opentrack_e.html (21.09.2012)) it is no problem to plan a high frequency train service for a given railway line. Once the timetable planner has created the basic train runs for each travel direction, these are copied throughout the timetable to provide the desired headway times between trains at given time intervals. This is an easy task for a timetable planner.

Creating timetables becomes easier for timetable planners when working with repeating patterns. Patterns appear in the periodic timetable classes. Non-symmetric periodic timetables are the most flexible, of the periodic timetables and therefore potentially contain the most work for a timetable planner. The workload increases if the timetable consists of several timetable patterns and frequent shifts between these.

Symmetric periodic timetables are less flexible due to the required symmetry in train runs for both driving directions for train services. This reduced flexibility makes the work easier for the timetable planner. Modern timetabling software tools have no problem with creating copies of existing train runs and reversing them to go in the opposite travel direction. On the other hand, symmetry can create more work for a timetable planner. One must be aware of where the axes of symmetry are placed geographically in the timetable and all train services must be placed accordingly.

In IFIT-timetables the axes of symmetry are geographically placed in the selected stations hubs. Time wise the axes of symmetry are based in minute 00, 15, 30 or 45. These are easy to remember for passengers and timetable planners. By doing so it is possible to achieve the wanted train meetings at a given time at a given hub. The planning of these very concentrated train arrivals and departures at station hubs can be a difficult task for a timetable planner. The capacity utilization in the station area and on the railway lines leading to/from it is very high.

4.11.15 Total score for timetable classes

In the bottom row of Table 4.8 a total score of advantages and disadvantages as a sum of **÷/+**is presented. Amongst the non-periodic timetables the highest score of -2 is achieved by the symmetric non-integrated interval timetable (T1-2). It is the best compromise of flexibility and a minimum level of structure in a non-periodic timetable. The high frequency timetable class (T2) succeeded in getting the highest score of all timetable classes. It scored +19. The advantage of structured high frequent train services is much bigger than the disadvantages. It must be remembered that this timetable class is only suitable for certain categories of train services such as metro and suburban train lines. A common feature for the three categories of periodic timetables is that the timetable class using the same timetable pattern all day is most attractive. Changing timetable patterns make the timetable more complicated for customers, TOCs and IMs and therefore less attractive. The periodic non-symmetric timetable class (T3-1) scores +13, the periodic symmetric timetable class (T4-1) got +10 and the IFIT timetable class (T5-1) achieved +8. The reduction in flexibility in timetable design going from a periodic non-symmetric to a IFIT timetable class explains the declining scores.

4.12 Summary

A railway timetable has structure if it contains repeating train traffic patterns. The level of structure in a given railway timetable is used to categorize it into seven basic timetable classes. Specific structural features: Symmetry followed by integrated train meetings at designated station hubs increase the level of structure in a timetable. Seven basic railway timetable classes have been identified by this thesis:

- Non-periodic non-symmetric timetables
- Non-periodic symmetric timetables
- Non-periodic integrated interval timetables

- High frequency timetables

- Periodic non-symmetric timetables
- Periodic symmetric timetables
- Integrated fixed interval timetables (IFIT)

This thesis has introduced the non-periodic symmetric, non-periodic integrated interval and high frequency timetable classes. High frequency timetables are defined as a cross between non-periodic and periodic timetables. That is the reason for the dotted lines in the list above, indicating high frequency timetables being in the transition zone between periodic and non-periodic timetables. Passengers perceive it as periodic but in regards to headway times it does not have to be so, since headways between train services are very small. The thesis defines and presents the seven basic timetable classes.

Two existing approaches for measuring the level of structure in a given timetable are presented: A Swiss and English approach. This thesis identifies weaknesses with the existing methodologies and concludes that improvements are needed. By introducing the concept of “timetable patterns”, a tool becomes available that can improve the way to measure the level of structure in timetables. This thesis defines a timetable pattern as follows:

Definition of a timetable pattern:

A timetable pattern is the shortest time period for which the regularity index (RI) for a given travel relation, a railway line or an entire network, including all relevant train services, is 100%. Starting from the beginning of the investigation time period or the end of the previous timetable pattern.

When considering the number of applied timetable patterns and the number of shifts between them in a timetable, the methods of timetable structure measurement are improved. In this way important periodicity characteristics of a given railway timetable are taken into consideration. The thesis proposes new improved timetable structure indexes based on the English and Swiss approaches. These look at the dominant timetable pattern during an investigation time period. If the difference between patterns is big then the longest continuous use of the dominant timetable pattern should be used as indicator for the level of

structure in the timetable. In case the differences are small, then the sum of the time the dominant timetable pattern is applied should be used. The thesis generally recommends the latter.
By adding three analysis steps for timetable periodicity characteristics the thesis identifies a total of 25 timetable classes. The three analysis steps consider the number of applied timetable patterns in a given railway timetable for an operational day and the amount of shifts between the timetable patterns. There can be from one to several timetable patterns and the number of shifts between patterns can be low or high.

The level of structure in a timetable can affect the perceived timetable attractiveness. A high level of structure can give a high level of attractiveness. This applies to railway customers, TOCs and timetable planners from the IM. Railway customers can experience repeating memorable train arrival and departure times, randomly arriving passengers to stations will experience a minimum of average waiting time and missed train to train transfers will give a minimal travel time prolongation. Preparing rostering plans becomes more manageable with repeating train patterns for TOCs and therefore more effort can be put into the optimization of utilization levels of rolling stock and train staff. Repetitions in the timetable makes the work of the timetable planners less complicated and timetables can be prepared in less time and more focus can be given to quality control.

The seven overall timetable classes are described, based on their general characteristics and the advantages and disadvantages they bring to railway customers, TOCs and timetable planners. An overview comparison of all 25 identified sub timetable classes in regards to 14 commonly used timetable evaluation criteria is made at the end of the chapter. This thesis has evaluated each sub timetable class and has rated it to have either a small, medium or big advantage or disadvantage according to the 14 timetable evaluation criteria. The timetable evaluation criteria have not been given any weight. Finally a short explanation is given for the evaluations made by this thesis. The high frequency timetable class achieved the best score when looking at the sum of rated advantages and disadvantages by this thesis and therefore can be proclaimed being the most attractive timetable class of the identified 25 timetable classes.

5 Railway timetable class analysis

On large railway networks with many different train services from different train operating companies (TOCs), the overall railway timetable covering the entire network may contain several of the identified basic railway timetable classes in chapter 4. In theory every single train service can be planned using one of the basic timetable classes defined in section 4.1. This can result in an overall railway network timetable consisting of several timetable classes mixed with each other in different ways depending on when and where in a railway network a timetable analysis is performed.

To get an overview of the structural setup of a railway network timetable an easy to use generic timetable analysis approach is developed. It can be applied for both simple cases, e.g. a single railway line section serviced by one train service to an entire national railway network containing several timetable classes. Based on the available railway infrastructure and timetable data a set of quantitative parameters can be calculated, giving an overview of the presence of different timetable classes in the selected geographical area of analysis and the chosen time window of the investigation. If some timetable classes are perceived as more attractive as others the share/ percentage of these timetable classes can be used as an attractiveness indicator for the overall network timetable.

There can be a number of reasons for using different basic timetable classes for different train services in a network timetable:

- **Available financial resources** – Limited levels of subsidies can make it infeasible to run train services according to certain timetable classes, e.g. symmetric periodic timetables or integrated fixed interval timetables (IFIT) with a periodicity time frame of 30 or 60 minutes, since these timetable classes can have high cost levels due to the high service level provided for all travel directions throughout the day. If there are no subsidies available, it is most likely that train services will be timetabled according to changing market demands during the day to minimize costs and optimize profits resulting in a non-periodic + non-symmetric timetable.

- **Market demand -** Train services can have a big variation in travel demand during an operational day and therefore it might not be feasible to use a rigid symmetric periodic timetable for an entire day. Changing to a non-symmetric periodic timetable could be an option during rush hours operating more trains in the primary travel direction. Two train services can run as coupled trains on a part of the network with a high market demand and be divided into two separate trains servicing two railway lines with lower market demands.

- **Infrastructure layout/capacity** – If parts of a railway network are dominated by single track lines, it can become very difficult to apply a symmetric periodic timetable because of the location of and thereby the possible travel times between crossing stations. To achieve that trains run according to a specific timetable class it can become necessary to deviate from planning rules by reducing or prolonging running time and dwell time supplements. This can be regarded as scheduled waiting time. The level of electrified railway lines and signaling system technologies can together with the characteristics of the rolling stock fleet have a big impact on which timetable classes are feasible.

- **Rolling stock fleet** – If a given TOC has a shortage of available rolling stock it can become necessary to adapt a non-periodic timetable to his train services to make the best use of the limited resources instead of running trains according to e.g. a symmetric periodic timetable.

- Lack of flexibility in the use of rolling stock e.g. missing signaling system equipment or only fitted for electric power supply by overhead contact wire, can also lead to reduced options when creating the timetable.

- **Train service facilities –** The location of depot tracks, tracks with train cleaning equipment and refueling stations for diesel locomotives and train sets, can have an effect on the possible feasible timetable classes. The capacity of the service facilities, e.g. how many trains can be cleaned simultaneously, can also have an influence on the possible timetables.

- **Train staff** – Shortages in available train staff members can result in reduced possibilities for using timetable classes. A lack in the necessary training of train staff e.g. a train driver must have local knowledge about railway lines he is driving on, the train conductor must have the necessary knowledge about emergency procedures with the rolling stock class he is working on, can restrict the possibilities to implement certain timetable classes.

A high level of flexibility in the timetable makes it more probable that an overall network timetable consists of several timetable classes whereas a low level of flexibility makes it unlikely to find more than one timetable class. Figure 5.1 shows the timetable flexibility (y-axis) as a function of timetable classes (x-axis). The latter are ordered according to falling levels of timetable flexibility beginning with non-periodic timetables and ending with the IFIT-timetable class. Change in flexibility levels between timetable classes is either rated big or small.

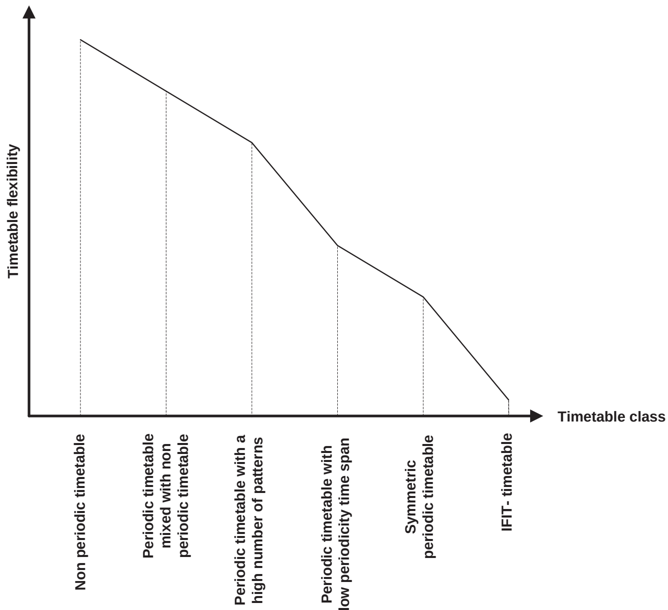


Figure 5.1: Timetable flexibility as a function of timetable class

Non-periodic timetables entail the highest level of timetable flexibility since there are no limiting timetable patterns that must be followed. Going from a timetable without structure to a timetable containing both structure, train services planned according to a timetable pattern, and no structure, train services planned to fulfill varying market demands during a day, reduces the flexibility level. If the periodicity time span of the periodic part of the network timetable is high, e.g. 120 minutes, there is enough room for variations for the non-periodic train services and the loss of timetable flexibility is estimated to being small. Network timetables consisting of both periodic and non-periodic parts, especially on shared railway lines, will require high periodicity time spans.

Taking the final step towards a completely periodic IFIT timetable can greatly reduce the level of timetable flexibility. This is especially the case if the periodicity time span of the timetable is reduced, to e.g. 60 minutes. If the timetable is made up of a high number of timetable patterns there is still room for big variations in the timetable during a day. Taking the step from a timetable consisting of a mix of periodic and non-periodic train services, to a completely periodic timetable using many different timetable patterns is not considered as big. If the periodicity time span of the timetable is further reduced to e.g. 30 or 20 minutes, then the timetable flexibility is drastically reduced. A TOC can now decide whether to run a given train service in a periodicity time interval or not. There is only little or no room for making changes to a single train run due to the restrictiveness of timetable patterns.

Introducing symmetry to the timetable by ensuring the same stopping pattern and similar travel times for both driving directions of a train service reduces again the flexibility of the timetable. If there is no specific focus on where to place the axis of symmetry, e.g. in or close to important transfer stations, the loss of timetable flexibility is estimated as being small. When going all the way by implementing an IFIT-timetable the timetabling flexibility is at its minimum.

Reduced timetable flexibility will often lead to a reduced potential for optimizing the utilization levels of both rolling stock and train staff. This can cause increased operational costs for the TOC and thereby in the end also for society.

In section 5.1 a general approach to analyzing a railway network for timetable features is presented. Issues that have to be considered during a timetable analysis are also presented. This is followed by a series of sections based on the analyzing methodology from section 5.1. The simplest scenario is presented in section 5.2 with a railway line serviced by one train service using one timetable class. In section 5.3 the train service runs according to several timetable classes. Section 5.4 looks at a railway line serviced by more than one train service but only one timetable class is applied. The same scenario but with several timetable classes being applied is presented in section 5.5. A timetable covering a railway network with several railway lines and trains services can consist of only one timetable class e.g. a non-periodic timetable or of several timetable classes e.g. non-periodic and periodic timetables. This is described in sections 5.6 and 5.7 respectively. Finally a summary is given in chapter 0.

5.1 Timetable class analysis for railways

This thesis presents an approach to analyzing a railway network timetable for different timetable classes in Table 5.1. Table 5.1 gives an overview of the possible combinations between groupings of train services and railway geography, in form of travel relations and smaller or larger parts of a railway network.

Analyzing railway geography can be approached in two ways:

- Looking at a given travel relation, going from station A to station B in the network
- Using administrative divisions of the railway network. Reaching from a railway line section, to a railway line consisting of several line sections, on to a group of railway lines forming a part of the network and finally the entire railway network. The dividing of a railway line in line sections can e.g. be based on the definitions presented in the UIC (International Union of Railways /

- Union Internationale des Chemins de fer) 406 leaflet for dividing a railway network into line sections for capacity analyzes (Landex 2008, UIC 2004).

<table>
<tr><th colspan="2" rowspan="2">Time window for timetable analysis</th><th colspan="5">Railway network</th></tr>
<tr><th>Line section</th><th>Railway line</th><th>Travel relation</th><th>Part of railway network</th><th>Entire railway network</th></tr>
<tr><th rowspan="3">Train service</th><th>Single train service</th><td></td><td></td><td></td><td></td><td></td></tr>
<tr><th>Group of train services</th><td></td><td colspan="3">See Table 5.2 for timetable analysis weighting parameters</td><td></td></tr>
<tr><th>All train services</th><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Table 5.1: Overview of analysis combinations between railway traffic and railway network for a selected investigation time window

An administrative division of a railway network does not necessarily correspond to the most interesting travel relations for passengers or freight. Stations with a high number of boarding and alighting passengers are not necessarily railway junctions or terminuses for train services. A Danish example is the station “Lyngby” on the suburban railway network of Copenhagen (Nielsen & Landex 2007). It is the 3rd largest station of the suburban railway network, when looking at passenger volumes (DSB & DSB S-tog 2008). Lyngby station is therefore interesting from a travel relation point of view, but in the present timetable it is neither a junction nor a terminus and is therefore situated in the middle of an administrative line section.

Train services can similarly be divided into three groupings:

- A single train service. This could be a specific train run of an Inter-City train service running once every hour during day time hours. The train service must either service the investigated travel relation or run through the relevant geographical area of the railway network.

- Train services could be grouped according to their train category, e.g. Inter-City, regional and freight trains. Another possibility is to group trains according to servicing a given travel relation or to be travelling on a section of analyzed infrastructure.

- One can include all train services that provide a transport option for a given travel relation. When analyzing the timetable for a given part of the railway network all train services running through the area can be part of the timetable investigation.

Following the overview of possible analysis combinations, based on railway traffic and geography, Table 5.2 presents a number of analysis parameters that are recommended by this thesis. The use of parameters is based on the available railway infrastructure and timetable data. First suggested parameter is the train services. Each train service must be linked to the most restrictive timetable class it can fit into. This can vary according to the time of day, e.g. rush hour and day hour timetable. Therefore each train run of a given train service must be linked to a timetable class and the time interval for the use of a given timetable class can then be registered.

Going further into detail, it is possible to calculate the number of train-kilometers that are scheduled with each timetable class. Train-kilometers can be segmented into passenger and freight train-kilometers. The supply of passenger seating and freight storing capacity provided by the timetabled trains can then be split up and allocated to each identified timetable class. If an estimated number of passengers or tons of freight per train run is available for the analysis a similar calculation can be made for the demand for railway transportation.

Analysis parameter	Timetable class X	Timetable class Y	Timetable class Z
Number of train services			
Number of train runs			
Time interval in hours			
Number of train-km - **Passenger** - **Freight**			
Number of km - **Freight (ton-km)** - **Passenger (pass-km)**			

Table 5.2: Timetable analysis weighting parameters

5.1.1 Timetable analysis issues

Single tracked railway lines make train crossings at dedicated crossing stations necessary. Some crossing stations may allow trains to arrive simultaneously; other stations require that one train arrives a few minutes before the other due to a combination of track geometry and functionality of the station interlocking/signaling system (Landex 2008). Such conditions can lead to minor differences in travel times for the two travel directions of a given train service. To create a feasible timetable for a single tracked railway line it can become a possibility to add extra running time and/or stopping time to one driving direction because of the location and the functionality of the railway stations where train crossings take place. By doing so the timetable planner adds scheduled waiting time to the timetabled train paths.

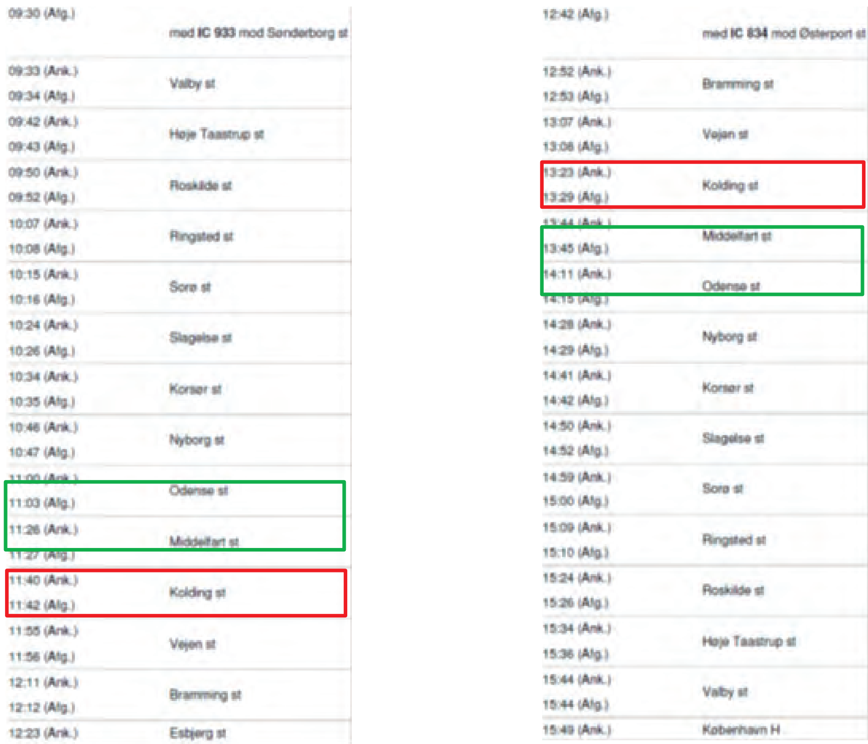
Sometimes there can be found differences in the speed profiles for the two driving directions on a given railway track. This can be caused by e.g. poor visibility of wayside signals and/or level crossings. Reduced visibility for the train driver can be caused by landscape features and/or flora on both sides of the railway line. This can result in a difference in running time per driving direction.

Differences in stopping times between driving directions at a given station is also possible. Splitting up a train consisting of two multiple units into two separate trains by a decoupling maneuver takes shorter time than coupling two trains made up of one multiple unit together and continue as one train. Hereby a difference in travel time can occur in the timetable.

The level of scheduled waiting time can vary between the two driving directions of a train service. Location of suitable overtaking stations, where fast passenger trains can pass by slower freight trains is a key factor, especially when looking at structured timetables. Non-periodic timetables are prone to differences in scheduled waiting time between driving directions, since they have no structure and the timetable planner therefore can decide from train conflict to train conflict how to make the timetable feasible (Wendler 2007).

Design of railway junctions, level or flying, can also have an effect on the degree of scheduled waiting time per driving direction for a train service. The potential for conflicting train paths is higher in level junctions than for flying junctions. This can result in a difference in travel time for the two driving directions of a train service (Landex 2008, Landex 2009, Schittenhelm 2011a).

An example of a train service with a big difference in travel times between driving directions is given in Figure 5.2. The hourly Inter-City train from Copenhagen to Esbjerg has a timetabled travel time of 173 minutes. Going from Esbjerg to Copenhagen takes 187 minutes. There is a difference of 14 minutes between travel times. The Inter-City train performs a decoupling maneuver at Kolding station going towards Esbjerg and a coupling maneuver going towards Copenhagen. A difference of 4 minutes in stopping time at Kolding station can be noticed. Other differences in running times e.g. between Odense and Middelfart and stopping times must be attributed to differences in scheduled waiting time per driving direction.



09:30 (Afg.)	med IC 933 mod Sønderborg st
09:33 (Ank.) 09:34 (Afg.)	Valby st
09:42 (Ank.) 09:43 (Afg.)	Høje Taastrup st
09:50 (Ank.) 09:52 (Afg.)	Roskilde st
10:07 (Ank.) 10:08 (Afg.)	Ringsted st
10:15 (Ank.) 10:16 (Afg.)	Sorø st
10:24 (Ank.) 10:26 (Afg.)	Slagelse st
10:34 (Ank.) 10:35 (Afg.)	Korsør st
10:46 (Ank.) 10:47 (Afg.)	Nyborg st
11:00 (Ank.) 11:03 (Afg.)	Odense st
11:26 (Ank.) 11:27 (Afg.)	Middelfart st
11:40 (Ank.) 11:42 (Afg.)	Kolding st
11:55 (Ank.) 11:56 (Afg.)	Vejen st
12:11 (Ank.) 12:12 (Afg.)	Bramming st
12:23 (Ank.)	Esbjerg st

12:42 (Afg.)	med IC 834 mod Østerport st
12:52 (Ank.) 12:53 (Afg.)	Bramming st
13:07 (Ank.) 13:08 (Afg.)	Vejen st
13:23 (Ank.) 13:29 (Afg.)	Kolding st
13:44 (Ank.) 13:45 (Afg.)	Middelfart st
14:11 (Ank.) 14:15 (Afg.)	Odense st
14:28 (Ank.) 14:29 (Afg.)	Nyborg st
14:41 (Ank.) 14:42 (Afg.)	Korsør st
14:50 (Ank.) 14:52 (Afg.)	Slagelse st
14:59 (Ank.) 15:00 (Afg.)	Sorø st
15:09 (Ank.) 15:10 (Afg.)	Ringsted st
15:24 (Ank.) 15:26 (Afg.)	Roskilde st
15:34 (Ank.) 15:36 (Afg.)	Høje Taastrup st
15:44 (Ank.) 15:44 (Afg.)	Valby st
15:49 (Ank.)	København H

Figure 5.2: Public timetable for the hourly Inter-City train service between Copenhagen and Esbjerg. Copenhagen → Esbjerg (left) and Esbjerg → Copenhagen (right) (DSB 2011c). Difference in stopping time at Kolding station is marked red and difference in travel time between Odense ←→Middelfart is marked green

When analyzing railway timetables, differences in travel times between the two driving directions of an investigated train service must be accepted. Focus must be on the overall structure of the timetable in regards to the frequency and stopping pattern of train services.

5.2 Railway line served by a single train service – one timetable class

If a railway line is only served by one train service, the timetable can both contain one basic timetable class or several timetable classes. This is illustrated by the two following examples.

The Copenhagen suburban railway network is served by 7 train lines. Figure 5.3 shows the line map of the railway network, marking the used example from the suburban railway network with red. This section looks at the railway line section from Holte to Hillerød on the most northern part of the train service called line E. It is a double tracked railway line and there are no other train services using this railway line. The line has a length of 17.5km (RND 2011a).

The public timetable for S-train line E between Holte and Hillerød can be seen in Figure 5.4. In this example we look at the driving direction from Holte to Hillerød. The departures from Holte marked grey begin at 5:28 and stop at 00:48 and run all weekdays. This ensures a 20 minute basic frequency on line E. Departures marked with white, run in daytime hours from Monday to Friday beginning at 6:38 and ending at 19:18. Hereby the line frequency is doubled from 20 to 10 minutes. There are no differences in stopping patterns or running times for the grey and white timetable times.

Figure 5.3: Line map of the Copenhagen suburban railway network (DSB 2011d) with indication of the used timetable class analysis example marked with a red circle.

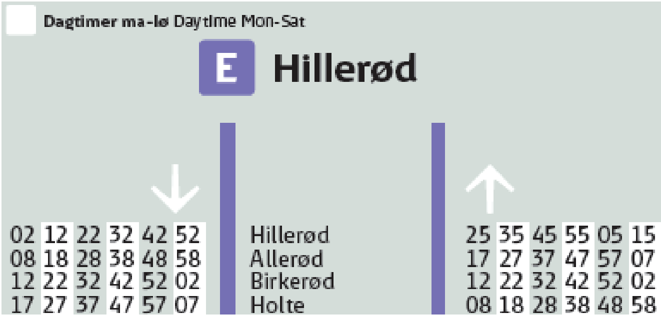


Figure 5.4: Part of public timetable for S-train line E (DSB S-tog 2011)

Railway line	Driving direction	Train service	Timetable pattern	Train-km	Timetable class
Holte – Hillerød	Holte → Hillerød	One train service: DSB S-tog, suburban train, line E	1 – Departures (4): 5:28 - 6:28 (20min)	70.0	Symmetric periodic
			2 – Departures (76): 6:38 – 19:18 (10min)	1330.0	Symmetric periodic
			3 – Departures (17): 19:28 – 00:48 (20min)	297.5	Symmetric periodic

Table 5.3: Timetable analysis for the railway line Holte – Hillerød at Holte station, with one train service

Table 5.3 gives an overview of the timetable analysis for this train service at Holte station. There are three timetable patterns during an operational day: From 5:28 to 6:28 with a train running every 20 minutes, followed by a pattern with 10 minute frequency from 6:38 to 19:18, then going back to a service level of a train every 20 minutes ending at 00:48. This gives 97 trains per day. All three timetable patterns belong to the symmetric periodic basic timetable class (DSB S-tog 2011).

5.3 Railway line served by a single train service – several timetable classes

A second example is the railway line from Varde to Skjern in the western part of Jutland – the Danish peninsular. See red encircled area in Figure 5.5. This is a regional single tracked railway line. The length of the railway line section is 42.4km (RND 2011a)

Figure 5.5: Line map of the railway lines serviced by TOC Arriva (http://www.mitarriva.dk/om-arriva-tog/straekningsoversigt (21.09.2012))

A public timetable for the train service running on this line from Monday to Friday is presented in Figure 5.6 and Figure 5.7. There are sixteen trains running from Varde to Skjern and vice versa every weekday. The timetable analysis in Table 5.4 shows that there are four timetable patterns during an operational day including both driving directions. When looking at the driving direction Varde → Skjern, the first train departure at 5:37 to the departure at 9:00 the timetable contains five train runs and is non-periodic with individual scheduled trains with varying departure times and/or running times. This is followed by a periodic timetable pattern with hourly departures starting at 9:54 and ending at 15:54. A single train is used as transition between two periodic patterns. This train departs at 16:50 and solely makes up the third timetable pattern. This is followed by the last pattern which again is periodic with a departure every two hours from 18:00 to 22:00 o'clock.

Varde	afg.	5:37	6:30	7:02	.....	8:02	.....	9:00	.....	9:54	.....	10:54	.....	11:54	.....
Varde Nord		5:39	6:32	7:04	.....	8:06	.....	9:02	.....	9:56	.....	10:56	.....	11:56	.....
Sig		5:45	6:38	7:10	.....	8:11	.....	9:08	.....	10:02	.....	11:02	.....	12:02	.....
Tistrup		5:50	6:46	7:15	.....	8:16	.....	9:13	.....	10:10	.....	11:10	.....	12:10	.....
Gårde		5:55	6:51	7:20	.....	8:22	.....	9:18	.....	10:15	.....	11:15	.....	12:15	.....
Ølgod		6:00	7:02	7:25	.....	8:26	.....	9:23	.....	10:20	.....	11:20	.....	12:20	.....
Tarm		6:13	7:12	7:35	.....	8:36	.....	9:33	.....	10:30	.....	11:30	.....	12:30	.....
Skjern	ank.	6:18	7:16	7:39	.....	8:40	.....	9:37	.....	10:34	.....	11:34	.....	12:34	.....

Varde	12:54	.....	13:54	.....	14:54	.....	15:54	.....	16:50	18:00	.....	20:00	.....	22:00
Varde Nord	12:56	.....	13:56	.....	14:56	.....	15:56	.....	16:52	18:02	.....	20:02	.....	22:02
Sig	13:02	.....	14:02	.....	15:02	.....	16:02	.....	16:58	18:08	.....	20:08	.....	22:08
Tistrup	13:10	.....	14:10	.....	15:10	.....	16:10	.....	17:03	18:13	.....	20:13	.....	22:13
Gårde	13:15	.....	14:15	.....	15:15	.....	16:15	.....	17:08	18:18	.....	20:18	.....	22:18
Ølgod	13:20	.....	14:20	.....	15:20	.....	16:20	.....	17:13	18:23	.....	20:23	.....	22:23
Tarm	13:30	.....	14:30	.....	15:30	.....	16:30	.....	17:23	18:33	.....	20:33	.....	22:33
Skjern	13:34	.....	14:34	.....	15:34	.....	16:34	.....	17:27	18:37	.....	20:37	.....	22:37

Figure 5.6: Public timetable for Arriva Denmark regional trains between Varde → Skjern (Monday - Friday) (http://www.mitarriva.dk/kundeservice/koreplaner (21.09.2012))

Skjern	.....	5:25	.....	6:22	6:47	.....	.....	8:09	.....	.....	9:46	.....	10:46	.....	11:46	.....	12:46	.....	13:46	.....	14:46	.....	15:46	16:38	17:47	18:41	.....	20:41	.....	22:41
Tarm	.....	5:29	.....	6:26	6:51	.....	.....	8:13	.....	.....	9:50	.....	10:50	.....	11:50	.....	12:50	.....	13:50	.....	14:50	.....	15:50	16:42	17:51	18:45	.....	20:45	.....	22:45
Ølgod	.....	5:39	.....	6:36	7:02	.....	.....	8:28	.....	.....	10:00	.....	11:00	.....	12:00	.....	13:00	.....	14:00	.....	15:00	.....	16:00	16:52	18:01	18:55	.....	20:55	.....	22:55
Gårde	.....	5:43	.....	6:40	7:07	.....	.....	8:33	.....	.....	10:04	.....	11:04	.....	12:04	.....	13:04	.....	14:04	.....	15:04	.....	16:04	16:56	18:05	18:59	.....	20:59	.....	22:59
Tistrup	.....	5:51	.....	6:45	7:15	.....	.....	8:39	.....	.....	10:11	.....	11:11	.....	12:11	.....	13:11	.....	14:11	.....	15:11	.....	16:11	17:02	18:14	19:04	.....	21:04	.....	23:04
Sig	.....	5:56	.....	6:50	7:20	.....	.....	8:44	.....	.....	10:16	.....	11:16	.....	12:16	.....	13:16	.....	14:16	.....	15:16	.....	16:16	17:07	18:19	19:09	.....	21:09	.....	23:09
Varde Nord	.....	6:01	.....	6:56	7:26	.....	.....	8:49	.....	.....	10:21	.....	11:21	.....	12:21	.....	13:21	.....	14:21	.....	15:21	.....	16:21	17:13	18:24	19:15	.....	21:15	.....	23:15
Varde ank.	.....	6:04	.....	6:58	7:29	.....	.....	8:52	.....	.....	10:24	.....	11:24	.....	12:24	.....	13:24	.....	14:24	.....	15:24	.....	16:24	17:15	18:27	19:17	.....	21:17	.....	23:17

Figure 5.7: Public timetable for Arriva Denmark regional trains between Skjern → Varde (Monday - Friday) (http://www.mitarriva.dk/kundeservice/koreplaner (21.09.2012))

Railway line	Train service	Driving direction	Timetable patterns	Train-km	Share [%]	Timetable class
Varde – Skjern	One train service: Arriva, regional train, Esbjerg - Skjern	Varde → Skjern	1 – Departures (5): 5:37, 6:30, 7:02, 8:03, 9:00	212.0	31	Non- periodic
			2- Departures (7): 9:54, 10:54, 11:54, 12:54, 13:54, 14:54, 15:54	296.8	44	Symmetric periodic
			3 – Departures (1): 16:50	42.4	6	Non- periodic
			4 – Departures (3): 18:00, 20:00, 22:00	127.2	19	Symmetric periodic
		Skjern → Varde	1 – Departures (4) 5:25, 6:22, 6:47, 8:09	169.6	25	Non- periodic
			2 – Departures (7) 09:46, 10:46, 11:46, 12:46, 13:14, 15:46, 16:46	296.8	44	Symmetric periodic
			3 – Departures (2) 16:38, 17:47	84.8	12	Non- periodic
			4 – Departures (3) 18:41, 20:41, 22:41	127.2	19	Symmetric periodic

Table 5.4: Timetable analysis for the railway line section Varde – Skjern

For the driving direction Skjern → Varde there is first a non-periodic timetable pattern including five trains with departure at 5:25, 6:22, 6:47 and 8:09. This is followed by a periodic timetable pattern with an hourly departure from 9.46 until 15:46. A non-periodic timetable pattern is then identified with two train runs with departures at 16:38 and 17:47. Finally, a periodic pattern appears from 18:41 to 22:41 with a departure every two hours.

In this example two basic timetable classes are used by a single train service during an operational day on the railway line section between Varde and Skjern. The first example included changes in frequencies but it was a simple doubling of number of train departures per hour – going from a frequency of 20 to 10 minutes. This made it possible to keep the basic timetable class throughout the operational day.

5.4 Timetable for a railway line with several train services – one timetable class

An example of a railway line section with three different train services and only one basic class of timetable used is the line section between Odense and Ringe. It is situated on the Danish island of Funen between the peninsular Jutland to the west and the island Zealand with Copenhagen to the east. This railway line section is the northern part of the railway line between Odense and Svendborg. See Figure 5.8 to the left. It is a single tracked regional railway line with a length of 22,4km which is served by three train services operated by the TOC DSB (Danish State Railways). The public timetable can be seen in Figure 5.8, in the middle driving direction Odense → Ringe and to the right driving direction Ringe → Odense. Notice the difference in stopping patterns for the third train service. Going from Odense to Ringe it does not stop at the halt Odense Sygehus whereas in the opposite driving direction a stop is timetabled.

Odense	09	23	54
Odense Sygehus	13 x	27 x	|
Fruens Bøge	17	|	00
Hjallese	19 x	|	|
Højby	23	|	|
Årslev	27	|	09
Pederstrup	30 x	|	|
Ringe	35	40	15

Ringe	39	43	03
Pederstrup	|	47 x	|
Årslev	|	50	09
Højby	|	54	|
Hjallese	|	57 x	|
Fruens Bøge	|	00	16
Odense Sygehus	51 x	02 x	18
Odense	55	07	22

Figure 5.8: Location of the railway line - Svenborgbanen (left), public timetable Odense → Ringe (middle) and public timetable Ringe →Odense (right) (DSB 2011b). Difference in stopping pattern is marked red

Table 5.5 gives an overview of the timetable analysis. Beginning with the driving direction Odense → Ringe: The first train service (marked red) stops at all stations between Odense and Ringe and also has it's terminus at Ringe. Train service number two (marked yellow) is a nonstop train between Odense and Ringe, only stopping at Odense Sygehus (in English Odense hospital). This train service catches up with the first train service at Ringe station and continues then on to Svendborg with stops at all stations. The third train service (marked green) does only stop at selected stations and is travel speed wise a cross between train service one and two. Each of the three train services is operated with a frequency of 60 minutes and has 19 departures every weekday. A similar picture can be seen for the driving direction Ringe → Odense.

When comparing timetabled running times for the two driving directions some minor differences appear for each train service. The first train service has 26 minutes of running time going from Odense to Ringe and only 24 minutes in the opposite direction. For the other two train services a similar picture can be recognized. It is interesting to notice that all three train services have shorter travel times from Ringe to Odense and that the shorter running time for the third train service is in the driving direction with one additional stop.

All three train services are running according to the symmetric periodic timetable class with a periodicity time span of 60 minutes. When combining these results it can be concluded that the examined railway line section as a whole is serviced by a symmetric periodic timetable and all train services have a frequency of 60 minutes.

Railway line section	Driving direction	Train services	Timetable patterns	Running time [min]	Timetable class
Odense – Ringe	Odense → Ringe	DSB, regional train: 1. Odense – Ringe	Departures (19): 5:09 – 23:09 (every hour)	26	Symmetric periodic
		DSB, regional train: 2. Odense – Ringe - Svendborg	Departures (19): 5:23 – 23:23 (every hour)	17	Symmetric periodic
		DSB, regional train: 3. Odense – Ringe - Svendborg	Departures (14): 5:54 – 23:54 (every hour)	21	Symmetric periodic
	Ringe → Odense	DSB, regional train: 1. Ringe – Odense	Departures (21): 5.43 – 23:43 (every hour)	24	Symmetric periodic
		DSB, regional train: 2. Svendborg - Ringe – Odense	Departures (19): 5.39 – 23:39 (every hour)	16	Symmetric periodic
		DSB, regional train: 3. Svendborg - Ringe - Odense	Departures (14): 5.03 – 23:03 (every hour)	19	Symmetric periodic

Table 5.5: Timetable analysis for the railway line section Odense – Ringe. The three identified train services have been given a color each.

5.5 Timetable for a railway line with several train services – several timetable classes

For a railway line served by several train services the timetable may consist of several basic timetable classes. This can be seen on the heavily used railway line between Copenhagen central station (København H) and the station Copenhagen Airport Kastrup. Figure 5.9 gives a schematic overview of the passenger train services running on this railway line. See the area marked by the dotted red circle in the figure.

Figure 5.9: Schematic map for train services between Copenhagen Central Station (København H) and Copenhagen Airport Kastrup (DSB 2011d)

The green line represents the regional Øresund train services between Denmark and Sweden. Inter-City trains are represented by the red line. This covers both the InterCity-Bornholm train service, starting at Copenhagen Central Station and terminating at the ferry harbor in Ystad (Sweden), and the national Danish InterCity-trains going to/from Copenhagen, terminating at Copenhagen Airport. The orange line represents the InterCity-Express trains (Lyntog) following the same route as the InterCity-trains but with fewer stops.

Looking at the driving direction from Copenhagen central station towards Copenhagen Airport, the regional Øresund trains are running according to a symmetric periodic timetable shown in Figure 5.10. Trains run with headway times of 8 or 12 minutes. See timetable times within the red rectangle. The reason for this is that the minimum allowed scheduled headway time between two trains on the analyzed railway line is set to 4 minutes. Therefore it is not possible to run trains every 10 minutes without wasting valuable line capacity.

køredage	alle dage	alle dage	alle dage	alle dage	ma-fr: 6.01-7.21
tidsinterval	4.30-5.10	4.38-5.16	5.43-19.43	6.01-20.01	14.21-17.21
					lø: 16.01-17.01 1
Helsingør		38 58 16	43 03 23		
Snekkersten		42 02 22	47 07 27		
Espergærde		45 05 25	50 10 30		
Humlebæk		48 08 28	53 13 33		
Nivå		52 12 32	57 17 37	01 21 41	01 21 41
Kokkedal		55 15 35	00 20 40	04 24 44	04 24 44
Rungsted Kyst		58 18 38	| | |	07 27 47	07 27 47
Vedbæk		02 22 42	| | |	11 31 51	11 31 51
Skodsborg		06 26 46	| | |	15 35 55	15 35 55
Klampenborg		10 30 50	| | |	19 39 59	19 39 59
Hellerup		15 35 55	15 35 55	24 44 04	24 44 04
Østerport	30 50 10	21 41 01	21 41 01	30 50 10	30 50 10
Nørreport	33 53 13	24 44 04	24 44 04	33 53 13	33 53 13
København H ank.	37 57 17	28 48 08	28 48 08	37 57 17	37 57 17
København H	40 00 20	32 52 12	32 52 12	40 00 20	40 00 20
Ørestad	46 06 26	38 58 18	38 58 18	46 06 26	46 06 26
Tårnby	49 09 29	41 01 21	41 01 21	49 09 29	49 09 29
CPH Kastrup ✈	52 12 32	46 06 26	46 06 26	52 12 32	54 14 34

Figure 5.10: Basic timetable for the regional Øresund train service (DSB Øresund 2012)

The daily timetable for the InterCity-Bornholm trains between Copenhagen Central Station and Ystad in Sweden can be seen in Figure 5.11. To the left is the timetable valid from April 4 to May 2 in 2012. To the right is the timetable valid from May 3 to June 29 in 2012. In the top of the figure, black numbers on white background indicate that this train only runs on a given weekday: Number 5 being Friday and 7 being Sunday. A white number on black background indicates that this train only runs on selected days. If there are no markings the train runs every day.

10 10/4 - 2/5 2012 InterCity Bornholm

Køredage		2	5 7	2	5 - 7	3
Rønne	6.30	10.30	14.30	16.30	18.30	20.30
Ystad	7.50	11.50	15.50	17.50	19.50	21.50
Ystad	8.09	12.09	16.09	18.09	20.09	22.09
Skurup	8.25	12.25	16.25	18.25	20.25	22.25
Svedala	8.42	12.42	16.42	18.42	20.42	22.42
Kbh./Kastrup ✈	9.05	13.05	17.09	19.09	21.09	23.09
København H	9.19	13.19	17.23	19.23	21.23	23.23
Tognummer	IC 1453	IC 1457	IC 1461 IC 21461	IC 1465	IC 1469	IC 1473

10 3/5 - 29/6 2012 InterCity Bornholm

Køredage		1	5 - 7 2	1 - 4 3	5 - 7 4	1 - 4 5	5 - 7 6
København H	6.36	10.36	14.45	16.36	18.45	20.36	22.36
Kbh./Kastrup ✈	6.50	10.50	14.58	16.50	18.58	20.49	22.49
Svedala	7.15	11.15	15.17	17.15	19.17	21.15	23.15
Skurup	7.29	11.29	15.29	17.29	19.29	21.29	23.29
Ystad	7.49	11.49	15.49	17.49	19.49	21.49	23.49
Ystad	8.30	12.30	16.30	18.30	20.30	22.30	0.20
Rønne	9.50	13.50	17.50	19.50	21.50	23.50	1.40
Tognummer	IC 1450	IC 1454	IC 1458 IC 21458	IC 1462	IC 1466	IC 1470	IC 1474

Figure 5.11: Basic timetables for the InterCity-Bornholm train service from Copenhagen central station to Copenhagen Airport Kastrup. Validity 10 April – 2 May 2012 (left) and validity 3 May – 29 June 2012 (right) (DSB 2011a)

This train service is operated according to a non-periodic timetable. In regards to travel times there are two model trains, one departing XX:36 and the other XX:45 from Copenhagen central station but the departure times do not follow a pattern. When looking at the operational days of trains it becomes clear that these trains mainly transport people between Copenhagen and Bornholm when the weekend begins and ends.

A København – Stockholm

køredage		1-5 6	1-5 1	1-5	1-5 7 2	6 3	7	1, 5 4	1-6 4	7 8	9	6 7 5	
Østerport		3.58	4.47	4.47	6.01	6.15	6.21	7.01	8.24	8.01	8.21	9.01	10.01
Nørreport		4.01	|	|	6.04	|	6.24	7.04	|	8.04	8.24	9.04	10.04
København H		4.12	4.56	4.56	6.12	6.29	6.32	7.12	8.37	8.12	8.32	9.12	10.12
Kbh./Kastrup ✈		4.26	5.10	5.10	6.26	6.42	6.46	7.26	8.50	8.26	8.46	9.26	10.26
Malmö C	o	4.46 *	5.29	5.29 *	6.46 *	6.59	7.06 *	7.46 *	9.09	8.46 *	9.06 *	9.46 *	10.46 *
Malmö C		5.13	5.33	6.11	7.11	7.11	7.33	8.05	9.13	9.13	9.33	10.13	11.13
Lund C		5.25	5.45	6.25	7.25	7.25	7.43	8.17	9.25	9.25	9.43	10.25	11.25
Hässleholm C		5.53	6.15	6.53	7.53	7.53	8.16	8.59	9.53	9.53	10.16	10.53	11.53
Alvesta	o	6.28	|	7.28	8.28	8.28	8.59	9.41	10.28	10.28	10.59	11.28	12.28
Nässjö C	o	7.02	|	8.02	9.02	9.02	9.39	10.22	11.02	11.02	11.39	12.02	13.02
Mjölby	o	7.46	|	|	9.46	9.46	|	|	11.46	11.46	|	|	13.47
Linköping C	o	8.02	|	9.01	10.01	10.01	10.43	11.37	12.01	12.01	12.43	13.01	14.02
Norrköping C	o	8.26	|	9.26	10.26	10.26	11.12	12.06	12.26	12.26	13.12	13.26	14.26
Södertälje Syd	o	9.24	|	10.24	11.24	11.24	|	13.19	13.24	13.24	|	14.24	15.24
Flemingsberg	o	|	|	|	|	|	|	|	|	|	|	|	|
Älvsjö	o	|	|	|	|	|	12.33	|	|	|	14.32	|	|
Stockholm C	o	9.50	10.05	10.50	11.50	11.50	12.44	13.45	13.50	13.50	14.45	14.05	15.50
tognr.		ø 1144 SJ522	SJ500	SJ500 SJ524	ø 1012 SJ526	SJ526	ø 1014 Veo7140	ø 1018 SJ200	SJ530	ø 1024 SJ530	ø 1026 Veo7150	ø 1030 SJ532	ø 1036 SJ534

Figure 5.12: Timetable for trains between Copenhagen and Stockholm via Copenhagen Airport Kastrup (DSB 2011a)

B København - Helsingborg - Göteborg

Køredage			1-5		1-5		1-5	1-5		1-5							
Østerport		3.58		5.21	5.31	6.21	6.50	7.10	7.21	7.50	8.21	9.21		10.21	11.21	12.21	13.21
Nørreport		4.01		5.24	|	6.24	6.53	7.13	7.24	7.53	8.24	9.24		10.24	11.24	12.24	13.24
København H	o	4.05		5.28	5.37	6.28	6.57	7.17	7.28	7.57	8.28	9.28		10.28	11.28	12.28	13.28
København H		4.12		5.32	5.41	6.32	7.00	7.20	7.32	8.00	8.32	9.32	9.45	10.32	11.32	12.32	13.32
Kbh./Kastrup ✈		4.26		5.46	5.54	6.46	7.14	7.34	7.46	8.14	8.46	9.46	9.58	10.46	11.46	12.46	13.46
Hyllie		4.39	4.59	5.59	|	6.59	7.29	7.49	7.59	8.29	8.59	9.59	|	10.59	11.59	12.59	13.59
Triangeln		4.42	5.02	6.02	|	7.02	7.32	7.52	8.02	8.32	9.02	10.02	|	11.02	12.02	13.02	14.02
Malmö C	o	4.46	5.06	6.06	6.09	7.06	7.36	7.56	8.06	8.36	9.06	10.06	10.14	11.06	12.06	13.06	14.06
Malmö C		4.48	5.08	6.08	6.17	7.08	7.39	8.00	8.08	8.38	9.08	10.08	10.20	11.08	12.08	13.08	14.08
Lund C		4.58	5.20	6.20	6.27	7.20	7.50	8.12	8.20	8.50	9.20	10.20	10.30	11.20	12.20	13.20	14.20
Landskrona			5.36	6.36	|	7.36	8.06	8.29	8.36	9.06	9.36	10.36	|	11.36	12.36	13.36	14.36
Helsingborg C	o		5.48	6.48	|	7.48	8.20	8.43	8.48	9.20	9.48	10.48	|	11.48	12.48	13.48	14.48
Helsingborg C			5.53	1 6.53	|	7.53			1 8.53		9.53	1 10.53	|	11.53	12.53	13.53	14.53
Ängelholm			6.15	7.15	|	8.15			9.15		10.15	11.15	|	12.15	13.15	14.15	15.15
Båstad S			6.37	7.37	|	8.37			9.37		10.37	11.37	|	12.37	13.37	14.37	15.37
Laholm			6.44	7.44	|	8.44			9.44		10.44	11.44	|	12.44	13.44	14.44	15.44
Hässleholm C			|	|	6.55	|			|		|	|	10.58	|	|	|	|
Halmstad C	o		6.56	7.55	7.58	8.56			9.56		10.56	11.55	11.58	12.56	13.56	14.56	15.55
Halmstad C			7.02	8.02	7.58	9.02			10.00		11.02	12.02	11.58	13.02	14.00	15.02	16.02
Falkenberg			7.21	8.21	|	9.21			10.19		11.21	12.21	|	13.21	14.19	15.21	16.21
Varberg			7.36	8.36	|	9.36			10.36		11.36	12.36	|	13.36	14.36	15.36	16.36
Kungsbacka			7.59	8.59	|	9.59			10.59		11.59	12.59	|	13.59	14.59	15.59	16.59
Mölndal	o		8.08	9.08	8.52	10.08			11.08		12.08	13.08	|	14.08	15.08	16.08	17.08
Göteborg C	o		8.17	1 9.17	9.05	10.17			1 11.17		12.17	1 13.17	13.00	14.17	15.17	16.17	17.17
Tognummer		ø 1144	ø 1002	ø 1008	SJ484	ø 1014	ø 1316	ø 1318	ø 1020	ø 1322	ø 1026	ø 1032	SJ486	ø 1038	ø 1044	ø 1050	ø 1056

Figure 5.13: Timetable for trains between Copenhagen and Gothenburg via Copenhagen Airport Kastrup (DSB 2011a)

Figure 5.12 and Figure 5.13 show the international trains operated by Swedish passenger TOC SJ between Copenhagen - Stockholm and Copenhagen – Gothenburg respectively. The trains are marked with red boxes. Please notice that in each case there is an alternative to SJ by using other TOCs. When travelling to Stockholm and Gothenburg it is possible to use DSB Øresund and then continue on with Veolia – without a transfer. The listed DSB Øresund trains are a part of the 8/12minute frequency on the Øresund railway line as seen earlier in Figure 5.10. Both train services, Copenhagen – Stockholm/Gothenburg, are running according to a non-periodic timetable.

An overview of the Inter-City (IC) and InterCity-Express (Lyn) trains running between Copenhagen central station and Copenhagen Airport Kastrup is given in Figure 5.14. The InterCity-Express train service has the following departures from Copenhagen: 7:29, 8:49, 9:49, 10:29, 11:29, 13:29, 15:29, 17;29, 17:49, 18:29, 18:49, 19:29, 21:29, 22:29 and 23:29. It begins the morning hours with four departures, marked red, running according to a non-periodic timetable pattern. This is followed by two periodic timetable patterns whose departures are marked green and blue. Periodicity time spans are two and one hour respectively. The evening begins with a single departure marked brown. Late evening departures, marked violet, are forming a periodic timetable pattern with a periodicity time span of one hour. Overall the InterCity-Express train service between Copenhagen central station and Copenhagen Airport Kastrup has 15 daily train runs of which ten belong to periodic timetable patterns and five to a non-periodic timetable pattern.

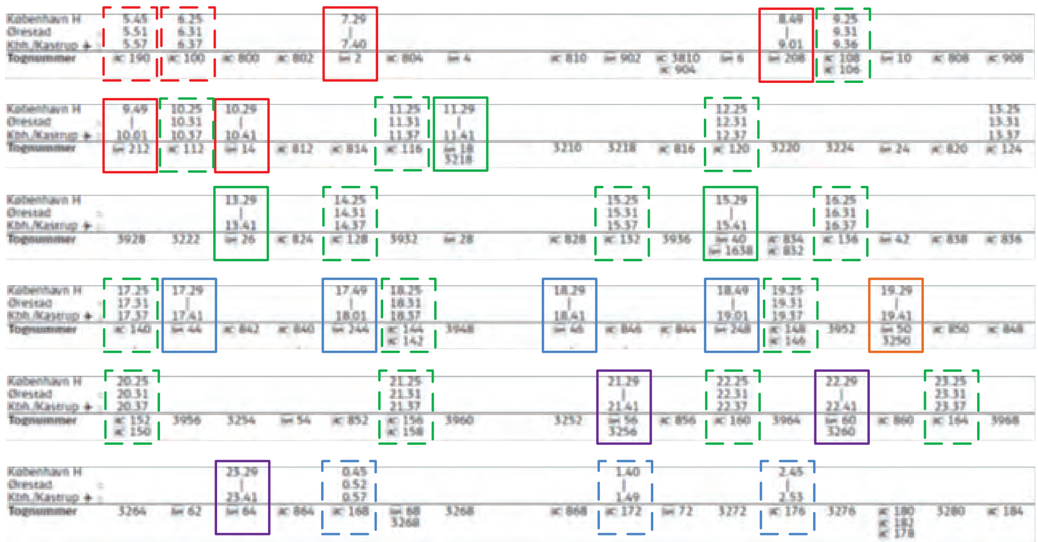


Figure 5.14: Timetable for InterCity (IC) and InterCity-Express (Lyn) trains between Copenhagen central station and Copenhagen Airport Kastrup. Timetable patterns are marked with different colors. InterCity-Express (Lyn) trains are marked with solid lines and InterCity (IC) trains are marked with dotted lines (Based on DSB 2011c)

Looking at the InterCity-train service, it has the following departures from Copenhagen: 5:45, 6:25, 9:25, 10:25, 11:25, 12:25 – 23:25, 00:45, 01:40 and 2:45. This train service also begins with a non-periodic timetable pattern, marked red, in the early morning hours with departures at 5:45 and 6:25. Then follows a very long time interval using a periodic timetable beginning with the departure at 9:25 and ending with the departure 23:25, with one departure every hour. These departures are marked green. The last three departures at 0:45, 1:40 and 2:45 form a non-periodic timetable pattern, marked blue. The last two IC-trains have a different stopping pattern by skipping Ørestad station. This train service has a total of 15 departures following an hourly periodic timetable pattern and five departures in the early morning and late night hours that are non-periodic.

Train service	Timetable class(es)	Time period	Number of departures
Øresund trains	Periodic timetable	All operational day	97
Inter-City train to Bornholm (Ystad)	Non-periodic timetable	All operational day	4-6
SJ trains train service to Stockholm	Non-periodic timetable	All operational day	9
SJ trains train service to Gothenburg	Non-periodic timetable	All operational day	4
DSB train service Inter-City-Express trains	Periodic timetable	11-19	7
	Non-periodic timetable	07-11, 19-23	7
DSB train service Inter-City trains	Periodic timetable	09-24	15
	Non-periodic timetable	05-09, 24-03	5

Table 5.6: Overview of train services and their timetable classes for the Øresund railway line between Copenhagen central station and Copenhagen Airport Kastrup

Table 5.6 gives an overview of the identified train services and the timetable class(es) they follow during an operational day. Both periodic and non-periodic timetables are being used. When looking at all train services between Copenhagen central station and Copenhagen Airport Kastrup it can be noticed that all trains have the same travel times. Even DSB InterCity-Express trains that due not stop at Ørestad station. This timetabling practice has been introduced to make the train paths homogenous and thereby increase the capacity of the railway line section and the robustness of the timetable (Johansson 2011).

5.6 Timetable for a railway network – one timetable class

The Dutch railways, Nederlandse Spoorwegen (NS), were the first to introduce a periodic timetable for long distance train traffic in 1938. In 1970, a symmetric periodic timetable was introduced on a national level, hereby introducing one timetable class for the entire Dutch railway network. In 2006 it was no longer possible to keep making adjustments to the 1970 timetable to accommodate the increased demand for railway traffic. In this period passenger transport (passenger kilometers) had almost doubled and freight transport had increased with 285%. In December 2006 a new timetable was introduced with two basic classes of train services: Long distance passenger trains (InterCity-train services) servicing only larger stations and regional trains calling at all stations. Both train services are running every 15 minutes on the busiest parts of the network and every 30 minutes on the rest of the network (Kroon et al. 2009, http://de.wikipedia.org/wiki/Taktfahrplan (21.09.2012)).

The basic timetable concept for the year 2012 is still the same as the one introduced in 2006. Two examples from the Dutch national timetable are presented to give an insight into the national timetable concept. The busy railway line between Den Haag HS and Delft main station is the first example. This line has partly four tracks and two tracks[2]. A single tracked regional line between Barneveld and Ede is the second example. See Figure 5.15 for geographical maps of the selected examples.

[2] The railway line is currently being extended to four tracks on the entire line section

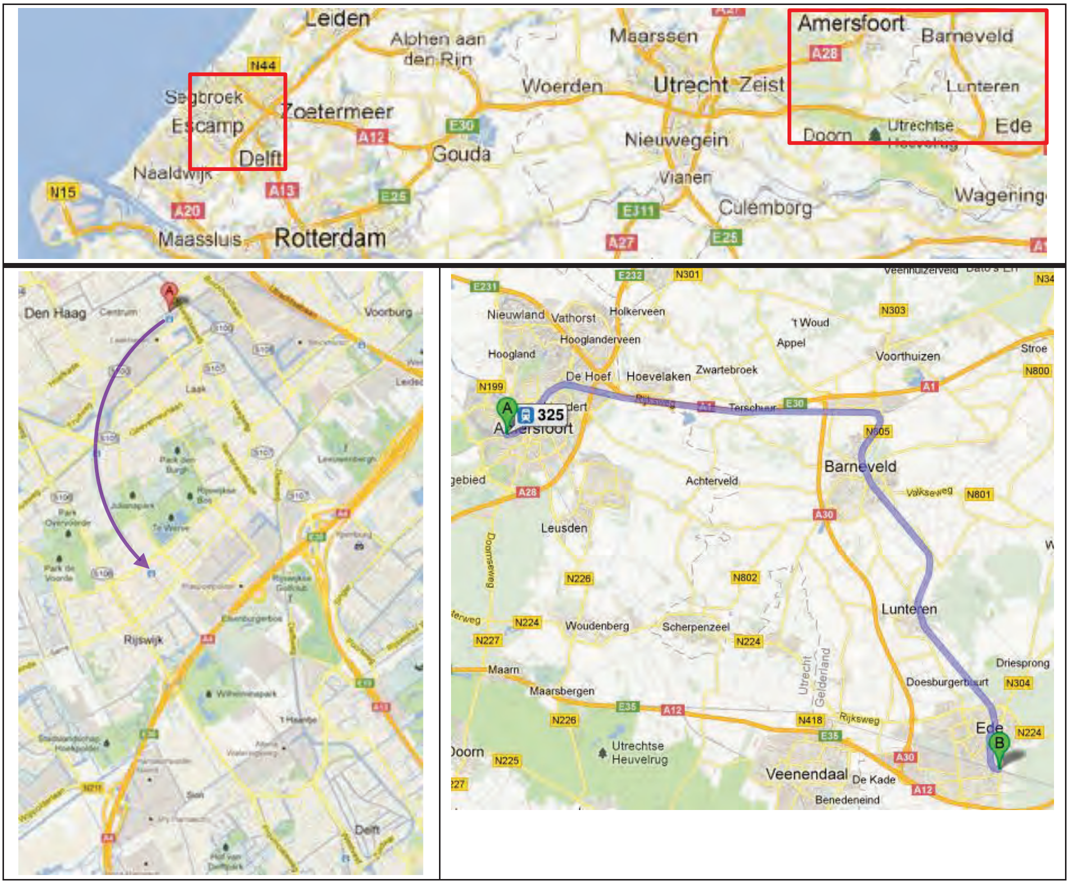


Figure 5.15: Map of timetable example locations (top). Detailed maps of the railway lines between Den Haag HS and Delft (bottom left) and between Amersfoort and Ede-Vageningen (bottom right) (http://www.maps.google.com (02.08.2012))

Figure 5.16 shows two examples of Dutch public timetables. One for InterCity-train services between Den Haag HS station and Delft central station and the other for regional train services between the stations Den Haag HS and its suburb Rijswijk. Two InterCity-train services can be identified in the public timetable: One service running every 15 minutes, departing at minute 03, 18, 33 and 48. Another service runs every 30 minutes departing at minute 27 and 57. Regional trains run every 15 minutes and depart simultaneously with the InterCity-trains. This is only possible since there are four tracks available between Den Haag HS and Rijswijk, two per driving direction. One track is dedicated to fast train services, such as InterCity-trains, and one for slower trains, such as regional and freight trains (Kroon et al. 2009).

The regional train service has one additional stop between Den Haag HS and Rijswijk whereas the InterCity-train services do not stop between Den Haag HS and Delft central station. In this way the necessary headway distance between the two train services is achieved, when the two tracks per driving direction merge to one track per direction shortly after Rijswijk station.

Bahnhof/Haltestelle	Datum	Zeit		Dauer	Umst.	Produkte
		↑ Früher				
Den Haag HS Delft	Do, 02.08.12 Do, 02.08.12	ab an	10:57 11:04	0:07	0	IC
Den Haag HS Delft	Do, 02.08.12 Do, 02.08.12	ab an	11:03 11:09	0:06	0	IC
Den Haag HS Delft	Do, 02.08.12 Do, 02.08.12	ab an	11:18 11:24	0:06	0	IC
Den Haag HS Delft	Do, 02.08.12 Do, 02.08.12	ab an	11:27 11:34	0:07	0	IC
Den Haag HS Delft	Do, 02.08.12 Do, 02.08.12	ab an	11:33 11:39	0:06	0	IC
Den Haag HS Delft	Do, 02.08.12 Do, 02.08.12	ab an	11:48 11:54	0:06	0	IC
Den Haag HS Delft	Do, 02.08.12 Do, 02.08.12	ab an	11:57 12:04	0:07	0	IC
Den Haag HS Delft	Do, 02.08.12 Do, 02.08.12	ab an	12:03 12:09	0:06	0	IC
Den Haag HS Delft	Do, 02.08.12 Do, 02.08.12	ab an	12:18 12:24	0:06	0	IC
Den Haag HS Delft	Do, 02.08.12 Do, 02.08.12	ab an	12:27 12:34	0:07	0	IC
Den Haag HS Delft	Do, 02.08.12 Do, 02.08.12	ab an	12:33 12:39	0:06	0	IC
Den Haag HS Delft	Do, 02.08.12 Do, 02.08.12	ab an	12:48 12:54	0:06	0	IC

Bahnhof/Haltestelle	Datum	Zeit		Dauer	Umst.	Produkte
		↑ Früher				
Den Haag HS Rijswijk	Do, 02.08.12 Do, 02.08.12	ab an	11:03 11:09	0:06	0	RE
Den Haag HS Rijswijk	Do, 02.08.12 Do, 02.08.12	ab an	11:18 11:24	0:06	0	RE
Den Haag HS Rijswijk	Do, 02.08.12 Do, 02.08.12	ab an	11:33 11:39	0:06	0	RE
Den Haag HS Rijswijk	Do, 02.08.12 Do, 02.08.12	ab an	11:48 11:54	0:06	0	RE
Den Haag HS Rijswijk	Do, 02.08.12 Do, 02.08.12	ab an	12:03 12:09	0:06	0	RE
Den Haag HS Rijswijk	Do, 02.08.12 Do, 02.08.12	ab an	12:18 12:24	0:06	0	RE
Den Haag HS Rijswijk	Do, 02.08.12 Do, 02.08.12	ab an	12:33 12:39	0:06	0	RE
Den Haag HS Rijswijk	Do, 02.08.12 Do, 02.08.12	ab an	12:48 12:54	0:06	0	RE
Den Haag HS Rijswijk	Do, 02.08.12 Do, 02.08.12	ab an	13:03 13:09	0:06	0	RE

Figure 5.16: Two examples of Dutch public timetables. InterCity (IC) trains between Den Haag HS and Delft (to the left) and regional (RE) trains between Den Haag HS and Rijswijk (to the right) (http://www.bahn.de 08.01.2012)

In Figure 5.17 an example of a graphical timetable for a little part of the national Dutch railway timetable is shown. The basic hourly timetable pattern for the railway line Amersfoort (Amf) – Barneveld (Bnn) - Lunteren (Ltn) – Ede (Edc) - Ede-Vageningen (Ed) is presented. To the far left in Figure 5.17, the number of available railway line tracks is displayed. The first short part of the line from Amersfoort towards Barneveld has four tracks, following a junction this is then reduced to two tracks and shortly before Barneveld it becomes a single track line until the final station Ede-Vageningen. Density of the train traffic is much higher on the quadruple and double tracked part of the investigated railway line than on the single track part. An interesting timetable feature can be seen at Barneveld station where a half hourly regional train service terminates and has a turnaround time of only 4 minutes. Barneveld is a standard crossing station on a single tracked line with two platform tracks and has no additional platform tracks for terminating trains (Google Earth version 6.2 (02.08.2012)). Due to the single track part of the railway line it has not been possible to achieve a regular regional train service every 15 minutes between Amersfoort and Barneveld.

The regional train service that runs between Amersfoort and Ede-Wageningen runs every 30 minutes and crosses at the junction (Bnva), where the single track line separates from the double tracked main line between Amersfoort and Apeldoorn and at Lunteren crossing station. There are no station platforms at the junction (Bnva). Terminus is at Ede-Vageningen station which is a junction on the main railway line between the cities of Utrecht and Arnhem.

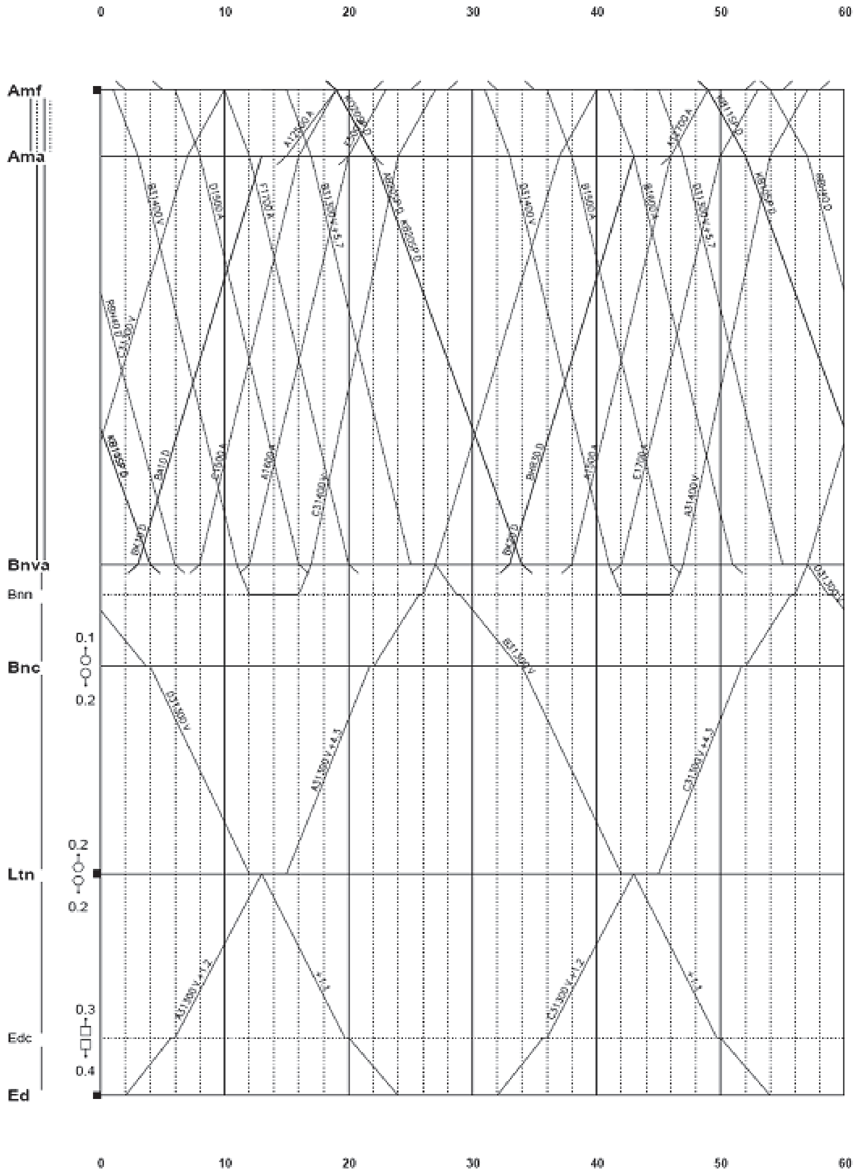


Figure 5.17: Graphical timetable showing the hourly timetable pattern for the railway line Amersfoort - Lunteren - Ede-Wageningen in The Netherlands (Huisman 2012)

5.7 Timetable for a railway network – several timetable classes

France is known for that the French TOC SNCF (Société Nationale des Chemins de fer Français, in English: French National Railway Corporation) is running the major part of its long distance passenger train services according to a market oriented timetable. This results in the extensive use of the non-periodic non-symmetric timetable class. In Figure 5.18 the graphical timetable for the high speed railway line between Marseille and Paris via Avignon and Lyon is shown.

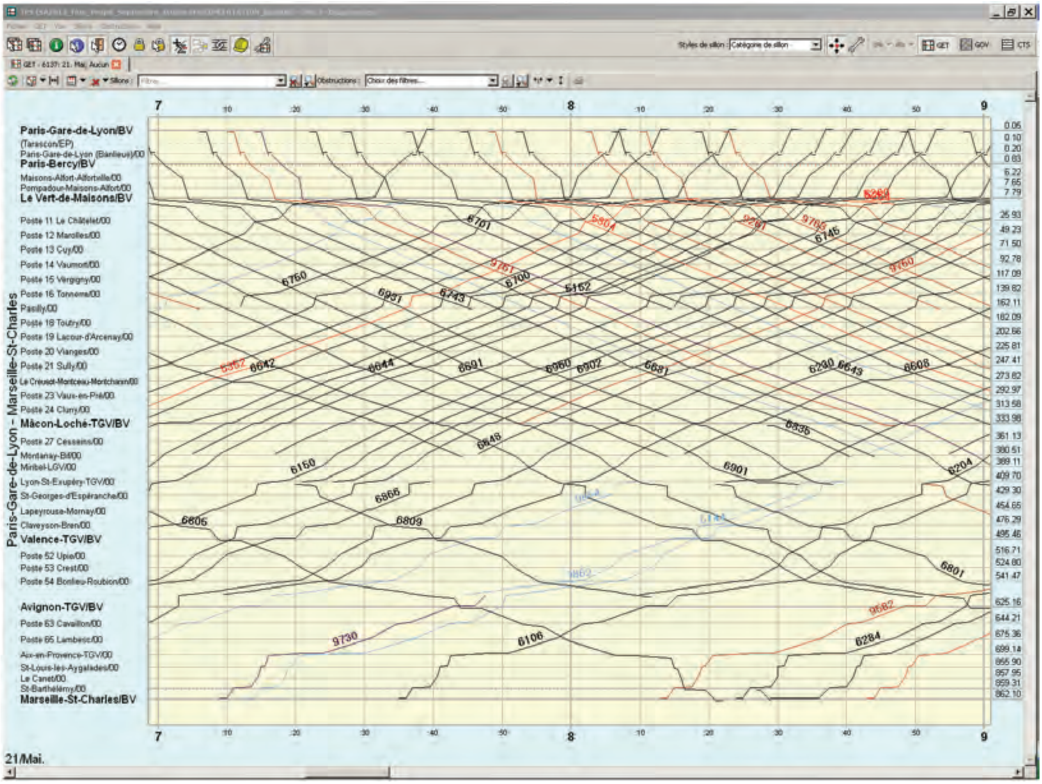


Figure 5.18: Screen shot from the timetabling tool TPS at SNCF showing the non-periodic graphical timetable for high speed TGV train services between Paris and Marseille in the time span 07:00 – 09:00 (Julien 2012).

Bahnhof/Haltestelle	Datum	Zeit	Dauer	Umst.	Produkte
		↑ Früher			
Marseille-St-Charles Paris Lyon	Mi, 21.11.12 Mi, 21.11.12	ab 05:36 an 08:53	3:17	0	TGV
Marseille-St-Charles Paris Lyon	Mi, 21.11.12 Mi, 21.11.12	ab 06:10 an 09:23	3:13	0	TGV
Marseille-St-Charles Paris Lyon	Mi, 21.11.12 Mi, 21.11.12	ab 06:14 an 09:53	3:39	1	TGV
Marseille-St-Charles Paris Lyon	Mi, 21.11.12 Mi, 21.11.12	ab 06:18 an 10:45	4:27	1	TGV
Marseille-St-Charles Paris Lyon	Mi, 21.11.12 Mi, 21.11.12	ab 07:36 an 10:53	3:17	0	TGV
Marseille-St-Charles Paris Lyon	Mi, 21.11.12 Mi, 21.11.12	ab 08:40 an 11:41	3:01	0	TGV
Marseille-St-Charles Paris Lyon	Mi, 21.11.12 Mi, 21.11.12	ab 09:36 an 12:53	3:17	0	TGV
Marseille-St-Charles Paris Lyon	Mi, 21.11.12 Mi, 21.11.12	ab 10:36 an 13:44	3:08	0	TGV
Marseille-St-Charles Paris Lyon	Mi, 21.11.12 Mi, 21.11.12	ab 11:35 an 14:56	3:21	0	TGV

Bahnhof/Haltestelle	Datum	Zeit	Dauer	Umst.	Produkte
		↑ Früher			
Lyon Part Dieu Paris Lyon	Mi, 21.11.12 Mi, 21.11.12	ab 06:04 an 08:13	2:09	0	TGV
Lyon Part Dieu Paris Lyon	Mi, 21.11.12 Mi, 21.11.12	ab 06:36 an 08:33	1:57	0	TGV
Lyon Part Dieu Paris Lyon	Mi, 21.11.12 Mi, 21.11.12	ab 06:52 an 08:49	1:57	0	TGV
Lyon Part Dieu Paris Lyon	Mi, 21.11.12 Mi, 21.11.12	ab 07:04 an 09:03	1:59	0	TGV
Lyon Part Dieu Paris Lyon	Mi, 21.11.12 Mi, 21.11.12	ab 07:36 an 09:33	1:57	0	TGV
Lyon Part Dieu Paris Lyon	Mi, 21.11.12 Mi, 21.11.12	ab 08:04 an 10:15	2:11	0	TGV
Lyon Part Dieu Paris Lyon	Mi, 21.11.12 Mi, 21.11.12	ab 09:04 an 11:03	1:59	0	TGV
Lyon Part Dieu Paris Lyon	Mi, 21.11.12 Mi, 21.11.12	ab 10:04 an 12:07	2:03	0	TGV
Lyon Part Dieu Paris Lyon	Mi, 21.11.12 Mi, 21.11.12	ab 11:04 an 13:03	1:59	0	TGV
Lyon Part Dieu Paris Lyon	Mi, 21.11.12 Mi, 21.11.12	ab 11:36 an 13:33	1:57	0	TGV
Lyon Part Dieu Paris Lyon	Mi, 21.11.12 Mi, 21.11.12	ab 13:04 an 15:03	1:59	0	TGV
Lyon Part Dieu Paris Lyon	Mi, 21.11.12 Mi, 21.11.12	ab 14:04 an 16:07	2:03	0	TGV

Figure 5.19: Public timetables for high speed TGV train services between Marseille → Paris (left) and Lyon → Paris (right) (http://www.bahn.de/p/view/index.shtml (15.11.2012))

Figure 5.19 shows two examples of public timetables for TGV train services: To the left between Marseille and Paris and to the right between Lyon and Paris. When looking at the departure times for TGV trains at Marseille St-Charles station it becomes clear that the timetable consist of both repeating train patterns e.g. departure times 05:36, 07:36 and 9:36 with a travel time of 3 hours and 17 minutes. The remaining six train runs have unique departure and travel times. A similar picture appears when looking at the public timetable between Lyon and Paris. Here is a train pattern with departure times 07:04, 09:04, 11:04 and 13:04 with a travel time of 1 hour and 59 minutes. The remaining eight train runs are unique in regards to departure time and/or travel time.

Figure 5.20 shows the graphical timetable for the RER (Réseau Express Régional, in English: Regional Express Network) line D train services between the stations Orry-la-Ville-Coye via the centre of Paris and Melun in the time span between 17:00 and 19:00 on a Monday. This part of the railway network is clearly operated according to a symmetric periodic timetable.

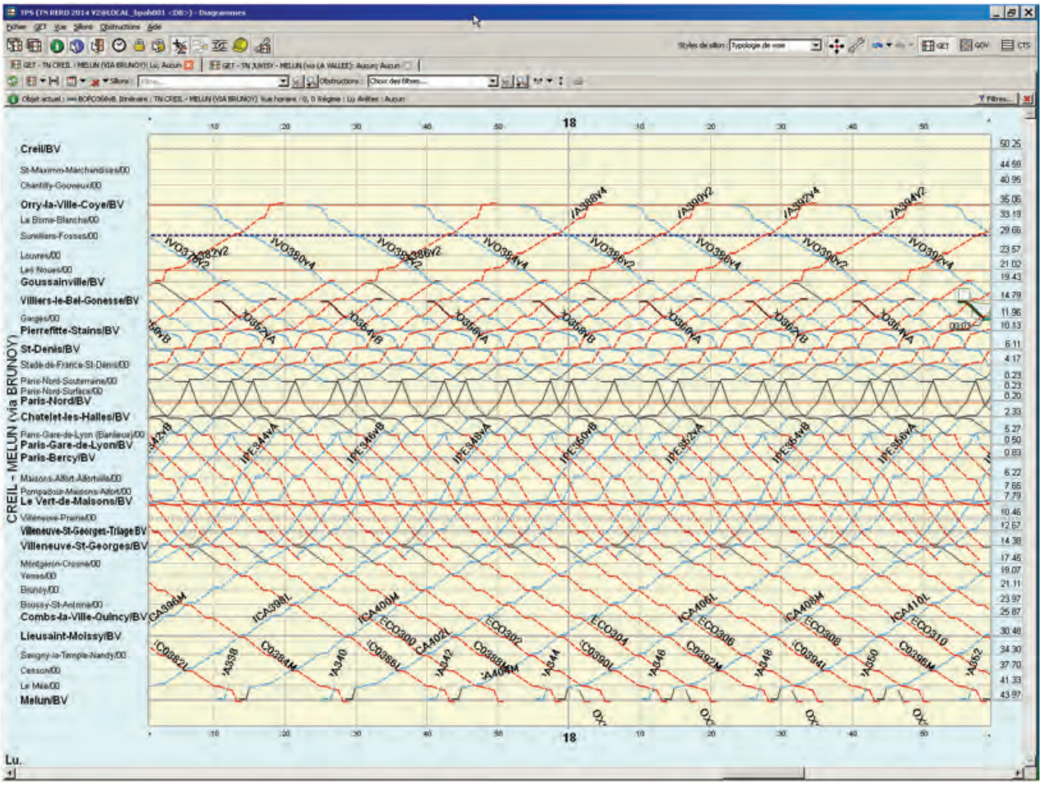


Figure 5.20: Screen shot from the timetabling tool TPS at SNCF showing the periodic graphical timetable for line D RER train services between Creil and Melun through Paris center between 17:00 – 19:00 (Julien 2012).

An overview of the RER train services in the region of Paris is given with a line map in Figure 5.21. RER Line D is marked green on the map. The graphical timetable from Figure 5.20 covers the RER line D from terminus Orry-la-Ville-Coye (D1) to Melun (D2). It does not cover the branch line to the terminus Malesherbes (D4). RER line D has a length of 197km, it services 59 stations and has a yearly ridership of 145 million journeys every year (http://en.wikipedia.org/wiki/RER_D (15.11.2012)).

Figure 5.21: Line map of the RER train services in the Paris region. RER line D is marked green on the map. (http://www.ratp.fr/ (5.11.2012))

5.8 Summary

In this chapter the thesis develops a simple generic timetable class analysis approach for railway timetables. A timetable analysis can create an overview of the share of different basic railway timetable classes in an overall railway network timetable. If there are preferences in regards to the attractiveness of different timetable classes, then this analysis can be an indicator of the overall timetable attractiveness for the investigated area in the investigated time window.

There are three basic analysis approach parameters: The geographical area of analysis, the time window of the investigation and the investigated train services.

When analyzing the overall timetable for a railway network one might find that it contains several timetable classes. There can be several reasons for this:

- Available financial resources (symmetric periodic timetables + IFIT have high costs levels)
- Market demands (big variations during a day and also geographical variations)
- Infrastructure layout/capacity (regions with single track, level of electrification and signaling system)
- Rolling stock fleet (number of locomotives, carriages and train sets and their flexible use)
- Train service facilities (location and capacity)
- Train staff (number of staff and their training)

The level timetable flexibility is reduced as the level of timetable structure increases. Non-periodic non-symmetric timetables have the highest level of flexibility and IFIT has the lowest. A high level of flexibility allows a higher level of influence from the parameters listed above.

One can analyze a given travel relation or investigate a smaller or greater part of a railway network, ranging from a single railway line section to the entire network. It is possible to only investigate the rush hours or the entire operational day. Within the analysis area it is possible to focus on a single train service, a group of train services or all present train services. All selected train services must be allocated to one or more timetable classes. Several analysis parameters are recommended for use:

- Number of train services
- Number of train runs
- Timetable application time interval in hours
- Number of train-km (both passenger and freight)
- Number of km (both freight-ton-km and passenger-km)

When undertaking a timetable class analysis one must be aware of that minor differences for each travel direction of an investigated train service can occur. Focus for a timetable class analysis must be on the overall timetable structure such as train service frequency and stopping pattern. Minor differences in travel time for each driving directions must be considered and accepted when e.g. looking for symmetry in a railway timetable class investigation.

This thesis presents examples of timetable class analysis for the following possible scenarios:

- **One railway line section and one train service – one timetable class**
  (Copenhagen suburban train service run by TOC DSB S-tog)

- **One railway line and one train service – several timetable classes**
  (A regional railway line section in the western part of Denmark serviced by a train service operated by TOC Arriva)

- **One railway line section and several train services – one timetable class**
  (DSB train services on a regional branch line on the island of Funen)

- **One railway line and several train services – several timetable classes**
  (Train services on the railway line Copenhagen central station to Copenhagen Airport)

- **One railway network – one timetable class**
  (A national symmetric periodic timetable is implemented on the Dutch railway network. This is exemplified for a main line and a regional branch line)

- **One railway network – several timetable classes**
  (The majority of the long distance train services in France are running according to a non-periodic non-symmetric timetable. High speed TGV train services are used as an example. On some regional train networks periodic timetables have been implemented. RER line D from the Paris region is used as a showcase)

6 The Danish railway timetabling process

The present Danish railway timetabling process is shaped by the liberalization of the European railway sector, driven by the European Union (EU). Therefore, a brief overview of the liberalization process generally in Europe and specifically in Denmark is given in section 6.1.

After the liberalization of the Danish railway sector, the number of railway timetable stakeholders has increased and with them different interests in the timetable. The list of stakeholders includes the Danish Transport Authority (DTA), passenger train operating companies (TOCs), freight TOCs and the infrastructure manager (IM) Rail Net Denmark (RND). In the end it is the IM RND that must prepare the yearly valid timetable, trying to fulfill as many requests from the TOCs as possible. The timetabling process at RND follows the relevant EU legislation and the guidelines given by Rail Net Europe (RNE). Section 6.2 gives an overview of the overall timetabling process in Denmark.

The DTA works with timetables when preparing documentation for tenders for public service railway traffic. These can be more or less detailed, depending on how much room for timetabling creativity is given to TOCs when making a bid. The DTA also uses timetables to investigate potential future improvements of the national railway network. This work can be based on a specific national timetable concept that is to be implemented, e.g. the Danish “Timeplanen” (in English: “The One Hour Plan”) which is an integrated fixed interval timetable (IFIT) with station hubs in the largest Danish cities with one hour travel time between them (DTA 2013). Or it can be analyzed which timetables are possible with a given improvement of the existing railway infrastructure, e.g. opening of the new high speed railway line between Copenhagen and Ringsted. The timetabling processes at the DTA are described in section 6.3.

Passenger and freight TOCs prepare timetables for their train services to make feasible applications for infrastructure capacity with the IM. The timetabling process within the largest Danish passenger TOC, DSB (Danish State Railways), is presented in section 6.4.

IM RND is responsible for preparing the national yearly timetable, based on the received capacity applications from both passenger and freight TOCs. RND is a member of the professional body RNE and therefore follows the RNE guidelines for the timetabling process. These again are founded on the EU railway timetabling legislation. Section 6.5 describes both the RNE and RND timetabling processes.

The presented timetabling processes are shortly discussed in section 6.6. Finally a summary of the chapter is given in section 6.7.

6.1 Liberalization of the European and Danish railway sector

With Directive 91/440 (EC 91/400), the European Union set the path for a liberalization of the European railway sector based on open access to state-owned railway infrastructure for train operating companies (TOCs) that wish to and are allowed to run trains on these railway lines. This demands a complete separation of train operating companies (TOCs) from infrastructure managers (IMs), which was ensured with directives 2001/12/EC (EU 2001/12), 2001/13/EC (EU 2001/13) and 2001/14/EC (EU 2001/14). These form the first European Railway Package. Competition between the various TOCs should create a more attractive market for railway customers – both passenger and freight – with regards to price and service levels. In 2004 the EU launched the second railway package. Directive 2004/51/EC ensured the opening of competition for both national and international railway freight traffic from January 2007 (EC 2004/51). Focus on the competiveness of railway freight traffic within the EU increased and in 2007 the European Commission decided that freight trains should be given a higher priority in the timetabling process (EC 2007).With the implementation of the third railway package in 2007, international railway passenger train services were opened to competition from January 2010 (EC 2007/58). Figure 6.3 gives an overview of these European Union railway directive milestones together with historic milestones of the liberalization of the Danish railway sector.

Britain was the European pioneer in railway liberalization. In 1987, the Adam Smith Institute published a model to reconstruct the British railway sector based on commercial contracts between various private stakeholders optimizing the benefits (Shaw 2000). A complete separation between TOCs and IM was established in 1994 and the IM, Railtrack plc, sub-contracted the infrastructure tasks to more than 2000 private companies. In 1996, Railtrack plc was listed on the stock market, but was taken off in 2002 due to bankruptcy. Shareholders had drained the company of its assets and the company had a debt of £7,000 m. Infrastructure assets were transferred to a new state-owned IM called Network Rail. The liberalization of the British railway sector has since been used as an example of how not to do things (Sameni 2012, Shaw 2000).

IBM Germany, in collaboration with Professor Christian Kirchner at the Humboldt University in Berlin, has been publishing the Rail Liberalization Index (LIB index) for the member countries of the EU plus Switzerland and Norway since 2002. This benchmarking index is based on the accessibility of the given country's railway market to a new TOC with regard to legislation and other more practical barriers. The LIB-index has been published for the years 2002, 2004, 2007 and 2011 (IBM 2011). Figure 6.1 shows the LIB-index for the year 2007 and Figure 6.2 for 2011. According to the Rail Liberalization Index, Denmark and Austria have improved from being countries in the "On schedule" group to being members of the exclusive "Advanced" group. This group contains the following countries: Austria, Denmark, Germany, the UK, Sweden and the Netherlands. Scandinavia is strongly represented with two out of the six countries, Denmark and Sweden. Sweden even holds the top rank in this benchmarking analysis.

The total separation between the IM, the TOCs and the DTA is the basis for the high score Denmark receives in the LIB-index for the year 2007. Advancement from the "On schedule" to the "Advanced" group was achieved by creating the Danish Rail Regulatory Body in 2010. With this step, Denmark fully lives up to EU legislation (IBM 2011).

Liberalization creates a railway sector which consists of several interest groups with common and/or conflicting interests – e.g. TOCs for freight and passenger train services requesting the same infrastructure capacity. There can be conflicting interests even within a single interest group – e.g. competing passenger TOCs wanting to run trains on the same railway line at the same time. A situation like this can make it very difficult to create a railway timetable, allocating the infrastructure capacity to the various TOCs, in a way which is satisfactory for all TOCs.

A national railway timetable has all interest groups in the railway sector as stakeholders. European Union legislation gives the IM responsibility for creating a feasible and acceptable timetable (EU 2001/14). This is not necessarily the case in other parts of the world, where both private and public railway companies own and operate both infrastructure and rolling stock and develop their own timetables, e.g. in the USA (private companies such as Union Pacific) and China (national railway operator China Railways under the Chinese Ministry of Railways).

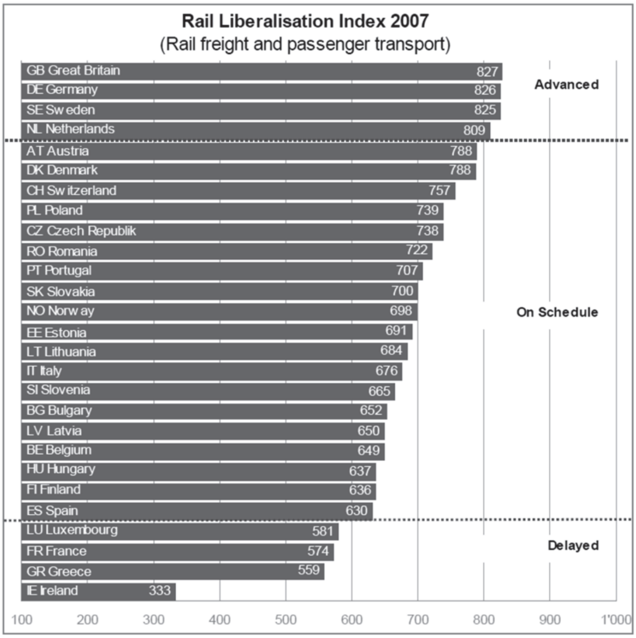


Figure 6.1: Rail Liberalization Index 2007 (IBM 2011)

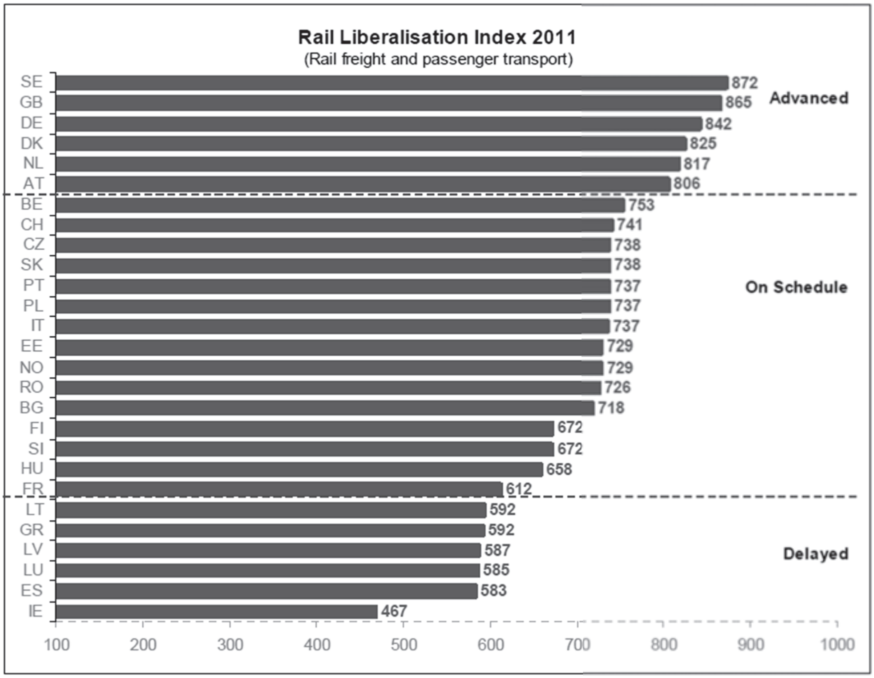


Figure 6.2: Rail Liberalization Index 2011 (IBM 2011)

Each TOC will have individual wishes for the national timetable based on specific boundary conditions, such as railway traffic contracts (e.g. with governments or traffic authorities) and availability of rolling stock and train crews. Potential conflicting interests can make it very difficult for the IM to create a timetable that satisfies all stakeholders.

When creating the yearly timetable several objectives must therefore be considered and weighted. This makes the timetabling process very complicated (Ceder 2007). If a mathematical approach is taken by using an operations research methodology the picture is the same. A multi criteria objective function must be used which makes the used algorithms/heuristics much more complicated and makes it more difficult to find the optimal solution (Chang et al 2000, Kwan & Mistry 2003).

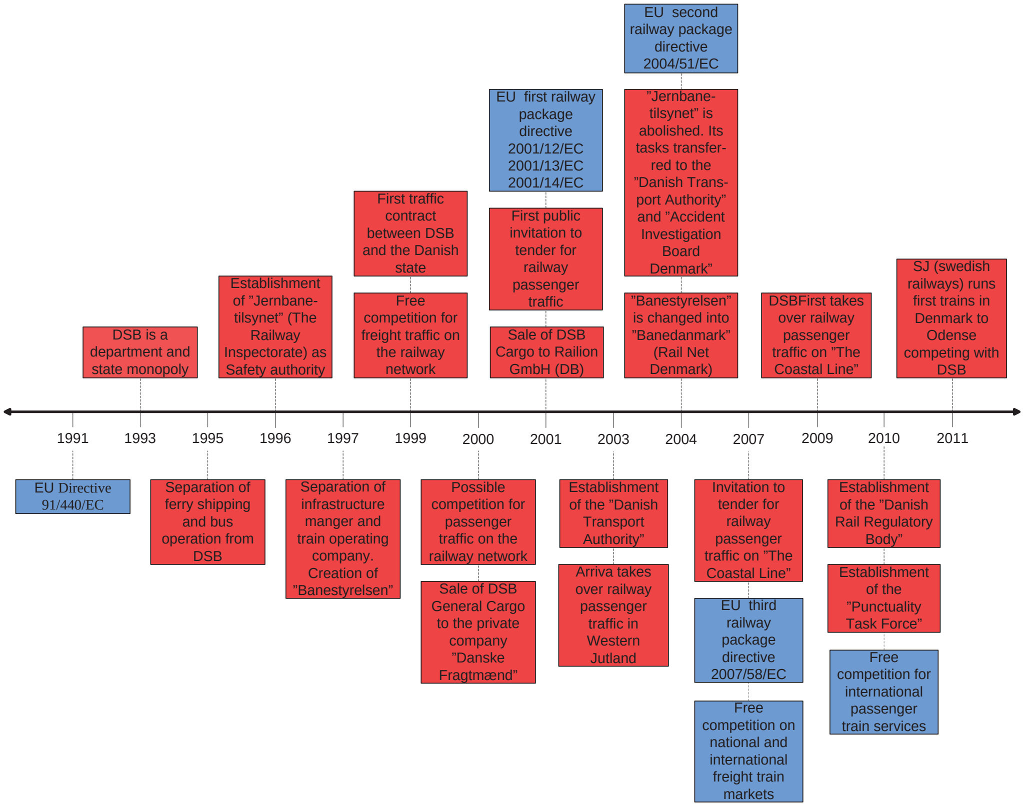


Figure 6.3: Timeline of the liberalization of the Danish railway sector (based on BCG2009, Schittenhelm & Landex 2012). Text boxes with red fill are Danish milestones and text boxes with a blue fill are EU milestones

The liberalization of the Danish railway sector started in 1997, when the Danish State Railways (DSB) was divided into an infrastructure manager and authority part, called "Banestyrelsen", and a freight and passenger TOC part, which retained the name DSB. Already in 1996 "The railway inspectorate" was founded as the national railway safety authority. Until know these matters had been taken care of internally in DSB. During 1999, the Danish railway freight market was completely liberalized. The national railway passenger traffic market was opened to free competition in the following year, 2000. In 2001, DSB sold its non-profitable railway freight division to Deutsche Bahn's daughter company "Railion GmbH" – today's "DB Schenker Rail Scandinavia" (BCG 2009, Schittenhelm & Landex 2012).

This was the same year where the first public invitation to tender for railway passenger traffic took place in Denmark. The contract was won by the British TOC Arriva, now owned by Deutsche Bahn (DB), and train operations started in 2003. Train services covered regional railway lines in the western and central parts of the Danish mainland, Jutland (BCG 2009).
During 2003, "Banestyrelsen" was divided into a purely IM part called "Banedanmark" (in English Rail Net Denmark) and an authority part called "Trafikstyrelsen" (in English: The Danish Transport Authority). In 2004 the tasks of The Railway Inspectorate were taken over by the DTA and the Accident Investigation Board Denmark (BCG 2009, http://www.bane.dk/visArtikel.asp?artikelID=256 (21.09.2012)).

The second public invitation to tender for railway passenger traffic was sent out in 2007. The TOC DSB First, an established collaboration company by DSB and the British TOC First Group took over passenger railway traffic on the Coastal Line (Elsinore - Copenhagen) and the Øresund Line (Copenhagen – Copenhagen Airport - Sweden) in 2009 (BCG 2009).

To live up to EU legislation the "Danish Rail Regulatory Body" was formed in 2010. This forum consists of technical, financial and legal experts. In the same year the Danish Ministry of Transport set up a punctuality task force because punctuality levels for DSB First passenger train services on the Coastal and Øresund Line were unsatisfactory low. IM RND was given the coordinating role and therefore also got the chairmanship of the task force (BCG 2009).

In 2011 the Swedish TOC SJ (Statens Järnvägar, in English: Swedish State Railways) extended one train service in Denmark from Copenhagen to the third biggest city Odense. This service was in direct competition with the InterCity and InterCity-Express trains from the Danish TOC DSB but it was only one train per direction per day.

An overview of these recent Danish railway history milestones is given in Figure 6.3. Text boxes with a red filling are Danish milestones whereas boxes with blue filling are EU milestones.

6.2 The overall structure of the railway timetabling process in Denmark

The liberalization of the Danish railway sector has led to an overall structure of the Danish timetabling process as presented in Figure 6.4. The political decision makers define the overall goals for the Danish railway sector by allocating financial resources to the expansion, renewal and maintenance of the Danish railway infrastructure. This is to make wanted national timetable concepts, such as the "Timeplanen" (in English: The one hour plan), an IFIT, possible.

State owned TOCs, such as DSB, are given resources to buy or lease rolling stock and are paid to run public service traffic train services. In connection with tenders for public service railway traffic the politicians can allocate funds for buying or leasing new rolling stock to improve the future rail train services.

Tenders for public service traffic are prepared and decided by the DTA. When preparing the timetabling documents of a traffic tender, the DTA is collaborating closely with the IM RND. During the tendering phase and the operational time afterwards, when the public service traffic trains are running, there is cooperation between the DTA and the involved TOCs. Railway timetables can be adjusted and the DTA must ensure that the TOCs live up to the contractual obligations.

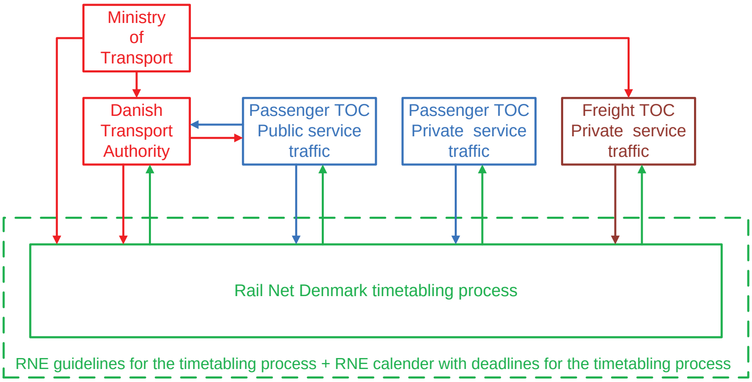


Figure 6.4: Schematic overview of the overall structure of the timetabling process in Denmark.

Not all railway traffic is subsidized by public funding and is then mostly operated to make profit. A different reason for this train traffic could be to move rolling stock from one place to another. Railway freight traffic has been completely liberalized and gets no public funding but Danish politicians have ensured that freight trains get a low level of subsidization due to their environmental friendliness. A few passenger train services in Denmark are not publicly subsidized. An example is the daily night train service between Copenhagen and the cities Amsterdam, Basel and Prague operated by TOC City Night Line, a subsidiary company of TOC Deutsche Bahn (DB). Furthermore is the InterCity-Express train traffic between Aarhus and Hamburg, operated in cooperation between DSB and DB, also private service traffic.

RND is a member of RNE and therefore the timetabling process is set up according to the RNE guide lines that again are based on EU legislation. IM RND is a completely state owned company and the available financial resources are defined by the politicians and come through the Ministry of Transport. The DTA is responsible for public service traffic tenders and therefore also the requested service level (timetable) for the tendered trains services. A close collaboration between DTA and RND about feasible timetables is necessary. Finally RND is collaborating with every TOC that applies for infrastructure capacity on the railway network, both public service and private service traffic. Based on the tight cooperation between IM RND and TOCs, RND prepare possible timetables for the future, taking into account the potential demand for future train paths by the TOCs. These timetables and the potential infrastructure capacity problems they reveal can be useful for political decision makers when allocating resources to the national railway sector.

6.3 The timetabling process at the national railway authority - The Danish Transport Authority

This section is based on an interview with members from the team “Public Transport” in The Danish Transport Authority (DTA). The DTA is a departmental organization under the Danish Ministry of Transport. The interview took place on the 23rd of May 2012 and the DTA was represented by senior consultant Jens W. Brix, senior consultant Claus Jørgensen, consultant Jacob Møldrup Petersen and senior consultant Benny Mølgaard Nielsen.

It was emphasized by the representatives that it is not the task of the DTA to prepare detailed timetables for actual railway traffic. As part of their project work, they prepare timetable examples for planning purposes. Timetable concepts can be tested and if approved, they form the basic structure in a timetable example. A given timetable example can then later be developed into a full scale production timetable for the affected part of the Danish railway network.

No formal process exists within the DTA when preparing timetable examples for a given project. Each project is unique with its own milestones and deadlines and therefore the timetabling process is adapted to every new project. Figure 6.5 gives a simplified overview of the basic public transport planning project process at the DTA. Throughout the project process an ongoing collaboration with The Ministry of Transport takes place. This is to ensure that potentially changing political expectations and demands during the project process are met by the authority. A recent example for application of this process is the investigation of extending the Copenhagen S-train services to Roskilde and Elsinore.

To perform the analysis of consequences the used timetable examples must have a high level of detail. Train running times are calculated in the software tool TPS (Timetable Planning System) (Kaas & Goossmann 2004, Barber et al 2007), where data for existing railway infrastructure is provided by RND and rolling stock data are made available from the relevant TOCs. Timetable examples are rarely prepared in TPS, instead this is done in a spread sheet or simply by making a freehand drawing.

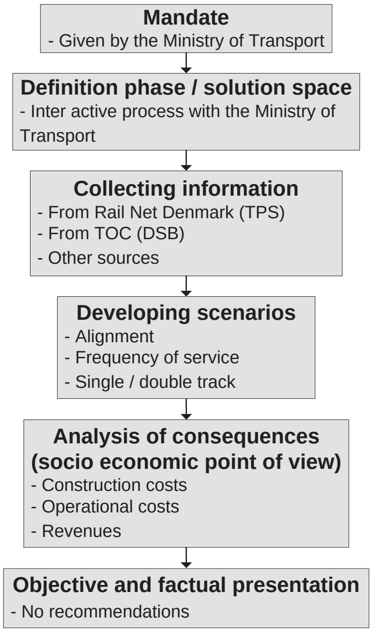


Figure 6.5: Planning public transport project process diagram for The Danish Transport Authority

From the detailed timetable examples and from actual or estimated passenger numbers/freight volumes, it is possible to calculate the needed capacity of trains and thereby the numbers of rolling stock and necessary train staff. With this information the analysis of socio-economic consequences can be made and presented for The Ministry of Transport.
The public transport team works with two main groups of projects that involve railway timetables:

- The National Public Traffic Plan
- Railway traffic tenders

These two project groups are described in the following two sections.

6.3.1 The National Public Traffic Plan

This publication is prepared minimum every four years and was published for the first time in February 2009. The first plan was valid for the time period 2008-2018 (2009b). In February 2013 the second edition of the national public traffic plan was published. This is valid in the time period 2012-2027 (DTA 2013). Identified stakeholders such as Danish administrative regions, municipalities, traffic companies and RND were given the opportunity to give feedback to the DTA before both plans were published (DTA 2009b, DTA 2013).

Both plans give an overview of the public service train traffic which is supported financially by the Danish state and runs according to valid contracts between the DTA and the relevant TOCs. This is done by looking at the numbers of passenger and freight trains running in a given time span. Next an overview is presented of the development of numbers of train-kilometers, train journeys and passenger-kilometers from 1994 till now (DTA 2009b, DTA 2013).

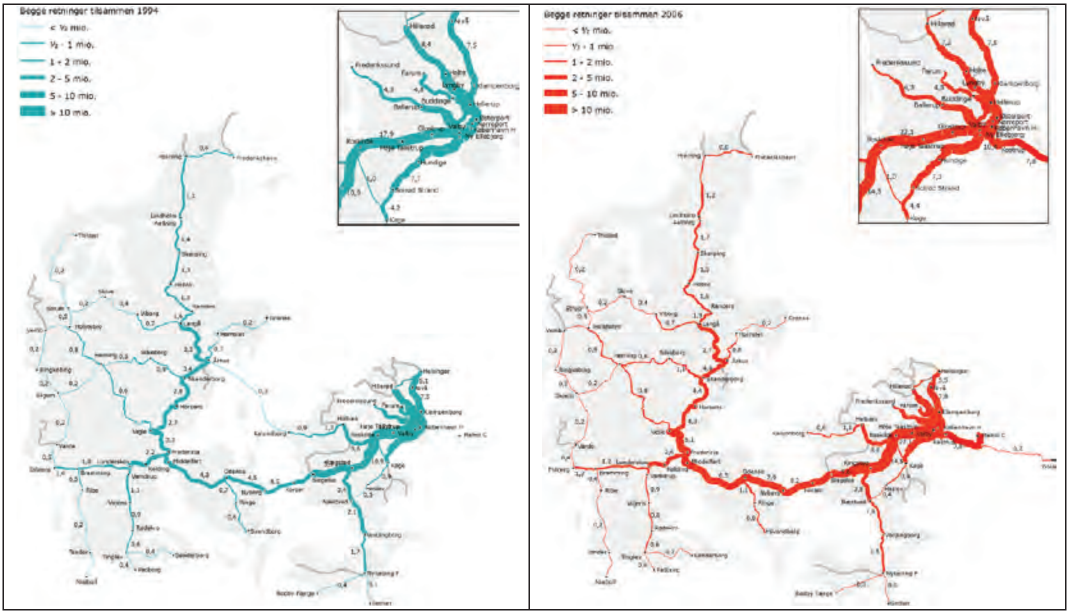


Figure 6.6: Number of train journeys [millions] for both travelling directions. In 1994 to the left and in 2006 to the right (DTA 2009b)

The first published plan gives a detailed presentation of numbers of journeys in the year 1994 and 2006 for both travelling directions in the entire railway network. See Figure 6.6. This shows a significant increase in railway journeys. The fixed links across The Great Belt (opened in 1997) and Oresund (opened in 2000) with the resulting reductions in travel times, as well as the opening of the Copenhagen metro in 2002, are the main reasons for this positive development. The same approach is used for the numbers of boarding and alighting passengers per station in the years 1994 and 2006. Increased numbers of train journeys give rise to a higher number of boarding and alighting passengers at stations. Odense station has e.g. doubled its numbers of passengers, this is caused by the fixed link over the Great Belt and the infrastructure and timetable improvements on the regional railway line between Odense and Svendborg (DTA 2009b).

Possible guidelines for the future tendering of public service train traffic are presented in the plan, to be used when the existing valid tender contracts between DTA and TOCs run out. The major part of the public service traffic has to be renegotiated in the year 2014. This year the contracts with TOC DSB and DSB S-tog run out. Future service levels of public service train traffic depend on:

- The financial means set aside for it
- Political decisions about minimum service levels
- Available infrastructure capacity
- The compliance with valid public service traffic contracts

To estimate the need for future public train services the DTA has developed a traffic model with focus on socio-economic costs and benefits. This model takes into account the expected ticket revenue, operational costs and passengers' travel time consumption. All modeled factors are estimated and valued and in this way the consequences for society are evaluated (DTA 2009b, DTA 2013).

A disadvantage of the applied traffic model is that it only considers the railway and does not take into account that improvements in train traffic service levels can affect other modes of transportation e.g. busses. Furthermore, the model investigates one line section at a time and does not analyze the entire railway network as a whole. A socio-economic optimal train traffic service level is not necessarily equal to the in praxis most appropriate timetable e.g. with repeating timetable patterns (DTA 2009b, DTA 2013)

A detailed national railway timetable is not being presented as a result of the analyses made in The National Public Traffic Plan. What is being offered is an overview of recommended train traffic service levels on railway line section level. Both the number of trains running on a given line section per hour per direction and the socio-economic optimal stopping pattern for train services on the line section are presented. This should then be the basic input for the development of a national railway timetable.

The Danish network has been divided into railway sections and an overview of the present capacity consumption levels is given. This gives an indication of how many more trains potentially will be able to run on the network in the future. The national traffic plan must take into consideration that railway infrastructure capacity must also be available for commercially run freight trains, regional TOCs and commercially operated passenger trains (DTA 2009b). A detailed map of the capacity consumption levels for railway line sections and major stations on the Island of Zealand can be seen in Figure 6.7. Reduced capacity within a station, due to track layout and number of platform tracks, can often be a limiting factor for the railway lines to/from this station. The S-train railway line to Frederikssund and Frederikssund station is an example of this (DTA 2012).

The close connection between national and regional + local traffic planning is described in the plan. If public traffic is to become more attractive, a better coordination between the national railway traffic, financed by the Danish state, and the regional + local public traffic, financed by regions and municipalities, is necessary (DTA 2009b, DTA 2013).

The low production frequency of this plan is reason for ongoing changes in expectations and demands from the orderer: The Ministry of Transport. Therefore it becomes difficult to have a structured follow up and using experiences made from earlier published traffic plans. This can further be made difficult by internal and external changes such as new IT-structures and potentially new timetable planning rules used by RND in regards to e.g. running time supplements.

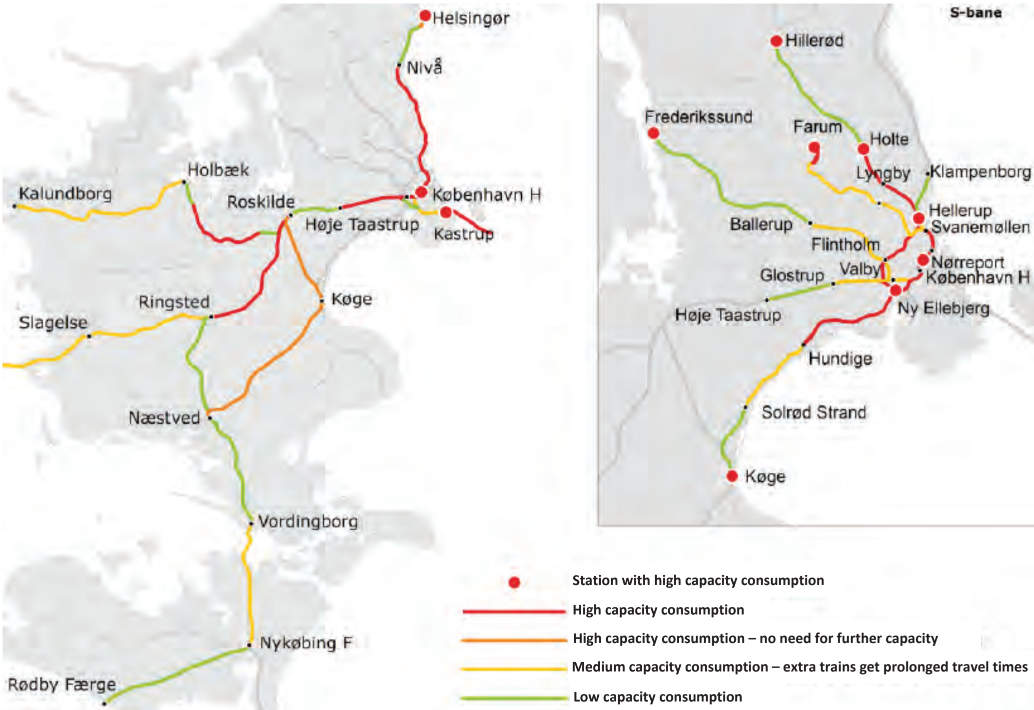


Figure 6.7: Map of capacity consumption levels for railway line sections and major stations on the island of Zealand. Regional and long distance network (left) and Copenhagen suburban trains (right) (DTA 2012)

When looking at the Danish planning traditions within the area of railway transportation, these are generally characterized by short time horizons and discount solutions in regards to investments in infrastructure and rolling stock. Only in the recent ten years, a new trend has started with political agreements covering longer time spans and including strategic goals for the railway sector, such as travel times below one hour between the biggest cities in Denmark (DMT 2009a, DMT 2009b).

6.3.2 Railway traffic tenders

No railway traffic tender project is alike. That said, it is noticeable that the current valid traffic tender contracts with TOC DSB and Arriva, and the first contract with Arriva are very similar. After having entered the first contract with Arriva it proved necessary to work out an additional contract to ensure the needed train service levels during rush hours. The increased traffic service level demands during rush hours where not described in detail in the tender documents, assuming that the bidding TOCs would run more trains during these time periods. To be able to give a lower price, Arriva did not plan with extra rush hour trains and simply extended the time span with day hour service levels to early morning and late evening hours. Rush hour trains are far more expensive to operate, since these train services increase the number of needed rolling stock. The additional rolling stock for extra rush hour services is not needed outside rush hours and thereby becomes an extra cost for the TOCs.

The DTA had to learn by doing how to create a successful process for railway traffic tenders. The experience with the first contract with Arriva lead to the development of the document called “Priknotat” (in English: Dot

Memorandum) which is appendix 2.1 to the main tender contract between The DTA and TOC Arriva (DTA 2009a).

Strækning (Railway line)	Ugedag (Week day)	Antal tog pr retning (Number of trains per direction)	Trafikering time (Traffic hour)																							
				4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	1	2
Århus – Viborg	Ma-Fr (Mon-Fri)	19			●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			
		9				○	○	○	○					○	○	○	○	○								
	Lø (Sat)	19			●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			
	Sø (Sun)	17					●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			
Viborg - Skive	Ma-Fr	19			●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			
	Lø	19			●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			
	Sø	17					●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			
Skive – Struer	Ma-Fr	16			●	●	●	●	●	●	●	●	●	●	●	●	●	●		●		●				
	Lø	13				●	●	●	●	●	●	●	●	●		●		●		●		●				
	Sø	11						●		●		●	●	●	●	●	●	●		●		●				
Thisted – Struer	Ma-Fr	12			●	●		●		●		●	●	●	●	●		●		●		●				
	Lø	9				●		●		●		●		●		●		●		●		●				
	Sø	8						●		●		●		●		●		●		●		●				
Struer - Skjern	Ma-Fr	16			●	●	●	●	●	●	●	●	●	●	●	●	●		●		●		●			
	Lø	10			●		●		●		●		●		●		●		●		●		●			
	Sø	9					●		●		●		●		●		●		●		●		●			
Århus H - Skanderborg	Ma-Fr	19			●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			
		13				●	●	●	●	●	●	●	●	●	●	●	●	●								
	Lø	19			●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			
		6						●	●	●	●	●	●													
	Sø	17					●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			
Skanderborg – Silkeborg - Herning	Ma-Fr	19			●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			
		13				□	□	□	□	□	□	□	□	□	□	□	□	□								
	Lø	19			●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			
	Sø	17					●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			

Figure 6.8: Train traffic service level table from the "Priknotat" (Dot memorandum). ●: Regional train with stop at all stations once per hour ○: Regional train with stop at all stations. Frequency should be as close as possible to 30 min □: Regional express train only with selected stops (DTA 2009a)

Figure 6.8 shows how the requested train service levels are presented in the tender document. The DTA must check if a feasible timetable exists that fulfills the train service level demands presented in the table shown in Figure 6.8. The second important part of the service level demands, is the connectivity between different cities. TOCs use line diagrams to document that they live up to these demands.

A negative experience was made in the following traffic tender process covering traffic in the Danish-Swedish Oresund region. In Denmark the railway lines between Elsinore – Copenhagen and Copenhagen – Copenhagen Airport - Swedish border were part of this tendering process. This time the applied philosophy was that the TOC should take ownership of the already prepared detailed timetable, but this did not happen. The prepared timetable had been approved by IM RND and should therefore be feasible but it turned out not to be the case. When trains from the TOC DSB-First started running from December 2009 the punctuality levels dropped drastically on these two tender railway lines. This experience convinced the DTA even more about the usefulness of the dot-memorandum approach when creating future timetables in connection with traffic tender processes. In this way the responsibility for the detailed timetabling process, and thereby the ownership of the timetable, is given over to the biding TOCs.

Train service demands presented in tender documents are based on passenger numbers in trains, number of alighting and boarding passengers at stations and separate political agreements that most likely dictate higher service levels than suggested by the DTA on selected railway line sections. Finally it is a basic demand that the timetable is as periodic/systematic as possible. If the service level demands require two trains per hour per driving direction, the trains should preferable run with an interval of 30 min. Characteristics of the infrastructure, rolling stock and the overall national timetable can make this impossible. This has led to a relaxation of this demand to a flexibility of fixed train intervals of ±10min.

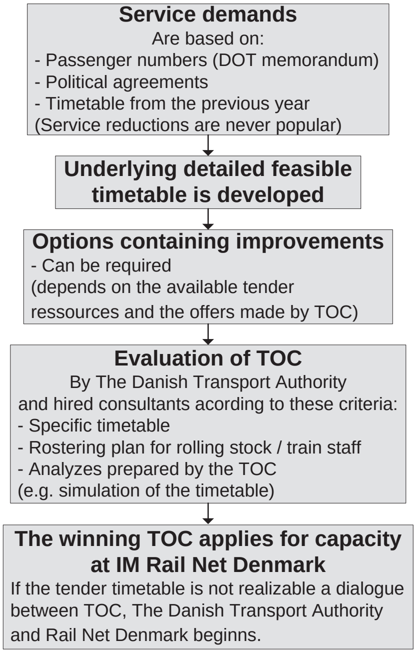


Figure 6.9: Process diagram for the railway traffic tender process at The Danish Transport Authority

In this thesis an attempt has been made to create a process diagram for a standard traffic tender process at the DTA. This is shown in Figure 6.9. Train service demands are based on registered passenger numbers in earlier years (leading to a train service level), existing political agreements and last year's timetable. If a reduction in service level is introduced on a railway line, this most often generates protests from local citizens and politicians.

The next step in the tendering process at the DTA is to ensure that biding TOCs can create a feasible timetable that fulfills the service demands presented in the tender documents. Therefore the DTA prepares a feasible timetable of its own. This timetable is generated in the timetabling software tool TPS. A detailed infrastructure model is provided by IM RND and rolling stock data are provided by the TOCs or the rolling stock production companies. The DTA only prepares the rush hour parts of the timetable, since these normally create the biggest difficulties for timetable planners due to the increased number of running trains.

Some invitations to public service train traffic tenders include options for traffic service level improvements. Here, the biding TOCs can give a price for implementing the wished improvements. Based on the price level in the made bids from TOCs and the political decided available tender financial resources, all or some of the options can be pulled in the final traffic tender contract between the DTA and the TOC. This is the third step in the tendering process at the DTA. See Figure 6.9.

The prepared bids by TOCs are evaluated by employees of the DTA and hired consultants. Consultants are needed due to the very limited timespan for tender bid evaluation and their valuable expertise within tendering processes and railway traffic. The bids are evaluated according to several evaluation criteria. The primary criteria are:

- Overall price of the bid by the TOC
- The detailed timetable prepared by the biding TOC
- Efficient rostering plans for rolling stock and train staff
- Initiatives taken by the biding TOC to prove the attractiveness of their bid e.g. a simulation analysis in regards to the robustness of the presented timetable

A winner is chosen and this TOC must follow the steps in the standard timetabling process at IM RND and apply for infrastructure capacity, together with all other TOCs. If the bid timetable cannot be implemented a dialogue begins between the involved parties: DTA, RND and TOC. If necessary the Ministry of Transport will be involved as well. It has never been a problem to realize the timetable proposed in the winning traffic tender bid.

6.4 The timetabling process at the largest Danish passenger train operator - DSB

The following description of the timetabling process at DSB is based on two presentations given by timetable project managers Emil Madsen and Lars Christian Krogsdam from the Department of Timetabling at DSB in connection with DTU student visits on the 14th of March 2010 and the 21st of September 2011.

A detailed overview of the basic timetabling process at DSB is given in Figure 6.10. There are five basic phases in the process:

1. Ideas for next year's timetable are collected amongst DSB employees
2. A project timetable is created
3. A detailed timetable covering train traffic for the entire timetable year is produced
4. Rostering plans for rolling stock are drawn up
5. Rostering plans for train staff and other necessary functions such as train cleaning, catering and maintenance are generated.

Each of these phases is described in Figure 6.10. Phase 1-4 takes place in the Department for Timetabling, whereas phase 5 takes place at the Department of Traffic Production. The main tool for preparing the detailed timetable is the timetabling tool TPS.

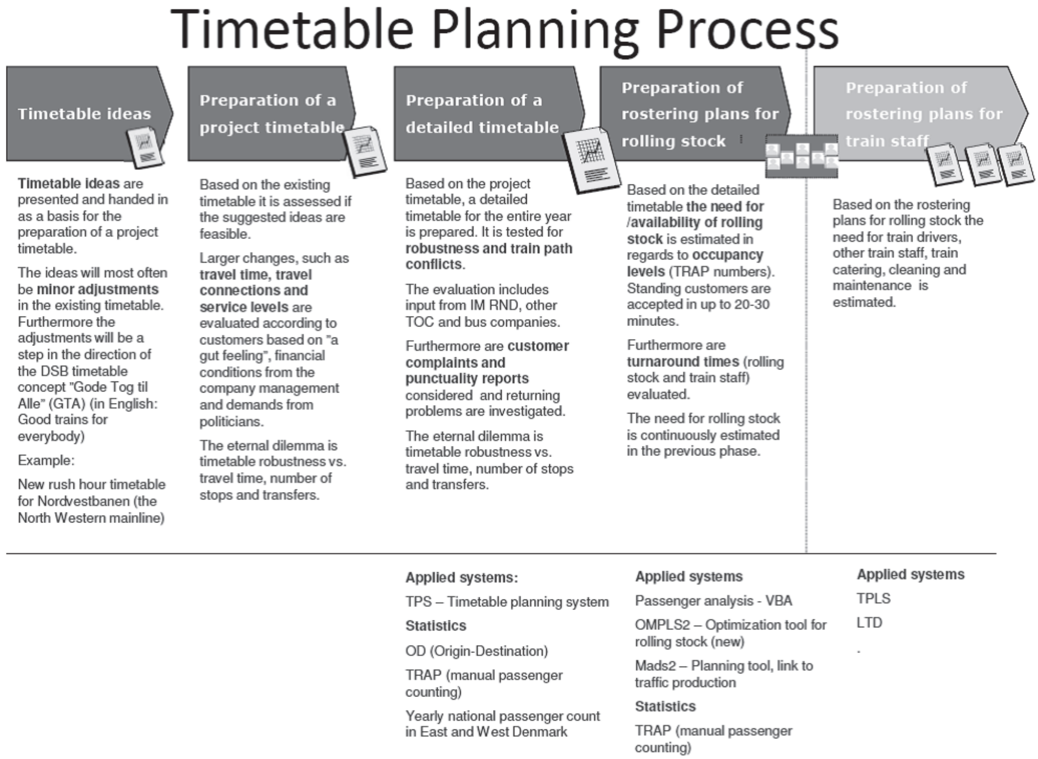


Figure 6.10: Overview of the basic timetable planning process at DSB (Madsen 2010)

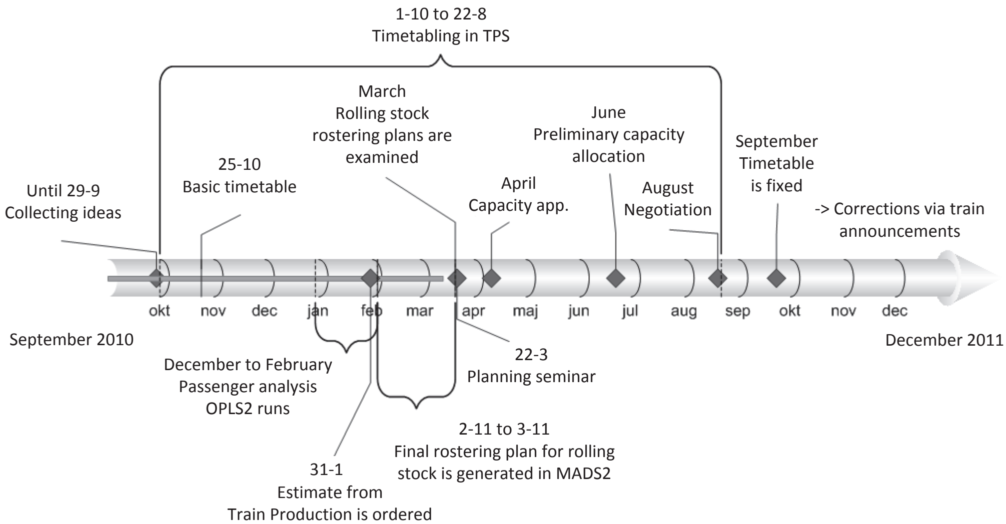


Figure 6.11: Timeline for the timetabling process at DSB for the timetable 2012 (K12) (Madsen 2010)

Rolling stock is a limited resource. TOC DSB only owns or leases a certain number of rolling stock units. Furthermore, one must consider the needed time for servicing the rolling stock every day e.g. cleaning and filling water tanks. Finally, rolling stock follows a very rigid maintenance scheme depending on the number of run kilometers. For allocation of rolling stock a new operations research based tool OMPLS2 is used. This is supplemented with the older manual tool MADS2. See section 3.6 for more details. If it is not possible to allocate rolling stock to each timetabled train run then it is necessary to go back and make adjustments to the proposed detailed timetable. This is an iterative process where adjustments to the timetable can be made several times, until rolling stock can be allocated to each scheduled train run.

A similar problem arises when allocating train staff to the timetabled train runs and their allocated rolling stock. See more in section 3.7. Allocating train staff to train runs generally creates fewer problems than allocating rolling stock. If a need arises to increase the number of DSB train staff or give employees new skills, it is easier to hire new people or let existing employees undergo further training than getting new rolling stock.

Figure 6.11 shows the detailed timeline with the most important milestones for the timetable 2012 (K12). Ideas for the timetable are collected in the Department of Timetabling until the end of September 2010. These ideas come from the entire DSB organization. Some of them are completely new thoughts, others are a reaction on made experiences with earlier timetables. The frame work for the future timetable is also received:

- Contractual obligations – train service levels (from DTA)
- Infrastructure – availability and condition (from RND)
- Rolling stock – availability and condition (internal)
- Economy – how many resources are available to DSB (internal)

At the big planning seminar, taking place during March, the plans are presented to a wider audience of DSB employees and both the detailed timetable and rolling stock rostering plan are finalized.

This is followed by submitting the application for infrastructure capacity with the IM RND. The deadline for capacity applications is given by the RND timetabling process. DSB must adapt its own timetabling process accordingly. In June 2011 IM RND sent out preliminary timetables to all applicant TOCs. DSB received a preliminary timetable only containing DSB train paths. The same applies to the other TOCs. DSB had time until August 2011 to consider this preliminary national timetable proposal from RND. In August 2011 IM RND invited all TOCs to a negotiation meeting where change requests and potentially resulting conflicts between timetabled train paths could be discussed. At the same time a quality control was made of the finalized timetable involving both TOCs and IM. After this meeting RND made the final capacity allocation during September 2011. With this step the timetable process started all over at DSB. During September 2011 new ideas were collected for the timetable 2013 and an updated frame work for the timetable was received. In December 2011 the timetable for the year 2012 was put into service.

6.5 The timetabling process at the Danish infrastructure manager Rail Net Denmark

Rail Net Denmark (RND) is a member of the organization Rail Net Europe (RNE). This is a professional body of European railway IMs, whose main goal is to improve international passenger and freight railway operations – with focus on freight traffic. One way to achieve this is by developing and implementing a

common timetabling process with all members (RNE 2005, RNE 2006, http://www.rne.eu/timetabling.html (09.21.2012), Schittenhelm & Richter 2009).
After becoming a member of RNE, RND had to adjust its own timetabling process to adapt it to the general timetabling process developed by RNE. In the following two sections the general RNE and adjusted RND timetabling process are presented.

6.5.1 RNE timetabling process

One of the most important roles of the professional body RNE is to coordinate railway timetabling in Europe. A detailed process calendar showing deadlines for TOCs (applicant activities) and IMs (Infrastructure Management activities) is prepared. Figure 6.12 shows a screenshot from the RNE online process calendar. This process calendar shows all railway timetable relevant deadlines from the year 2010 up to the beginning of 2014 (http://www.rne.eu/process-calendar.html (03.12.2012)). All members of RNE must follow these deadlines in their individual timetabling processes.

Figure 6.12: Screenshot from the RNE online process calendar (http://www.rne.eu/process-calendar.html (03.12.2012))

From conceiving the first thoughts on a future timetable to the day of implementation a time span of 48 months will pass according to the general RNE timetabling process, as shown in Figure 6.13. The timetable becomes effective on the Sunday following the 2nd Saturday in December of the year before the actual timetable year (RNE 2006). A common European date for timetable implementation makes it easier to plan international border crossing train paths.

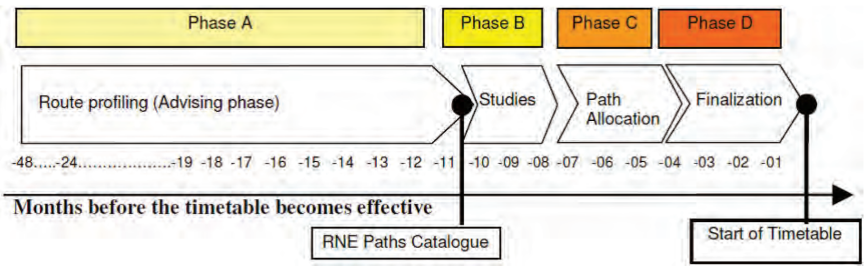


Figure 6.13: The RNE general timetabling process from (RNE 2005)

A short description of the phases A to D, indicated in Figure 6.13, follows:

Phase A - Corridor profiling and TOC advising (time X-48 → X-12):
In the first half of phase A, the IMs need to get an overview of future available infrastructure capacity and wishes for capacity allocation from TOCs. IMs gather strategic long term information which may influence

railway traffic and infrastructure capacity. This could be changes in traffic pattern by TOCs and major maintenance works on the infrastructure (RNE 2005, Schittenhelm & Richter 2009).

It is important for IMs to try and harmonize corridor capacity profiles by e.g. extending bottlenecks or minimizing constraints for corridors. An example of a capacity profile is shown in Figure 6.14. It is less complicated to create a timetable for a corridor with a harmonized capacity profile than without (RNE 2005, RNE 2006, Schittenhelm & Richter 2009).

7																								
6							F						F					F						
5							F	F	F		F	F	F					F	F	F				
4							L	L	L		F	F	F				F	L	L	L	F			
3						F	L	L	L	L	L	F	L		L	F	L	L	L	L	F	F		
2					F	L	R	R	R	R	R	R	R		R	R	R	R	R	R	L	F	F	
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Heure	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23

Figure 6.14: RNE capacity profile for a given corridor section. F = Freight trains, R = Fast trains (Rapide), L = Slow trains (Lent), Blue = Infrastructure maintenance (RNE 2005, RNE 2006)

Figure 6.14 shows an example of communicating consumption of infrastructure capacity. Each column is one hour (0-23) and each row is a standard train path (1-7). The latter can be allocated to either a category of train service or to maintenance. Green colored train paths are allocated for freight trains, red for fast and pink for slow passenger trains. Blue areas are capacity restrictions due to maintenance works. Train paths marked with a letter are in use according to preliminary path requests. Illustrating use of capacity in this way gives an intuitive understanding of the degree of capacity consumption for both TOCs and IMs (RNE 2005, RNE 2006, Schittenhelm & Richter 2009).

In the annual Network Statement from Rail Net Denmark, an overview of the capacity bottlenecks, according to the UIC (International Union of Railways / Union Internationale des Chemins de fer) 406 methodology, and officially declared congested railway line sections in the Danish railway network is given. Figure 6.15 shows this overview presented in the Network Statement valid for the year 2013. Railway lines marked with yellow are officially declared congested infrastructure. This is done according to valid EU railway legislation. Red lines have a level of capacity consumption which is higher than the recommended level for peak hours in then UIC 406 leaflet. Railway lines that are close to the recommended maximum capacity consumption levels for peak hours are colored green. This is the only way in which RND communicates capacity with other railway stakeholders and it does not resemble the RNE capacity profile example in Figure 6.14.

In the second half of phase A, IMs may help any TOC to define their needs in form of train paths. Simultaneously with this, the creation of international RNE catalogue train paths takes place. This is done by connecting standard national freight paths at national borders (RNE 2005, Schittenhelm & Richter 2009).

Phase B - Feasibility Studies (time X-18 → X-9):
Feasibility studies can be requested by TOCs to give an insight into how wanted types of train paths can fit into a future timetable. The results give TOCs a better foundation for making decisions in regards to path requests. Requested studies will be carried out by IMs or be based on catalogue train paths or prepared schemes from phase A (RNE 2005).

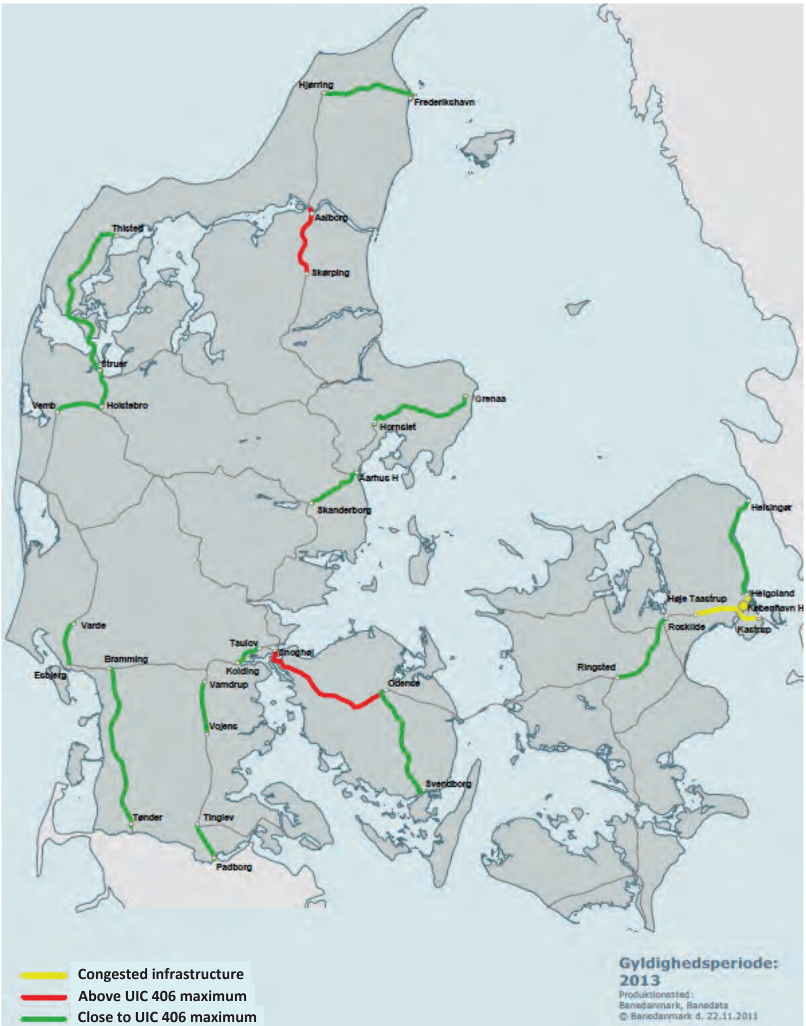


Figure 6.15: Overview of capacity bottlenecks and officially declared congested infrastructure in the Network Statement 2013 by Rail Net Denmark (RND 2012a)

Phase C - Detailed Path Allocation for Yearly National Timetable (time X-8 → X-5):

Deadline for path requests delivered to an IM is the 2nd Monday in April before implementation of the new yearly timetable. RNE organizes meetings for all involved IMs to ensure coordination of international path requests before allocating capacity. At these meetings IMs can gather national path orders for international traffic and make sure they are harmonized for international train paths at national borders (RNE 2005, RNE 2006, Schittenhelm & Richter 2009).

IMs publicize new timetables at X-6 / X-5. A document, containing all international border crossing train paths; is prepared and send to all relevant IMs. This makes it possible to check train times at borders (RNE 2005, RNE 2006, Schittenhelm & Richter 2009).

Phase D - Path allocation within the remaining capacity (time X-4 → X+12):
Requests for train paths after X-8 are treated on the basis of the remaining available capacity. This includes both already ordered train paths and planned infrastructure possessions caused by maintenance and/or renewal work. Train paths can be allocated by using the RNE international train path catalogue, national train paths or available capacity (RNE 2005, RNE 2006, Schittenhelm & Richter 2009).

6.5.2 Timetabling process for the national yearly timetable

Rail Net Denmark has adjusted its timetabling process to the RNE guidelines. A process chart of the valid timetabling process for the yearly national timetable is shown in Figure 6.16.

In Figure 6.16 each horizontal lane represents an involved administrative team within the Rail Net Denmark Traffic Operations organization. Boxes represent and in short describe the involvement from a team in the timetabling process. Involvement can be giving input, produce output or quality control.

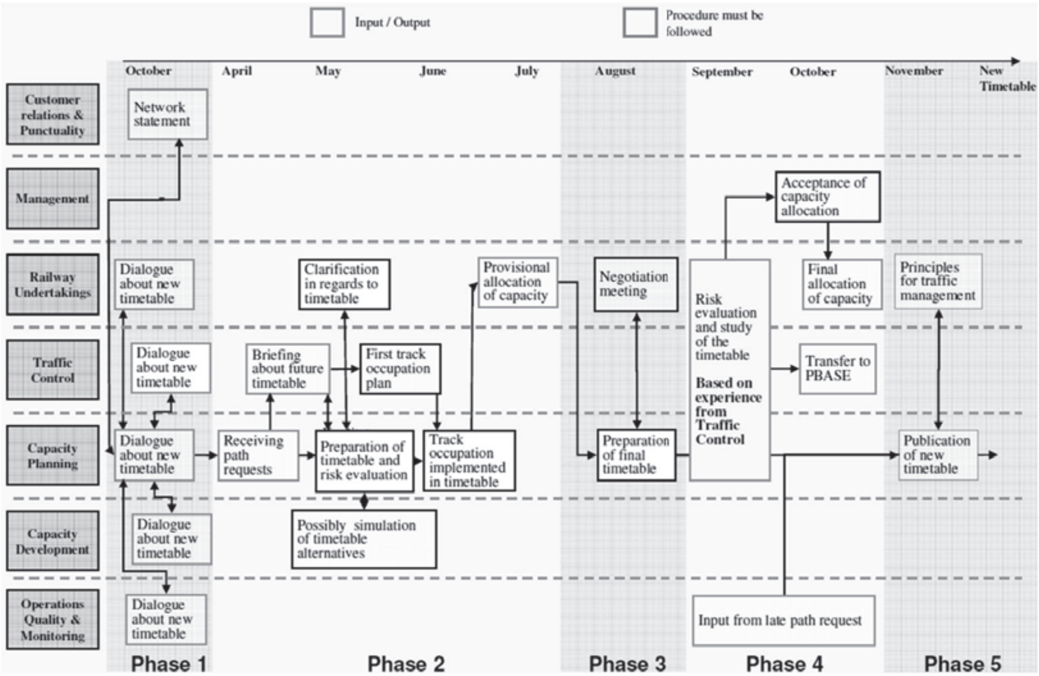


Figure 6.16: Timetabling process chart for the yearly timetable at Rail Net Denmark from (Toylsbjerg 2009).

Rail Net Denmark is communicating with other timetable stakeholders during phase 1, from October to April. Timetable train path applications are received from TOCs and a draft version of a feasible timetable is made and evaluated in phase 2 - between April and July. In Phase 3 the primary goal is to achieve a compromise between all TOCs by hosting one or several negotiation meetings, as required. The result is a finalized timetable. This happens around August. During phase 4 the timetable is evaluated in regards to robustness. Two approaches are applied: Simulation of critical parts of the timetable using the railway traffic simulation tool RailSys and utilization of local knowledge and experiences made at the traffic control centers. The timetable is approved by the management level of Rail Net Denmark during October. The timetable is made operational in phase 5 lasting from November into December (Schittenhelm & Richter 2009).

The fundamental timetable class used in Denmark is a symmetric periodic timetable with a periodicity interval of one hour. It is developing towards an IFIT for the fastest passenger trains. Today there are some structural changes in connection with rush hours, where the timetable becomes non-symmetric due to primary and secondary travel directions. These changes entail higher/lower frequencies of train services, new and cancelled train services and partial cancellations of train services to optimize the extent of train services on the network. During late evening/night time/early morning periods the timetable can become non-periodic (Schittenhelm & Richter 2009).

6.6 Discussion of the presented timetabling processes

The railway end customers, passengers and freight shippers, are not directly included in any of the presented timetabling processes. Their interests must be taken care of by the TOCs and the DTA. This can be seen as a weakness but the timetabling process must follow EU and Danish national legislation and this does not include direct involvement of customers. The liberalization of the Danish railway sector should ensure that customer preferences are taken more into consideration in the timetabling process. If railway customers were directly involved in the timetabling process, a common agreement about a timetable would probably never be reached due to the many different interests.

It is surprising that the DTA does not follow a formal timetabling process when preparing timetable examples for public service traffic tender documents or the national traffic plan. Since most of the interviewed employees from DTA have a railway background it is assumed that they follow a traditional approach as presented for e.g. the TOC DSB. Figure 6.17 shows a simplified process diagram for a timetabling process. The DTA must focus on all three steps since they take a socio-economic point of view when preparing their timetable examples and must include all costs.

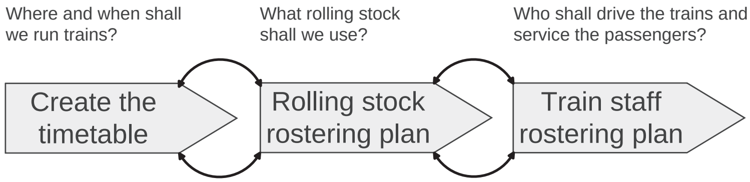


Figure 6.17: Simplified process diagram for a TOC timetabling process (Krogsdam 2011)

There are no formal learning loops in the project processes within the DTA that have been presented by this thesis. The DTA relies on the memory of its employees so that they use their made experiences when starting on a new project. This can be a weakness in their work.

No surprises are found in the DSB timetabling process. The process follows the basic steps as seen in Figure 6.17. Also here, there are no formally build in learning loops in the overall process. Informally there are two learning loops present. First in form of the collecting of ideas from DSB employees that can be based on practical experience made with an older timetable. Secondly, in form of the big planning seminar, where a wide audience can contribute to the finalization of a given timetable and the attached rostering plans. Informal learning loops do not have the same power as formal ones and therefore DSB must be careful to make sure to use the input from the company’s employees.

Surprisingly the RNE general timetabling process has no build in formal learning loop(s) or in no other way formally ensures the use of experience from earlier timetables. See Figure 6.13. The responsibility for learning from and using experience from older timetables is given to each IM from RNE. Systematic follow

-up on timetable performance is not an issue dealt with in the RNE general timetabling process (Haltner 2009).

Figure 6.18 shows a simplified process diagram for a standard IM timetabling process. The described process at RND follows this model and contains therefore no surprises. After receiving the train path request from the TOCs a preliminary timetable is prepared. This can be is an iterative process due to the necessary quality control of the preliminary timetable. Quality control can e.g. be a robustness analysis carried out with a simulation tool like RailSys. This is followed by one or more negotiation meetings between IMs and TOCs. Meetings are held until a compromise is reached. The final timetable must also pass a quality control before it can be implemented. If this is not the case a revision of the timetable is necessary, which can lead to new negotiation meetings. The timetabling process diagram for RND shown in Figure 6.16 uses single headed or double headed arrows between text boxes to indicate non-iterative and iterative process steps.

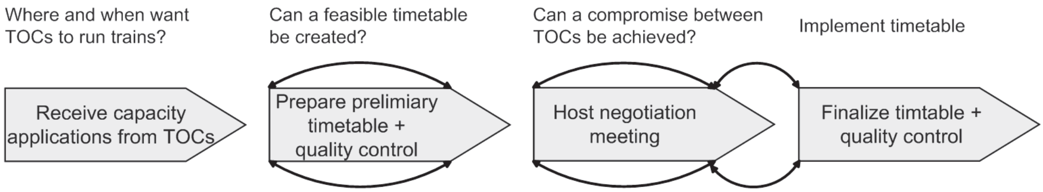


Figure 6.18: Simplified process diagram for an IM timetabling process (inspired by Krogsdam 2011)

The timetabling process for the yearly national timetable at Rail Net Denmark has a formal build in learning loop. The use of experience from both traffic control staff and members of the “Operations Quality & Monitoring” team is integrated in the early dialogue phase. See Figure 6.16 (phase 1). This is an advantage in the process but there has not been allocated enough time to evaluate and follow-up on the input from this year to year learning loop. Besides this feature there are no other formal and/or systematic build in learning loops. Improved learning loop processes are necessary in the overall timetabling process. See section 8.2.

To know which learning loop processes to implement, where to fit them into the timetabling process and how to utilize them to their fullest, it is necessary to have a common understanding of timetable attractiveness. Such a common understanding is created in chapter 7, in form of a common Danish list of prioritized timetable evaluation and optimization criteria is created.

6.7 Summary

The liberalization of the European railway sector through EU legislation has had an impact on the timetabling processes for TOCs and IMs. This is also the case in Denmark. This chapter starts by giving a brief historical overview of the liberalization process in Europe followed by a zoom-in on the liberalization of the Danish railway sector.

The overall structure of the present Danish railway timetabling process has been marked by the European liberalization process. A brief description is given of the overall structure in the Danish timetabling process and the most important stakeholders are introduced.

The timetabling processes at three of the most important railway timetable stakeholders in Denmark: The Danish Transport Authority, the largest passenger train operating company DSB and the state owned infrastructure manager Rail Net Denmark are then presented. These presentations are based on interviews with timetabling employees from these organizations. It can be noted that the railway customers, passengers and freight shippers, are not directly involved in the processes.

It becomes clear that the DTA has no formal process for preparing timetable examples for tender documentation or the national traffic plan. This thesis creates a process diagram for projects that can entail the creation of timetable examples at the DTA based on the interview. This project process does not include formal learning loops in regards to timetables. It is therefore up to the employees of the DTA to improve the process from project to project on their own.

The timetabling process at DSB follows a basic scheme and contains no surprises. Again there are no formal build in learning loops. Informal learning loops are present in the form of the possibility of DSB employees to send in ideas for future timetables; and in form of a big company planning seminar, were a broad audience can come with input before the timetable is finalized.

IM RND is a member of the professional body of European IMs called “Rail Net Europe” (RNE). RNE has prepared a set of general guidelines for the timetabling process which all of its members must implement. Focus is on a rigid time schedule for the entire tabling process. A detailed RNE process calendar ensures this focus. It is for each IM to ensure to use the made experiences from earlier timetables in the planning process for creating new ones. Therefore there are no formal learning loops in the RNE timetabling process.

The RND timetabling process for the yearly timetable contains no surprises. It follows the standard scheme for IM timetabling processes. In the first phase of the process, a dialogue takes place between railway timetable stakeholders. This is the only formal learning loop in the timetabling process. Stakeholders can exchange views on experiences made with older timetables. This is an advantage compared to the other presented timetable planning processes. Unfortunately there is not reserved enough time for an in-depth evaluation of earlier timetables. To improve future learning loops in a timetabling process it is recommendable to have a common understanding of timetable attractiveness.

7 Creating a common list of Danish railway timetable evaluation and optimization criteria

What is an attractive timetable? This depends on the given circumstances surrounding the timetable construction process. What is considered being an attractive timetable in a monopolized state owned railway sector is not necessarily an attractive timetable for a completely liberalized railway sector.

It was decided by the member states of the European Union to liberalize their railway sectors and this liberalization process is currently still ongoing (Knieps & Zenhäusern 2011). Some member states have made more progress and reached higher levels of liberalization than others. Denmark is in the group of the most advanced countries in regards to liberalization of the national railway sector (IBM 2011).

A liberalized railway sector entails a division of the sector in several players: The national transport authority covering railway transport, infrastructure managers, railway undertakings (train operating companies), accident investigation board and a regulatory body monitoring that European Union (EU) directives are implemented and followed. For a railway timetable to be considered being attractive in Denmark, wishes from several railway stakeholders must therefore be fulfilled.

The railway sector liberalization process within the European Union is described in section 6.1. This has driven major changes in the Danish railway sector and an overview of these is also given in section 6.1. In section 7.1 the most important Danish railway timetabling stakeholders are identified, whose wishes must be taken into consideration when creating an attractive Danish railway timetable. Since no train passenger interest groups are interviewed an overview of their general preferences is given in section 7.3. Through a series of interviews each selected stakeholder was asked to present the five most important timetabling criteria and then give them a ranking. The results from the held interviews are presented in section 7.2. Following the interviews all stakeholders were invited to participate in a timetabling criteria workshop, here the goal was to achieve a common list of timetabling criteria based on the results from the interviews. The held workshop is described in section 7.4. In section 7.5 the held workshop and the achieved results are discussed. Following the workshop some supplementary timetable stakeholders were identified and an additional series of interviews was set up. The results from these interviews are presented in section 7.6. An overview of all the achieved prioritized criteria lists from the interviews is given and discussed in section 7.7. Final conclusions are made in section 7.8. A summary of this chapter is given in section 7.9.

7.1 Identification of Danish railway stakeholders

The development and evaluation of railway timetables must be based on the acceptance of timetabling criteria by all major timetable stakeholders. If this is not the case, there is no common understanding between stakeholders with regard to timetable construction and optimization, and as a result, serious conflicts can arise between train operating companies (TOCs) during the infrastructure manager (IM) timetabling process. Similar, it becomes more difficult for the IM to develop and evaluate possible timetable variants for future valid national railway timetables. The effects of this situation will most likely be a lower quality level of railway timetables which again leads to a reduced attractiveness of the railway as a transportation system (Schittenhelm 2011b).

Based on the presented liberalization process of the Danish railway sector in section 6.1 the most important Danish railway timetable stakeholders were identified. These are (Schittenhelm 2011b):

- **DSB (Danish State Railways):** Biggest passenger train operating company in Denmark. It is owned by the Danish state and run like an Independent Public Company (in Danish Selvstændig Offentlig Virksomhed - SOV).
- **Arriva Denmark:** Passenger train operating company. Today owned by Deutsche Bahn and thereby the German state. Originally it was a private British transportation company. Arriva Denmark is the biggest external/foreign passenger TOC in Denmark.
- **DB Schenker Rail Scandinavia:** Largest freight train operating company owned by Deutsche Bahn and thereby the German state. It is specializing in international transit freight trains through Denmark running between Sweden and Germany.
- **Rail Net Denmark:** Biggest infrastructure manager in Denmark and owned by the Danish state. Rail Net Denmark is responsible for more than 90% of the Danish railway infrastructure.
- **The Danish Transport Authority:** Public railway authority in Denmark. It is a department under the Danish Ministry of Transport. Public train service traffic tenders are handled by the authority.

To get a better understanding of the interests in and wishes for the national Danish railway timetable an interview was set up with each of the above identified key stakeholders. These interviews and their results are presented in section 7.2.

7.2 Identification of railway timetable evaluation and optimization criteria by stakeholder interviews

This section provides the results of the first attempt to create a common Danish list of railway timetabling optimization and evaluation criteria. This list was the result of a workshop hosted by the Department of Transport at the Technical University of Denmark in November 2011, in which the most important timetable stakeholders took part. With this list, the Danish railway sector as a whole and the national IM – Rail Net Denmark – in particular has an improved basis for creating both better timetables and timetables that are satisfactory to all stakeholders.

A series of interviews have been held with selected timetable stakeholders. These were identified in section 7.1 based on the liberalization history of the Danish railway sector. The stakeholders are: Passenger TOC DSB and Arriva, freight TOC DB Schenker Rail Scandinavia, IM Rail Net Denmark and the Danish Transport Authority.

It must be noticed that there are no organizations representing train passengers or customers of freight TOCs. It has been assumed that nothing new would be added to this process and that the interests of passengers and freight customers would be covered by the respective TOC and the Danish Transport Authority (DTA). Both passenger and freight TOCs are in day to day contact with their customers and the DTA represents the political and thereby society's interests (Schittenhelm 2011b).

The agenda for all interviews was the same and it was given to the stakeholders in advance so that they could prepare themselves for the interview. Figure 7.1 shows the agenda for the stakeholder interviews (Schittenhelm 2011b).

Agenda for the stakeholder interviews:

1. List the most important timetable evaluation criteria for your company.
   1.1 Describe/explain each criterion thus making it operational in a timetable context.
   1.2 How can each criterion be recognized in the timetable?
   1.3 Make suggestions for how to measure the presence of the criterion in the timetable.

2. Prioritize the company's list of timetable evaluation criteria.

Figure 7.1: Agenda for the stakeholder interviews (Schittenhelm 2011b)

Each stakeholder should look inward and identify the timetable evaluation criteria used by their company/organization. To create the best basis for developing a set of future timetable key performance indicators (KPIs), each stakeholder was asked to give a detailed description of each criterion and explain how it can be recognized in a given timetable. Each stakeholder was encouraged to give inspiration for future measuring methods or a presentation of existing procedures. Finally a prioritization of the identified evaluation criteria was needed for the coming joined timetabling criteria workshop (Schittenhelm 2011b).

In the following five sections a summary of the outcome from each interview is given. The presented facts and statements are coming from the stakeholder representatives. Each interview summary starts by stating the stakeholder´s prioritized list of timetable evaluation criteria, followed by an elaboration on each criterion. Based on this, each criterion is divided into timetable effects.

7.2.1 Interview with passenger train operator DSB

DSB operates regional and long distance passenger trains and must not be mixed up with TOC DSB S-tog, who operates the suburban S-trains in the Copenhagen area. The company was represented by head of timetabling Niklas Kohl and senior timetable planner Per Elgaard. The interview took place at DSB's head office in Copenhagen on 28 September 2010.

The DSB prioritized list of timetable evaluation criteria:

1. Robustness of the timetable
2. Fast, high frequent and direct connections
3. Possibility for train services calling at smaller stations
4. Efficient use of the railway infrastructure
5. Scalability of the timetable

7.2.1.1 Robustness of the timetable

DSB has committed itself to achieving a punctuality level of 95%. This means that 95% of all carried out train runs must be on time – less than 5:00 minutes delayed. The punctuality level is specified in the traffic contract entered by DSB and the Danish Ministry of Transport.

To achieve a punctuality level of 95% it is important to DSB that the timetable is realistic. A realistic timetable is based on actual rolling stock driving characteristics data such as speed-force (speed as a function of traction power) and start-up diagrams (speed as a function of driven distance), see Figure 7.2, and breaking capabilities of a given rolling stock class – the possible retardation in the metric unit [m/s^2]. These data are provided by the supplier of rolling stock and are easily entered into software timetabling tools. These data describe a new train running on well-maintained infrastructure and in good weather conditions. Running time calculations based on these input data for rolling stock can thus be too optimistic and thereby increasing the risk of delayed trains. In real-life weather conditions such as very low temperatures can reduce the available traction effort of a given train and during autumn the fallen leaves from trees can decrease the friction between wheel and rail. Lack of or poor maintenance of rolling stock can also lead to reduced traction power. These issues must be taken into account when preparing running time calculations for a timetable.

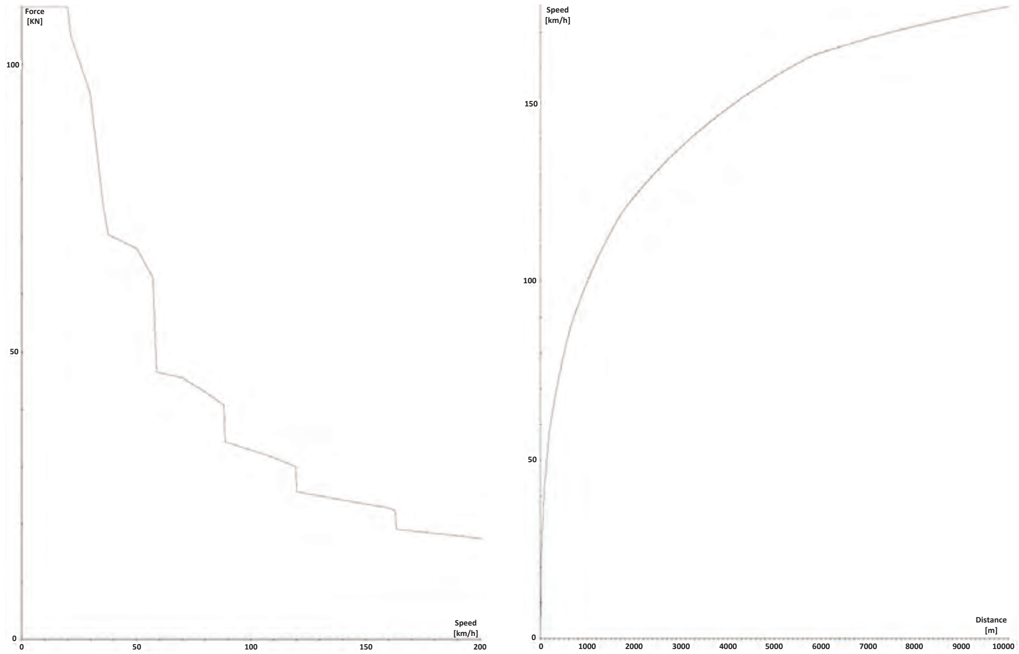


Figure 7.2: Speed-force diagram (left) and start-up diagram (right) for DSB train set Litra MF (IC3)

Planned stopping times for trains at stations should be based on collected trustworthy data from real-life operations. This can be done by e.g. manually timing stopping trains, using footage from platform surveillance cameras or analyzing data for occupation of track circuits by trains. Necessary stopping times for trains depend on time of day, e.g. longer stopping times during rush hours and rolling stock characteristics such as longer stopping times when using double-decker carriages and shorter stopping times for longer trains due to fewer passengers per door.

Turnaround times for trains at their terminus must be physically possible and fulfill any agreements between DSB and relevant worker unions. This leads to e.g. minimum turnaround times of 6 minutes on the Copenhagen suburban railway network. Longer turnaround times, including time buffers, increase the probability of rolling stock being available for the next scheduled train run in time for a punctual departure.

7.2.1.2 Fast, high frequent and direct connections

These are the classic wishes for train services from train passengers. To make a railway journey an attractive alternative to a journey made with different means of transportation the travel time of the train has to be within a given time window depending on the price difference between alternatives. Often the travel time of the train must be close to or equal to the alternative. If the train is faster than the alternative it becomes very attractive if the prices are similar. The shorter travel time has a value for travelers and therefore the price to use the train could be set higher than the alternative.

A high frequency of a train service gives the passenger a high level of flexibility when planning his journey. This makes the train journey more attractive but it will never be able to compete with the car since this gives the owner the maximum level of flexibility. Very high frequent train services, such as metro lines, can be an attractive alternative to the car but they might only cover a small part of a big city and much less of an entire country.

Necessary transfers are considered much more negative by train passengers than the prolongation of travel time that they may cause. Passengers do not seem to differentiate between "easy transfers", such as changing trains at the same platform and more "demanding transfers", e.g. having to use an underpass to get to a different platform some distance away. Either you have an attractive direct connection or a far less attractive connection including one or more necessary transfers.

Measuring these parameters by using "passenger minutes spent in the train" as an evaluation methodology is not good enough for DSB. This measurement does not take the frequency of train services into account. A more sophisticated approach must be used. DSB focuses on the experienced travel time for train passengers. This consists of three parts:

1. Timetable travel time – given by the valid timetable
2. Average waiting time at stations – this depends on the train frequency and periodicity of the timetable. See Equation 7.1.
3. Felt time costs with transfers – according to DSB this should minimum be set to 15 minutes of travel time

$$\text{Average waiting time at station} = \frac{T_{1-2}}{2} \times \frac{T_{1-2}}{I_{periodicity}} + \ldots + \frac{T_{X-1'}}{2} \times \frac{T_{X-1'}}{I_{periodicity}} \qquad \text{(Equation 7.1)}$$

$T_{1\text{-}2}$	= Time between train 1 and train 2
$T_{X\text{-}1'}$	= Time between train X and the first train of the next periodicity interval
$I_{periodicity}$	= Interval of periodicity in the timetable

DSB's applications for future timetable train paths should be based on available and detailed up to date Origin-Destination (OD) matrices. This gives both TOCs and politicians, and hereby the DTA and IM, a possibility to optimize the national timetable, based on analyzed experienced train passenger travel time.

7.2.1.3 Possibility for train services calling at smaller stations

DSB has contractual obligations towards the political government to give smaller stations on railway lines serviced by DSB a minimum level of service. The service level is defined as the number of stopping trains per hour per driving direction. The timetable must allow for DSB to live up to these minimum contractual obligations.

According to DSB there should be allocated enough capacity in the timetable to make it possible for trains to call at smaller stations more often than necessary in regards to the traffic contracts. This makes the train service more attractive for passengers and can potentially achieve a rise in passenger volumes. Going from one train per hour to two trains per hour calling at a given smaller station increases the attractiveness of the train service drastically.

Future timetables must contain the possibility to (re)open new stations on the railway network. Even on sections of railway lines that are defined as capacity bottlenecks. By doing so the railway is given the possibility to service a larger geographical area and thereby gaining a bigger passenger potential.

7.2.1.4 Efficient use of the available railway infrastructure

Short travel times for fast service passenger trains must not be affected negatively by slower freight and regional trains. Potential conflicts between trains catching up with each other must be handled by well-planned overtakings of freight trains and a suitable timetable structure for passenger trains with different travelling speeds. Sometimes it is possible for freight trains to achieve similar travelling speeds as some passenger train services and if this is the case it should be utilized in a given timetable.

There should be no timetable train paths available for freight trains during rush hour periods on parts of the railway network in the area of larger cities, such as Copenhagen, and their surrounding areas. All the available infrastructure capacity should be used for extra passenger trains. If this is not possible the freight trains should receive the lowest priority when creating the rush hour timetable for these parts of the railway network.

7.2.1.5 Scalability of the timetable

The very basic timetable structure must contain the flexibility for TOCs to increase the frequency of train services during rush hours and reduce their frequency again afterwards, without changing the basic timetable structure. This can be done by adding/removing train systems and/or lengthen/ shorten the route of train systems in given time periods. Therefore, the timetable must have a modular structure where modules in form of entire train services, to increase the frequency on a railway line, and modules extending an existing train service to new parts of the railway network, to increase the service level at selected stations, can be added/removed as needed.

The timetable should allow enough time for changing the composition of trains at relevant stations with depot facilities, terminus stations for train services and also en route to optimize the available seating capacity of trains according to the time period of the day and the demand for a given railway line. Using a fleet of compatible train sets with automatic couplers as rolling stock makes it possible to quickly change the composition of trains at stations and therefore easier to implement in a timetable. Lengthening or shortening of locomotive hauled trains requires a more complex process involving a second locomotive, maybe a shunting tractor, to add or pick up carriages. A quick lengthening or shorting of a locomotive hauled train can only take place at the rear of the train. This reduces the flexibility of this maneuver and thereby its attractiveness when preparing a timetable.

A fleet of compatible train sets makes it also possible to couple two or even more train services together if they partly have the same route. DSB takes greatly advantage of this concept since it operates a fleet of compatible train sets and the Danish geography and railway network favors a tree like train service line structure, with the tree trunk beginning in Copenhagen and then railway lines branching of throughout the country. Figure 7.3 shows the line map of DSB’s long distance passenger train services (InterCity and InterCity-Express trains).

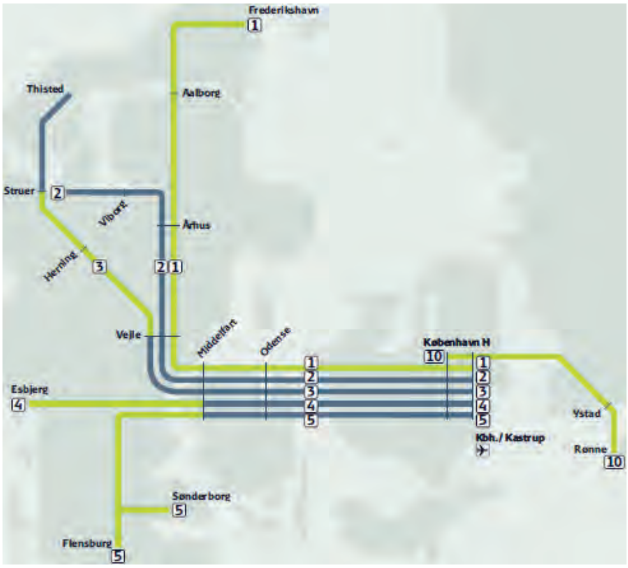


Figure 7.3: Line map of DSB InterCity and InterCity-Express (lyntog) trains (DSB 2011c)

7.2.2 Interview with passenger train operator Arriva Denmark

The interview was carried out by a phone call and Arriva Denmark was represented by senior traffic planner Kent Nielsen. Director of Arriva train services in Denmark, Michael Selvig Hansen, helped setting up the interview. The interview took place during December 2010.

The Arriva Denmark prioritized list of timetable evaluation criteria:

1. Compliance with traffic tender demands
2. Attractive transfer options to/from DSB trains and local busses
3. Periodic timetables are preferable
4. Servicing starting hours of schools and larger workplaces
5. A realistic timetable

7.2.2.1 Compliance with traffic tender demands

The DTA has entered a contract with Arriva (DTA 2009a) which contains demands for minimum service levels for all stations in the area covered by the train traffic tender. The minimum service level is only focusing on train departures and arrivals per hour per station. It is defined as shown in Equation 7.2.

$$\text{Minimum service level} = \frac{\text{Number of departures and arrivals}}{\text{Station} \times \text{Hour} \times \text{Driving direction}} \qquad \text{(Equation 7.2)}$$

Travel times between stations are not part of the service level demands prepared by the DTA. This can provide a higher level of freedom for Arriva Denmark when creating a timetable and it must probably be assumed that TOCs will minimize travel times to keep the needed number of rolling stock as low as possible.

A tight cooperation between the DTA, Rail Net Denmark (RND) and Arriva exists about the timetabling process. Hereby a quality control is ensured, where the DTA makes sure that the timetable complies with the set demands for minimum service levels and RND controls that applied running times for trains are feasible. The latter is very important since Arriva Denmark has not invested in timetabling software and therefore has no advanced train running time calculation tools.

Arriva Denmark has also a close cooperation with the timetabling department at DSB to ensure a minimum of conflicting wishes for timetable train paths on shared railway lines and to provide very attractive transfer options between DSB and Arriva trains at selected stations. This is advantageous for both TOCs since the attractiveness of the railway as a transport system increases and the risk of having to make work heavy adjustments to the proposed timetable is reduced.

Likewise it is also an advantage for IM Rail Net Denmark since the coordination of timetable train paths on parts of the railway network is being done by the involved TOCs. This means a lower workload for timetable planners and in the end probably a better compromise between the relevant TOCs that could be achieved by a negotiation meeting during the timetabling process. See Figure 6.16.

If a station has more than one arrival/departure per driving direction per hour these should be spread out evenly during the hour – e.g. 2 departures should give a frequency of 30 minutes. The tender documents allow for some flexibility and make it possible to having between 20 and 40 minutes between trains respectively. Conditions given by the infrastructure, mainly single track lines, and a potential wish for running both fast train services with few stops and slower train services that stop at all stations, necessitate this flexibility in service level demands.

7.2.2.2 Attractive transfer options to/from DSB and local busses

Since Arriva-trains often have the role as feeder trains to DSB's national InterCity and InterCity-Express train services, it is very important to have attractive transfer options between DSB and Arriva trains. As mentioned earlier there is a close cooperation with DSB to ensure these attractive transfer options. Arriva readily accepts some scheduled waiting time in the timetable to achieve these transfer options[3].

The next step for Arriva is to expand the cooperation with bus operators in the public transport sector. Attractive transfer options to local busses that service station catchment areas have become very important to Arriva. To attract more passengers it is necessary to provide a coherent journey from start to end point when using public transport.

7.2.2.3 Periodic timetables are preferable

Arriva divides an operational day in to three time periods:

1. Morning rush hour 05:00 to 10:00
2. Day time hours 10:00 to 18:00
3. Evening + night 18:00 to 01:00

It is noticeable that Arriva is not planning with an afternoon rush hour. The flow of returning passengers must be spread out over enough hours that it permits to keep the day time hour service level. However some train compositions are changed from one train set to two train sets to provide increased seating capacity.

[3] Longer stopping times than necessary are used in Arriva's timetable to give passengers the optimal transfer conditions to and from DSB trains at selected stations.

During the day time hours the timetable is periodic following an hourly pattern. A market oriented timetable is used for the morning rush hour. Longer and more frequent trains run in the primary traffic directions. In the evening and during the night the frequencies of train services are reduced and do no longer follow an hourly pattern (DSB 2011c, DSB 2011d).

7.2.2.4 Starting hours of schools and larger workplaces

In the mornings a substantial part of Arriva's customers have to be at specific stations to a specific time. These are e.g. school children, students and workers in manufacturing companies. This aspect has to be taken into account when preparing the timetable since the train services are operated with a low frequency (1 or 2 trains per hour). The same focus is not given to departure times at the same selected stations in the afternoon and evening hours. Reason for this is that passengers get off from work or school at various times and are generally more flexible with regards to the return journey.

7.2.2.5 Realistic timetable

The cooperation with IM RND during the timetable creation process ensures that the final timetable is realistic and feasible. Arriva uses the same approach to running time supplements as DSB and applies the planning rules defined by the IM RND.

Arriva uses two categories of stopping times for stations, depending on the number of alighting and boarding passengers at the given station. These times are based on practical experience (Johansson 2011):

1. Large stations: 1 minute
2. Small stations: 30 seconds

Type of rolling stock does not affect stopping times at stations. Before the implementation of the timetable for year 2012, Arriva was using two types of rolling stock: The old train sets of class MR and train sets from the new class Coradia Lint. See Figure 7.4. Accessibility to the Coradia Lint train sets has been increased by widening the doors and having the doors placed in the low floor section of the train sets, thereby minimizing the height difference between platform and the train floor (Pedersen 2003).

Figure 7.4: Arriva train set litra MR (left) and train set Coradia Lint 41 (right)

Differences in the composition of trains e.g. one or two coupled train sets is also not taken into account when allocating stopping time to trains. The result is that the timetable has to be prepared for the worst case scenario: Train services consisting of one MR class train set giving the longest stopping times and running times. This ensures a realistic timetable but can potentially reduce the possibilities to optimize costs for the TOC and thereby in the end also for society.

The minimum turnaround time for Arriva trains at terminus stations is set to 4 minutes. This is less than for similar DSB train services. A minimum turnaround time is primarily based on what is physically and technically possible, e.g. walking the length of a train and time needed to switch on/off the drivers desk. Secondly, it is based on agreements made with the train driver plus train personnel worker unions and the TOC. Arriva tries to keep turnaround times down to 4 minutes to achieve a highly efficient use of both rolling stock and train crews.

7.2.3 Interview with freight train operator DB Schenker Rail Scandinavia

Head of planning at DB Schenker Rail Scandinavia, Claus Jensen, made the interview possible. The interview was held with traffic planner Susanne Olling Nielsen at the company's offices in Høje Taastrup. The interview took place on 11 October 2010.

DB Schenker Rail Scandinavia assumes that IM RND is allocating enough infrastructure capacity in the timetable to freight services, so that no requests in the application for timetable train paths are rejected. Until now only one TOC was not given the requested capacity (RND 2010a). In Denmark more and more freight TOCs are applying for timetable train paths and therefore this picture can change in the near future (Landex 2009).

Prioritized list of DB Schenker Rail Scandinavia timetable evaluation criteria:

1. Coordinated international timetable train paths
2. Train paths give flexibility to where change of train drivers can take place
3. Robustness of the timetable
4. Low level of scheduled waiting time
5. Periodic timetables are preferable

7.2.3.1 Coordinated international timetable train paths

A coordination of international timetable train paths between the IMs in different countries ensures no or only little scheduled waiting time for transit freight trains at border stations. There can be a necessary minimum stopping time for e.g. changing the settings for the brakes of the train. Waiting time at border stations is an important cost driver and competiveness factor for freight TOCs focusing on international freight train traffic.

To ensure a European coordination of border crossing train paths a series of Rail Net Europe (RNE) hosted timetabling conferences are held each year, where representatives from relevant IMs meet and prepare train paths for the different freight corridors through Europe.

7.2.3.2 Train paths give flexibility to where a change of train driver can take place

For an international transit freight train to pass through Denmark, minimum one train driver change is necessary. The reason for this is a maximum of 5½ hours of consecutively driving for train drivers. This is a combination of Danish railway safety legislation and the collective agreement between TOCs and train driver unions (DI 2010).

On the transit freight corridor through Denmark, three to five stations can be relevant for changing the train driver. If stations have the necessary staff facilities, the change of train driver can optimally be done simultaneously with planned stops. These planned stops can be necessary because of faster passenger trains overtaking slower freight trains, servicing customers and technical issues such as changing the settings for the braking system when crossing a national border. In any case the timetable should allow for

possible stops at these selected relevant stations even if no stop is planned. This could be done by concentrating the running time supplements around these selected stations.
For traffic planners at DB Schenker Rail Scandinavia it is important to be able to fix the location(s) of train driver changes only just before the yearly timetable becomes effective. This makes it possible to improve the optimization of planning staff logistics in regards to efficiency and reduced costs.

7.2.3.3 Robustness of the timetable

If an international transit freight train reaches the Danish border on time it should also be on time when leaving Denmark again (EU 2010, Richter 2011). Freight trains must also be able to catch up with minor delays. To ensure this it is important that the agreed upon planning rules are used when constructing the timetable. For freight train paths a running time supplement of 3% + 1 minute per 100km is used (UIC 2000).

7.2.3.4 Low level of scheduled waiting time in the timetable

To increase the competiveness of freight trains towards other means of transportation, e.g. trucks on the roads, travel times must be kept as low as possible. This means that the level of scheduled waiting time for freight trains in the timetable has to be as low as possible. In accordance with EU recommendations, a higher level of priority has to be given to freight trains when preparing the yearly timetable (EU 2010). Focus must be on keeping the number of necessary stops to be overtaken by faster passenger trains on a minimum and not letting freight trains being caught behind the slowest local passenger trains, resulting in prolonged running time.

7.2.3.5 Periodic timetables are preferable

The use of periodic timetables in Denmark, with an overall hourly pattern, and thereby implementing the concept of “systematic international freight train timetable train paths” through Denmark makes future timetables more predictable. This creates the basis for a more efficient traffic planning process at the freight TOC and makes it easier to prepare future applications for timetable train paths that are send to the IM in the beginning of the timetabling process.

Even though freight TOCs can be exposed to much more fluctuation in customer demand than passenger TOCs, due to changing global financial conditions or changes in EU or national transport politics, a maybe more flexible market oriented timetable is not preferable to a periodic timetable. The difference in optimization potential for market oriented versus periodic timetables plays a crucial role.

7.2.4 Interview with the Danish Transport Authority

Senior consultants Benny Mølgaard Nielsen and Claus Jørgensen and consultant Jacob Møldrup Petersen represented the Danish Transport Authority for the interview. The interview took place at the main office of the DTA in Copenhagen on 28 October 2010.
A main concern for the DTA is that the experienced quality of the railway timetable by passengers is taken into account in the timetabling process. This can be quantified by socio-economic calculations where improvements in regards to travel time or train service frequency can be translated into monetary terms (DTRI 2007). Table 7.1 gives an overview of the travel time values of the different parts of a journey, planned and unplanned. Values are presented for both railway passengers, car drivers and bicyclist. Please notice that the socio-economic value of transfer time (116 Danish kr. per hour, home-work) is ca. 50% higher than the value of travel time (77 Danish kr. per hour, home-work).

Danish kr. per person-hour	Home-work	Business	Other	Weighted average
Public transport (railway)				
Travel time	77	325	77	91
Delay time	154	650	154	181
Waiting time	154	650	154	181
Scheduled waiting time	62	260	62	72
Transfer time	116	488	116	136
Transfer inconvenience (Danish kr. per transfer)	8	33	8	9
Car drivers				
Travel time	77	325	77	95
Delay time	116	488	116	143
Bicyclists				
Travel time	77	325	77	81
Delay time	116	488	116	121

Table 7.1: Socio-economic time values for passenger traffic, Danish kr. per person-hour in year 2010 levels (DTU Transport 2010)

The DTA has two tasks regarding railway timetables. Firstly, it undertakes strategic analyses for the future development of the Danish railway infrastructure. Secondly a national traffic plan is prepared in regular intervals of 1-2 years, which defines the minimum service level for all stations and halts. See Equation 7.2). As mentioned in section 7.2.2, the service level only focuses on train arrivals and departures. Based on this, traffic tender documents are prepared and contracts entered with DSB and other passenger TOCs.

The Danish Transport Authority's prioritized list of timetable evaluation criteria is:

1. Periodic timetables are preferable
2. Robustness of the timetable
3. Attractive transfer options
4. Travel time for trains
5. A reserve of freight train timetable train paths

A holistic approach to railway timetables is essential for the DTA. There must be cohesiveness throughout the public transport system: Trains, busses and ferries must constitute a seamless network. Inspiration can be taken from the Swiss Rail 2000 (Bahn 2000) traffic master plan (Bösch et al. 2012, Jacobi et al 2004, Keller et al 2008).

7.2.4.1 Periodic timetables are preferable

In Denmark work has begun to implement "Timeplanen" (in English "The One Hour Plan"). The idea of this Danish traffic concept is old and the DSB director general P. E. N. Skov already described it an interview in the newspaper "Aalborg Stiftstidende" in 1964 (Aalborg Diocese Gazette 1964) and re-launched by a collaboration between DTU Transport – Department of Transport and the six biggest cities in Denmark (Landex & Nielsen 2006). This means a travel time of maximum one hour between the biggest cities in Denmark with the fastest non-stop passenger train services. These cities will naturally become transfer hubs where trains and busses meet every hour or half hour – similar to the Swiss Bahn 2000 timetable concept (DTA 2013).

Furthermore the timetable must be easy understandable and easy to remember for passengers. This means that frequencies of exact 10, 15, 20, 30 or 60 minutes should be achieved for train services. A service level of two trains per hour running with 23/37 minutes between trains is not desirable.

7.2.4.2 Robustness of the timetable

The agreed upon planning rules for timetable construction must be used by the IM. Planning rules should be based as much as possible on international standards and guide lines, e.g. European Norms and UIC (International Union of Railways / Union Internationale des Chemins de fer) leaflets (Schittenhelm 2011c, UIC 1996, UIC 2004, UIC 2000).

7.2.4.3 Attractive transfer options

From a Danish socio-economic point of view the waiting time in connection with transfers is more valuable than prolonged travel time (DTU 2010). See Table 7.1. This is due to that people most likely cannot be as productive/work while making a transfer, whereas a longer travel time can be utilized in a productive way such as working on a computer. Therefore short attractive transfer options are more important than a reduction in travel time between cities if the same number of passengers is affected. Attractive transfers are a very important part of a well-functioning public transport system.

7.2.4.4 Travel time for trains

In the timetable construction process the shortest possible travel times for trains should be achieved. This is based on the characteristics of the railway infrastructure and rolling stock. To create a feasible timetable, scheduled waiting time can be unavoidable. Reasons can be the overtaking of slow freight trains by fast passenger trains and to avoid that fast passenger trains catch up with slower passenger trains. Scheduled waiting time must be kept to a minimum since prolonging train travel times makes the timetable less attractive in a socio-economic perspective. On the other hand scheduled waiting time can be unavoidable to achieve a specifically wanted periodic timetable pattern.

7.2.4.5 A reserve of freight train timetable train paths

The present valid timetable has a pattern of two train paths per driving direction per hour for transit freight trains running through Denmark between Sweden and Germany. During the morning and afternoon rush hours this is reduced to one train path per driving direction per hour (Johansson 2011). The DTA recommends increasing this number of train paths to three per driving direction per hour outside rush hours. Not because of expected increasing demand for freight train paths but to create a reserve of train paths that can be used by freight trains that do not enter the network of RND in their scheduled train path. The traffic management of delayed freight trains should become more effective since the trains can follow a prescheduled train path and thereby the risk of causing consecutive delays can be minimized. Both passenger and freight trains should profit from this timetable concept. A RND investigation has shown that freight trains running outside a scheduled train path do not cause more delays than freight trains following a planned timetable train path (Richter 2011). To convince RND about this idea might prove difficult for the DTA.

7.2.5 Interview with railway infrastructure manager Rail Net Denmark

Head of the timetabling section at RND, Lasse Toylsbjerg-Petersen and timetabling team leader Ib Flod Johansson participated in the interview, which was held at the main offices of RND (Banehuset) in Copenhagen. The interview took place on 7 October 2010.

Rail Net Denmark's prioritized list of timetable evaluation criteria:

1. Robustness of the timetable
2. Complexity of traffic in and around stations
3. Utilization of timetable train paths
4. Travel time for trains
5. The timetable is prepared within the given deadline

7.2.5.1 Robustness of the timetable

RND is in the process of writing a "book of planning rules" for their timetable planners. This manual ensures that both national and local planning rules are known and used by timetable planners at RND. Parts of this book will be made available to TOCs to improve the quality of their future timetable train path applications.

Since several years often pass between major changes to the national timetable, an evaluation project for future timetables has been developed. It is being investigated how well next year's timetable can handle the worst traffic incidents from last year's timetable validity period. This is done by e.g. using the railway traffic simulation tool RailSys, where trains in the future timetable are submitted to delays based on statistical train delay data from last year's timetable. RailSys can then show how well the future timetable copes with these delays compared to last year's timetable.

Minimum turnaround times for trains at their terminus are agreed with each TOC. These or recommendable longer times must be used to ensure a robust timetable. Time reserves added to minimum turnaround times improve the ability for delayed arriving trains to depart on time or at least less delayed. Turnaround time reserves cannot be lost during a train run which can happen with evenly spread running time reserves since trains are not allowed to depart a station ahead of the timetable.

There is a need for differentiating stopping times for trains according to the following parameters (Pedersen 2003):

- Type of rolling stock – e.g. double-decker carriages often demand longer stopping times due to the build in stairs that slow down alighting and boarding passengers
- Length of the train / doors per train - passengers per door is a very important factor for exceeding the planned stopping time at a station.

It is the task of RND to make an efficient use of the available railway infrastructure that allows a given number of timetable train paths and provides a wished level of punctuality of trains. The latter is defined by a contract with the Danish Ministry of Transport.

Conflicts between applications from TOCs for timetable train paths should preferable be resolved before the final negotiation meeting between TOCs and IMs in the timetabling process, see Figure 6.16. Resolving big differences between TOCs at such a late state in the timetabling process can lead to hasty and poor compromises and in the end reduce the quality of the entire timetable. RND does therefore encourage TOCs to cooperate and coordinate timetable train paths as much as possible before handing in the application for capacity allocation.

7.2.5.2 *Complexity of traffic in and around stations*

Rail Net Denmark is working on a traffic complexity index for the busiest stations which depends on the used timetable variant. Several approaches to this subject have been investigated (Landex 2011, Jensen 2009, Schittenhelm 2011a) and RND wants to build on these investigations. The index will be based on:

- Track layout of the stations
- Properties of the interlocking system (possible headways between trains)
- The planned timetable
- Deduced timetable planning rules for a given station (based on traffic dispatcher experience)

Based on these factors a probability of potential conflicting train paths index for a given station can be calculated and used when evaluating the timetable before its implementation. A high traffic complexity index will indicate a potential negative effect on the punctuality of trains and could lead to a re-planning of train traffic on the line sections leading to/from the relevant station, changing of the platform track usage of train services at the station or the introduction of a set of special instructions for train drivers and traffic dispatchers to ensure a smooth handling of the train traffic.

7.2.5.3 *Utilization of timetable train paths*

An IM is interested in selling as many timetable train paths to TOCs as possible but still keeping the contractual demanded punctuality levels of trains. Rail Net Demark wants to look at the number of sold timetable train paths out of the maximum available in the used periodic timetable structure. It is RND that defines how the limited railway infrastructure capacity can be utilized in the most efficient way under the given circumstances for a given national timetable.

7.2.5.4 *Travel time for trains*

Rail Net Denmark has made agreements with all TOCs in regards to applied standard running time supplements and if relevant also stopping time supplements. Running time supplements depend on the maximum line speed and are a fixed percentage based on the recommendations from the UIC 451 leaflet (UIC 2000). The national timetable must follow these agreements.

International transit freight trains are difficult to plan when preparing the national timetable. Necessary stops to change train drivers and changing the settings for the train braking system to the standard of neighboring countries must be taken into account.

7.2.5.5 *The timetable is prepared within the given deadline*

Rail Net Denmark is obliged to present a feasible and agreed upon national timetable – including international timetable train paths – within the given deadline by the RNE timetabling process, see Figure 6.12 (RNE 2005, RNE 2006).

7.2.6 Criteria and their timetable indicators

Robustness of timetable • Using realistic train data for running time calculations • Using empiric measurements for estimating stopping times at stations • Differentiating stopping times according to time of day and rolling stock (passengers per door) • Comply with IM planning rules • Timetable train path structure (number and order) • Using complexity indexes for stations • Unused freight train paths are available to delayed trains • Conflicts between TOCs solved early	**Efficient use of the railway infrastructure** • Low level of scheduled waiting time (stopping trains, slowing fast trains, overtaking of freight trains) • Priority of freight trains (in/outside rush hours) • Comply with IM planning rules (running time and stopping time supplements) • Passenger felt travel time (timetable time + station waiting time + transfers) • Direct connections/minimizing need for transfers • Minimize transfer waiting times • Transfer conditions
Periodic timetables are preferable • Attractive towards passengers • Predictability of timetable train path structure gives more efficient planning process for TOCs • Use of periodic freight train paths	**Compliance with traffic tender demands** • Minimum service level is offered at each station • Even time intervals between train services
Coordinated international timetable train paths • Prolonged stopping times (scheduled waiting time) at border stations/shunting yards	**Scalability of the timetable** • Easy to adjust the number of trains services and frequencies of train services to time of day • Time to change composition of trains to optimize seating capacity to time of day
Timetable train paths give flexibility to where change of train drivers can take place • Demand for specific timetable train path design • Efficient logistics planning	**Service starting hours of schools and larger workplaces** • Trains being at a specific station at a specific requested time
Possibility for train services calling at smaller stations • Timetable train path structure allows for better service than minimum service levels for smaller stations • Timetable allows opening of new stations	**Timetable is prepared within the given deadline** • The timetabling process is based on a realistic time span

Figure 7.5: Overview of stakeholder railway timetable evaluation criteria and the deduced indicators based on the interviews (Schittenhelm 2011b).

As a result of the completed interviews, this thesis has categorized the stakeholders prioritized railway timetable evaluation criteria. Based on the criterion descriptions given by the stakeholders, the thesis has defined a set of timetable indicators for each evaluation criterion. An overview of the found indicators during the interviews is given in Figure 7.5. The identified indicators can potentially directly affect the timetable and the timetabling process (Schittenhelm 2011b).

7.2.7 *Reflections on the held interviews*

This series of interviews has given a new insight into different railway timetable stakeholders' approaches to the national Danish timetable and the challenges they are facing when preparing/receiving the timetable train path applications. It is a snapshot of the years 2010-2011 and the results of these interviews cannot be seen as static. The Danish railway sector is highly affected by the ever-changing Danish political climate and therefore future outcomes of similar railway timetable stakeholder interviews could be different from the presented results in this thesis.

Table 7.2 gives an overview of the chosen evaluation criteria, the stakeholders that stated them and their given prioritization. The listed criteria have been grouped into categories/themes. Hereby the criteria "Reserve of freight train timetable train paths" and "Complexity of traffic in and around stations" have been put under the overall criterion "Timetable robustness". The criterion "Attractive transfer options to trains and busses" has been integrated into the "Efficient use of the railway infrastructure" criterion. This has been done because these criteria cover the same aspects in the timetabling process.

Some of the listed criteria are potentially in conflict with each other. These are "Scalability of the timetable" versus "Periodic timetables are preferred" and "Robustness of timetable" versus "Efficient use of the railway infrastructure" (UIC 2004). The criterion "Incorporating flexibility for train driver changes for freight trains" is also possibly conflicting with "An efficient use of the railway infrastructure". The prioritization of two conflicting criteria will determine which of the criteria will be preferred. In case of that two conflicting criteria have achieved the same level of prioritization then a balanced compromise must be made.

Assuming that passenger and freight TOCs handle the interests of their customers is justified when looking at the chosen evaluation criteria. TOC DSB has listed the criterion "fast, high frequent and direct connections" and wants the possibility for train services to call at smaller stations. Attractive transfer options to trains and busses and starting hours of schools and working places has been important to the TOC Arriva. Freight TOC DB Schenker Rail Scandinavia is focusing on the attractiveness and thereby the competiveness of their product with criteria such as coordination of international freight train paths and low level of scheduled waiting time. The Danish Transport Authority focuses on the socio-economic aspects of railway operation by listing criteria as travel times for trains and periodic timetables are preferable. IM Rail Net Denmark wants to ensure a robust timetable but still being able to offer attractive travel times to trains.

Some of the potential conflicts in the timetabling process have become visible with these interviews. An example is that a heavily utilized railway infrastructure based on a periodic timetable can make it very difficult to adapt the timetable to changing market demands during a day. Scaling the timetable by adding new train services or lengthening existing ones can be very difficult due to the rigid overall structures in a periodic timetable. A second example is if focus is given to achieving very high levels of punctuality with a timetable by adding big time supplements. The potential of an efficient use of the infrastructure capacity can be reduced since a lower number of trains can run on the infrastructure. Furthermore can the incorporation of flexible freight train driver changes in the timetable make freight train paths less flexible and can therefore result in a less efficient use of the infrastructure.

A simple attempt has been made to show which evaluation criteria show up on more than one list of prioritized criteria and what ranking they got. A criterion gets 5 prioritization points for rank 1 and 4 for rank 2 and so forth. See the far right column in Table 7.2. The "Robustness of timetable" criterion gets by far the best score with 18 points. It is followed by the "Periodic timetables are preferred" criterion. On third place comes “Low level of scheduled waiting time” and “Attractive Transfer Options to trains and busses” is ranked fourth (Schittenhelm 2011b).

Timetable evaluation criterion	Rail Net Denmark	DSB	Arriva Denmark	DB Schenker	Danish Transport Authority	Prioritization points
Robustness of timetable	1	1	5	3	2	18
- Complexity of traffic in/around stations	2	-	-	-	-	4
- Reserve freight train timetable train paths	-	-	-	-	5	1
Efficient use of infrastructure						
- Low level of scheduled waiting time	4	4	-	4	4	8
- Capacity consumption of infrastructure	3	-	-	-	-	3
- Attractive transfer options for trains and busses	-	-	2	-	3	7
- Fast, high frequent and direct connections	-	2	-	-	-	4
Periodic timetable is preferable	-	-	3	5	1	9
Compliance with traffic tender demands	-	-	1	-	-	5
Coordinated international timetable train paths	-	-	-	1	-	5
Timetable train paths give flexibility to where change of train driver can take place	-	-	-	2	-	4
Train service for smaller stations	-	3	-	-	-	3
Servicing starting hours of schools and larger workplaces	-	-	4	-	-	2
Scalability of timetable	-	5	-	-	-	1
Timetable is prepared within given deadline	5	-	-	-	-	1

Table 7.2: Overview of stated timetable criteria, the stakeholders and their prioritization (Schittenhelm 2011b).

It must be assumed that the interviewed people representing the organizations of timetable stakeholders were affected by their current situation regarding e.g. competition, project schedules and the RNE timetabling process, resulting in biased inputs to the process. This can have had a very big impact on the selected timetable evaluation criteria and especially their prioritization. An example for this, are the prioritized criteria from TOC DSB. When the interview with DSB was held, there was a political focus on the possibility of reopening or opening new stations on the Danish railway network. This most likely lead to, that the criterion “Possibility for train services calling at smaller stations” was on the DSB list of criteria and achieved a third place on this list. Another example is the RND criterion “Complexity of traffic in and around stations”. At the time of the interview, traffic dispatching on Copenhagen central station was experiencing to be reason for an increase in numbers of delayed trains due to a higher complexity level of the planned railway traffic in and around Copenhagen central station. These circumstances can very well be reason for that this criterion is on RND’s list and was seen as the second most important criterion.

There is a risk of that the interviewed stakeholders created their lists of prioritized lists of criteria by looking at timetabling topics where they themselves or the political decision makers see a present need for improvement. At the same time assuming that high quality levels of other timetable evaluation criteria can be kept. Hereby neglecting criteria where current performance levels are ok. Contractual obligations between the TOC/IM and the DTA and/or Ministry of Transport can affect this risk. An improvement for future stakeholder interviews is to ask the following questions for each criterion to be prioritized (Liebchen 2012):

- How is the attained level of quality for the stated criterion evaluated at present (unacceptable, acceptable or excellent)?
- How urgent is the need for substantial improvements? (here the risk can be revealed)
- Would it be acceptable to decrease the present level of quality, if this opens an option to implement substantial improvements for some other evaluation criterion

Based on these observations it is therefore recommendable to carry out improved and adapted railway timetable stakeholder interviews like these with regular intervals, e.g. every second year, to get a better understanding of which timetable evaluation and optimization criteria presently have a high priority with TOCs and IMs.

7.3 Railway customer preferences

Train passengers and train passenger interest groups have not been identified as stakeholders in regards to preparing railway timetables. Neither are freight customers who want to transport their commodities by train. This is done under the assumption that their interests are taken care of by both TOCs and the DTA, the latter being a departmental organization under the Danish Ministry of Transport.

7.3.1 Passenger preferences

Since passengers provide the income of TOCs, these should have a big interest in providing an attractive timetable for passengers. Passengers are voters and therefore politicians have an interest in ensuring that the railway is a central part of an attractive public national transportation system. Figure 7.6 gives an overview of an approach to evaluate the competiveness of passenger train services made by the consultancy “Incentive Partners” for the Danish Ministry of Transport. The categorization and selection of the competiveness parameters was made by a project working group with representatives from TOC DSB and Arriva, DTU Transport – Department of Transport, The Danish Transport Authority, The Danish Ministry of Finance, The Danish Ministry of Transport and Incentive Partners (Incentive 2010).

A general reduction of price levels for train services is an expensive mean to attract more passengers. Experience shows that a price reduction of 10% attracts 3% more passengers in the short run and up to 6% in a long term. Price differentiations focusing on leisure travelers and passengers who most often travel by car have a big potential. Price reductions for these customer groups do not necessarily have to result in a lower income (Incentive 2010).

The market share of train services drops drastically if the travel time for a train is 75% higher than for a car. This is especially the case for longer journeys. Travel time is not so important for commuters who normally travel short distances in local or regional train services. Reason for this is that the difference in travel time compared with the car is relatively small and that it can be a hassle finding a parking space (Incentive 2010).

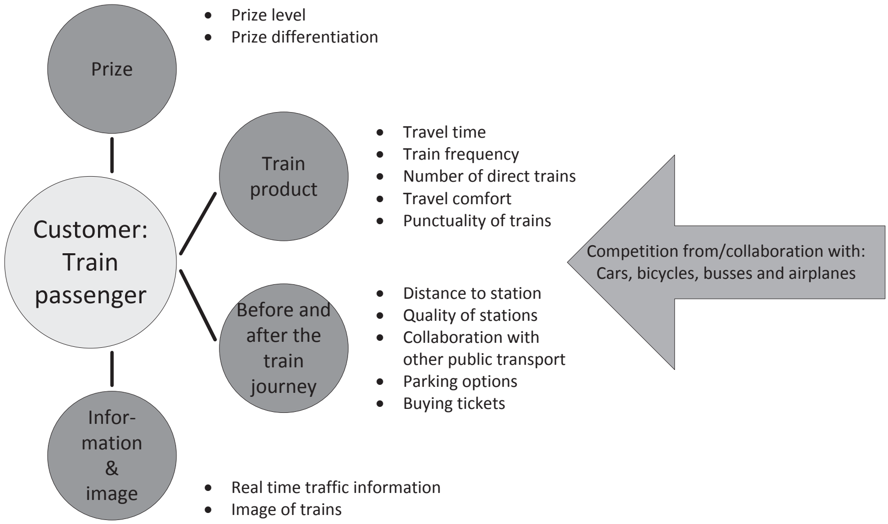


Figure 7.6: Approach to evaluate the competiveness of passenger train services (Incentive 2010)

Preference	Main mean of transportation			Main purpose				Age			
	Bus passengers	Cyclists	Car drivers	Work	School / education	Shopping	Visit	Children	Young	Middle aged	Elderly
Lower price	**	***	*	*	**	***	***	**	**	*	***
Shorter walking distance	**	**	*	*	*	***	***	***	**	*	***
Higher speed	*	***	***	***	*	*	*	*	*	***	*
More frequent departures	***	***	*	**	***	*	*	*	***	**	*
Avoid transfers	**	**	***	**	*	*	*	**	*	**	*
Better infor-mation	*	*	***	**	*	*	**	*	*	**	**
Better comfort / seating	*	*	***	***	*	***	**	**	*	**	***
Punctu-ality	**	*	**	***	***	*	*	*	**	**	*

*Table 7.3: Preferences for choice of mean of transportation. * = Less important, ** = Important, *** = Very important (based on Landex & Nielsen 2007)*

The statistics from the yearly Danish Transportation Habits Study (in Danish: Transportvaneundersøgelsen) show that the effect of increasing the train service frequency on the train market share for longer journeys decreases drastically when going from three trains to four trains per hour (DTU 2012, Incentive 2010). For shorter train journeys with e.g. suburban train services or metro systems a higher frequency is much more important (Incentive 2010). Studies show that train passengers on the Copenhagen suburban train services

(S-tog) prefer timetables with shorter travel times and lower train frequencies to timetables with higher train frequencies and longer travel times (Bak & Pilegaard 2007).

There is a close connection between the achieved punctuality levels of train services and the perception of these train services by the passengers. There is not much knowledge available on the relation between poor train punctuality and passenger demand. Recent experiences from the Coastal Railway Line (in Danish: Kystbanen) indicate that there is a tight connection between poor train service performance and reduced passenger numbers. The effect of train delays is higher for short journeys than longer journeys (Incentive 2010).

Transfers between trains or different means of public transportation are perceived as annoying by passengers and it is therefore important to ensure a close collaboration/coordination between all traffic companies in the public transportation sector. Example calculations show that reducing the number of necessary transfers by one can attract up to 20% more passengers on journeys with a length of 40 km. By reducing the transfer time by 5 minutes a passenger increase of 7% can be achieved. Effects are normally larger for shorter trips than longer trips. For travel relations with several necessary transfers, focus should be on a high frequency (Incentive 2010).

It is very difficult to get the precise preferences of passengers using public transportation. Potential passengers have different preferences according to the purpose of their trip and their age (Nielsen & Landex 2009). Table 7.3 gives an overview of preferences for choice of mean of transportation.
In 2006 TOC DSB S-train conducted a survey to map the preferences of their passengers in order to prepare the yearly timetable 2007 according to these preferences. The prioritization of the S-train passengers can be seen in Table 7.4.

Preference	Weighted importance (1-7)
Cheaper tickets	2.44
Better transfer options between S-trains and other public transport	2.88
Reduced waiting time	3.04
Shorter travel time	3.24
Less delays	3.26
Less cancellations	3.38
Less transfers en route	3.38
More departures	3.45

Table 7.4: Priority of preferences from Copenhagen S-train passengers (the higher the value the more important for passengers, from 1 to 7) (Landex &Nielsen 2007)

Quantifying passenger preferences based on qualitative interviews is difficult. Alternative methods include “Stated Preference” and “Revealed Preference”. The stated preference methodology is based on going through systematic scenarios with passengers where they are asked what they would choose to do in certain hypothetical situations. In revealed preference studies, the observed behavior of passengers is used to state their preferences. Revealed preferences are normally based on a large number of random samples and therefore a trustworthy statistical correlation is achieved (Nielsen & Landex 2009).

7.3.1.1 Waiting and transfer time

Waiting time at the station and prolonged travel time due to a transfer is not popular with passengers. Recent analyses indicate that the time-value of waiting and transfer time is between 10 and 210% higher than travel time in trains. For the greater Copenhagen area this difference in time-value is estimated to be between 10 and 50%. The high time-value of transfer time shows that timetable planners should minimize transfer times in the timetable and introduce as many direct train services as possible (Nielsen & Landex 2009).

7.3.1.2 Physical transfers

The transfer between trains itself is experienced as a big nuisance by passengers. The time-value of a transfer varies a lot and is estimated to be between 6 to 25 minutes. This means that a transfer must generate a great reduction in travel time before a passenger considers making two transfers instead of one and that passengers prefer slower direct connections to faster connections with necessary transfers (Nielsen & Landex 2009).

7.3.1.3 Frequency (hidden waiting time)

Hidden waiting time is experienced by passengers because a given train service is not running as frequent as wanted. For some passengers the hidden waiting time is just as long as normal waiting times due to fixed journey starting or ending times. Journey start and/or end times can be fixed because of e.g. working hours. The time-value of hidden waiting time compared with normal waiting time is between 40-100%. This means that low frequent public transport systems are seen as a nuisance by passengers. This can explain the increase in passenger volumes for the Copenhagen S-trains when the timetable was changed from a frequency of 20 minutes to 10 minutes for certain train services (Nielsen & Landex 2009).

For a railway system a tradeoff exists between high frequent and direct train services. Focusing on direct train services reduces the possibility of high frequent services and vice versa. This is a schism in railway timetabling. Traffic models incorporating detailed railway timetables can help with providing necessary data that can form the basis for a decision, either to focus on direct or high frequent train services (Nielsen & Landex 2009).

Another tradeoff exists between travel time and frequency. A travel time reduction can be achieved by skipping stops or by increasing the frequency and thereby reducing the waiting time at the starting station and potentially later at transfer stations. If the frequency for train services is increased, the overall travel time can be reduced. A given railway infrastructure provides a limited capacity for train services and an increase in frequency will increase the capacity consumption of the infrastructure and it then becomes impossible to skip stations (Landex 2008).

Table 7.5 gives an overview of potential travel time reductions with improved train service frequencies. It is assumed that train passengers arrive randomly at the starting station. The average waiting time will then be half the headway time between trains. Potential travel time reductions are presented for the most common timetabled train service frequencies.

TOC DSB S-train performed a passenger survey were they asked their potential passengers if they preferred high frequency train services or short travel times. Different timetable variants were presented. The question was directed at commuters and their daily journeys. When asked directly 55% of the passenger preferred a higher frequency and 45% a short travel time (Bak & Olsen 2004). Focusing on commuters and their travel patterns and thereby deselecting other passenger segments created some degree of bias in the survey.

Starting headway [min]	Improved headway [min]							
	120	60	30	20	15	10	5	2.5
120		30	45	50	52.5	55	57.5	58.75
60			15	20	22.5	25	27.5	28.75
30				5	7.5	10	12.5	13.75
20					2.5	5	7.5	8.75
15						2.5	5	6.25
10							2.5	3.75
5								1.25
2.5								

Table 7.5: Travel time reduction with improved train service frequencies – based on average waiting times

When the potential passengers were faced with two alternative timetables the preferences were not so clear anymore. Railway line sections with many short journeys preferred a high frequency and line sections with longer journeys preferred shorter travel times (Bak & Olsen 2004).

7.3.1.4 Delays and variation in travel time

Delays are considered to be a major nuisance by passengers. The time-value of delays is experienced by passengers to be between 80-250% higher than the time-value of scheduled travel time. This means that 10 minutes of delay correspond to between 18 and 35 minutes of scheduled travel time. These high values can be explained with the need to take an earlier train to be sure to arrive at a certain station before a given time threshold (Nielsen & Landex 2009). To ensure the punctuality of train traffic, time supplements are added to the timetable. These can be added as extended train running and dwell times. A high level of time supplements helps to ensure a high level of punctuality but also creates a scheduled prolonged travel time. From a socio-economic utility point of view, it is a balance between ensuring a certain level of train service punctuality and keeping timetabled travel times as low as possible. See Figure 7.7.

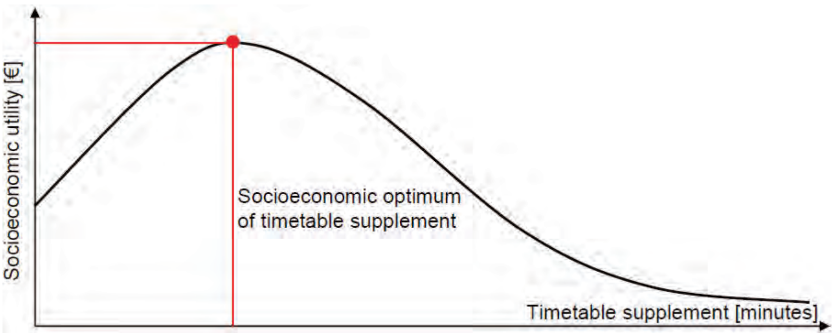


Figure 7.7: The balance of socio-economic utility for timetable supplements (Landex 2008)

7.3.1.5 Timetable class

Passenger preferences for timetable classes depend on the scheduled travel time. For a short scheduled travel time, passengers do not want to invest time in planning and therefore a high frequency timetable (metro systems) or a high frequent periodic timetable (S-trains) is preferred. A long scheduled travel time (long distance trains or airplane) justifies investing more time in the preparation of the journey and therefore passengers will not have a problem with non-periodic timetables for this category of journey.

7.3.1.6 Value of time

Table 7.6 gives an overview of the relative values of time that have been found for single mode Danish railway passenger transport. These values are based on stated preferences. It can be seen that for short train trips the value of access/egress time is about 30% higher than the in vehicle time. Transfer time values depend highly on the transport mode. For high frequent transport system as metro and S-trains it is between 1.5-5.2 minutes of in vehicle time. For long distance trains it is up to 13 minutes. The value of transfer waiting time varies between 1.40 and 2.45. The highest in vehicle time values are found with high frequency and short journey transport systems (metro and S-train) (Fosgerau et al. 2007).

Parameter		**Metro**	**S-train**	**Train**	
Trip length		-	-	≤50 km	>50 km
Headway (standard)		-	10 minutes	15 minutes	15 minutes
Value of in vehicle-time (ivt)		1 DKK/min 60 DKK/hour	0.9 DKK/min 54 DKK/hour	0.87 DKK/min 52 DKK/hour	2.88 DKK/min 173 DKK/hour
Relative values of time (in minutes of ivt)	Acess/egress time	1.32	1.26	1.29	0.88
	Per transfer	1.55	5.18	12.92	
	Transfer waiting time	2.45	1.86	1.40	
	Headway (≤H)	1.32	0.70	1.59	
	Headway (>H)		0.93	0.38	

Table 7.6: Relative time values for single mode Danish railway passenger transport (Fosgerau et al. 2007)

This knowledge about value of travel time can be used comparing, evaluating or developing different theoretical timetable variants from a socio-economic point of view. If knowledge is available about planned and realized passenger travel times, the difference can be quantified using the values from Table 7.6.

7.3.2 Freight customers

Generally there is less knowledge about freight transport mode choice than about passenger transport mode choice. Research has focused on the latter. One explanation can be the greater complexity of freight transport systems. One must consider the diversity of commodities and the characteristics of carriers (freight train operating companies), forwarders (logistic service providers/ shippers), production companies and end-customers and the way each does business. There can be business cultural differences between countries. Compared to passenger transport, there are multiple decision making agents in the logistic chain of freight transport (Arunotayanun & Polak 2011).

Another factor that complicates freight transport mode choice is “taste heterogeneity” amongst decision making agents. Taste heterogeneity can be seen when (Arunotayanun & Polak 2011):

- Agents consider different factors before making their decision
- Agents consider same factors in different ways before making their decision

Research shows that there are significant levels of taste heterogeneity amongst decision making agents and that it only partly can be ascribed to commodity diversity. Amongst the same segment of commodities there also exists taste heterogeneity midst the decision making agents (Arunotayanun & Polak 2011)

Table 7.7 gives an overview of the most important mode choice parameters in freight transport. The parameters are grouped into four categories: Performance, costs, service quality and general parameters.

Freight transport mode choice parameters	
Performance: • Transport time (door to door) • Frequency (number of weakly departures) • Reliability (Percent of the risk of the shipment being delayed at the destination) • Regularity (Periodic departure times) • Capacity limits (freight volumes)	**Costs:** • Price (door to door) • Price effects due to variations in volumes • Index agreements • Credit agreements
Service quality: • Loss and damage rate and its administration • Tracking and tracing • Documentation • Communication • Reception confirmation • Customer delivery and handling services • Schedule flexibility	**General parameters:** • Company structure / organization • Government interventions • Available transport facilities (e.g. intermodal terminals)

Table 7.7: Overview of freight transport mode choice parameters (Jovicic 1998, Golias & Yannis 1998)

Golias and Yannis found the following trends in stated preferences for freight transport in Greece (Golias & Yannis 1998):

- The majority of Greek carriers and forwarders are not willing to pay more for reduced transport times
- A tradeoff between longer transport times for lower cost rates is acceptable to carriers and forwarders
- There is no interest in paying for a guaranteed delivery time for the transported goods.
- 78% of carriers would change to intermodal transport if this would result in a 20% increase in the annual profit rate. Only 52% of the forwarders would do the same

The earliest freight transport mode choice models only focused on transportation costs, ignoring non-cost factors such as service quality parameters. During the 1970s, with an increasing complexity in freight transport systems, it became apparent that non-cost factors often were more important than pure shipment costs when making the mode choice (Arunotayanun & Polak 2011).

Presently there is a European focus on shifting freight transport from road to railway. Reasons for this are a congested road system and that the railway is more environmental friendly. One of the challenges in achieving this shift is the characteristics of the railway infrastructure. Railway networks do not have as much area coverage as road networks do and have a very limited number of access points. A lot of transport relations e.g. from a production company to a given customer are not possible by freight train because one or both of them are not serviced by a railway line. This is called “structural inelasticity”. If the railway is to be used then the commodity must first be driven by road to an intermodal terminal in a trailer or container. At the terminal the trailer/container is loaded unto railway carriages and then taken to the customer or to the closest intermodal terminal for the customer, where it again is put on the road. These operations take time and are costly. Research in Scandinavia shows that for journey lengths below 500 km it becomes a critical factor when making the mode choice. The use of state-of-the-art transport models shows that the introduction of road prizing systems for trucks is not enough; it must be supported by railway infrastructure improvements to achieve a significant impact (Rich et al. 2011).

7.3.3 Train operating companies and customer preferences

To find out how train operating companies take their customers' preferences into account when preparing the capacity application for the coming yearly timetable, the passenger TOCs DSB and Arriva and freight TOCs DB Schenker Rail Scandinavia and Hector Rail were contacted. They were asked to describe what they do to try to fulfill wishes and demands of their customers.
Unfortunately DB Schenker Rail Scandinavia did not respond to this.

The timetabling basis for most passenger TOCs is one or more contracts for running public service railway passenger traffic financed by the public. These contracts contain requirements in regards to running train services e.g. number of trains per hour per direction per line per day period (Elgaard 2013, Nielsen 2013).

The companies themselves rely heavily on information gained from automatic passenger counting systems installed in the trains and/or manual performed passenger counting by train staff. This is supplemented with input given by train staff based on their real life experiences. Regular meetings are conducted with spokespersons of commuter associations. Received individual customer enquiries are also studied. Ideas generated in the marketing departments of the TOCs and new ideas from the Danish Transport Authority or other traffic buyers are also investigated. Passenger TOCs do not have the necessary resources available to conduct large scale market analyses when preparing railway timetables (Elgaard 2013, Nielsen 2013).

Freight TOCs are keeping themselves updated with customer demands on railway timetables through constantly ongoing discussions with present but also potential future customers. In these discussions other factors such as price impact of timetable changes e.g. due to changed demand of rolling stock are on the agenda. Freight TOCs have a great variety of customers types, ranging from intermodal operators via shippers of finished products in conventional railway traffic to large raw material purchasers e.g. timber transports to the paper and pulp industries. It takes great effort to get a good picture of customer preferences/demands (Gustavsson 2013).

Within Hector Rail there is a fixed process for preparing timetables. Every year during winter time future timetable ideas are coordinated with customers before Hector Rail submits the train path applications to the IMs (Gustavsson 2013).

Feasibility studies for future timetables are performed in cooperation between freight TOCs and IMs. These studies can also look into new kind of solutions such as the possibility of running longer heavier, and faster freight trains. Long term suggestions, such as extending the loading gauge of freight trains, are also discussed (Gustavsson 2013).

7.3.4 Reflections on customer preferences

Recent research within the field of customer preferences in regards to public transport puts focus on connectivity within the transportation system as a whole, including all modes of public transport – e.g. trains, busses and ferries. Travel time of a journey must be considered from door to door/terminal to terminal and not just as a sum of travel times by using different means of transportation (Ceder 2004, Ceder 2007, Ceder & Varghese 2011).

Looking at the statements from the TOCs it becomes clear that within the Danish railway sector not much attention is given to customer preferences. Passenger TOCs are spending much effort on focusing on fulfilling stated demands in public service traffic contracts, trying to get bonus payments for e.g. running a certain number of trains on time. These contracts appear to not give enough incentive for TOCs to focus on passenger preferences by e.g. looking at door to door transport services. Passenger TOCs DSB and Arriva have both attractive transfer options in the timetable as the second most important timetable evaluation criteria. The Danish Transport Authority, who is the buyer of public service traffic, has attractive transfer options and travel times as third and fourth most important timetable evaluation criteria. Infrastructure manger Rail Net Denmark, who is responsible for preparing the yearly railway timetable, has travel time as the fourth most important timetable evaluation criteria.

The TOCs say it is impossible for them to allocate many resources for passenger preferences investigation projects since such resources are not made available to them by the public in form of the won traffic tender contracts. Society, in form of the Ministry of Transport and the Danish Transport Authority, seems to be reluctant to put funds into this important area either by initiating own research projects or by allocating funds to TOCs to do this work.

Freight train operators transport goods between terminals and thereby automatically get focus on door to door (terminal to terminal) transport services compared to passenger train operators. Reason for this is the infrastructure and business model setup.

7.4 Joined timetabling criteria workshop

In the autumn of 2011 all interviewed stakeholders were invited to participate in a timetabling criteria workshop. The single goal for this joined workshop was to create a common Danish list of railway timetable evaluation and optimization criteria based on the results from the stakeholder interviews. Monday 21 November 2011 was chosen as the date for this workshop. Earlier attempts to organize a workshop during the spring and summer of 2011 had failed due to many cancellations from the invited stakeholders. To make the situation equal for all participants, it was decided to host the workshop on neutral territory and the Technical University of Denmark, DTU Transport - Department of Transport was chosen as location. It was also decided that a person from the Decision Management research group at the Department of Transport should act as facilitator of this workshop. This ensured that the facilitator had a minimum insight to the topic of the workshop, had experience and expertise within the field of decision making processes and was a neutral outsider. (Goodwin & Wright 2004, Schittenhelm & Landex 2012)

7.4.1 The planned workshop

Goal of the timetabling criteria workshop was to reach a common agreed upon list of prioritized timetable optimization and evaluation criteria for the Danish railway sector. The first step was to get prioritized inputs from the stakeholders via the earlier described interviews. Next step was to prepare the gathered input for a joint decision making event – a timetabling criteria workshop – at which a commonly accepted list of Danish prioritized list of timetable evaluation criteria could be created. The workflow of the process can be seen in Figure 4 (Schittenhelm & Landex 2012).

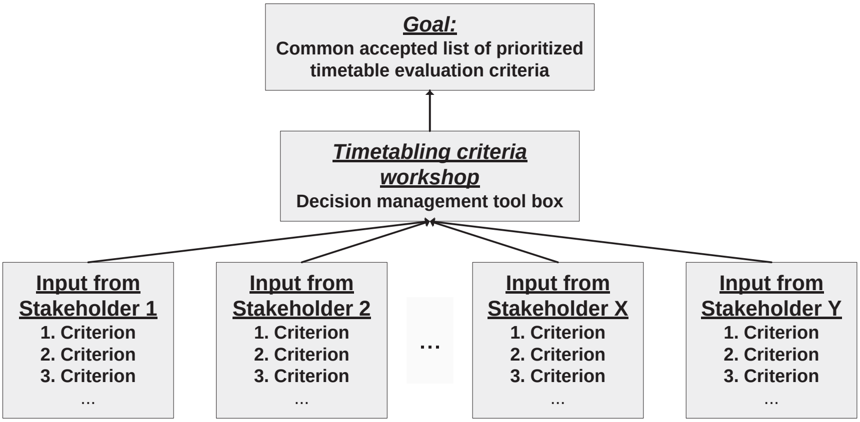


Figure 4: The basis for reaching an agreement on a prioritized list of timetable evaluation and optimization criteria in the Danish railway sector (Schittenhelm & Landex 2012).

It is very important for the success of a decision making process that all invited stakeholders are committed to and participate in workshops like this. This ensures that all perspectives of the topic are covered and can be taken into account during the decision making process (Goodwin & Wright 2004).

Figure 7.8 shows the prepared agenda for the timetabling criteria workshop held at DTU on the 21st of November 2011. A presentation describing the found results from the interviews would be sent out to the stakeholders before the workshop took place. At the beginning of the workshop the author would present the found results from the series of interviews and in cooperation with the stakeholders make the necessary corrections and additions to create a common accepted basis for the rest of the workshop. Items 2 to 4 would make certain that the lists of prioritized timetabling criteria were updated and accepted by the present stakeholders. The next step was to reduce the number of different timetabling criteria to a more manageable number. This was done in items 5 to 7. The applied methodology would be “simple scoring”. Each stakeholder would receive 5 votes and had to give 1 vote to 5 different criteria. It would not possible to give one criterion more than one vote by one stakeholder. The criteria with the most votes would be kept and the rest removed from the criteria gross list. The voting pattern would decide how many criteria would go on to the next phase in the workshop. Items 8 and 9 should cover the next phase, where each participant first would have to prioritize the remaining criteria and afterwards agree upon a common rank order of criteria with the other stakeholders. If reaching an agreement turned out be impossible, then there would be an option to work with more than one common rank order profile. Finally the workshop would end and a discussion about the next possible steps in this decision making process should take place and lastly an evaluation of the workshop should be made by the participants by filling out a prepared evaluation questionnaire (Schittenhelm & Landex 2012).

Agenda for the timetabling criteria workshop

1. **Welcome and presentation of the goal of this workshop:**
   A common Danish list of timetable evaluation and optimization criteria
2. **Review of the prepared prioritized lists of timetabling criteria. All list are being presented to all stakeholders**
3. **Addition of new criteria / Deletion of existing criteria. Updating the prioritized lists of timetabling criteria if needed. New criteria must be defined and described by the stakeholder**
4. **Updated gross list of criteria is presented (on wall)**
5. **Simple scoring of criteria. Each stakeholder has 5 votes. Must give one vote to five timetabling criteria. It is not possible to give more than one vote to one criterion**
6. **Sorting criteria according to their score**
7. **Reduced pool of timetabling criteria**
8. **Individual ranking of criteria. Each stakeholder has to rank the remaining criteria and state his arguments for doing so**
9. **Achieving a common rank order of timetabling criteria. Maybe creating several rank order profiles if necessary**
10. **Closing. Further developments and evaluation of the workshop**

Figure 7.8: Agenda for the timetabling criteria workshop held on November 21, 2011

There would be a risk of not being able to reach one common accepted lists of prioritized timetable evaluation criteria at the workshop. Reasons for this could be many e.g. not achieving a matching of expectations or a lack of will to make compromises from stakeholders. The process would then become iterative and it would possibly be necessary to host more than one workshop before a useful result was produced (Schittenhelm & Landex 2012).

7.4.2 The held workshop

A few days before the agreed upon date for the complex planning workshop at DTU, TOC Arriva Denmark unfortunately had to cancel their participation. It was not possible to find a substitute for Kent Nielsen. In the communication regarding the cancellation, Arriva Denmark pointed out that their interests would be handled by the representatives from DSB (Schittenhelm & Landex 2012).

Table 7.8 gives an overview of the company representatives at the separate interviews and the following timetabling criteria workshop at DTU. It can be seen that a few changes in representatives had taken place between the interviews and the workshop. DSB’s head of timetabling, Niklas Kohl, was not able to attend, but he did send a substitute in form of Lars Christian Krogsdam. Lars was project manager for the project “Timetable 2012”. Susanne Olling Nielsen had left DB Schenker Rail Scandinavia since the interview had taken place and therefore the company had to send a different representative. DB Schenker Rail Scandinavia did actually send two representatives: Head of planning Claus Jensen and strategic planner Thomas Vestergaard. Jacob Møldrup Petersen from the DTA was not able to participate in the workshop but the other two participants from the held interview, Benny Mølgaard and Claus Jørgensen, were able to attend. There were no changes in representatives from RND (Schittenhelm & Landex 2012).

The noticed changes in company representatives is probably due to the unfortunate large time span between the held company interviews, during spring and summer 2010 and the complex planning workshop ultimo November 2011 (Schittenhelm & Landex 2012).

Besides the representatives from the invited stakeholders, the Ph.D.-students Anders Vestergaard and Michael Barfod from the Decision Management research group at the Department of Transport at the DTU participated in the workshop as facilitator and minute taker, respectively (Schittenhelm & Landex 2012).

Company	**Representatives**	
	Interview	**Workshop**
DSB	Niklas Kohl Per Elgaard	Lars Christian Krogsdam Per Elgaard
Arriva Denmark	Kent Nielsen	
DB Schenker Rail Scandinavia	Susanne Olling Nielsen	Claus Jensen Thomas Vestergaard
Danish Transport Authority	Benny Mølgaard Claus Jørgensen Jacob Møldrup Petersen	Benny Mølgaard Claus Jørgensen
Rail Net Denmark	Lasse Toylsbjerg-Petersen Ib Flod Johansson	Lasse Toylsbjerg-Petersen Ib Flod Johansson

Table 7.8: Company representatives for interviews and the complex planning workshop (Schittenhelm & Landex 2012)

The long time span between the company interviews and the timetabling criteria workshop, as well as the changes in company representatives greatly increased the risk of having to make corrections to the lists of prioritized timetabling evaluation and optimization criteria made by the stakeholders during the interviews. Therefore items 2 and 3 on the workshop agenda had become very important and would require special attention from the organizers (Schittenhelm & Landex 2012).

7.4.3 Deviation from the workshop agenda

While presenting the DSB list of prioritized timetabling criteria to the participants of the workshop, it became apparent that any changes to the list would be made during and just after the presentation. In connection with DSB's list the question of which criteria are controlled by DSB and which are controlled by contractual obligations towards the Danish Ministry of Transport arose (Schittenhelm & Landex 2012).

Amongst the participants of the workshop there was consensus about that Arriva Denmark's list of prioritized timetabling criteria should be presented. This was done without any comments.

After the presentation of DB Schenker Rail Scandinavia's prioritized list of timetabling criteria a question was raised in regards to the last criterion. It was asked how long a time period could and should be in a periodic timetable. The author described that a period could be as little as 10 minutes and as long as 2 hours. It was decided by the participants of the workshop to generally use the term "systematic timetable" as replacement for "periodic timetable". Hereby avoiding the uncertainty in regards to the periodicity of a given timetable. This change was made in all the stakeholders prioritized criteria lists (Schittenhelm & Landex 2012).

Following the presentation of the DTA's list of timetabling criteria, an uncertainty in regards to the difference in socio-economic value of "transfer time" and "travel time" arose. It was clarified that a reduction in transfer time is given double the value than the same reduction in travel time. Not all participants agreed with this socio-economic assumption (DTU 2012). Furthermore an elaboration of the criterion regarding the use of extra freight train timetable train paths was wanted. It was stated that the freight train traffic is growing and a question was raised about how many international freight train paths there was capacity for during a given time period before the passenger train traffic was affected by prolonged travel times or fewer train paths. Some stakeholders claimed that there was not enough capacity for more transit freight train timetable train paths. It was suggested to put existing train paths closer together or put new ones between them. If a reserve of freight train paths in a timetable should be possible then the robustness level of the timetable in general must be very high. It was suggested to get inspiration from the planning processes for flight traffic (Schittenhelm & Landex 2012).

The representatives from RND wanted the criterion “Utilization of timetable train paths” renamed so it would treat the topic “capacity consumption on a line section”. Differences in systematic time periods (e.g. 3 during a day) in the timetable could be taken into account. Besides this there were no questions or changes to the prioritized list of timetable evaluation and optimization criteria from IM RND (Schittenhelm & Landex 2012).

After the presentations there was a general doubt amongst the participants about the purpose of using timetabling evaluation and optimization criteria. Some of the stated criteria are given demands from the Danish Ministry of Transport. The DTA has several contractual obligations to fulfill towards the ministry and additionally must handle the interests of the ministry towards all other railway stakeholders (Schittenhelm & Landex 2012).

It was stated from several participants that a robust timetable is essential for railway traffic and therefore should be considered being a basic prerequisite that was always taken care of. A non-robust timetable would never be considered by any railway stakeholder. A robust timetable has the following key preconditions: Working infrastructure, functional rolling stock and enough available staff. These preconditions must be fulfilled before a robust timetable can be achieved. The issue with the robust timetable criterion originates from the instability within the group of the other timetabling criteria. This discussion depends very much on individual opinions (Schittenhelm & Landex 2012).

A discussion started about the goal of the workshop and it was stated by the organizers that the goal was to get a snapshot of today’s situation and that this kind of workshop could be repeated every time larger changes take place in the preconditions for railway timetabling in Denmark. This process will go on as long as there is a running railway system. There can only be one timetable and therefore a compromise must be made between the different railway stakeholders (Schittenhelm & Landex 2012).

It became apparent for all stakeholders, that an intelligent surveillance and evaluation system for railway timetables was needed in the future.

All participants agreed to that the criterion “Societal acceptance” was missing and should be added to a first version of a common list of timetabling criteria. It became clear to the organizers that the participants of the workshop by themselves started working on creating a common list of timetable evaluation and optimization criteria from the presented lists of timetabling criteria (Schittenhelm & Landex 2012).

7.4.4 Results from the workshop

The participants arrived at the following not prioritized first version of a list of common timetable evaluation and optimization criteria (Schittenhelm & Landex 2012):

- Robustness of timetable (what parameters can be controlled by each stakeholder?)
- Attractive transfer options

- Capacity consumption on line sections
- Travel time
- Societal acceptance (coordination between stakeholders)
- Systematic timetable (e.g. 3 time periods during a day with an hourly repeating timetable pattern)

After creating the list of criteria above, it was mentioned that the cost side of timetabling was not covered. It was also stated that it cannot be assumed that availability of rolling stock and train staff is known beforehand in the timetabling process. The theoretical timetable cannot take into account all possible flaws during the practical execution (Schittenhelm & Landex 2012).

Likewise the socio-economic aspect of trains running on time should also be included in the list of timetabling criteria. Questions like, how many timetable train paths are lost and/or how many passenger trains are obstructed by stopping a freight train on its run should be given a socio-economic answer in form of the value loss for society (Schittenhelm & Landex 2012).

A common approach of the concept of timetable robustness was discussed. The result was that robustness consists of the following main elements:

- Elements that can be controlled by stakeholders, e.g. timetabling process with a high quality level and maintenance level of rolling stock and infrastructure
- Elements that cannot be controlled, e.g. extreme weather conditions and vandalism

Furthermore it was discussed that a punctuality level of 90% of on time trains should be delivered by DSB to its customers. This was not happening at the time of the workshop. The punctuality level of the requested timetable train paths at RND is above the 90% level. In the end reached punctuality levels depend on human and material factors.

To ensure that all stakeholders present at the workshop agreed on the listed timetabling criteria they were given a short description:

1. Robustness of timetable
    - Trains are running on time.
    - The ability to absorb delays
    - Other topics beyond formal demands to the timetable

2. Attractive Transfer options
    - Connectivity in public transport

3. Capacity consumption on line sections
    - Choice of train path structure in the timetable
    - Infrastructure perspectives

4. Travel time
    - Direct connections

5. Societal acceptance
    - Minimum service levels
    - Prioritization between freight and passenger traffic
    - Socio-economics (how do we get the most value for society?)
    - National traffic politics (strategy for railways)

6. Systematic timetable
    - Repeating timetable patterns
    - Scalability (increasing and decreasing service levels during a day)

According to the workshop agenda this reduced list of timetable evaluation and optimization criteria should have been reached by using the simple scoring technique. As the workshop progressed it turned out that this was not necessary as the participants could create this list by their own initiative through dialogue and discussions (Schittenhelm 2011b, Schittenhelm & Landex 2012).

The organizers decided that the ranking of these selected timetabling criteria should be done by applying the simple scoring technique. Each stakeholder received 3 votes and had to give 3 different criteria 1 vote each. Table 7.9 gives an overview of the selected timetabling criteria and the number of stakeholder votes each criterion received (Schittenhelm & Landex 2012).

Criterion	Number of votes
Robustness of timetable	2
Capacity consumption on line sections	3
Systematic timetable	3
Societal acceptance	2
Travel time	1
Attractive transfer options	1

Table 7.9: Selected timetabling criteria and their votes

Realizing that the criteria fell into three groups of two criteria each with the same number of votes, a discussion started about the necessity to differentiate the importance of two criteria with the same number of votes. The three groups were considered separately.

Capacity consumption on line sections vs. Systematic timetable
For the stakeholders at the workshop it made perfect sense that these two criteria had achieved the same number of votes. They are very much interlocked with each other. Therefore it was decided not to make one criterion more important than the other.

Robustness of timetable vs. Societal acceptance
Both criteria contain a societal aspect on railway traffic. Society can and must accept that train delays will occur. On the other hand you cannot have a timetable that is not accepted by the society. Other aspects of timetable robustness are covered by the other timetable evaluation and optimization criteria. In the end timetable robustness is the quality level of the puzzle of compromises that the timetabling process is. The conclusion of the discussion was that these two criteria should have equal importance.

Travel time vs. Attractive transfer options
To make the railway attractive as a transportation system it has to offer attractive travel times. Here one must also think about the socio-economic aspect of planned travel times in a timetable. If you are working with a

systematic timetable structure it becomes easier to plan with attractive transfer options. There is a big potential in reducing travel times for passengers using the public transport system if transfer times are coordinated within the same mean of transportation but also between different means of transportation such as trains and busses. Since there can be argued for and against both criteria, the workshop participants again decided that these two criteria have the same importance.

The final result of the complex planning workshop in regards to creating a common Danish list of timetable evaluation and optimization criteria is shown in Table 7.10 (Schittenhelm & Landex 2012).

Level of importance	Timetable evaluation and optimization criteria
High (3 votes)	Capacity consumption on line sections & Systematic timetable
Medium (2 votes)	Robustness of timetable & Societal acceptance
Low (1 vote)	Travel time & Attractive transfer options

Table 7.10: Final result of the complex planning workshop (Schittenhelm & Landex 2012)

7.4.5 Workshop conclusions

The timetabling criteria workshop was rounded off and the organizers and participants took stock of the made experience. It was concluded that there had been some good and useful discussions that had helped to create a better mutual understanding about timetables and the evaluation and optimization of these. A first version of a common Danish list of timetable evaluation and optimization criteria had been created and it was hoped that this could become a first step in improving the future timetabling process and thereby also future timetables (Schittenhelm & Landex 2012).

The Danish railway sector, as any other European railway sector, is very much affected by the present political climate. Therefore today's focus and strategy can be different next year. This can make it necessary to repeat the process from the timetabling criteria workshop in a few years. Representatives from the railway sector have to take this kind of specific railway discussions and bring them to the attention of the surrounding society and find out what point of view the society has towards these topics. The basis for this could be the found six timetabling criteria and present them to the Danish society. A possibility to get access to a wider audience could be to work through organizations such as Transportøkonomisk Forening (in English Danish Association of Transport Economics) and maybe contact traffic political spokesmen from the different Danish political parties in the parliament (Schittenhelm & Landex 2012).

The found criteria should be defined according to a higher level of detail to make them more operational. One or several key performance indicators should be attached to each of them. This might prove straight forward for some criteria and more complex for others. Different opinions were presented at the workshop and this can have made the criteria descriptions and definitions ambiguous. Ambiguous criteria descriptions can make it more difficult to create KPIs (Schittenhelm & Landex 2012).

To the question if a workshop like this should be repeated, the participants answered that it would be interesting to see how things had developed in a few years' time. It would be of big advantage if the qualitative and quantitative version of this timetabling topic could be presented at the same time. The quantitative explanation could back up the qualitative description of each timetabling criterion (Schittenhelm & Landex 2012).

Finally it was stated that a new quantitative methodology, based on a socio-economic approach, has to be developed for the balancing between future passenger and freight railway traffic when allocating the limited infrastructure capacity to the different applying TOCs. Which mixture of passenger and freight trains should be used and which priority should be given to each train category in the timetabling process (Schittenhelm & Landex 2012).

During the workshop all company representatives participated actively in the ongoing discussions. The facilitators did not have a feeling of some participants holding back opinions or being suppressed by other participants. It could be feared that some participants would be holding back their opinions due to their own role in the railway sector and that of other participants at the workshop, e.g. being the national railway authority or the only national IM responsible for preparing the timetable (Schittenhelm & Landex 2012).

Sometimes dominating personalities can take control of a workshop session but the facilitators did not register this behavior at the workshop. The facilitators had not discussed what to do in this case prior to the workshop and would have needed to improvise actions to overcome this potential problem. It must also be said that all workshop participants knew each other beforehand and that this fact also can be considered being a danger for affecting how the participants acted during the workshop (Schittenhelm & Landex 2012).

7.4.6 Participants evaluation of the workshop

At the end of the timetabling criteria workshop each participant received an evaluation survey for the workshop and was asked to fill this out anonymously before leaving DTU. All eight participants did so and the results are presented in Table 7.11 and Figure 7.9.

The workshop participants were faced with ten prepared statements, see second column in Table 7.11, and they had to decide whether they agreed with this or not. Statements 1-4 are focusing on the timetabling criteria presented during the workshop and statements 5-10 are looking at the workshop and the processes applied. It was possible to choose between five categories of agreement: Agree very much, agree, neither nor, disagree and disagree very much. See right side of Table 7.11 for the sums of each category for each statement. Figure 7.9 shows the same sums but as a bar chart. This is to improve the overview of the evaluation survey results.

Nr.	Statement	☺☺	☺	😐	☹	☹☹
1	I agree to that the selected criteria are relevant	5	3			
2	I think the definitions of the criteria are unambiguous		4	2	2	
3	I think the criteria are applicable		6	2		
4	I agree with the selection of criteria	3	4	1		
5	I think there was enough time available for the workshop	3	4		1	
6	I think the applied methods were easy to understand	3	5			
7	I think the applied methods made it easy to participate	5	3			
8	I think my opinions were heard	3	5			
9	I think I learned something by participating in the workshop	2	6			
10	I would recommend others to participate in a similar workshop	2	5	1		

Table 7.11: Results of the evaluation survey for the timetabling criteria workshop at DTU Transport

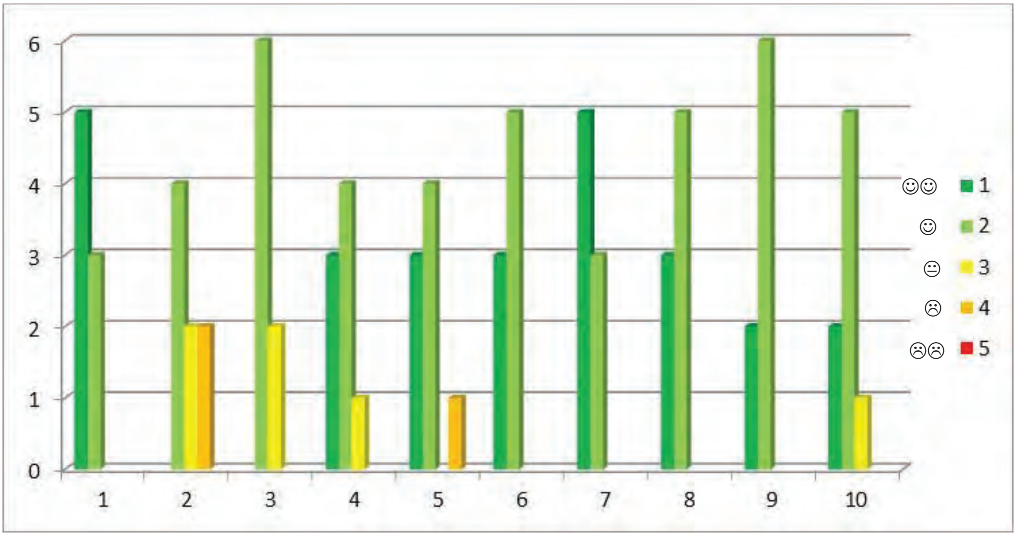


Figure 7.9: Results from the evaluation survey shown as a bar chart

The evaluation survey also gave the participants the possibility to give written comments about the just experienced timetabling criteria workshop. These have been translated from Danish to English and are listed below.

Received written comments:

1. The participants at this workshop are very diverse and have different and sometimes conflicting interests which can make the interpretation of the criteria ambiguous. More detailed definitions of the criteria are needed.
2. Good initiative.
3. Good selection of invited participants giving an appropriate broad representation of the railway sector.
4. Even though the criteria were discussed and "dissected" you are sitting with a feeling of "no one gave way".
5. It is doubtful if the workshop can "move" things forward. The railway sector is very anarchistic and one's own qualities outshine everything else.

None of the workshop participants disagreed very much with any of the ten statements. Two participants disagreed with statement two (unambiguous criteria) and one participant disagreed with statement five (enough time). Statement two was given the most "negative" evaluation followed by statement three (applicable criteria). Statements 1, 6, 7, 8 and 9 only got agreeing votes. The most probable reason for the registered disagreement with statement number two and three is actually very well described in the first written comment. Diversity of participants and conflicting interest make it highly necessary to agree on a very detailed definition of each criteria presented at such a workshop. This is a very important lesson learned for future workshops of this kind in the Danish railway sector.

Statement one (agreement with criteria) and seven (easy to participate) achieve the best scores with six "I agree very much" and two "I agree" votes each. There is agreement among the participants about the selected overall timetabling criteria for the Danish railway sector. This also indicates that no participant felt overruled at the workshop. Achieving a short list of timetabling criteria by participant initiated dialogues and discussions and prioritizing these found criteria by giving each participating company a number of votes was a good way for all workshop participants.

Second best score was achieved by statements six (methods were easy to understand) and eight (every opinion was heard) with three votes “I agree very much” and five votes “I agree” each. This shows that the held workshop with its agenda as a concept was a success and could be reused for future timetabling criteria workshops.

Finally it should be pointed out that all participants learned something by participating in the first held Danish timetabling criteria workshop. Statement nine (I learned something) got two votes “I agree very much” and six votes “I agree”. This is very positive and hopefully indicates that future dialogues between Danish railway timetable stakeholders can be more fruitful.

7.5 Discussion of results from interviews and workshop

It was very unfortunate that so much time passed between the initial stakeholder interviews and the joined timetabling criteria workshop at DTU. A year passed between the two events and this had an effect on the workshop. When looking at Table 7.8 big differences between interviewed company employees and workshop company participants can be seen. The long time span and this missing continuity of participants could potentially have caused many changes in the prioritized lists of evaluation criteria from the interviews and have prolonged the first part of the workshop substantially and thereby have made progress more difficult. New stakeholder representatives bring with them new opinions and this could have led to bigger disagreements at the workshop. On the other hand this unwanted process prolongation indicates a high level of continuity amongst stakeholders in regards to their timetable evaluation and optimization criteria which increases the trustworthiness of the interview results (Schittenhelm & Landex 2012).

Table 7.12 gives an overview of the results achieved with the round of stakeholder interviews and the timetabling criteria workshop. This is based on Table 7.9 and Table 7.10. From the round of interviews it was possible to get a specific ranking of the first four criteria. The following two criteria both got five prioritization points and are therefore considered equally important. At the workshop it was not possible to give individual ranks to the identified timetabling criteria. They were grouped in three layers with two equal important criteria in each layer (Schittenhelm & Landex 2012).

<table>
<tr><th>Rank</th><th>Interview criteria</th><th>Workshop criteria</th></tr>
<tr><td>1</td><td>Robustness of timetable</td><td rowspan="2">Capacity consumption on line sections & Systematic timetable</td></tr>
<tr><td>2</td><td>Periodic timetable is preferable</td></tr>
<tr><td>3</td><td>Low level of scheduled waiting time</td><td rowspan="2">Robustness of timetable & Societal acceptance</td></tr>
<tr><td>4</td><td>Attractive transfer options for trains and busses</td></tr>
<tr><td>5</td><td rowspan="2">Compliance with traffic tender demands & Coordinated international timetable train paths</td><td rowspan="2">Travel time & attractive transfer options</td></tr>
<tr><td>6</td></tr>
</table>

Table 7.12: Overview of interview and workshop results (Schittenhelm & Landex 2012)

When looking at rank one and two criteria, only one common criterion can be found in the results: “Systematic/periodic timetable”. This is no surprise. A surprise is that the criterion “Robustness of timetable” only was ranked third/fourth at the workshop but attained the first rank when looking at the interviews. Reason for this shift in priority is probably the workshop discussion about assuming that a given prepared timetable is robust. Taking this criterion for granted in all timetables reduces its priority potential. The introduction of “Societal acceptance” of the timetable as an evaluation criterion also reduced the priority potential of the “Robustness of timetable” criterion since they due overlap to some extent (Schittenhelm & Landex 2012).

The last shared timetabling criterion is “Attractive transfer options” This was put in the third layer with the fifth and sixth rank at the workshop but held a fourth rank in the interview results. With the introduction of the new “Societal acceptance” criterion during the workshop the “Attractive transfer options” criterion was pushed down to a lower workshop priority. Reason for this could again be an overlap between these two criteria (Schittenhelm & Landex 2012).

Evaluation criterion ”Societal acceptance” holds many aspects and thereby connections to other criteria. If society in general demands a very high service level on the railway network, this will increase the number of running trains, hereby also the capacity consumption on line sections, and the complexity of the train path structure in a given timetable. Hereby the risk of train delays gets higher and fewer trains will run on time. A similar potential conflict exists between the criterion “Travel time” and the aspect of a high service level. It must be assumed that there is an increasing risk of higher levels of scheduled waiting time in a timetable with a heterogeneous traffic mix to provide more direct connections (Schittenhelm & Landex 2012).

The workshop criterion “Utilization of capacity on line sections” is not found directly among the interview criteria. But to be able to have a “Low level of scheduled waiting time” the “Utilization of capacity on line sections” must follow some rules in regards to the mix of traffic (Schittenhelm & Landex 2012).

TOC Arriva Denmark was not present at the workshop and this might be the reason for that the interview criterion “Compliance with traffic tender demands” is not found among the workshop criteria. It can be assumed that both the DTA and TOC DSB do not see this as an evaluation criterion but merely as a necessity for being allowed to run trains on the Danish railway network (Schittenhelm & Landex 2012).

Even though TOC DB Schenker Rail Scandinavia was present at the workshop, their top ranked “Coordinated international timetable train paths” timetable evaluation criterion from the interview did not make it to the list of workshop criteria. Most probably the complete change in representatives from DB Schenker Rail Scandinavia between the interview and the workshop is reason for this (Schittenhelm & Landex 2012).

7.6 Supplemental stakeholder interviews

After the timetabling criteria workshop had been conducted it was decided to arrange a series of supplemental interviews with timetable stakeholders that had not been part of the first round of interviews. Some of these are not as closely involved in the preparation of the national timetable as the earlier interviewed stakeholders, whereas the newest stakeholder has a big influence on the preparation of the timetable. For these interviews, the agenda was the same as for the first round of interviews. See section 7.2.

The supplementary stakeholders are: “The Danish Ministry of Transport”, The regional railway companies “Lokalbanen” and “Regionstog”, which are both IMs and passenger TOCs for small regional railway networks, the Swedish freight TOC Hector Rail and the recently formed ministerial “Punctuality Task Force for the Danish railway sector”. In the following five sections the interviews are presented. Danish ministry of transport in section 7.6.1, the railway companies Lokalbanen and Regionstog in section 7.6.2 and 7.6.3

respectively, freight TOC Hector Rail in section 7.6.4 and the Punctuality Task Force of the Danish railway sector in section 7.6.5.

7.6.1 Interview with the Danish Ministry of Transport

This interview was conducted at the Danish Ministry of Transport in Copenhagen. Chief consultant Bastian Zibrandtsen from the railway department was representing the ministry.

To the ministry it is generally very important that the national railway timetable is socio-economically beneficial for society and in the best case achieves an optimal socio-economical score. From the ministry's point of view there are several levels on where to improve future timetables. A key issue is to be able to calculate the socio-economic value of different train types, such as an InterCity-Express train, a local train, a transit freight train and a local freight train. Based on these values a socio-economic optimal mix of trains can be calculated. Similarly a socio-economic optimum must be calculated for the relation between number of trains, level of capacity consumption, and punctuality of a given timetable.

The list of prioritized timetable evaluation criteria created by the Danish ministry of transport can be seen below:

1. Train travel times - including scheduled waiting time
2. Punctuality and reliability of the timetable
3. Transportation capacity with the timetable
4. Average waiting time at stations – frequency of train services
5. A socio-economic approach to timetable train path conflict resolution between TOCs

7.6.1.1 Train travel times

To make the railway an attractive means of transportation it must be able to achieve competitive timetabled travel times compared to alternative forms of transportation. Train travel time is basically dependent on rolling stock and infrastructure characteristics, stopping patterns of trains and the potential necessary scheduled waiting time for trains to create an overall feasible timetable. Travel time is an important parameter in a socio-economic calculation.

7.6.1.2 Punctuality and reliability of the timetable

Punctuality refers to train delays. Delayed passengers are an expense to society from a socio-economic point of view. It is assumed that passengers are losing productive working time and/or quality leisure time when being delayed. With today's information technology the first is necessarily not the case for a business trip since it has become possible to work with computers and being online while traveling by train and therefore no productive time is being lost when delays occur. If passengers get delayed on a leisure trip the delay will most likely reduce the leisure time to some degree.

Delayed freight trains are also an expense to society since they can cause costs for production companies. This is specially the case for just in time deliveries or narrow delivery time spans for e.g. car production factories or coal power plants.

Reliability of a timetable refers to the number of train runs that have been carried through compared to the number of planned trains. Cancellations of trains occur e.g. in case of rolling stock break down and major infrastructure problems reducing capacity drastically. If a train is not available to a customer this will cause a delay equal to the frequency of the specific train service or the headway time to the next train servicing the given destination. Cancelled trains can therefore be reason for big delays and passengers are not likely to be able to use the delay in the same productive way as when sitting in a train when being delayed.

7.6.1.3 Transportation capacity with the timetable

Depending on the attractiveness of the railway as a transportation system there will be a need to transport a certain number of passengers and amount of goods throughout the railway network. Based on the available rolling stock and infrastructure capacity the timetable must ensure that the necessary transportation capacity is being provided for the society. This demand for transportation capacity will vary during the day and therefore the timetable must be flexible and adapted accordingly. A certain degree of planning freedom in the timetabling process is therefore necessary. Periodic timetables are preferable but different timetable patterns during the day must ensure an optimal transportation capacity. To achieve optimality there may occur major differences between timetable patterns, since modern information technology makes real-time detailed timetable information easily available to passengers. The need for repeating and memorable patterns is therefore lower compared to earlier.

Train operation creating too much transportation capacity is costly for society due to several reasons:

1. Payments for more train staff
2. Purchases of not needed rolling stock units
3. Maintenance costs for rolling stock – both material and staff
4. Maintenance costs for infrastructure – both material and staff

The attractiveness of the railway depends mainly on train travel times and frequency of train services. A minimum frequency of passenger train services is given through the minimum service level defined in traffic contracts between the National Transport Authority and TOCs and therefore paid for by the Danish government. TOCs can run additional trains on their own costs to increase the attractiveness of their train services and thereby improve passenger numbers and their earnings.

7.6.1.4 Average waiting time at stations

According to the earlier presented interview with TOC DSB, this parameter depends on the frequency of train services at a given station. See section 7.2.1. The Danish ministry of transport agrees with DSB on how to calculate the average waiting time at railway stations.

7.6.1.5 A socio-economic approach to timetable train path conflict resolution between TOCs

In the case of a conflict between two TOC in regards to their capacity application to the IM, the conflict must always be solved with a socio-economic optimal approach. Thereby the solution will always be beneficial for society. This approach demands that a socio-economic value can be calculated for each of the involved trains for each possible conflict solution. Calculation of the socio-economic value for an individual train is difficult and not being done today. The most socio-economic valuable conflict solution should be given priority in the conflict.

This new socio-economic approach to timetable train path conflict resolution should be developed and replace the present legislation for the IM when dividing the infrastructure capacity between TOCs. It must consider the consequences of the operating economy for the involved TOCs.

7.6.2 Interview with the regional railway company "Lokalbanen"

Lokalbanen is both IM and TOC for a smaller regional railway network north of Copenhagen consisting of five railway lines: Nærumbanen (Jægersborg - Nærum), Frederiksværkbanen (Hillerød – Frederiksværk -

Hundested), Lille Nord (Hillerød – Fredensborg - Helsingør), Gribskovbanen (Hillerød – Kagerup – Tisvildeleje/Gilleleje) and Hornbækbanen (Gilleleje – Hornbæk - Helsingør). Figure 7.10 shows a map of the railway network. All lines are single tracked. The rolling stock fleet consists of 25 Alstom Coradia Lint DMU. Ten of these train sets are equipped with a passenger counting system and GPS. These trains provide very detailed data for passenger numbers and arrival and departure times at stations. The interview took place at the company's main office in Hillerød and head of planning Henrik Henriksen was the representative of Lokalbanen.

Figure 7.10: Map of the railway network of Lokalbanen (http://www.lokalbanen.dk/Køreplaner.aspx (05.01.2013))

Lokalbanen's list of prioritized timetable evaluation criteria is as follows:

1. A realistic/feasible and robust timetable
2. Attractive transfer options to other trains and busses
3. A periodic timetable with fixed frequencies of train services adapted to market demands
4. Short train travel times - including non-stop express trains
5. High level of production efficiency - using optimal rostering plans for rolling stock and staff

7.6.2.1 A realistic/feasible and robust timetable

This is by far the most important criterion. Applied running times for trains between stations must be feasible and thereby realistic. At Lokalbanen feasible running times are based on the many years of experience from train drivers and planners plus data collected from the ten train sets with extra equipment. Running times of trains are not calculated and simulated with a computer at Lokalbanen.

If a timetable is realistic it is also robust according to Lokalbanen. When preparing the timetable there are no specific planning rules according to the use of running time supplements or buffer times between trains. This is again based on the vast experience of the employees, the collected data from the ten equipped trains and the detailed timetable structure itself. Planned running times depend e.g. on whether a train crossing takes place at a given crossing station or not. On some line sections the running times for trains are tight due to the long distance between crossing stations. Train drivers are informed about this and drive accordingly.

7.6.2.2 Attractive transfer options to other trains and busses

To make public transportation more attractive as a whole it is important to provide attractive transfer options to passengers. Lokalbanen has a close collaboration with TOC DSB and the regional transport services organization, called MOVIA, to ensure attractive transfers to other train and bus services. Lokalbanen is working with a hub concept in Hillerød where it is possible to transfer between all Lokalbanen train services twice per hour during day hours and once per hour during evening and night hours. It has become clear to Lokalbanen that train passengers transfer between the train services to/from Frederiksværk and to/from Helsingør in Hillerød.

Recently Lokalbanen has increased the focus on attractive transfers to bus services at Frederiksværk, Helsinge and Fredensborg stations. If possible a hub concept is implemented, where trains from Lokalbanen cross at the given station and all bus services do the same at the same time. If a station is the terminus for a bus service the turnaround time of the bus ensures transfers options to both trains and other buses.

A peculiar transfer options is to the ferry between Hundested and Rørvig. To have an attractive transfer between the ferry and Lokalbanen is very important to the local communities in Hundested and Rørvig. Furthermore, this ferry line is also connected by bus with the ferry line between Sjællands Odde and Ebeltoft/Aarhus. The latter being an important traffic link on a national level.

During day time hours Lokalbanen is not waiting for delayed trains or busses to ensure planned transfers. Only during evening and night hours when Lokalbanen is running with a lower frequency do the trains from Lokalbanen wait – but only a little. Lokalbanen is though willing to make changes to the timetable during evening and night hours to achieve better transfer options to other train and bus services.

7.6.2.3 A periodic timetable with fixed frequencies of train services adapted to market demands

Except for the railway line between Nærum and Jægersborg, Lokalbanen has implemented a fixed periodic timetable where train services have a frequency of 30 min during day hours and run once per hour during evening and night hours (DSB 2011d). Figure 7.11 shows the timetable for the train service running between Hillerød and Tisvildeleje.

Hverdage	5.50–19.20		19.50–23.50
København H	05	B 35	05
Hillerød	45	15	45
Hillerød	50	20	50
Slotspavillonen	53	23	53
⊗ Gribsø	A 57	–	57
⊗ Kagerup	59	29	59
⊗ Duemose	01	31	01
Helsinge	07	37	07
⊗ Laugø	–	39	09
⊗ Ørby	11	–	11
Vejby	15	45	15
⊗ Holløse	A 16	46	16
⊗ Godhavn	A 18	48	18
Tisvildeleje	21	51	21

Hverdage	5.24	5.54–19.54		20.24–23.24
Tisvildeleje	24	24	54	24
⊗ Godhavn	26	26	56	26
⊗ Holløse	27	27	57	27
Vejby	30	30	00	30
⊗ Ørby	32	32	–	32
⊗ Laugø	34	–	04	34
Helsinge	38	38	08	38
⊗ Duemose	41	41	11	41
⊗ Kagerup	44	A 44	14	44
⊗ Gribsø	–	A 45	–	45
Slotspavillonen	52	52	22	52
Hillerød	56	56	26	56
Hillerød	02	02	B 32	02
København H	42	42	B 12	42

Figure 7.11: Timetable for the train service between Hillerød and Tisvildeleje on weekdays. Driving direction Hillerød → Tsivildeleje (left) and Tisvildeleje → Hillerød (left) (Lokalbanen 2012a)

7.6.2.4 Short train travel times - including non-stop express trains

To increase the attractiveness of Lokalbanen on the line between Hundested and Hillerød the railway infrastructure was upgraded from a maximum speed of 75 to 100 km/h between the towns of Frederiksværk and Hillerød. Additionally a new express train service between Hundested and Hillerød has been introduced. This train service has fewer stops and reduces travel time between Hundested and Hillerød by ca. 13min. It has become a great success and increased the number of passengers with more than 10% on this Lokalbanen railway line.

Lokalbanen is now looking at the possibility to implement a similar traffic concept on the railway line between Hillerød and Helsinge. An analysis of the infrastructure is needed to find out how much must be invested to upgrade the line speed from 75 to 100 km/h and feasible timetable concepts with express train services must also be investigated. To begin work on the analyses, Lokalbanen needs funding from the local regional politicians. With the success from the Frederiksværk – Hillerød line in mind, Lokalbanen is optimistic about getting the necessary local political support.

7.6.2.5 High level of production efficiency - using optimal rostering plans for rolling stock and train staff

The owners of Lokalbanen, the regional politicians, expect a high level of production efficiency from the railway company. To achieve high production efficiency the rostering plans for both rolling stock and train staff must ensure an efficient use of company resources - optimal if possible. Preparation of rostering plans is again based on the experience from employees at Lokalbanen. No operational research tools are applied in the creation of rostering plans. Agreements between worker unions and Lokalbanen, but also local agreements between the company and its employees must always be respected when creating rostering plans.

7.6.3 Interview with the regional railway company "Regionstog"

As is the case with the railway company Lokalbanen, Regionstog is also both IM and TOC for a smaller regional railway network. The network consists of several separated single tracked railway lines: One south (Østbanen), two west (Tølløsebanen & Odsherredsbanen) and one southwest (Lollandsbanen) of Copenhagen. Figure 7.12 shows a map of the railway network. Rolling stock consists of 17 Alstom Coradia Lint DMU and 13 IC2 DMU produced by Adtranz (today Bombardier). More than half of the train sets are equipped with advanced passenger counting and GPS location equipment. This equipment makes it possible to get very precise data for passenger numbers and punctuality levels for arrival and departure times at stations. Senior timetable planner Michael Jensen was representing Regionstog in a telephone-interview.

Regionstog's list of prioritized timetable evaluation criteria is as follows:

1. A feasible timetable
2. Attractive transfer options
3. Robustness of the timetable
4. Utilization level of rolling stock in rostering plans
5. Operational costs of the timetable

Regionstog is taking part in quarterly contact-meetings hosted by the public transport service company MOVIA, where all public traffic operators meet to amongst other things discuss next year's timetable. As soon as TOC DSB has described their detailed vision for the future timetable, Regionstog starts to prepare their matching timetable. Regionstog must apply for infrastructure capacity when running on Rail Net Denmark's railway network. The final detailed timetable is prepared during September and handed in to MOVIA for acceptance in the beginning of October. Getting the acceptance from MOVIA normally takes two weeks. In the second half of October the timetable is transferred from the timetabling office to Regionstog's customer center where it is readied for publication and data fed into the national online journey planner "Rejseplanen".

Figure 7.12: Map of the railway network of Regionstog (http://www.regionstog.dk/koereplaner/ (28.09.2012))

7.6.3.1 A feasible timetable

The number of potential feasible timetables is limited by restrictions given by the infrastructure and rolling stock characteristics. Line speeds, location of crossing stations and driving characteristics of the rolling stock are the most limiting parameters in regards to feasible timetables. In the start phase of preparing the yearly timetable for next year, several timetable variants are investigated but these are quickly reduced to one.

Regionstog has bought the software tool "Trapeze" which amongst other things can help with the creation of rostering plans for public transport (www.trapezegroup.com.au (28.09.2012)). Trapeze is applied when creating the rostering plans for rolling stock and train staff matching the yearly timetable. Using Trapeze ensures the feasibility of the prepared rostering plans.

7.6.3.2 Attractive transfer options

Regionstog has special focus on providing attractive transfer options between Regionstog and DSB trains. Up to 15% of the daily passengers are commuting between stations served by Regionstog trains and the Copenhagen area. To optimize the transfer options at Holbæk station to fit the primary traffic direction in rush hours, the timetable pattern changes at midday. This can be seen in Figure 7.13. Trains coming from Copenhagen in the morning have one attractive transfer option per hour at Holbæk station (arrival 08+38 – departure 13+32). This is increased to two in the afternoon (arrival 08+38 – departure 13+44). Same concept can be seen for the travel direction towards Copenhagen. Here there are two attractive transfers in the morning and only one in the afternoon. Scheduled transfer times in the late evening ensure that transfers can be kept even if trains are running with minor delays. Transfer time from Copenhagen is 15 minutes and to Copenhagen 12 minutes. The minimum defined transfer time between trains at Holbæk station is 4 minutes. This timetable concept is also applied for Tølløsebanen in regards to train transfers at Tølløse station.

Tog fra København:				Faste minuttal 5.06 - 12.06		Faste minuttal 13.06 - 18.06			Faste minuttal 19.36 - 22.36
København H	afg.	–	–	06	–	06	36	18.36	36
Roskilde	afg.	–	–	33	–	33	03	19.03	05
Holbæk	ank.	–	–	08	–	08	38	19.38	38
Mandag - fredag				Faste minuttal 6.12 - 13.32		Faste minuttal 14.12 - 19.12			Faste minuttal 20.53 - 23.53
Holbæk	afg.	5.12	5.32	12	32	12	43	19.43	53
Stenhus		5.13	5.33	13	33	13	44	19.44	55
Ny Hagested		|	5.38	|	38	|	50	19.50	59
Gislinge		5.21	5.45	21	45	21	56	19.56	04
Svinninge		5.25	5.49	25	49	25	00	20.00	08
Hørve		5.29	5.53	29	53	29	03	20.03	12
Fårevejle		5.33	5.57	33	57	33	07	20.07	16
Asnæs		5.36	6.01	36	01	36	10	20.10	20
Grevinge		5.39	6.04	39	04	39	13	20.20	24
Vig		5.45	6.09	45	09	45 *	18	20.25	30
Nr. Asmindrup		5.50	6.13	50	13	50 *	23	20.30	34
Sommerland Sj. ✦		5.51	6.14	51	14	51 *	24	20.31	35
Højby		5.54	6.18	54	18	54 *	28	20.35	38
Nyled		5.56	6.20	56	20	56 *	30	20.39	40
Nykøbing Sj.	ank.	6.01	6.26	01	26	01 *	36	20.43	43

Mandag - fredag		Faste minuttal 5.04 - 13.31		Faste minuttal 14.04 - 19.04			Faste minuttal 20.56 - 22.56	
Nykøbing Sj.	afg.	04	31	04	39	20.00	56	23.56
Nyled		06	33	06	41	20.02	58	23.58
Højby		09	36	09	44	20.05	01	0.01
Sommerland ✦		10	37	10	45	20.06	02	0.02
Nr. Asmindrup		13	40	13	50	20.09	05	0.05
Vig		18	45	18	54	20.14	11	0.11
Grevinge		24	50	24	58	20.20	17	0.17
Asnæs		28	54	28	02	20.24	20	0.20
Fårevejle		33	57	33	07	20.28	25	0.25
Hørve		37	01	37	11	20.32	29	0.29
Svinninge		40	05	40	15	20.35	32	0.32
Gislinge		45	09	45	20	20.40	37	0.37
Ny Hagested			11		22	20.42	39	0.39
Stenhus		51	19	51	29	20.46	43	0.43
Holbæk	ank.	55	22	55	33	20.50	47	0.47
Skift til tog mod København:		Faste minuttal 5.59 - 14.29		Faste minuttal 14.59 - 19.59			Faste minuttal 21.59 - 23.59	
Holbæk	afg.	59	29	59	–	20.59	59	–
Roskilde	ank.	32	02	32	–	21.32	32	–
København H	ank.	00	30	00	–	22.02	02	–

Figure 7.13: Weekday timetable for Odsherredbanen 2012. Travel direction from Copenhagen central station (København H) (left) and travel direction to Copenhagen central station (København) (right) (Regionstog 2012)

7.6.3.3 Robustness of the timetable

Ensuring the robustness of the yearly timetable is mainly based on experience, both that of the timetable planner and that of Regionstog as a railway company. Most of the experience has been gained by “learning by doing”, but train test runs have also been conducted in connection with larger changes in the yearly timetable.

Train punctuality data is collected from the train sets fitted with GPS equipment. These data are analyzed by the timetable planner and can give rise to future timetable adjustments if e.g. a train delay trend can be recognized and explained.

As mentioned earlier, the potential number of feasible timetables is rather low due to infrastructure and rolling stock restrictions. In continuation of this, Regionstog does not use a fixed percentage in running time supplements but works with flexible running time supplements. This makes timetable creation easier.

Since attractive transfer options to/from DSB trains are very important to Regionstog, a buffer time is added to the minimum needed transfer times at stations. In rush hour time intervals this buffer time is kept to a minimum since there are more transfer options per hour whereas the buffer time is increased during evening hours where trains only run once per hour.

To ensure that delays do not spread from Odsherredbanen to Tølløsebanen, rolling stock and train staff are dedicated to only one of these lines throughout an operational day. If a train set should be transferred during the day, it is only after a longer service break at the depot, thereby guaranteeing a large buffer time that can absorb potential delays. Train staff is dedicated to one railway line only.

Traffic dispatchers at the centralized traffic control center continuously follow up on the actual traffic situation and based on this give prioritization to each train. This is done to minimize train delays and thereby passenger delays as much as possible.

7.6.3.4 Utilization level of rolling stock in rostering plans

A large train fleet gives the railway company Regionstog a rather large reserve of train sets. Percentage wise this is up to 33% on several railway lines. This is both a luxury and a problem. A luxury because trains do not have to run more kilometers than minimum necessary before they must be inspected and cleared for further train runs. When a train set is scheduled to be moved from one railway line to another it is possible to make it in two steps rather than one. The train set is put on standby before it is finally moved, thereby building in a large buffer time. A problem because train sets should be in use with only short intervals of standby or service time, to keep all technical parts “in shape”. When preparing rostering plans for rolling stock the timetable planner takes these issues into consideration.

Rolling stock rostering plans are first roughly prepared in an Excel spread sheet and then finalized in the software tool Trapeze. Both process steps are done manually by the timetable planner. Trapeze is also used for the publication of both train staff and rolling stock rostering plans internally in the company.

The railway company Regionstog is looking into future possibilities of extending their train services on the railway network of Rail Net Denmark. This is to make its services more attractive for passengers and thereby hopefully increasing the level of ridership. These future plans are possible because of the large reserve of train sets available to Regionstog.

7.6.3.5 Operational costs of the timetable

MOVIA is the transport services organization that operates public bus and part of the train transport in the greater Copenhagen area and on the island of Zealand. Regionstog is operating their train traffic for MOVIA and must therefore keep the operational costs of the yearly timetable within a given budget. Minimizing the operational costs is based on earlier made experiences and is done in a simple approach. Until now there has always been some margin in the yearly budget from MOVIA and therefore estimated operational costs for the yearly timetable have always been accepted.

A future possibility to reduce operational costs is to lengthen the train services on Tølløsebanen from their current terminus at Tølløse station to Holbæk station. See Figure 7.12. Hereby only one train driver facility is necessary, at Holbæk station, compared with today, where Tølløse station also has a train driver facility.

7.6.4 Interview with the Swedish freight train operator Hector Rail

Since the beginning of 2008 the Swedish freight train operator Hector Rail has been running trains on the Danish railway network. Most of the freight trains are transit trains running between locations in Germany, e.g. the Ruhr industrial district and the shunting yard Hamburg-Maschen, and Sweden, e.g. the shunting yards at Halsberg and Malmö.

The interview was conducted via phone and Hector Rail was represented by planning director Hans-Åke Gustavsson.

Hector Rail’s list of prioritized timetable evaluation criteria is as follows:

1. The timetable fulfills the business demands given by the customers of Hector Rail
2. Robustness of the timetable
3. Train path capacity
4. Day to day stability of the timetable
5. Travel time of the trains

When looking at a list of timetable evaluation criteria all of them will be driven by customer demands. Therefore the name of the first criteria in the list prepared by Hector Rail can seem to entail all other criteria. A clarification is necessary and it must be underlined that the criterion focuses specifically on the business aspects.

Hans-Åke Gustavsson was of the opinion that Hector Rail's prioritized list of timetable evaluation criteria would not change drastically from year to year since Hector Rail is a private owned freight TOC and therefore is not directly affected by political issues as other state owned railway timetable stakeholders could be.

Another timetable evaluation criterion for Hector Rail would be the flexible pricing of freight train paths during an operational day. If it would be possible to avoid paying the additional fees for trains running through predefined infrastructure capacity bottlenecks during day time and rush hours a noticeable reduction in train path costs could be achieved. If these train paths could fulfill the customers' demands for departure, arrival and travel times they would be preferable. An optimized deployment of rolling stock and staff must still be possible or else a risk of increased overall production costs exists.

7.6.4.1 The timetable fulfills the business demands given by the customers of Hector Rail

The customers of Hector Rail create different kinds of business demands for Hector Rail but also the IMs:

- Number of train paths: A customer has a need to transport an amount of goods between two locations. Infrastructure characteristics and overall timetable constrains create limitations to maximum length and weight of a freight train. Therefore, more than one freight train can be necessary to transport the given amount of goods.

- Limitations to departure (origin) and arrival (destination) times for freight trains: If a freight train is loaded with raw materials for production or newly produced products there can be requirements for latest acceptable arrival and earliest possible departure. The timetabled train paths must make it possible for Hector Rail to fulfill these time limitations given by the customer.

- If a train service starts or terminates at a shunting yard, necessary connections to/from other freight train services must be ensured by the scheduled arrival and departure times at the shunting yard. When a freight train arrives at a shunting yard it is split up and carriages are sorted according to their next destinations. Minimum handling times of freight trains in a given shunting yard must be taken into account to ensure connections. This creates constrains on possible arrival and departure times for trains.

- Fixed handling times at intermodal terminals: The intermodal terminals in middle and southern Europe are heavily utilized and have become capacity bottlenecks for intermodal railway freight transport. Today the customers of Hector Rail are responsible for the booking of train handling times at intermodal terminals. Restricted flexibility of train handling times due to the high level of terminal utilization trains must arrive and depart at the terminal within short time spans.

7.6.4.2 Robustness of the timetable

It should be possible for freight trains to recover from delays of a certain magnitude. If a major traffic disruption incident has occurred it should be possible to recover a part of the train delay. The ability to recover from delays should be provided by adding buffer times to train travel times. A timetable planner does this by adding an agreed upon running time supplement to the minimum running times of the train. Hector Rail and IM RND have agreed upon a fixed running time supplement of 3% of the minimum running time. RND uses the same value for all freight train paths in the timetable. This is a part of the timetable planning rules.

Experience has shown that train paths based on the use of ad hoc capacity are more robust than train paths created during the yearly timetabling process. The reason for this is that ad hoc train paths are most often not as optimized in regards to attractive travel times as preplanned train paths are. Ad hoc train paths often contain a higher level of scheduled waiting time in form of overtakings by faster passenger trains and other freight trains(!) and prolonged travel times to avoid conflicts with other preplanned train paths.

When applying for infrastructure capacity with RND, Hector Rail plans with additional buffer times in connection with:

- Train stopping time at border crossing stations, e.g. Padborg station on the border between Denmark and Germany
- Stopping times at stations where the train driver is changed
- At stations where the train driver has a break
- Shunting maneuvers at stations and terminals

Hector Rail uses primarily Høje Taastrup station for train driver changes; train driver breaks and also performs shunting maneuvers to/from the intermodal terminal situated close to the railway station area. Shunting maneuvers also take place within the intermodal terminal at Taulov station and at Kolding station.

7.6.4.3 Train path capacity

To increase the ability of freight TOCs to compete with trucking companies each freight train should be able to run with maximum length and weight. This gives the potential to optimize the use of resources and thereby minimize the costs for the freight TOCs. Every scheduled freight train path in a given timetable should allow running freight trains with maximum length and weight. This is not the case today since infrastructure restrictions such as length of station tracks on used overtaking stations for a given train path can limit the length of a freight train.

To ensure that every freight train path allows for maximum length and weight of freight trains, the use of a periodic timetable is a big advantage. Once a basic timetable pattern allows for running freight trains with maximum length and weight this can be copied to other time periods of the day.

When preparing train paths for freight trains with maximum weight it is important that these trains are not planned to stop, for e.g. overtaking by a fast passenger train, shortly before uphill line sections with steep gradients. Long and heavy freight trains will not perform well when accelerating to higher speeds on a steep uphill railway line section.

In large railway networks, where a freight train can come from its origin to its destination along several different railway lines, on some of the railway lines there can be maximum axle load restrictions that can put limitations on the maximum weight of the train. There can potentially be differences in the permissible maximum train weight for train paths between two stations on a network reducing the ability to reduce costs for the freight TOCs.

7.6.4.4 Day to day planning stability of the timetable

IM RND prepares a yearly timetable for its entire railway network. This does not mean that the timetable is fixed for the entire timetable validity time period. There can be daily changes in the timetable due to smaller renewal and maintenance activities, e.g. track works or vegetation control, and due to immediate necessary repairs caused by infrastructure failures. Such activities can reduce the infrastructure capacity and therefore demand alterations to the timetable.

If these daily changes to the timetable have a certain magnitude, such as cancelations of train paths, larger translations of train paths or changes to an existing train path causing prolonged train travel times, it requires a high level of re-planning for the TOC. This is a costly affair for the TOC. Frequent changes in departure, arrival and travel times for freight trains combined with increased costs can reduce the attractiveness of the freight train product towards potential customers.

Freight TOC Hector Rail is therefore concerned with the day to day stability/uniformity of the yearly timetable. When preparing the yearly timetable, IM RND must aim for a high level of day to day stability of the timetable to ensure the competiveness of railway freight transport. This can be done by taking as many as possible of maintenance and renewal activities into account during the timetabling process and by adding the necessary level of time supplements to the timetable to minimize the impact of such activities.

7.6.4.5 Travel time of the train

As with passenger train traffic, the travel time of a freight train is an important competiveness parameter for the freight TOCs. The possible travel time of the freight train must fulfill the business demands of the customers, as described earlier, and it will be compared to possible travel times of trucks using the road system.

Hector Rail's opinion about freight train travel times through Denmark is that these times are attractive for the freight TOCs. Attractive travel times are a contradiction to timetable robustness. A high level of time supplements in the timetable will increase the robustness of the timetable towards minor delays but will lead to prolonged travel times. There will always be a tradeoff between these two factors when preparing a timetable. This trade of depends on many parameters such as: Reliability of railway infrastructure, reliability of rolling stock, reliability of terminals and reliability of train staff.

7.6.5 Interview with the Danish Rail Punctuality Task Force

The Danish Rail Punctuality Task Force was created in 2010 after a longer period with falling punctuality levels, mainly on the Coastal Line operated by DSB First. It is a collaboration between IM Rail Net Denmark, TOCs and the DTA. Rail Net Denmark was given the chairmanship of the task force. In the beginning of 2012 this was handed over to TOC DSB. Chairman Kim Andersen (2010-2011), RND, was representing the Punctuality Task Force and the interview took place at RNDs offices in Copenhagen.

The task force had two approaches to improve train punctuality:

1. Evaluation of the basic timetable structures
2. Revised evaluation methods for train punctuality

Figure 7.14 gives an overview of how the punctuality task force views timetable structures. It consists of three layers: The basis is given by the IM, in this case RND, and their applied planning rules when creating the national timetable. Parameters like used running times, running time supplements, station stopping times and minimum headway time between trains are included in the planning rules. These parameters are primarily determined by infrastructure characteristics such as signaling systems, line speeds and the present maintenance level.

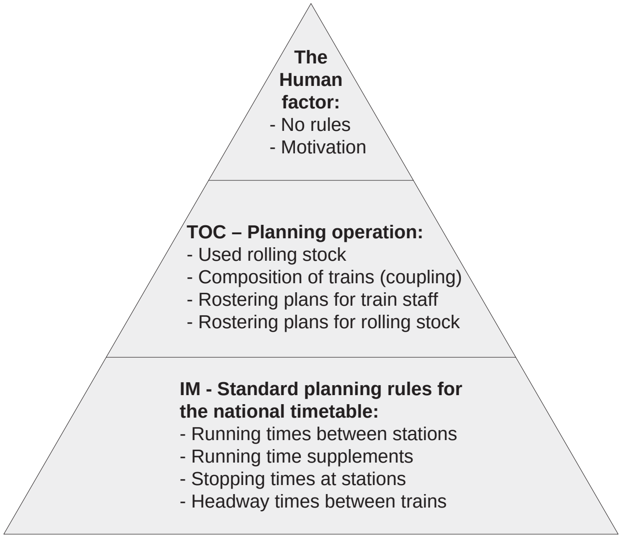


Figure 7.14: Punctuality task force point of view on timetable structures (based on Andersen 2011)

Based on the IM planning rules for the timetable, the TOCs must plan the detailed train operations. Available rolling stock must be allocated to individual train runs. When creating a timetable the IM assumes that the rolling stock is in good condition and the performance levels correspond to the data entered into the timetable planning system. This is not necessarily the case for every train run since performance levels depend on several parameters such as maintenance plans for rolling stock and weather conditions. Reduced rolling stock driving performance increases the risk of train delays and decreases the capability to catch up with minor delays.

The type of rolling stock assumed to be used for a given train run in the timetable may vary during the timetable validity period, creating potential differences in needed minimum running times. If minimum running times are increased compared to the assumed times in the timetable the risk of train delays is greater.

Finally, there is the human factor that can affect the punctuality of railway traffic. This factor is not based on rules but on motivation. The involved humans are train staff, train drivers and conductors, and traffic dispatchers on all levels, from a single station to a large network. If the traffic dispatcher is motivated he will inform the relevant train drivers about the current disrupted traffic situation and explain which traffic handling strategy is being applied and what effects this has for each train driver. This can again motivate the train drivers to behave in a manner that will help to keep the effects of the traffic disruption to a minimum and return to normal traffic conditions as fast as possible.

Experience has shown that a timetable with large running time supplements can become a pretext for inaction for both train staff and traffic dispatchers. Their motivation for keeping trains exactly on time is low and this increases the risk for train delays. The punctuality task force recommends a tactical placement of time supplements such as it is done in the S-train timetable (Schittenhelm 2011c).

Rail Net Denmark has one of the best a high resolution train registration systems in Europe called RDS (Regularitets og Drifts Statistik, in English: Punctuality and Operation Statistics). Trains are registered at given locations as soon as they occupy a specified track circuit. With the RDS system a massive amount of data is collected and it has proven to be difficult to get an overview of the collected data. The punctuality task force quickly realized that big tables with punctuality data were neither suitable for detecting patterns in train delays and to trace the reasons behind the repeatedly observed delays. Analyzing train delay data with a graphical approach was the way forward.

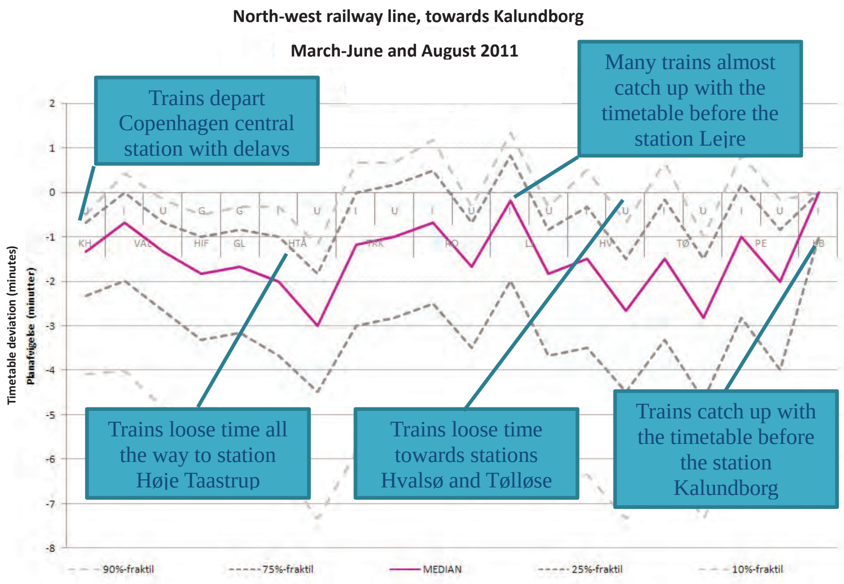


Figure 7.15: Punctuality analysis of the north-west railway line. Driving direction towards Kalundborg (based on Andersen 2011)

Figure 7.15 gives an example of a graphical analysis of train delay data for the North-West railway line for the time interval March-June and August 2011. Driving direction is towards Kalundborg. On the y-axis you have the deviation from the timetable in minutes and on the x-axis (at deviation 0 minutes) you have the distance, the railway line. The RDS registration points are shown above the station abbreviations e.g. Copenhagen central station (Kh) and Valby (Val). Registration points marked “I” are station entry signal track circuits, “G” are passing through station track circuits and “U” are station exit signal track circuits. Text boxes describe the found tendencies in the train delay data.

Not only train delays are investigated by the punctuality task force. Time periods, both short and longer, with a very high level of train punctuality are also analyzed to see what patterns are behind this. The graphical approach was again applied and parameters as the number of trains and the planned train order on a given railway line was found to be very important. On the railway line between Copenhagen central station and Copenhagen airport, punctuality levels dropped specifically in those hours where InterCity-Express train runs were extended to the airport from the central station. From a capacity consumption point of view there should be no problem. If the timetable train path was partially used by a freight train the same problems did not occur. Analyzes showed that the turning InterCity-Express trains caused several train path conflicts within the Copenhagen central station area.

The Punctuality Task Force's list of prioritized timetable evaluation criteria is as follows:

1. On time departure from selected stations - starting station, major junctions, transition station from double to single track line
2. Capability of catching up with delays on line sections - running time supplements
3. Coupling/decoupling of trains at stations - time of day and minimum stopping time
4. Efficient use of prepared dispatching plans in case of disruptions - if → then plans
5. Modular timetable - consisting of sub systems inspired by the S-train timetable

7.6.5.1 On time departure from selected stations

Analyzes made by the punctuality task force showed that on time departure times were more important on some stations than others. These selected stations are:

- The starting station of the train. It is important that the preparations of the train for the coming train run are completed on time. This includes cleaning, catering and shunting from a depot track to a platform track if needed. There are several risks of train delays at a trains starting station.

- Transition stations between double and single tracked railway lines. It is important that trains enter single tracked line sections on time since a possible delay would be transferred more or less to trains running in the opposite direction, depending on the number of and location of crossing stations.

- Border stations to capacity bottlenecks. Some double tracked line sections are capacity bottlenecks in the national railway network. Number of trains and heterogeneity of the train traffic combined with infrastructure characteristics such as minimum headway times between trains are the main reasons for line sections being capacity bottlenecks. To ensure punctual trains through these bottlenecks they must enter the bottleneck on time. Therefore, the punctuality task force recommends the use of running time buffer zones in front of capacity bottlenecks as it is done in the S-train timetable (Schittenhelm 2011c).

- Stations servicing many passengers. As many passengers as possible should be able to benefit from an improved punctuality and therefore a focused effort should be made to have trains depart on time from larger stations.

7.6.5.2 Capability of catching up with delays on line sections

The punctuality task force created a key performance indicator measuring the capability of trains to catch up with delays on line sections. IM RND has made an agreement with all TOCs about the applied running time supplements in the national railway timetable. These supplements should ensure that trains are able to catch up with delays along their route. The resolution of the working timetable is in 30 seconds. This means that calculated running times must be rounded up or down. The latter can lead to a reduced capability to catch up with delays. Timetable planners must make sure that there is a balance through a train run in regards to the rounding of times. Sometimes it is necessary to reduce running time supplements and planning headway times on line sections to achieve a feasible timetable. Neighboring line sections should then have increased running time supplements to make up for the tight part.

7.6.5.3 Coupling/decoupling of trains at stations

If the TOC applies a traffic concept where train lines create a tree structure, where several train services have a common origin and then spread out from the main railway it is a possibility to couple train services together on shared railway line sections. This reduces the need for train staff, specially train drivers, and the number of needed timetable train paths on the shared lines, which reduces infrastructure access costs and infrastructure capacity consumption. Coupling and decoupling maneuvers can also take place to adjust and thereby optimize seating capacity during a train run. Demand for seating capacity varies throughout the day and therefore the need for coupling and decoupling maneuvers does also.

A need for coupling and decoupling of train services can arise at selected stations. Such a maneuver increases the needed minimum stopping time at a given station, specially the coupling of two train services. These needed extended stopping times must be taken into account when the IM is preparing the timetable. Under normal conditions this is no problem since TOCs have decided on their traffic concept to be used before applying for infrastructure capacity. With a strict periodic timetable structure it becomes unavoidable to plan with potential extended stopping times at stations during all timetable pattern hours even though no coupling or decoupling maneuver takes place. Unnecessary extended stopping times can be used catch up with delays in case of disruptions in train traffic.

Every coupling and decoupling maneuver is connected with a risk of failure. A technical failure caused by the rolling stock itself can happen but there is also the possibility of human failure. A stressed train driver, maybe due to a delay, might rush the maneuver and couple two trains with too much speed. This might cause the maneuver to fail and can cause both a technical failure and minimum prolong the stopping time at the station since the maneuver must be tried again. Because of these added potential risks of delays to the timetable when (de)coupling trains, the punctuality task force recommends that coupling and decoupling maneuvers should be kept to a minimum during time periods where the infrastructure capacity consumption is high e.g. rush hours.

7.6.5.4 Efficient use of prepared dispatching plans in case of disruptions

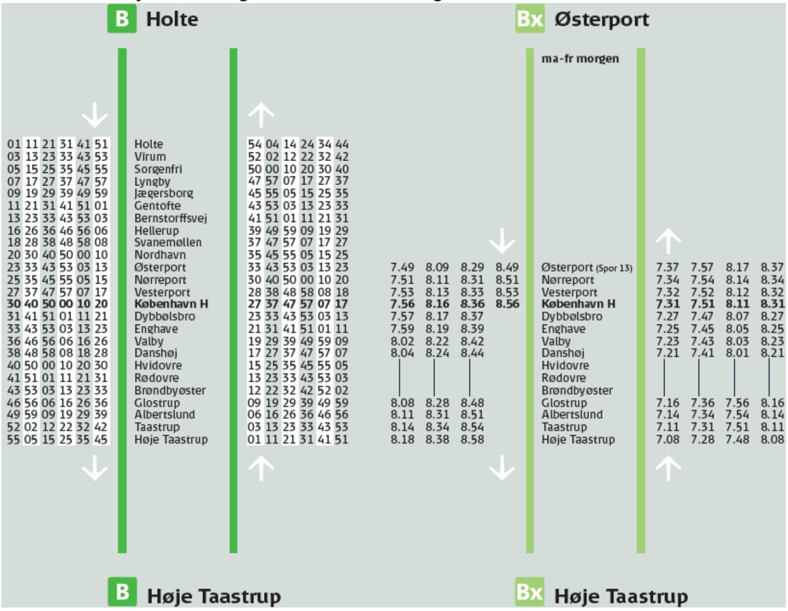
The tactical traffic control center for the entire RND railway network in Copenhagen (DCDK) must be able to respond quickly to traffic disruptions by implementing dispatching plans. These plans must describe a given traffic disruption scenario and then listing the necessary dispatching actions (if → then) to limit delays as much as possible and restore traffic to normal as quickly as possible. These dispatching plans will contain both actions for TOCs and IM Rail Net Denmark and it is therefore very important that all involved stakeholders are informed about the implemented dispatching plan and act accordingly.

If the used timetable is highly periodic/systematic throughout the day the effectiveness of these prepared dispatching plans will increase. The number of needed plans is reduced and the applied strategies will be similar in most dispatching plans.

7.6.5.5 Modular timetable

The national timetable should be build up by several subsystems, consisting of several traffic packages that can be turned on and off separately without influencing other traffic packages. This means that rolling stock and train staff must be allocated to a restricted number of services, hereby it becomes possible to contain a traffic disruption to a limited number of services. Today, the rostering plans for rolling stock and train staff focus on limiting the needed resources, to reduce costs for the TOC, and this can lead to a very flexible allocation of train staff and rolling stock. This increases the risk of a delay spreading to larger parts of the network because a train delay can follow both rolling stock and train staff.

Inspiration for a timetable consisting of subsystems can be taken from the Copenhagen S-train timetable. Here, each train service line consists of trains running on “white times” and other trains on “grey times”. Some train services are only run during rush hours. See Figure 7.16.



B Holte – **B Høje Taastrup**

						Station						
01	11	21	31	41	51	Holte	54	04	14	24	34	44
03	13	23	33	43	53	Virum	52	02	12	22	32	42
05	15	25	35	45	55	Sorgenfri	50	00	10	20	30	40
07	17	27	37	47	57	Lyngby	47	57	07	17	27	37
09	19	29	39	49	59	Jægersborg	45	55	05	15	25	35
11	21	31	41	51	01	Gentofte	43	53	03	13	23	33
13	23	33	43	53	03	Bernstorffsvej	41	51	01	11	21	31
16	26	36	46	56	06	Hellerup	39	49	59	09	19	29
18	28	38	48	58	08	Svanemøllen	37	47	57	07	17	27
20	30	40	50	00	10	Nordhavn	35	45	55	05	15	25
23	33	43	53	03	13	Østerport	33	43	53	03	13	23
25	35	45	55	05	15	Nørreport	30	40	50	00	10	20
27	37	47	57	07	17	Vesterport	28	38	48	58	08	18
30	**40**	**50**	**00**	**10**	**20**	**København H**	**27**	**37**	**47**	**57**	**07**	**17**
31	41	51	01	11	21	Dybbølsbro	23	33	43	53	03	13
33	43	53	03	13	23	Enghave	21	31	41	51	01	11
36	46	56	06	16	26	Valby	19	29	39	49	59	09
38	48	58	08	18	28	Danshøj	17	27	37	47	57	07
40	50	00	10	20	30	Hvidovre	15	25	35	45	55	05
41	51	01	11	21	31	Rødovre	13	23	33	43	53	03
43	53	03	13	23	33	Brøndbyøster	12	22	32	42	52	02
46	56	06	16	26	36	Glostrup	09	19	29	39	49	59
49	59	09	19	29	39	Albertslund	06	16	26	36	46	56
52	02	12	22	32	42	Taastrup	03	13	23	33	43	53
55	05	15	25	35	45	Høje Taastrup	01	11	21	31	41	51

Bx Østerport – **Bx Høje Taastrup**

ma-fr morgen

				Station				
7.49	8.09	8.29	8.49	Østerport (Spor 13)	7.37	7.57	8.17	8.37
7.51	8.11	8.31	8.51	Nørreport	7.34	7.54	8.14	8.34
7.53	8.13	8.33	8.53	Vesterport	7.32	7.52	8.12	8.32
7.56	**8.16**	**8.36**	**8.56**	**København H**	**7.31**	**7.51**	**8.11**	**8.31**
7.57	8.17	8.37		Dybbølsbro	7.27	7.47	8.07	8.27
7.59	8.19	8.39		Enghave	7.25	7.45	8.05	8.25
8.02	8.22	8.42		Valby	7.23	7.43	8.03	8.23
8.04	8.24	8.44		Danshøj	7.21	7.41	8.01	8.21
				Hvidovre				
				Rødovre				
				Brøndbyøster				
8.08	8.28	8.48		Glostrup	7.16	7.36	7.56	8.16
8.11	8.31	8.51		Albertslund	7.14	7.34	7.54	8.14
8.14	8.34	8.54		Taastrup	7.11	7.31	7.51	8.11
8.18	8.38	8.58		Høje Taastrup	7.08	7.28	7.48	8.08

Figure 7.16: Example of a modular timetable structure - Copenhagen suburban train services B (left) and rush hour line Bx (right) (DSB S-tog 2011)

To the left in Figure 7.16 the timetable for S-train line B is shown. Every second train run is either following white or grey times. Trains running according to white times run during day time hours, trains running on grey times run during the entire operational day. With this timetable it is possible to combine or switch on/off timetable times as wanted, e.g. grey + white, grey + rush hour or grey + white + rush hour. The modular timetable construction makes it is easy to cancel half the departures of line B in case of a severe traffic disruption.

7.7 Discussion of stakeholder interviews

Table 7.13 gives an overview of the results from the ten conducted interviews with selected Danish railway timetable stakeholders. A first view at the listed timetable evaluation criteria shows no immediate big surprises. However a few of the selected timetable evaluation criteria show new thoughts and approaches to railway timetabling. These are pointed out in the following. Generally

Passenger train operator DSB	Passenger train operator Arriva Denmark	Freight train operator DB Schenker Rail Scandinavia	The Danish Transport Authority	Infrastructure manager Rail Net Denmark
1. Robustness of the timetable 2. Fast, high frequent and direct connections 3. Possibility for train services calling at smaller stations 4. Efficient use of the railway infrastructure 5. Scalability of the timetable	1. Compliance with traffic tender demands 2. Attractive transfer options to DSB trains and local busses 3. Periodic timetables are preferable 4. Servicing starting hours of schools and larger workplaces 5. A realistic timetable	1. Coordinated international timetable train paths 2. Train paths give flexibility to where change of train drivers can take place 3. Robustness of the timetable 4. Low level of scheduled waiting time 5. Periodic timetables are preferable	1. Periodic timetables are preferable 2. Robustness of the timetable 3. Attractive transfer options 4. Travel time for trains 5. A reserve of freight train timetable train paths	1. Robustness of the timetable 2. Complexity of traffic in and around stations 3. Utilization of timetable train paths 4. Travel time for trains 5. The timetable is prepared within the given deadline
The Danish ministry of transport	**Regional railway company Lokalbanen**	**Regional railway company Regionstog**	**Swedish freight train operator Hector Rail**	**Punctuality task force for the Danish railway sector**
1. Train travel times - including scheduled waiting time 2. Punctuality and reliability of the timetable 3. Transportation capacity with the timetable 4. Average waiting time at stations – frequency of train services 5. A socio-economic approach to timetable train path conflict resolution between TOCs	1. A realistic/feasible and robust timetable 2. Attractive transfer options to other trains and busses 3. A periodic timetable with fixed frequencies of train services adapted to market demands 4. Short train travel times - including non-stop express trains 5. High level of production efficiency - using optimal rostering plans for rolling stock and staff	1. A feasible timetable 2. Attractive transfer options 3. Robustness of the timetable 4. Utilization level of rolling stock in rostering plans 5. Operational costs of the timetable	1. The timetable fulfills the business demands given by the customers of Hector Rail 2. Robustness of the timetable 3. Train path capacity 4. Day to day stability of the timetable 5. Travel time of the trains	1. On time departure from selected stations - starting station, major junctions, transition station from double to single track line 2. Capability of catching up with delays on line sections - running time supplements 3. Coupling/decoupling of trains at stations - time of day and minimum stopping time 4. Efficient use of prepared dispatching plans in case of disruptions - if → then plans 5. Modular timetable - consisting of sub systems inspired by the S-train timetable

Table 7.13: Overview of results from interviews with Danish railway timetable stakeholders - prioritized lists of timetable evaluation criteria

the presumed motivation factors of stakeholders when creating and/or evaluating timetables have been confirmed by the results of the interviews prepared for this thesis.

DSB's list of prioritized timetable evaluation criteria is characterized by the political influence on the railway sector. Politicians want a trustworthy robust timetable and are considering opening new stations to make the railway more attractive towards new potential passengers. Passengers and thereby also politicians demand fast, high frequent and direct travel connections.

Arriva Denmark was the first TOC to win a tender for public service train traffic in Denmark. This can clearly be seen in the list of evaluation criteria. Implementing a systematic/periodic timetable is a request in the tender demands. Arriva runs regional train traffic and the passenger volume is based on serving local schools and working places, and running trains as feeder lines to the national train traffic of DSB.

DB Schenker Rail Scandinavia's main product is to run transit freight trains between Sweden and Germany through Denmark. Therefore, the coordination of transit train paths becomes very important. Competiveness of the company depends amongst other things on flexibility and predictability in the planning of freight train traffic. Flexibility can be gained in the use of several stations for train driver changes and predictability by using a systematic/periodic timetable with homogenous freight train paths. Short travel times and a high level of punctuality increase the attractiveness of the freight train product.

The Danish Transport Authority buys public service train traffic. With their criteria they want to ensure an attractive timetable for passengers and the society in regards to a socio-economic perspective. One can wonder why attractive transfer options and travel time only make third and fourth most important timetable evaluation criteria. More focus on customer preferences could be recommended. A small surprise appears with the fifth criterion, introducing the concept of a freight train path reserve to minimize delays created by freight trains running outside their scheduled train path.

State owned infrastructure manager Rail Net Denmark is under constant political influence. The top three criteria are marked by a present political focus on the punctuality levels of passenger train traffic. Travel times for trains, is the fourth most important criteria. Transfer options have not made the list. A political focus on punctuality and a political lack of focus on customer preferences becomes visible. Preparation of the yearly timetable according to the deadlines given in the Rail Net Europe planning process is very important to ensure an effective cooperation between European IMs. This is the reason for the fifth criterion about keeping deadlines.

The Danish ministry of transport has a socio-economic approach to railway timetables. All five criteria are characterized by this. Very important cost factors in a socio-economic analysis of train traffic such as travel times, scheduled waiting time, punctuality levels, average waiting time and available transportation capacity are listed. Suggesting a socio-economic approach when solving train path conflicts in the timetabling process, is a new and interesting approach that can help in the case of that a compromise cannot be reached between the involved TOCs.

The regional railway companies Lokalbanen and Regionstog are both focusing on feasible and robust timetables and on attractive transfer options. Reason for the latter is that their train services often are feeder trains to/from national or regional DSB train services. Production efficiency in regards to optimized rostering plans for rolling stock and train staff is also important to both companies. Lokalbanen has lately increased their focus on implementing a periodic timetable and improving the attractiveness of the railway by introducing a new hourly non-stop train service during daytime hours.

Private freight train operator Hector Rail basically needs the timetable to provide train paths that fulfill the demands from their customers. Robustness of the timetable and possible travel times are key parameters. A very interesting criterion is the freight capacity of the scheduled train paths. The length, weight and available traction power of a train determines how a train path can be scheduled in the timetable. Freight train operators argue for longer and heavier trains to improve their competiveness. Timetable planners might plan with shorter and lighter trains to achieve a feasible timetable. A stable timetable makes the planning process at Hector Rail easier and holds a higher optimization potential. Maintenance and renewal projects in the railway infrastructure reduce available capacity and often lead to a short term rescheduling of trains. These changes make the preparation of rostering plans for both rolling stock and train staff more complicated.

The punctuality task force of the Danish railway sector has not surprisingly focus on the punctuality levels of passenger and freight trains. One of the most important new insights is, that at some locations on the railway network it is more important that a train is on time than others. These are starting stations, major junctions and transition stations between double and single tracked lines. Running time reserves and reduced complexity in planned train traffic increases the changes for more trains running on time. If a major disruption in train traffic is happening, the network effects can be minimized by having prepared detailed dispatching plans covering general disruption scenarios. A modular structured timetable also makes it easier to reduce effects in spreading by simply shutting down sub-modules of the timetable.

7.8 Conclusion

All invited railway timetable stakeholders were willing to participate in the process leading to a common Danish list of timetable evaluation and optimization criteria. Both the five primary stakeholders: Passenger TOC DSB and Arriva Denmark, freight TOC DB Schenker Rail Scandinavia, The Danish Transport Authority and IM Rail Net Denmark; as well as the five supplementary stakeholders: The Danish Ministry of Transport, freight TOC Hector Rail, regional railway companies Lokalbanen and Regionstog and The Punctuality Task Force of the Danish railway sector.

The results from the first series of individual interviews with the primary stakeholders, five lists with five prioritized timetabling criteria, did not contain any major surprises. It proved that the railway sector is much affected by the political climate. This is apparent in the chosen timetabling criteria by passenger TOC DSB and IM Rail Net Denmark. The Danish Transport Authority is a departmental organization under the Danish Ministry of Transport and has just as the ministry a focus on the socio-economic aspects of railway timetables. Parameters such as robustness, travel time and transfer options play a key role. Arriva Denmark won the first tender for public service train traffic and they are well aware of their situation. Focus is on fulfilling all tender demands and attracting as many passengers as possible by servicing schools and larger work places and ensuring good transfer options to/from DSB trains. A political focus on train punctuality rather than customer preferences becomes visible. DB Schenker Rail Scandinavia is in hard competition with other freight TOCs to run transit freight trains through Denmark. Their timetabling criteria focus on improving their competiveness through shortening the travel times for freight trains through Denmark and making production planning as easy and flexible as possible.

Cooperation between the five primary timetable stakeholders at the joined timetabling criteria workshop was surprisingly good. A constructive dialogue between the representatives of the stakeholders led to the creation of a short list of timetable evaluation criteria without any heated discussions or arguments.

Unfortunately it was not possible to achieve an unique ranking amongst the criteria on the short list and they were put into three layers of different importance. Table 7.14 shows the result of the workshop.

Level of importance	Timetable evaluation and optimization criteria
High	Capacity consumption on line sections & Systematic timetable
Medium	Robustness of timetable & Societal acceptance
Low	Travel time & Attractive transfer options

Table 7.14: Result from the joined timetabling criteria workshop

A reason for the good cooperation between stakeholders could be that none of them are direct competitors. The closest to direct competition is the relationship between DSB and DB Schenker Rail Scandinavia when applying for capacity on the Danish main lines for the national InterCity-Express and InterCity passenger trains and transit freight trains. The basic timetable structure for these train categories has not changed much over the last 10 years and therefore it is difficult to describe it as direct competition for infrastructure capacity.

The overall process, with individual stakeholder interviews followed by a joined workshop was appreciated by all participants. It was a new and valuable experience for most participants, giving insights to the point of view of other railway companies. Since the described process in this thesis was a Danish premiere, this thesis recommends repeating the process, continuously improving the process based on the made experience and evaluation from participants. This should be done with regular intervals, between 2-5 years, to keep the prioritized list of criteria up to date and thereby trustworthy. When larger timetable changes are expected in the near future, due to infrastructure improvements such as the opening of the new high speed railway line Copenhagen - Ringsted, it is very important to repeat the process to get the best possible basis for preparing the future timetable. Based on the feedback from the participants given at the workshop, the basic process can be reused. When repeating the process, participants will hopefully feel more comfortable and even better results, such as a unique ranking of timetabling criteria, might be achieved.

When looking at the results of the interviews with the supplementary stakeholders, no immediate surprises can be found. Even more than the Danish Transport Authority, the Danish Ministry of Transport focuses on the socio-economic side of railway timetables. The ministry suggests using a socio-economic evaluation when solving conflicts between train paths. Regional railway companies Lokalbanen and Regionstog focus on feasible timetables with attractive train services. Production efficiency and keeping costs within the given budgets are also important parameters to these companies. The private freight TOC Hector Rail follows in the footsteps of DB Schenker Rail Scandinavia by focusing on competiveness. A new aspect is the freight capacity of a given train path. Hector Rail wants to run longer and heavier trains to reduce costs.

Political focus on passenger train punctuality levels has led to the creation of the Punctuality Task Force for the Danish railway sector. The task force focuses on running time supplements in timetables, reducing complexity of train traffic and being well prepared with dispatching plans when major disruptions occur.

The interviews with passenger and freight TOCs have revealed that they do not have enough resources to put much focus on customer preferences. It is impossible for them to perform advanced large scale market studies. They have to rely on passenger counting, meetings with commuter associations' spokespersons and ideas coming from their own marketing departments etc. The Ministry of Transport or the Danish Transport Authority does not initiate detailed studies of railway customer preferences and how they can be implemented in the railway timetable. There is a missing focus on customer preferences in the Danish railway sector.

7.9 Summary

This chapter describes the first approach to a decision making process that led to the creation of a common Danish list of prioritized railway timetable evaluation and optimization criteria. The following key stakeholders were identified:

- Passenger TOCs: DSB (largest passenger TOC in Denmark), Arriva Denmark (first to win a tender for public service train traffic)
- Freight TOC: DB Schenker Rail Scandinavia (largest freight TOC in Denmark)
- IM: Rail Net Denmark (largest IM in Denmark)
- Society: The Danish Transport Authority (buyer of public service transport)

Stakeholders such as passengers and customers of freight train services were omitted since it was assumed that their interest would be handled by the selected stakeholders since these are dependent on the goodwill of their customers. The railway end customers are not directly involved in any timetabling process in Denmark.

An interview was held separately with each stakeholder; during which these had to create their own list of five described and prioritized timetable evaluation and optimization criteria. The results of these interviews are presented and described. It became apparent that the railway sector is much affected by the political climate and therefore much focus was on train punctuality and less on customer preferences.

Following this, a joined timetabling criteria workshop was held on neutral ground at the Technical University of Denmark, Department of Transport. All stakeholders besides TOC Arriva Denmark participated. Starting with a gross list of individual stakeholder timetabling criteria from the interviews, a first approach to a decision making process was completed. This resulted in a common list of prioritized timetable evaluation and optimization criteria. It was not possible for the stakeholders to give each criterion a unique prioritization, therefore the list consists of 3 layers with 2 criteria in each. Each criterion got its own priority based on the discussions and given votes during the workshop. The layers are as follows:

- Top priority layer – Capacity consumptions on line sections & Systematic timetable
- Medium priority layer – Timetable robustness & Societal acceptance
- Low priority layer – Travel time & Attractive transfer options

The achieved results from the held series of interviews and the timetabling workshop are discussed and commented. When comparing interview and workshop results, there are differences in the prioritization of timetable evaluation and optimization criteria. This thesis suggests two main reasons for this:

1. There was a long time span between the held interviews and the workshop
2. Some stakeholders had changed representatives between interviews and workshop

Customer preferences for both passenger and freight railway traffic are briefly described. This is followed by a description of what TOCs today are doing to ensure that they can fulfill the demands and wishes of their customers as much as possible. It becomes clear that TOCs do not have the necessary resources available to them to put much focus on customer preferences.

Following the workshop, it was decided to set up a series of interviews with supplementary timetabling stakeholders. These interviews followed the same agenda as the first series of interviews and are presented in the same way. The supplementary stakeholders are:

- The Danish Ministry of Transport
- Swedish freight TOC Hector Rail
- The regional railway company Lokalbanen
- The regional railway company Regionstog
- The Punctuality Taskforce of the Danish railway sector

An overview of the results from all conducted interviews is given and the overall results from the interviews are discussed. There were no major surprises but some interesting criteria such as e.g. freight capacity of train paths by Hector Rail and a socio-economic approach to resolving conflicts between train paths by the Danish Ministry of Transport.

Final conclusions entail a successful process that produced the wanted result: A common Danish list of railway timetable evaluation and optimization criteria. The participating stakeholders gave positive feedback about the process and therefore it is recommended to repeat this process with regular intervals. This is to achieve even better results and keeping the list of criteria up to date.

8 Revising the timetabling process

In this chapter recommendations for a revised timetabling process from the year 2021 within the Danish state owned infrastructure manager Rail Net Denmark (RND) (in Danish: Banedanmark) is presented. This is based on the found and prioritized timetabling criteria from the complex planning workshop described in section 7.4. The identified timetabling criteria and the most important parameters that have influence on each criterion are presented in the following sections: High priority timetabling criteria “Systematic timetable” and “Capacity consumption on line sections” in sections 8.1.1 and 8.1.2 respectively. Medium priority criterion “Robustness of the timetable” is described in section 8.1.3 and “Social acceptance of the timetable” in section 8.1.4. Low priority criteria “Attractive transfer options” and “Travel time” are presented in sections 8.1.5 and 8.1.6. This is followed by recommendations for a revised timetabling process at RND in section 8.2. Conclusions are made in section 8.3 and finally a summary of the chapter is given in section 8.4.

8.1 Timetabling criteria

The timetabling criteria and their influencing parameters are presented in the order of their prioritization from the complex planning workshop. First are the top priority layer criteria “Systematic timetable” and “Capacity consumption on line sections” presented. This is followed by the middle priority layer criteria “Robustness of the timetable” and “Social acceptance of the timetable”. Finally, the low priority layer criteria “Attractive transfer options” and “Travel time”. Each criterion description is based on a diagram that visualizes the criterion, the most important affecting parameters and how these parameters also can affect each other. The affecting parameters are grouped into society dependent, train operating company (TOC) dependent and infrastructure manager (IM) dependent parameters.

8.1.1 Systematic timetable

The term “Systematic timetable” was introduced by the participants of the complex planning workshop. A systematic timetable consists of one or several timetable patterns that are repeated throughout an operation day. It would be classified as a periodic timetable according to the presented timetable classification scheme in section 4.1. Figure 8.1 gives an overview of the parameters that have an influence on the timetabling criterion “Systematic timetable”. Societal parameters are shown with a red color, TOC dependent parameters are shown with a blue color and parameters affected by the IM are shown with a green color.

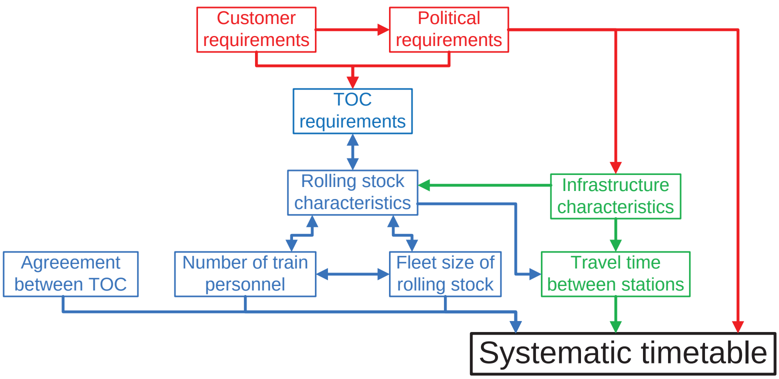


Figure 8.1: The influencing parameters of the “Systematic timetable” timetabling criterion. Red are society parameters, blue are TOC parameters and green are IM parameters.

Requirements from railway customers, both passenger and freight, have influence on both the requirements from the elected politicians and the TOCs wishes for the timetable. If customers prefer one timetable class to another the TOCs will most likely try, through their capacity applications to the IM, to influence the chosen applied timetable class by the IM.

By implementing a given traffic policy, the politicians can have a very high level of influence on both TOCs and IMs. This can e.g. be done through determining the “to be used” timetable class. To implement a given timetable class a set of conditions most have to be met. These conditions both cover railway traffic (TOCs) and infrastructure (IM) aspects. Through allocation of resources to TOCs and IMs the politicians have a high degree of influence on the prepared railway timetable.

A systematic timetable requires an agreement between all relevant TOCs on a given periodic timetable class. All TOCs, both large and small companies and both passenger and freight train operators, have to agree on the repeating timetable structures of the available timetable train paths offered by the IM. This can be a very difficult process since e.g. freight TOCs can experience big fluctuations in demand for freight train services due to the financial climate in one or several countries and therefore can be more interested in a more flexible timetable structure.

The characteristic of the rolling stock is the most important influence parameter for the TOCs. This covers:

- Driving characteristics such as acceleration and breaking capabilities and maximum achievable speed
- Number of required train staff to operate the type of rolling stock
- Passenger seating plus standing capacity or loading capacity of different kind of goods
- Propulsion system: Diesel, electric or hybrid

These issues have to be compared with the available fleet size of a given rolling stock type and the available numbers of train personnel that can operate the relevant type of rolling stock. Rolling stock characteristics, fleet size and numbers of available train staff create the basic conditions for possible TOC timetable requirements. See section 6.4 for a description of the timetabling process at TOC DSB (Danish State Railways). These three parameters depend on the resources that are available to a TOC and this can be affected by politicians (Elgaard 2011).

A basic condition for the possible timetable layouts is the characteristics of the railway infrastructure. This covers:

- Maximum line speed (track geometry and signaling system)
- Number of line tracks (single, double or more)
- Station layouts (number of platform tracks, level or flying junctions)
- Distance between crossing stations on single track railway lines
- Signaling system (possible headway times between trains, maximum line speed)

To have more or less attractive infrastructure characteristics depends on the amount of resources allocated to the railway network, which is decided by the politicians through their traffic policy.

Possible shortest travel times between stations depend on infrastructure and rolling stock characteristics. What speeds are allowed by the infrastructure and how well they can be utilized by the rolling stock. When implementing a given timetable class it can become necessary to prolong the planned travel times for trains to achieve a certain timetable pattern. This phenomenon is called scheduled waiting time (Landex 2008, Wendler 2007).

Applying a systematic timetable on the Danish railway network demands that IM RND implements one of the periodic timetable classes described in chapter 4. How systematic the reviewed timetable variant is can be determined by one of the presented periodicity indexes in section 9.1.1. A minimum value of the selected index can be chosen and a given timetable variant must achieve this value or higher in the performed timetable periodicity analysis.

A fast and effective calculation of values from one or more different periodicity indexes requires the implementation of one or more data-scripts that can access relevant timetable data from the timetable database of the timetabling software tool. From the extracted data the requested index values can then be calculated. This can either be done within the timetabling software tool as a build in functionality or be developed as a separate data-script in e.g. a SQL-tool.

If the analysis is carried out for all defined line sections on a given railway network and not the timetable as a whole, it can be argued for that the demanded periodicity index value can vary according to the number of e.g. train passengers or train numbers on the given line section. A higher number of passengers can demand a higher periodicity index value.

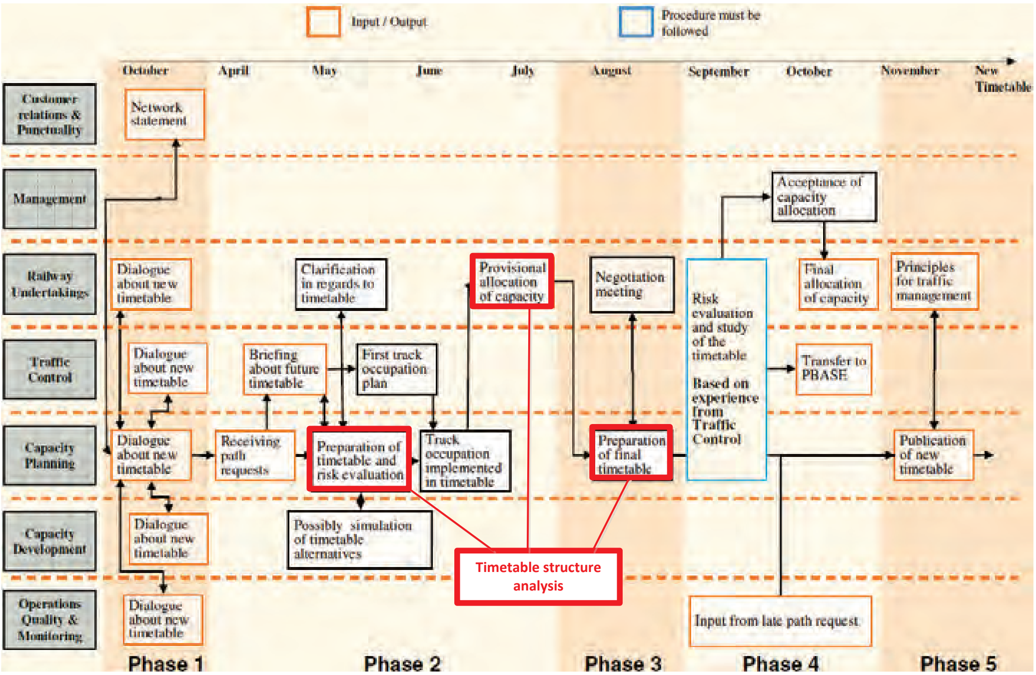


Figure 8.2: Rail Net Denmark timetabling process + suggested timetable structure analyses in process steps (marked red) (based on Toylsbjerg 2009)

To implement this timetabling criterion a timetable periodicity analysis must be carried out before a given timetable variant can be promoted to being the valid timetable. The results of the analysis must fulfill the required minimum values of the chosen periodicity index/indices. This analysis should be undertaken twice during phase 2 and once in phase 3 within the RND timetabling process. During phase 2 analyses should be carried out when preparing a draft timetable and when making the provisional allocation of capacity. In phase

3 it should be done when creating the final timetable. Figure 8.2 shows in which process steps in the timetabling process that the timetable periodicity analysis should take place.

8.1.2 Capacity consumption on line sections

The capacity consumption depends on how the available infrastructure capacity has been distributed between different train types, in form of the number of train paths allocated to freight trains, fast and slow passenger trains. This can be done in many ways and will depend on a given political prioritization. The available infrastructure capacity is restricted by the acceptable capacity consumption levels.

Figure 8.3 gives an overview of the "Capacity consumption on line sections" criterion and it's affecting parameters. This criterion is the second criterion in the high priority criterion layer created at the complex planning workshop. It was given the same top priority as the "Systematic timetable" criterion.

As with the "Systematic timetable" criterion the customers of railway services have an impact on both TOC requirements for the timetable and thereby also the timetable class, and the political point of view on how the overall structure of the timetable should be. Politicians again allocate resources to a countries railway infrastructure and to public owned TOCs to assure that a desired timetable class can be implemented.

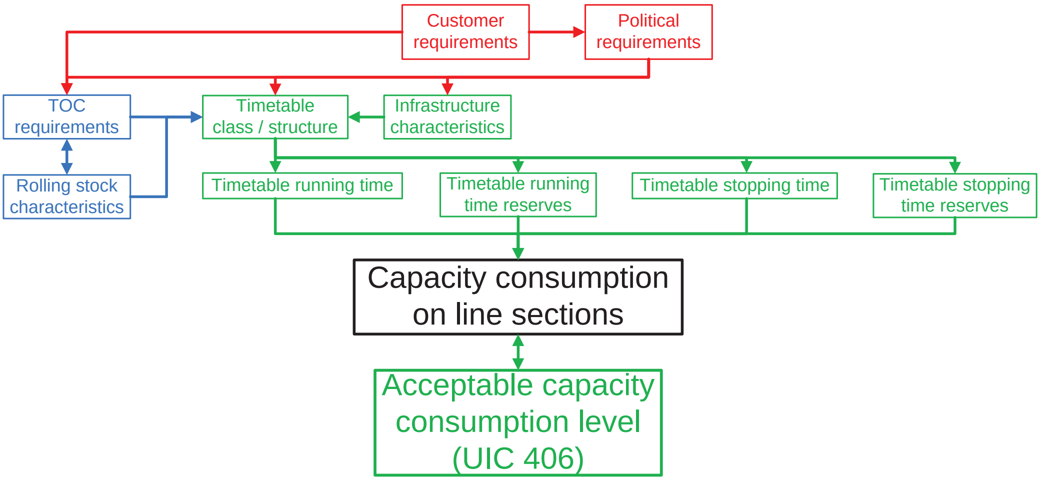


Figure 8.3: Capacity consumption on line sections criterion and the influencing parameters. Red are society parameters, blue are TOC parameters and green are IM parameters.

The requirements from the TOCs for a given timetable are influenced by both customers and politicians. Furthermore, the TOCs wishes for a timetable class/structure also depend on the characteristics of their rolling stock. This parameter has been described in section 8.1.1.

Characteristics of the infrastructure determine which timetable variants can be implemented. Depending on the funding from the political side the railway infrastructure can have more or less attractive features in regards to flexibility in timetable design. In section 8.1.1 this parameter is described in more detail.

The applied timetable class and the specific timetable structures will determine train running times between stations and stopping times at stations. Implemented time reserves both for travel and stopping times are also dependent on the specific chosen timetable variant but even more on the applied planning rules that the IM timetable planners follow during the timetabling process (Johansson 2011).

Rail Net Denmark is using the UIC (International Union of Railways / Union Internationale des Chemins de fer) 406 methodology when preparing capacity analyses of its network. This approach is recommended by the UIC (UIC 2004). Therefore, it is the UIC 406 methodology that is used to determine the level of capacity consumption on line sections with a chosen utilization of the available infrastructure capacity. Since this methodology has become more and more popular within the European railway sector (Wendler et al. 2012), it has been implemented as a functionality in several of the used railway timetabling and simulation software tools, e.g. OpenTrack, RailSys and TPS. Based on this development it should be straight forward for IM RND to conduct capacity analyses for line sections on the railway network in a fast and efficient way whenever needed during the timetabling process.

The RND division of its railway network into railway line sections is inspired by the principals presented by the UIC in the UIC 406 leaflet. The most important factor is the number of trains. Where ever the number of trains running on a given railway line changes, a division of the line is made. This means that junctions and terminus stations of train services become primary division points of the Danish railway network (Landex 2008). The network division is highly timetable dependent and can thereby potentially change every year. Other division points are transition stations between line sections with different numbers of line tracks e.g. single to double track. Transition stations between line sections with major differences in signaling technology that are often causing big changes in possible headway times between trains are also points of division. A map of the division of the RND railway network into line sections is shown in Figure 8.4.

It was decided not to divide the railway network at overtaking and crossing stations. This was due to the danger of getting a wrong picture of the capacity consumption level on a given railway line. Figure 8.5 shows a well-known paradox in the UIC 406 methodology when dividing the railway network at an overtaking station. It can be seen that the capacity consumption level can be reduced if the line is split into several smaller line sections: The difference between b and c1+c2. This might encourage the IM to sell more infrastructure capacity/timetable train paths that are actually not available.

The division of the railway network into line sections depends in general on the valid timetable and infrastructure. Major changes in a new timetable can result in a new division of the network caused by e.g. a new terminus station for one or several train services. An improved railway infrastructure can cause a different division into line sections due to e.g. the opening of a new railway line. Hereby creating new junctions and/or terminus stations, or upgrading a railway line from single to double track.

Each analyzed timetable variant and/or infrastructure variant can demand a different division of the railway network and therefore different capacity analyses results. Taking this into account, it can be very difficult to compare prepared UIC 406 capacity analyses for different timetable and/or infrastructure variants. These analyses can therefore not stand alone and must be accompanied by a description of the differences in the division of the railway network in the different investigated scenarios.

Figure 8.4: The Rail Net Denmark railway network divided into line sections (Landex et al 2008)

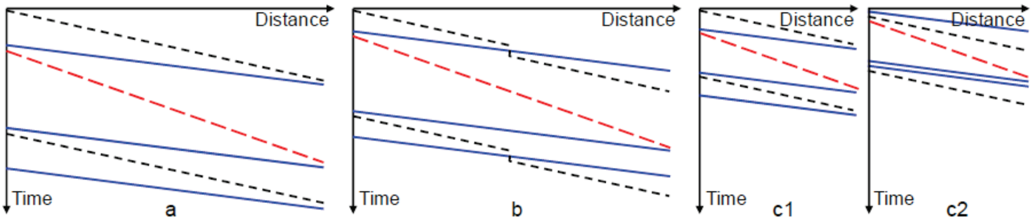


Figure 8.5: Dividing the railway network at overtaking stations or not (Landex 2008)

Table 8.1 shows the UIC guidelines for capacity utilization levels when applying the UIC-406 methodology. Railway lines are divided into three main categories: Suburban passenger, high speed and mixed traffic lines. The two first categories are normally operated with a homogenous traffic pattern whereas the last is normally operated with a heterogeneous mix of traffic, e.g. both fast and slow passenger trains and slow freight trains.

Type of railway line	Peak hour	Daily period
Dedicated suburban passenger traffic line	85%	70%
Dedicated high speed line	75%	60%
Mixed traffic line	75%	60%

Table 8.1: UIC guideline for capacity utilization levels for the UIC 406 methodology (UIC 2004)

The recommended levels of capacity consumption in Table 8.1are based on current experience from the European railway sector (UIC 2004). A maximum value of 75% indicates that the time wise longest occupied block section of the infrastructure is occupied 75% of the time in the investigation time window, which can be everything from a single peak hour to an entire day.

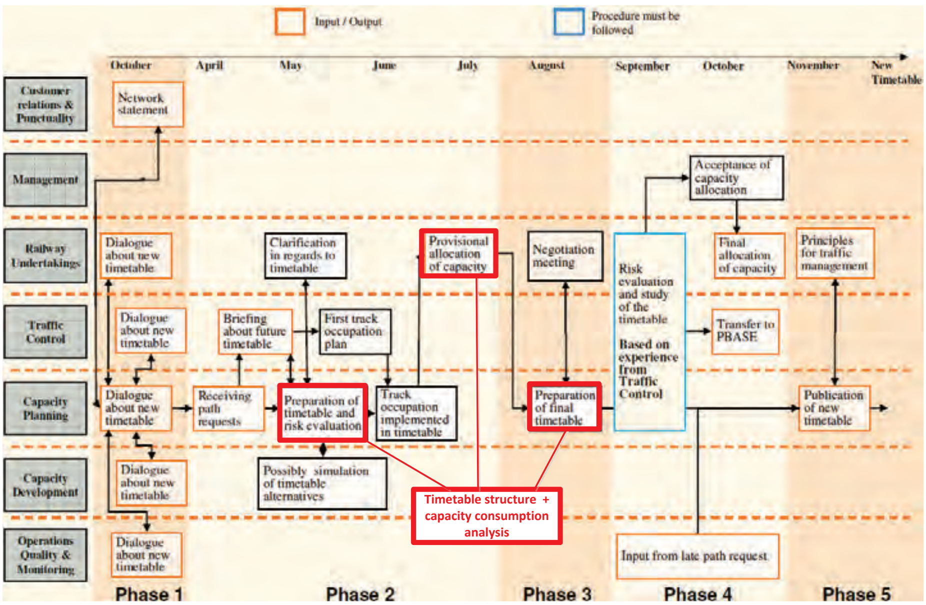


Figure 8.6: Rail Net Denmark timetabling process + suggested line section capacity consumption analysis in process steps (marked red) (based on Toylsbjerg 2009)

Capacity analyses of line sections should be carried out simultaneously with timetable periodicity analyses. Line section capacity analysis must be added to the box with timetable periodicity analysis in Figure 8.2. See the updated timetabling process diagram in Figure 8.6.

8.1.3 Robustness of the timetable

The timetabling criterion "Robustness of the timetable" belongs to the middle priority criterion layer together with "Social acceptance". Timetable robustness has been defined by several authors. Some selected definitions are presented below:

Goverde:	"A robust timetable must be able to deal with a certain amount of delay without traffic control intervention. Timetable robustness therefore determines the effectiveness of schedule adherence after disruptions." (Goverde 2005)
Schöbel & Kratz:	"Let a fixed waiting time rule be given as well as a set of source-delayed events. A timetable has the robustness R if all its transfers are maintained whenever all source delays are smaller than or equal to R." (Schöbel & Kratz 2009)
Kroon, Huisman & Maroti:	"Robustness of a timetable has one or more of the following effects (i) initial disturbances can be absorbed to some extent so that they do not lead to delays, (ii) there are few knock-on delays from one train to another, and (iii) delays disappear quickly, possibly with light dispatching measures. Both (i) and (iii) are a consequence of appropriately placed time supplements in the timetable, and (ii) is a consequence of appropriately placed buffer times between consecutive trains at certain locations. Note that, with light dispatching measures only, a timetable can only be robust against small disturbances." (Kroon et al 2008)
Dewilde, Sels, Cattrysse1 & Vansteenwegen:	"A railway timetable that is robust against small delays minimizes the real total travel time of the passengers, in case of small delays. Limited knock-on delays and a short settling time are necessary but not sufficient conditions for a timetable to be robust. Furthermore, different weights can be assigned to different kinds of travel time prolongation." (Dewilde et al 2011)

There are two focus points in the presented definitions above:

1. Delay propagation between trains – the timetable must be able to absorb primary delays of a limited magnitude or these can only have minor effects on the rest of the train traffic. There by making the re-scheduling of trains unnecessary.

2. Ensuring timetabled train to train transfer options up to a certain level of delay – the feeder train(s) in a train to train transfer can be delayed up to a certain threshold value and the transfer can still be made. If the delay is bigger than the defined threshold value then the second train is allowed to depart the transfer station on time.

In the end all definitions focus on minimizing the realized travel time prolongation of train passengers during a traffic incident causing train delays. Goverde, Kroon et al and Dewilde et al by focusing on minimizing the risk of delay propagation between trains, which also can lead to missed transfers. Schöbel and Kratz focus on maintaining train to train transfers during delays, since these can increase a minor passenger delay to the frequency of the train service that the transfer is made to.

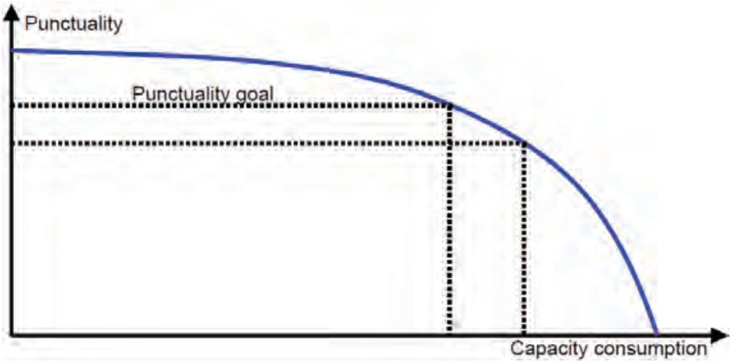


Figure 8.7: Correlation between punctuality and capacity consumption (Landex 2008)

Timetable robustness is dependent on TOC and IM influence parameters. There is a proven correlation between capacity consumption levels and achievable punctuality for railway timetables. A higher level of capacity consumption gives a lower achievable punctuality (Kaas 1998, Rasch 1998, Landex 2008). Figure 8.7 shows the correlation between punctuality levels and capacity consumption.

Besides capacity consumption on the railway infrastructure there are other IM influence parameters that affect the robustness of a given timetable. See Figure 8.8. The applied running times for different train types between stations have to be correct. If a used running time is below the shortest physical possible running time, trains will automatically be delayed. Same applies for train stopping times at station. If the scheduled stopping time is less than what is needed for alighting and boarding passengers the train will depart the station with a delay.

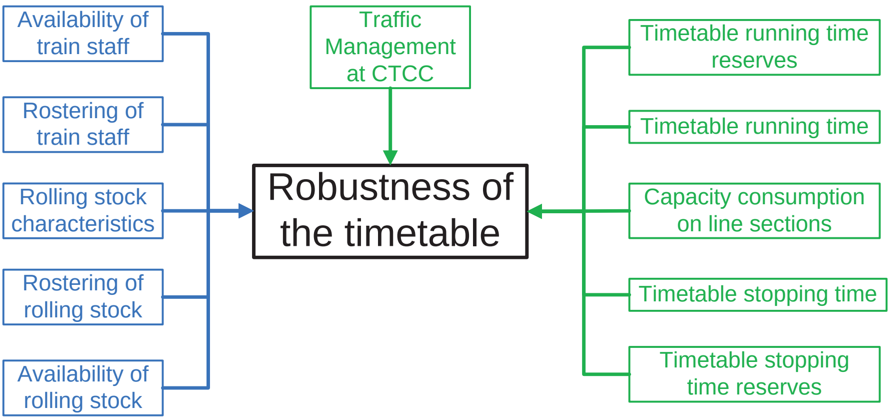


Figure 8.8: Timetable robustness timetabling criterion and the influencing parameters. Blue are TOC parameters and green are IM parameters.

To make it possible for trains to catch up with minor delays caused by e.g. line sections with reduced speed or stations with large number of passengers, time reserves are added in the timetable. These are added both to running and stopping times. In practice this is done by lengthening the running and stopping times. Trains are planned to run with a lower maximum speed than is possible with the given infrastructure and to spend longer time at stations than necessary. Figure 8.9 shows a speed-distance diagram for an InterCity-Express train between the cities of Copenhagen and Odense. The train is planned with a fixed running time reserve of 7%. If the rolling stock of the TOC is performing as expected it can utilize these running time reserves and the train can become punctual again, if not the delay can be kept to a minimum (Pachl 2008, Schittenhelm 2011c).

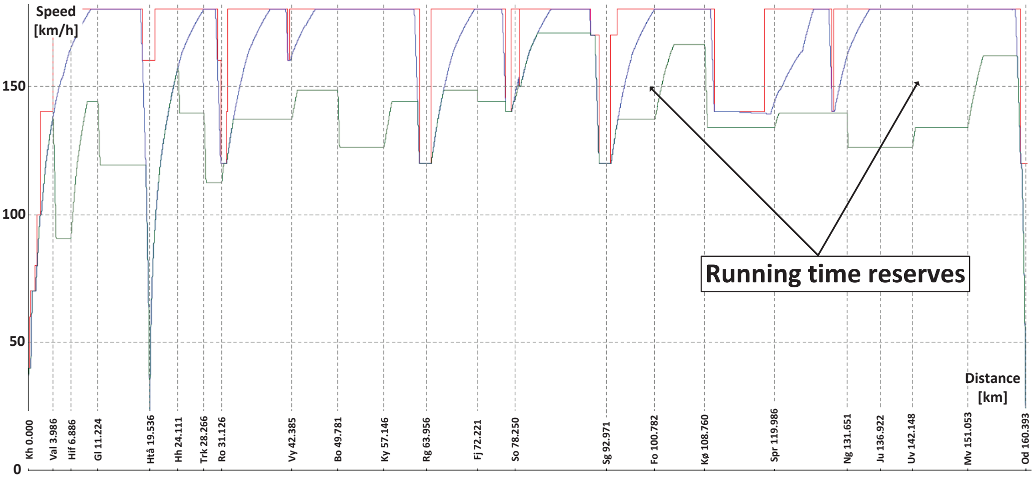


Figure 8.9: Speed-distance diagram for an InterCity-Express train with 7% running time reserves. Maximum line speeds are marked red, maximum achievable train speed is marked blue and timetabled speed is marked green. The running time reserves are the areas between the blue and green lines (Schittenhelm 2011c)

Besides performance levels of the rolling stock there are several other TOC influence parameters that can affect the robustness of the timetable. First of all the planned rolling stock and the necessary staff has to be available on time to execute the train run according to the timetable. If either one is not available the train will be cancelled or delayed.

Rostering of rolling stock and train crews can be done more or less complicated. The level of complexity in the rostering plans depends on how many changes between different train services take place with a given set of rolling stock during an operational day. A given train set could throughout a day both be used for InterCity and regional train services on two different railway lines. The same approach can be used for train personnel. A train crew can be appointed to both InterCity trains on one railway line and regional trains on a branch line. These changes between services create the risk of delays spreading to much larger parts of the railway network than if trains and crews were only allocated to one train service during an operational day. The latter scenario most often demands larger number of employees and rolling stock and is therefore economically less attractive for a TOC (Schittenhelm 2008, Schittenhelm & Landex 2009).

When delays occur in the railway system it is up to the centralized traffic control centers (CTCC) to confine delays as much as possible and keep them as low as possible. Delays should not spread throughout the railway network and traffic must be restored to run according to the timetable as quickly as possible. Based on the experience of the train traffic controllers and the available intelligent traffic management system at the CTCC, a strategy for handling a traffic disruption is selected. Hereby the CCTC can have a very big impact on how much time it takes to get railway traffic back to normal and how many trains were delayed and/or cancelled.

Rostering plans for rolling stock and train staff are prepared by each TOC for their train services. See section 6.4 for a description of the timetabling process within passenger TOC DSB. The timetabling process at IM RND can and does not take this issue into consideration.
To ensure the highest possible level of punctuality in the yearly timetable, RND has introduced a set of timetable planning rules. These are written down in a digital booklet and are mandatory to use for all timetable planners in their work. These planning rules entail:

- Minimum running time reserves between two stations (speed dependent)
- Minimum headway times between two train paths running in the same direction on all railway line sections (all possible combinations between different train types)
- Minimum headway time between two potentially conflicting train paths at a level junction or in a switch zone at larger stations, e.g. Copenhagen central station
- Minimum difference between arrival times for trains crossing at a given crossing station on a single track railway line (depending on the signaling technology and track layout)
- Minimum stopping time at a given station (based on experience and field measurements)
- Minimum transfer time between trains for scheduled transfer options (each station is given a minimum transfer time for train-train transfers and train-bus transfers)

As part of the quality control of a given timetable variant in RND's timetabling process, it should be checked if all planning rules are complied with. TOC DSB has already introduced such a quality control feature for their train services. Timetable data is extracted from the timetabling software tool TPS database and processed in the SAS (Statistical Analysis System) software tool provided by the SAS Institute Inc. (Madsen & Johansen 2012). Here all train runs that do not follow the planning rules are listed and their deviation(s) from the planning rule are also stated.

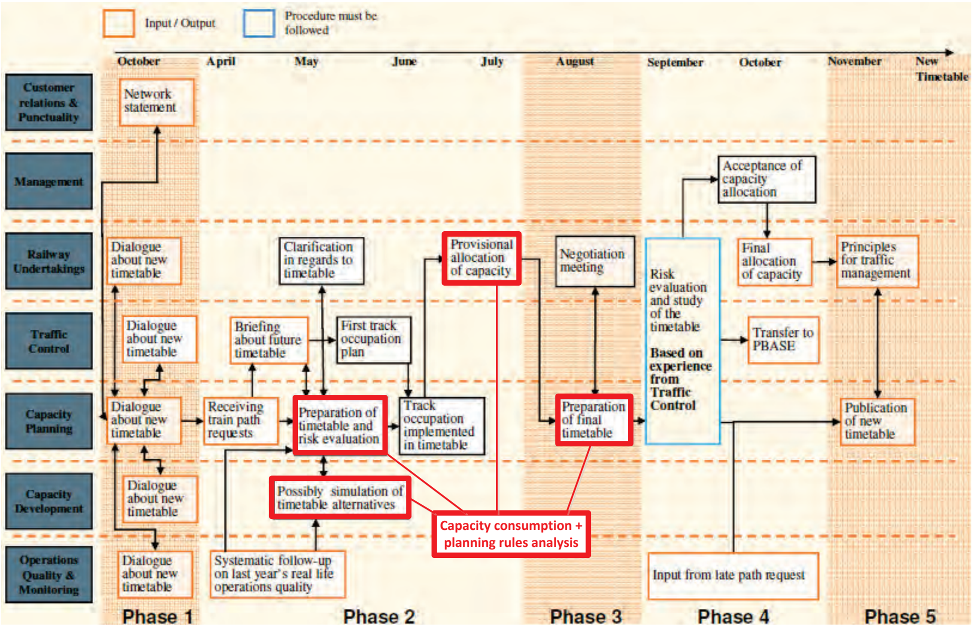


Figure 8.10: Rail Net Denmark timetabling process + suggested timetable robustness analyses in process steps (marked red) (based on Toylsbjerg 2009)

A similar timetable quality control feature can be introduced to the RND timetabling process. It should be implemented in the same stages as the control mechanisms for the systematic timetable and the utilization of capacity on railway line sections. See Figure 8.10.

8.1.4 Social acceptance of the timetable

The level of social acceptance of a railway timetable in society depends on how many of the requirements stated by the society that could be fulfilled in the yearly timetable. Societal request can be made by both railway customers (passenger and freight) and political decision makers. These requests can cover everything from frequencies of train services, seating capacity in trains, scheduled travel times and achieved punctuality levels. A recent Danish example for a non-acceptable timetable to society was the yearly timetable for Kystbanen (The Coast Line) between the cities of Copenhagen and Elsinore for the year 2010. Here punctuality levels dropped to very low levels and the credibility of the train services hit an all-time low with the train passengers. This lead to increasingly loud protests from passengers followed by critical statements from Danish traffic politicians. They demanded a new revised timetable. A new revised timetable was introduced during August 2010. This included longer turnaround times for trains at terminus stations plus “stand-by train sets” at selected stations that could be put into service with short notice to ensure on-time departures from these selected stations (baneavisen 2010).

Figure 8.11 shows how customers can influence both TOCs and politicians with their wishes for train services. Since TOCs want to attract as many train passengers or freight customers as possible, they will most likely listen to the wishes from their present and potential future customers and take them into account when preparing their own requirements for the next yearly timetable. These requirements are then handed in to the IM that must to try to fulfill as many wishes from as many TOCs as possible when preparing the future timetable. This is stated in the European Union (EU) railway legislation (Directive 2001/14/EC). If railway customers succeed to convince politicians about their requirements their level of influence increases dramatically and both TOCs (characteristics of train services) and IM (specific timetable structure) can be highly affected by intervening politicians.

The valid national yearly timetable with its basic features is what customers are exposed to when they use the railway transportation system. Therefore they will react on the performance level of the timetable. Primarily focus will be on achieved punctuality levels, travel times and frequencies (Nielsen & Landex 2009).

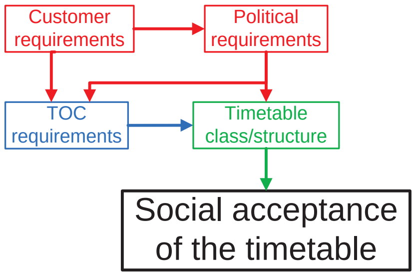


Figure 8.11: Social acceptance criterion and the influencing parameters.
Red are society parameters, blue are TOC parameters and green are IM parameters.

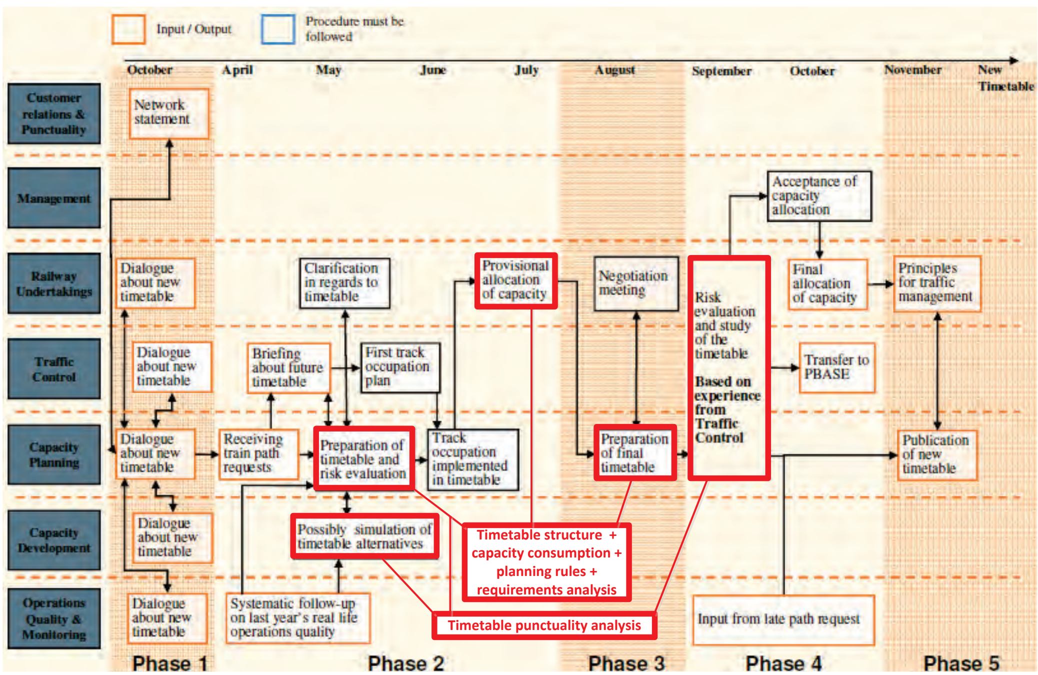


Figure 8.12: Rail Net Denmark timetabling process + timetable requirements and punctuality analyses in process steps (marked red) (based on Toylsbjerg 2009)

This thesis recommends adding two analyzing steps to the existing timetabling process to ensure societal acceptance of the timetable. In Figure 8.12 these are shown with the red text boxes. First step is a requirements analysis. It must be investigated to what degree requirements from both TOCs and political decision makers have been fulfilled. A high number of fulfilled requirements increase the chance of societal acceptance, whereas a low degree increases the risk of a societal rejection of the timetable. This analysis should take place during the same timetabling working steps as the timetable structure, capacity consumption and planning rules analyses.

The second recommended analysis step is a timetable punctuality analysis. Estimating the achievable punctuality levels for a future timetable can be done by carrying out railway traffic simulations and/or making a risk evaluation of potential train delays based on the vast experience of the RND employees working with timetabling and traffic control. At the present time, RND makes use of the railway simulation software tool RailSys version 8.x.x. for timetable robustness analyses and the trend is going towards preparing more and more of this kind of analyses when preparing future timetables.

Statistical data from the systematic follow-up on real-life train operations quality is becoming a more and more important input for timetable risk evaluation. The reason for this is that major timetable changes only take place every five to ten years and therefore train service punctuality statistics from earlier timetables can be useful for preparing and evaluating future timetables. Furthermore, these statistics are used to prepare the train delay probability distributions for the simulation of timetable alternatives. This can be seen in the lowest “lane” in Figure 8.12.

8.1.5 Attractive transfer options

The needed number of transfers to make a railway journey is an important attractiveness parameter. For passengers with heavy luggage it is not convenient to change trains on their journey. Each transfer entails the risk of extending the travel time compared to a direct train service. In most cases passengers will experience a scheduled waiting time in connection with transfers.

The timetabling criterion “Attractive transfer options” belongs to the low priority layer together with the “Travel time” criterion. This was defined by the participants from the complex planning workshop described in section 7.4. Figure 8.13 gives an overview of the influencing parameters on this criterion.

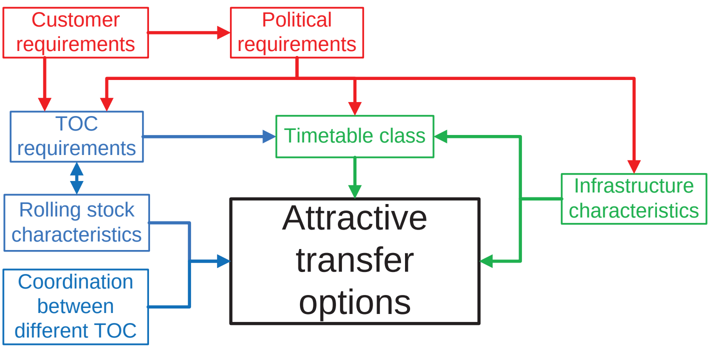


Figure 8.13: Transfer time criterion and the influencing parameters. Red are society parameters, blue are TOC parameters and green are IM parameters.

Railway customers, both freight and passenger can affect the TOCs and politicians with their wishes for running train services. Since politicians are elected by amongst others railway customers they can be affected by customer requirements and take these both to the TOCs and the IM who is responsible for preparing the final timetable. In the long term politicians can also affect the potential implementable timetable classes by allocating resources to the railway infrastructure and thereby affecting its traffic handling characteristics, such as maximum train speeds and possible headway times between trains.

TOCs will consider the requirements from both customers and politicians when creating their own requirements for next year's timetable. These wishes will also have an impact on the rolling stock that the TOC will acquire/lease and put into service, e.g. in regards to build in signaling systems to achieve short headway times between trains at stations, maximum speed and the number and width of doors to set the necessary train stopping times. These characteristics can have an effect on transfer times at stations.

Today it is not uncommon that different Danish TOCs coordinate their requirements for the future timetable before they are handed in to the IM. This happens e.g. between the Danish passenger TOC DSB and Arriva to ensure attractive transfer options between trains from these TOCs. Reason for this cooperation is that Arriva regional trains most often have the role as feeder trains for DSB national InterCity-Express and InterCity train services. Both companies profit from making transfers between their train services as attractive as possible. Cooperation between two directly competing passenger TOCs or a passenger and freight TOCs is rarely seen.

The possible timetable layouts depend on the requirements from the TOCs and the infrastructure characteristics. It is the task of the IM to fulfill as many wishes from TOCs as possible and the basic limiting condition to this is the characteristics of the infrastructure e.g. number of platform tracks at stations, minimum headway times between trains when reaching a station or possible simultaneously entry of trains coming from different directions to a given station.

The specific physical station layout is an infrastructure characteristic that has a big impact on transfer times between trains. Transfer times between two trains can be kept minimal if the transfer takes place on an island platform and the trains arrive and depart at the same times or shortly after each other. If a train to train transfer is only one-directional, then the shortest transfer time can be achieved when the trains use the same platform track shortly after each other.

Each railway station in Denmark has been assigned a minimum transfer time value in whole minutes. These are listed in the public timetable. If a transfer is possible according to the timetable then the time difference between the arrival time and the departure time of the two means of transportation must at least be the minimum transfer time value for the given station. If this is not the case the potential transfer possibility is not available to passengers. This thesis proposes a transfer time analysis for all major transfer railway stations. See Figure 8.14.

Such a transfer time analysis can unveil how much scheduled waiting time passengers will experience when making a given transfer. The scheduled waiting time is the excess time beyond the given minimum station transfer time.

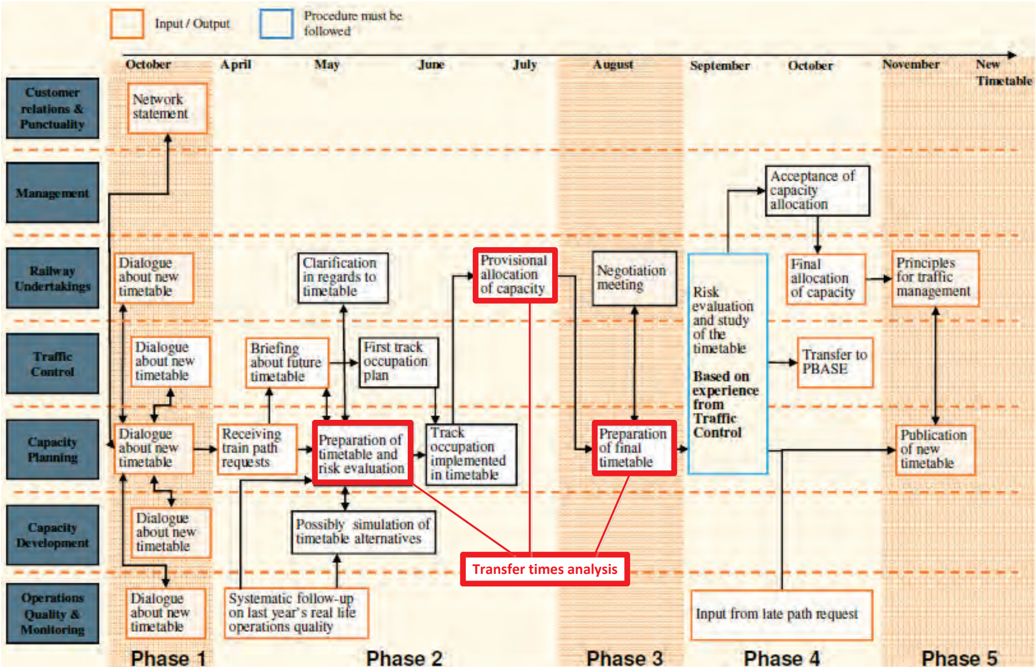


Figure 8.14: Rail Net Denmark timetabling process + transfer time analysis in process steps (marked red) (based on Toylsbjerg 2009)

8.1.6 Train travel times

Figure 8.15 shows the “Train travel times” criterion and its affecting parameters. Similar to the “Attractive transfer options” criterion the customers have influence on TOCs because they pay to use train services and the politicians because of elections. Politicians make the national transport policy and thereby have a very big impact on the wishes from the TOCs, the structure of the timetable itself and the characteristics of the railway infrastructure.

When preparing their requirements for next year’s timetable the TOCs must consider the abilities of their rolling stock. Considerations include fleet size of different types of rolling stock and their driving characteristics to set realistic travel times. Rolling stock types with good acceleration and breaking performance and a high maximum speed has the potential to achieve shorter travel times. These parameters are essential conditions when preparing realistic requirements for the future timetable.

From an IM point of view the infrastructure characteristics are the basic conditions for which specific timetable structures can be implemented. Combined with the requirements from the different TOCs this set of potential possible timetables is then reduced to none or a much smaller number of implementable timetables. To increase the number of potential feasible timetables, the travel times of trains can be adjusted. In some cases it can be necessary to reduce the travel time and hereby reducing the running time reserves or it can be necessary to prolong travel times by adding scheduled waiting time to a train’s timetable train path.

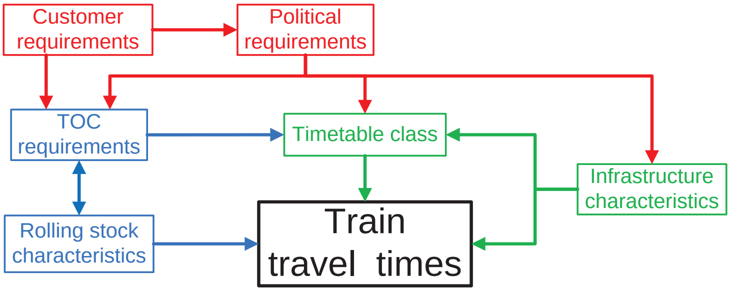


Figure 8.15: Travel time criterion and the influencing parameters. Red are society parameters, blue are TOC parameters and green are IM parameters.

Travel time calculations are based on the following input data for the timetabling software system:

- Rolling stock: Traction-force diagrams (acceleration capability)
- Rolling stock: Breaking-diagrams (breaking capability)
- Rolling stock: Maximum allowed speed, length and weight
- Infrastructure: Signaling system (possible restrictive surveillance breaking curves)
- Infrastructure: Maximum allowed speeds and gradients
- Timetable: Planning rules (agreed upon speed dependent running time reserves, minimum headway times, minimum station stopping times)

It is very important that these input data are correct and reflect the real-world situation. A big effort must be made to ensure that these data are at all-times updated and correct. If this is not the case then the prepared travel time calculations are not trustworthy and the basis for timetabling becomes uncertain. To guarantee that input data is valid and corresponds to reality this thesis proposes two additional analysis steps:

Infrastructure model and rolling stock data analyses. These have been added to the timetabling process in Figure 8.16.

The two proposed analyses must be made before any timetable variants are created. During the timetabling process it must continuously be ensured that the data basis for creating next year's timetable is valid. Sudden changes in the infrastructure model or performance levels of rolling stock must be taken into consideration as soon as possible.

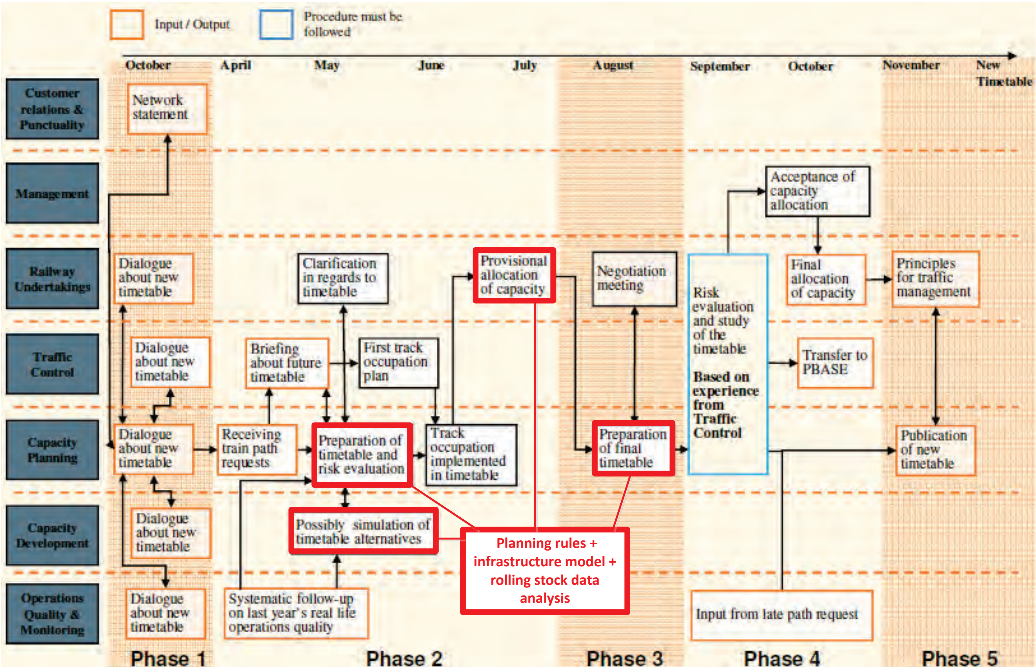


Figure 8.16: Rail Net Denmark timetabling process + suggested train travel time analyses in process steps (marked red) (based Toylsbjerg 2009)

8.2 Revising the timetabling process at infrastructure manager - Rail Net Denmark

The existing timetabling process at IM RND is described in detail in section 6.5. This section will present recommendable revisions to this timetabling process in accordance to the identified timetabling criteria during the complex planning workshop described in section 7.4.4. A simplified version of the present timetabling process at IM Rail Net Denmark can be seen in Figure 8.17.

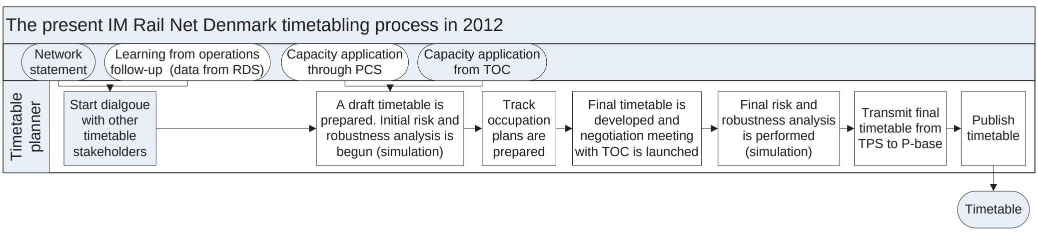


Figure 8.17: Overview of the present timetabling process at Rail Net Denmark (Schittenhelm & Landex 2012)

Figure 8.17 consists of two “swimming lanes”: A lane with the present work tasks of a timetable planner at IM RND and above that a lane showing external input to the timetabling process. The timetabling process results in the creation of a yearly timetable that is put into production and is made public in various ways both digitally and on paper (Schittenhelm & Landex 2012).

The basic structure of the timetabling process is set up according to EU legislation and guidelines from the professional body Rail Net Europe (RNE) for European IMs (Directive 2001/14/EC, RNE 2005, RNE 2006, Schittenhelm & Landex 2012):

- Based on the Network Statement provided by the IM the TOCs can send in their wishes in form of a capacity application.
- The IM prepares a first draft timetable and invites all TOCs to a negotiation meeting to resolve any train path conflicts there might be.
- When the negotiations are finished the timetable is finalized and published.

Foundation for the timetable is the document “Network Statement” which RND as an IM must prepare every year according to European Directive 2001/14/EC (Directive 2001/14/EC). This document presents information about the Danish railway network, focusing on commercial and legal access conditions. The aim is to provide all TOCs with a single source of up-to-date, relevant information on a fair and non-discriminatory basis. RNE is trying to harmonize the basic outline of the Network Statements prepared by its members (http://www.rne.eu/network-statement.html (02.12.2012), Schittenhelm & Landex 2012).

Next year’s timetable should be based on the experiences made from earlier timetables. This should ensure a continuous improvement of future timetables. Important input to the timetable comes from the systematic follow-up on real-life train operations. The RDS-system, punctuality and operations statistics system (in Danish: Regulatitets- og Driftsstatistik System), provides the necessary detailed data from realized train traffic operations. Other important input comes from RND traffic dispatchers and the timetable planners from the TOCs (Schittenhelm & Richter 2009, Schittenhelm & Landex 2012).

Second step is to receive the wishes for train operations from TOCs in form of capacity applications. Capacity requests from other RNE customers come in through the train path coordination system (PCS). Based on this input the timetable planners create a first feasible draft version of next year’s timetable. An initial robustness analysis of the draft timetable is performed. This can include simulation of selected parts of the timetable. Following this, traffic dispatchers prepare the detailed track occupation plan for larger stations. Potential conflicts between scheduled train paths must be avoided (Schittenhelm & Landex 2012).

A first version of the final timetable is presented to the TOCs at a negotiation meeting where minor conflicts between TOCs should be solved and small changes to the timetable can be made. A final robustness analysis of selected critical parts of the timetable is carried out. This can again include simulation of the train traffic. Then the timetable is transmitted from the timetable planning system (TPS) to the train traffic production database (P-base). Finally the timetable is published, both the public timetable and the working timetable (Schittenhelm & Landex 2012).

An overview of the recommended new analysis steps for the timetabling process by this thesis is given in Figure 8.18. They are marked with red. It is also indicated to which process step in the timetabling process the analyses should be attached. In total a set of seven analysis steps are introduced. Some of the timetabling criteria needed more than one analysis step and some analyses could be used in connection with more than one timetabling criterion.

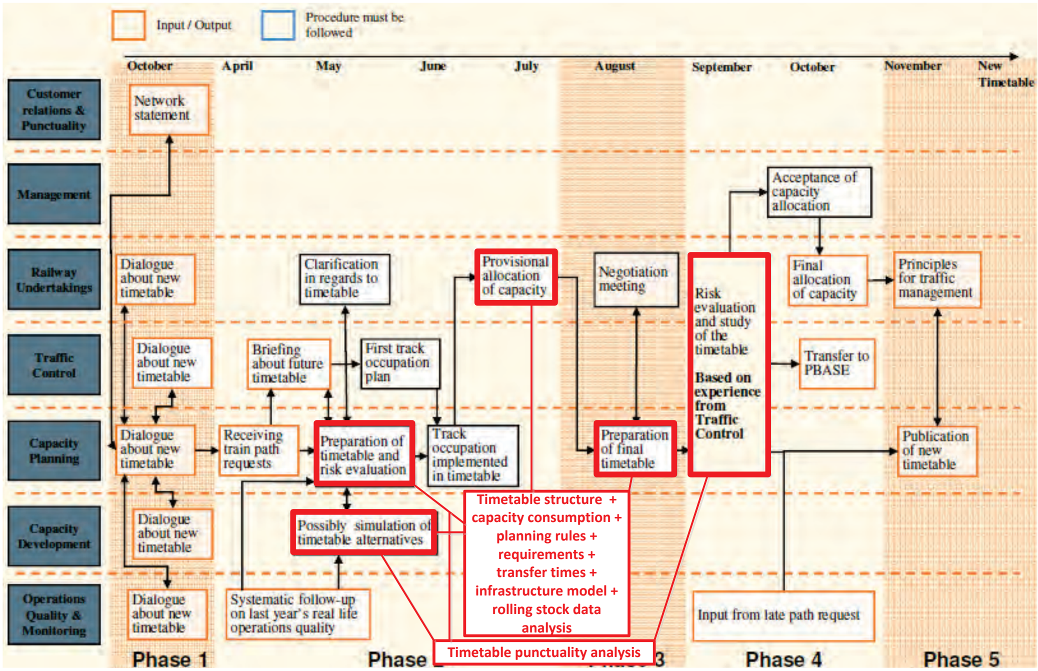


Figure 8.18: Overview of recommended new analysis steps to the timetabling process by this thesis (marked red) (based on Toylsbjerg 2009)

In Figure 8.19 this thesis presents a revised timetabling process at IM Rail Net Denmark. The timetabling process has the same basic working steps as today's process, see Figure 6.16. This is due to that present valid EU legislation and RNE guidelines must be followed. RNE has addressed the EU in regards to planned changes for the legislation covering railway timetables in the near future. The EU assured that no major modifications of the legislation would be implemented during the next ten years (Schittenhelm & Landex 2012, Toylsbjerg 2012).

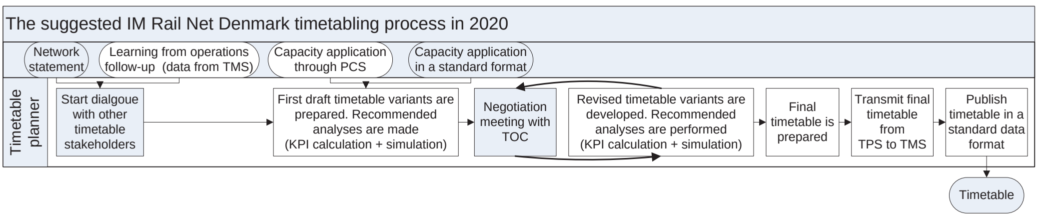


Figure 8.19: Revised timetabling process at IM Rail Net Denmark in 2020 as proposed by this thesis (Schittenhelm & Landex 2012)

With the common Danish list of railway timetable evaluation and optimization criteria and the earlier derived recommended analyses of a given timetable, it is possible to develop a series of key performance indicators (KPIs) based on the identified criteria. The risk and robustness analysis in today's timetabling process can be improved to a set of risk and attractiveness analyses, where a given timetable variant receives a KPI-score. These scores can be used to evaluate each timetable variant individually and compare it with other timetable variants (Schittenhelm & Landex 2012).

The major change in the recommended revised process is that the negotiation meeting with TOCs and the following revision of timetable variants should be an iterative process, with the goal to achieve the highest possible KPI-score for the final timetable. It is assumed that the future timetable planning system software will have more intelligent functionalities, e.g. timetable generation algorithms based on an operations research approach and therefore will be far more efficient than today's systems. Such features makes it possible, to simultaneously work with several timetable variants during the process rather than only one, as is the case today (Schittenhelm & Landex 2012).

In the last steps the final timetable is transferred from the off-line timetable planning system to the traffic management system (TMS) in the traffic control centers. This transfer of an off-line production plan to an on-line TMS is intended to take place daily – maybe even several times during a day. To increase the availability of the timetable data, it should be published in a standardized data format for the European railway sector e.g. RailML (Nash et al. 2004, Schittenhelm & Landex 2012).

Rail Net Denmark will implement the new European standard signaling system and traffic management system ETCS/ERTMS level 2 on its complete railway network until 2021. This project provides IM RND with the opportunity to rethink the entire timetabling process and it is therefore possible to take the recommended revisions by this thesis into consideration.

8.3 Conclusions

The six earlier identified common Danish railway timetable evaluation and optimization criteria by this thesis have been presented. The most important influencing parameters are shortly introduced. It becomes clear that certain key parameters such as “Customer requirements”, “Political requirements”, “TOC requirements” and “Infrastructure characteristics” can be found in almost all criterion descriptions. A parameter like “Timetable running times” is only present with two criteria. This is not unexpected since the Danish railway infrastructure is state owned and almost all passenger train traffic is subsidized by the state.

When introducing the common Danish list of six prioritized railway timetable evaluation and optimization criteria to the present timetabling process, this thesis has found a need for new analyses in the existing working steps in the timetabling process. For each timetabling criterion one or more analysis steps are recommended and it is indicated to which process step in the present timetabling process they should be attached. Some timetabling criteria need their own analysis steps whereas others can make use of an analysis step from another criterion. A total of eight new analyses are recommended by this thesis.

This thesis has presented a revised timetabling process for the IM RND. It does not differ much from the present timetabling process; since it must comply with present valid EU and Danish legislation and the guidelines prepared by the professional body RNE. The important differences are that the timetable planners will work with several timetable variants simultaneously during the process. An improved risk and attractiveness analysis is introduced, based on the new recommended eight analysis steps. Each timetable variant can receive an analysis-score. The revised process features a truly iterative process with negotiation meetings with TOCs and preparing revised timetable variants for new discussions. The goal is to achieve the highest possible score in the conducted analyses. This is possible since this thesis assumes that the future timetabling system software will support such a process by being far more intelligent and efficient than today's system.

The presented revised timetabling process should be considered when implementing the new timetabling process for year 2021. By that year the European standard ETCS/ERTMS level 2 has been introduced on the entire RND railway network and the next generation of the timetabling tool TPS, including a highly advanced timetable generator based on operations research methodologies, is in place.

8.4 Summary

The earlier found common Danish list of prioritized railway timetable evaluation and optimization criteria is the basis for this chapter. Each timetabling criterion is described by identifying the most important influencing parameters. Key parameters like “Customer requirements” and “Political requirements” can be found in all description except one whereas a parameter like “Timetable running times” is only used in the description of two criteria.

For each timetabling criterion this thesis presents a need for one or more new analysis steps in the timetabling process. Some criteria need their own specific analysis/analyses and others can reuse the recommended analysis from another timetabling criterion. Eight different analysis steps are recommended. It is furthermore indicated to which timetable process working task a given analysis should be connected.

Finally a revised timetabling process is presented by the thesis. It is similar to the existing process since it has to comply with presently valid EU railway timetabling legislation. The major changes compared with today’s timetabling process are:

- The timetable planners work simultaneously with more than one timetable variant
- The new analysis steps are introduced. Each timetable variant receives a KPI score
- An iterative process between negotiation meetings with TOCs and the revision of timetable variants. The goal is to achieve the highest possible timetable KPI-score

Rail Net Denmark is to create a new timetabling process for the year 2021 due to the implementation of ETCS/ERTMS level 2. This provides an opportunity to consider the recommended revised timetabling process presented by this thesis.

9 Danish key performance indicators for railway timetables

In today's society every business process has to be made measurable to evaluate a company's performance level. This is also the case for the European railway sector. Both infrastructure managers (IMs) and train operating companies (TOCs) are under political pressure to make their businesses more effective, by improving their product but reducing their costs at the same time. One important tool that is used to achieve this goal is the use of Key Performance Indicators (KPIs). The most important process for both TOCs and IMs is to create a feasible and attractive railway timetable. One possibility to measure the success of the timetabling process is to measure the quality of the produced timetable variants and the final implemented yearly national timetable.

KPIs for railway timetables must be based on a set of evaluation criteria on which all timetable stakeholders agree. Danish railway timetables must be based on a list of Danish railway timetable evaluation and optimization criteria that is accepted by the entire Danish railway sector. This thesis has created a first version of a common Danish list of railway timetabling criteria. See chapter 7. For each criterion one or more KPIs can be implemented. Some KPIs are already in use today and can be used in the future; others can be improved and some must be developed and are completely new KPIs. This thesis recommends a set of railway timetable KPIs and implements them using the Danish national timetable 2012 (K12) and 2013 (K13) as example. A detailed presentation of the KPIs and their implementation is given in section 9.1 to 9.6.

In section 9.1 the Systematic Timetable Index (STI) KPI is presented and calculated for the Coastal Railway Line between Elsinore and Copenhagen. The UIC (International Union of Railways / Union Internationale des Chemins de fer) 406 methodology is in use today to calculate the capacity consumption on the railway network of Rail Net Denmark. This is presented in 9.2. Robustness of a timetable depends on many aspects. A set of KPIs is needed. They cover the degree of deviations from timetable planning rules and describing the different aspects of traffic complexity in a given timetable variant. In section 9.3 these KPIs are presented. Section 9.4 shows a few examples of results from the half yearly published railway passenger satisfaction survey conducted by the organization “Passenger Focus” in United Kingdom. Deviations from the shortest possible travel time in the 2012 timetable are presented for the travel relations between the six largest Danish cities in section 9.5. Elsinore station is used as location for calculating the KPIs: Degree of transfer time prolongation and: Degree of optimal transfer conditions in section 9.6.

The described KPIs and the achieved results are discussed in section 9.7. This entails perspectives for future improvements and research. Conclusions on the presented KPIs are made in section 9.8. Finally a summary of the chapter is given in section 9.9.

9.1 Systematic timetable

Systematic timetables contain structure. They are periodic. This means that the railway traffic follows one or more patterns during an operational day. In the following sections two existing and some new approaches to measuring timetable structure are presented. Finally a recommendation for a KPI is given: The Systematic Timetable Index (STI).

9.1.1 Measuring timetable structure

Normal time periods for periodicity can range from 5 minutes, 10 minutes, 15 minutes, 20 minutes, 30 minutes, and 1 hour up to 2 hours. This depends on the used frequencies of the train systems in the timetable. The train service(s) with the lowest frequency of the given timetable pattern will determine the minimum periodicity time period. A timetable with a low periodicity time period has a higher level of homogenous structure than a timetable with a high periodicity time period. For train passengers it is easy to overview the structure in the timetable if most or all train services have the same frequency as the periodicity period of the timetable. Short periodicity time periods make it more likely that train services have the same frequency as the timetable periodicity period. It can be argued for, that a timetable with a periodicity time period of 10 minutes is 6 times more structured than a timetable with a periodicity time period of 60 minutes. For timetables with periodic repeating traffic patterns, this thesis recommends an index for measurement of the timetable structure potential. If the highest frequency of train services matches the periodicity period of the given timetable, the highest potential has been achieved. See Equation 9.1.

$$TSP = \frac{f_{high}}{PTP} \qquad \text{(Equation 9.1)}$$

TSP = Timetable Structure Potential
f_{high} = highest frequency of train service (in minutes)
PTP = Periodicity Time Period (in minutes)

A TSP-value of 1 can be achieved if the periodicity time period matches the highest frequency of a train service in the timetable. Low values of TSP such as 0,083 are obtained if the periodicity time period is e.g. 120 minutes and the highest frequency for a train service is 10 minutes.

In the following sections two existing approaches to measuring the level of structure in a timetable are presented. One developed in the United Kingdom and one from Switzerland. Following the presentations, this thesis presents how these approaches can be improved to give a better picture of the level of structure in railway timetables. To do so the thesis introduces the concept of timetable patterns to calculate the level of structure in a given timetable.

9.1.2 An English approach to measuring timetable structure

In England a clock face index (CI) was suggested to give an indication of how much structure a timetable has. See Equation 9.2 (Wardman et al 2004).

$$CI = \frac{\left\lceil \frac{NT-1}{SS} \right\rceil}{NDDT} \qquad \text{(Equation 9.2)}$$

NDDT = Number of Different Departure Times
NT = Number of Trains
SS = Service Span hours
CI = Clockface Index

This formula assumes that if a train has a different departure time from a given station, compared with other trains, it will have different departure times from all following stations as well. In the real practical world this does not have to be the case. Equation 9.2 is best suitable when applied for a single station. A timetable CI-index could then be calculated based on a set of CI-station indexes.

An index value of almost 1 is achieved by a perfect periodic timetable. The lower bound of the index is determined by the service span hours. In regards to using two or more individual train services during an operational day, the suggested index considers the differences between train services. It however does not consider the number of shifts between using different train services during a day. This is shown with the two following examples.

Example 1a: A given timetable has two train services. A peak hour service with 6 departures per hour and a day hour service with 3 departures. Every second train is skipped during day time hours (6 different departure times). Peak hours are 2x3 hours (36 departures) and the day hour service is running for 6 hours (18 departures). There are two shifts between services. The CI-index value is calculated to be:

$$CI = \frac{\left(\frac{NT-1}{SS}\right)}{NDDT} = \frac{\left(\frac{36+18-1}{6+2\times 3}\right)}{6} = \frac{\left(\frac{53}{12}\right)}{6} = 0.74$$

The CI-value would not change if there were six shifts between the two train services making the timetable less structured than the timetable used in this example.

Example 1b: A given timetable has two train services. A peak hour service with 4 departures per hour and a day hour service with 3 departures per hour. The departure times are unique for each service (7 different departure times). Peak hours are 2x3 hours (24 departures) and the day hour service runs for 6 hours (18 departures). The CI-index value is then calculated:

$$CI = \frac{\left(\frac{NT-1}{SS}\right)}{NDDT} = \frac{\left(\frac{24+18-1}{6+2\times 3}\right)}{4+3} = \frac{\left(\frac{41}{12}\right)}{7} = 0.49$$

The big differences between the two services, in both departure times and frequencies, is considered but that the timetable only operates with two train services during a day and only shifts twice between them is not rewarded. An adjustment of the CI-index methodology is recommendable.

9.1.3 A Swiss approach to measuring timetable structure

Switzerland contributed to the re-launching of integrated fixed interval timetables in Europe with their Bahn2000 timetable, which was implemented in December 2004 (Bösch et al 2012). Tzieropoulos asks the question of how regular a regular-interval timetable is and comes up with a set of indexes to measure this (Tzieropoulos & Emery 2009). See Equation 9.3, Equation 9.4 and Equation 9.5:

Regularity Index: $$RI = \frac{A}{A+B}$$ (Equation 9.3)

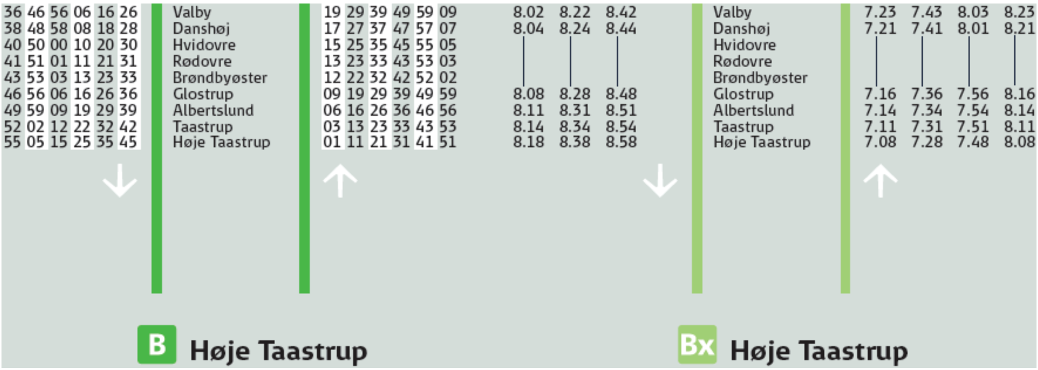
Structure Index: $$SI = \frac{A+C}{A+C+D}$$ (Equation 9.4)

Reinforcement Rate: $$RR = \frac{C}{A}$$ (Equation 9.5)

Where:
A = Number of train paths belonging to a service planned at regular time intervals
B = Number of missing train paths that would exist if a service was planned at regular intervals
C = Number of train paths that can be assigned to a service, but not planned at regular intervals
D = Number of train paths that cannot be traced back to a regular service

The results of the indexes are given in percent. A completely regular timetable would achieve a score of 100%. It is recommended to look at a time span of minimum 12 hours when applying the indexation methodology (Tzieropoulos & Emery 2009).

Example 2: Copenhagen S-train line B serves the railway line between Høje Taastrup and Valby. In the time span between 6:00 and 18:00 o'clock it runs every 10 minutes towards Copenhagen. During the morning rush hour an additional S-train line is running on the railway line, line Bx, with a different stopping pattern. It has 4 departures towards Copenhagen centre (Valby) with a headway of 20 minutes (DSB S-tog 2011). Figure 9.1 shows the public timetable.



↓							↑					
36	46	56	06	16	26	Valby	19	29	39	49	59	09
38	48	58	08	18	28	Danshøj	17	27	37	47	57	07
40	50	00	10	20	30	Hvidovre	15	25	35	45	55	05
41	51	01	11	21	31	Rødovre	13	23	33	43	53	03
43	53	03	13	23	33	Brøndbyøster	12	22	32	42	52	02
46	56	06	16	26	36	Glostrup	09	19	29	39	49	59
49	59	09	19	29	39	Albertslund	06	16	26	36	46	56
52	02	12	22	32	42	Taastrup	03	13	23	33	43	53
55	05	15	25	35	45	Høje Taastrup	01	11	21	31	41	51

B Høje Taastrup

↓				↑			
8.02	8.22	8.42	Valby	7.23	7.43	8.03	8.23
8.04	8.24	8.44	Danshøj	7.21	7.41	8.01	8.21
|	|	|	Hvidovre	|	|	|	|
|	|	|	Rødovre	|	|	|	|
|	|	|	Brøndbyøster	|	|	|	|
8.08	8.28	8.48	Glostrup	7.16	7.36	7.56	8.16
8.11	8.31	8.51	Albertslund	7.14	7.34	7.54	8.14
8.14	8.34	8.54	Taastrup	7.11	7.31	7.51	8.11
8.18	8.38	8.58	Høje Taastrup	7.08	7.28	7.48	8.08

Bx Høje Taastrup

Figure 9.1: Timetable of S-train lines B and Bx between Høje Taastrup and Valby (DSB S-tog 2011)

The presented indexes can now be calculated for this example:

$$RI = \frac{A}{A+B} = \frac{12hours \times 6trains/hour}{12hours \times 6trains/hour + 4trains + (12hours \times 3train/hour - 4trains)} = 69\%$$

$$SI = \frac{A+C}{A+C+D} = \frac{76}{76} = 100\%$$

We are looking at two separate train services and therefore the structure index will be 100%, whereas the regularity index only achieves a score of 70%. The reinforcement rate is 0% since we work with two individual train services. If line Bx would have the same stopping pattern as line B, the reinforcement rate would be:

$$RR = \frac{C}{A} = \frac{4}{72} = 6\%$$

In this case both the regularity and structure index would be 100%. The regularity index (RI)-value in this example of 69% is to low considering that line Bx only has 4 departures during the investigation time span of 12 hours. A revised approach is appropriate.

9.1.4 Introduction of timetable patterns

This thesis introduces the concept of timetable patterns to improve the calculation of structure levels in railway timetables. The definition of the term "timetable pattern" used in this thesis is given below.

Definition of a timetable pattern:

A timetable pattern is the shortest time period for which the regularity index (RI) for a given travel relation, a railway line or an entire network, including all relevant train services, is 100%. Starting from the beginning of the investigation time period or the end of the previous timetable pattern.

Timetable patterns should not have a periodicity time period of more than one hour – an absolute maximum of two hours is recommended. If the length of a timetable pattern is longer than two hours it becomes difficult for both professionals and customers to directly see the structure in the timetable. A timetable with very long periodicity periods will therefore tend to be perceived as non-periodic.

Since timetable patterns are based on the shortest time period, it is possible that a timetable pattern can be repeated several times, with or without interruption from other timetable patterns. The basic frequency of the Copenhagen suburban train services during day time hours is a train every 10 minutes. The timetable pattern therefore has a periodicity time of 10 minutes. During one hour the timetable pattern is repeated six times. When going from daytime to rush hour operation, the timetable pattern changes. See Figure 9.1.

When working with timetable patterns it must be decided if one only looks at passenger train services or also includes timetable train paths allocated to freight trains. Therefore, it has been chosen to use the word “relevant” in regards to trains that should be considered in the definition above.

Calculating the level of structure in timetables can be improved by introducing timetable patterns. When investigating the timetable for a single railway line section, a railway line, several railway lines or an entire network, one should consider the following four questions to get a better understanding of timetable structure:

1. How many different timetable patterns have been identified in the timetable?
2. How big are the differences between two succeeding timetable patterns?
3. How many shifts between timetable patterns take place in the timetable?
4. How many hours of the investigation time period is the dominant timetable pattern used?

A high number of different timetable patterns, during an investigation period, indicates that the level of structure in a given timetable is lower than for a timetable with only a few patterns.

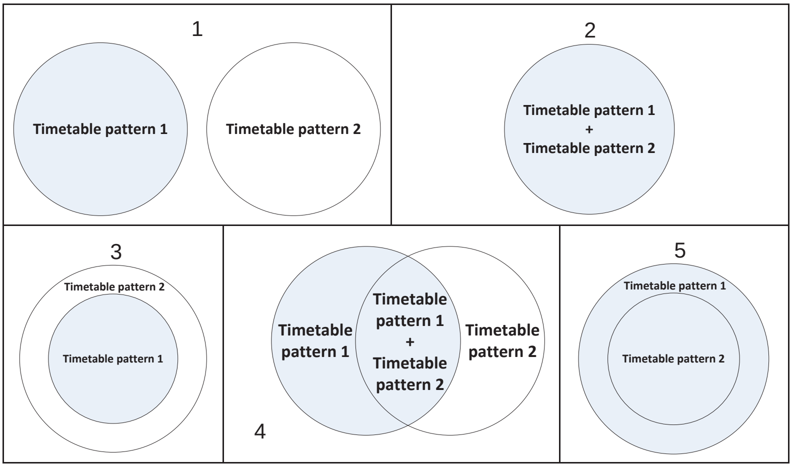


Figure 9.2: Schematic overview of timetable pattern differences

Two succeeding timetable patterns can be more or less different from each other, reaching from being completely identical to being completely different. See the top row in Figure 9.2. Timetable patterns can be partially identical. There are three possible scenarios:

- The succeeding timetable pattern contains the entire previous pattern and introduces some new train services. These can be completely new and/or lengthened existing train services – case 3 in Figure 9.2

- The succeeding timetable pattern is contained in the previous pattern and has a reduced number of train services. The reduction can be obtained by removing entire and/or shortening existing train services – case 5 in Figure 9.2

- The succeeding timetable patterns are partially identical. Some train services from the previous pattern are no longer in the timetable and some new have been added by the new pattern - case 4 in Figure 9.2. The removal and addition of services can take place as described in the two scenarios above

If the succeeding pattern contains all of the train services from the previous pattern, plus some train services of its own, the difference can be regarded “more positive” from a customer point of view than vice versa where train services are missing in the succeeding pattern.

The number of shifts between timetable patterns during the investigation period indicates if the level of structure is high or low. Numerous shifts indicate a lower level of timetable structure, whereas a small number of shifts points towards a higher level of structure.

When looking at the dominant timetable pattern, one can calculate the total sum of hours it is used, but it is also worth looking at the longest continuous time that a timetable pattern is used during the investigation period. A very long period with only one pattern makes the timetable more structured.

In the following section this thesis presents revised versions of the presented English and Swiss approaches to measure timetable structure, based on the listed questions above.

9.1.5 *New approaches to measuring timetable structure*

Taking timetable patterns into consideration can improve both the earlier presented English and Swiss approach. In the English approach two additions to the CI-formula, Equation 9.6, are recommended. By adding these, the number of timetable patterns and the number of shifts between timetable patterns is taken into consideration. See Equation 9.6. The latter addition can be omitted if so wished.

$$CI_{rev} = \frac{\frac{NT}{SS}}{NDDT} \times \frac{1}{NTP} \times \frac{1}{NSTP+1} \qquad \text{(Equation 9.6)}$$

Where:
CI_{rev} = Revised Clockface Index
NTP = Number of Timetable Patterns
NSTP = Number of Shifts between Timetable Patterns

In this approach to timetable structure, a non-periodic timetable is considered to have a rather high number of unique timetable patterns, e.g. for each operational hour, and would for a service span of 24 hours achieve an index value of approximately 0.0001. A timetable with only one pattern during its service span hours would achieve an index score of 1. Revisiting examples 1a and 1b from section 9.1.2, Equation 9.6 gives a CI_{rev}-value of 0.18 for example 1a, and 0.12 for example 1b. Here each train service represents a timetable pattern. If there were to be 6 shifts between the two timetable patterns in example 1a, a value of 0.061 would be achieved. These index values give a more nuanced picture of timetable structure. It is very important to remember that an index value of 0.18 shows a high level of structure in a timetable variant since a completely unstructured timetable candidate would receive an index value of 0.0001, a 1000 times less.

In example 2 we calculated the regularity (RI) + structure index (SI) for a time span of 12 hours. Within these 12 hours, two patterns in the timetable can be recognized:

- Pattern 1: The railway line is serviced only by line B
- Pattern 2: The railway line is serviced both by line B and Bx

Pattern 1 covers 11 hours and pattern 2 is used for little more than one hour. For both identified timetable patterns both the SI and RI-indexes would have the value of 100%. Table 9.1 gives an overview of the timetable structure in example 2.

Identified timetable patterns	Pattern 1: Morning	Pattern 2: Rush hour	Pattern 1: Day time
Time period of the timetable pattern	6-7 (1 hour)	7-8 (1 hour)	8-18 (10 hours)
Train services and their frequency	Line B: Every 10 minutes	Line B: Every 10 minutes Line Bx: Every 20 minutes	Line B: Every 10 minutes

Table 9.1: Overview of timetable patterns and train services for example 2 (S-train example)

From Table 9.1 it can be seen that the “Morning” and “Day time” timetable patterns are identical in regards to running train services. This means that in 11 out of 12 hours the service on the given railway line follows one specific timetable pattern.

This leads to the development of a new index for calculating how systematic the investigated timetable is[4]. See Equation 9.7.

$$STI_t = \frac{\sum TS_{mtp}}{TS_{inv}} \times 100\% \qquad \text{(Equation 9.7)}$$

Where:
STI_t = Systematic Timetable Index using the time wise most used timetable pattern
TS_{mtp} = Sum of Time spans for the most used timetable pattern
TS_{inv} = Time span for the investigation

For example 2 (S-train example) Equation 9.7 provides the following STI_t result:

$$STI_t = \frac{\sum TS_{mtp}}{TS_{inv}} \times 100\% = \frac{11 hours}{12 hours} \times 100\% = 92\%$$

A systematic timetable index of 92% gives a more correct picture of the timetable regularity in the presented timetable example.

It can be argued for that the interruption of the morning + day time timetable pattern by the rush hour timetable pattern reduces the regularity of the timetable as a whole. Instead of adding all the hours where a given timetable pattern is applied, only the longest continuous time span of a given timetable pattern is used in the calculation of a revised STI-index. See Equation 9.8.

$$STI_c = \frac{TS_{lctp}}{TS_{inv}} \times 100\% \qquad \text{(Equation 9.8)}$$

Where:
TS_{lctp} = Time Span for the longest continuous timetable pattern

Applying Equation 9.8 leads to the following result in example 2:

$$STI_c = \frac{TS_{lctp}}{TS_{inv}} \times 100\% = \frac{10\, hours}{12\, hours} \times 100\% = 83.3\%$$

The later methodology takes to some degree shifts between timetable patterns into consideration by only considering the longest continuous time span of a timetable pattern. A high number of shifts between timetable patterns would normally reduce the length of a time span with one timetable pattern.

The level of difference between two succeeding timetable patterns can both be experienced as significant or small. A number of train services can be identical for both patterns. This can both be a high or low number. A degree of timetable pattern resemblance is suggested by this thesis. See Equation 9.9.

[4] At the joint timetabling criteria workshop described in section 7.4, it was decided to use the term “systematic timetable” rather than regular or periodic timetable.

$$DTPR_{X-Y} = \frac{2 \times CTS_{X-Y}}{NTS_X + NTS_Y}$$ (Equation 9.9)

Where:
$DTPR_{X-Y}$ = Degree of Timetable Pattern Resemblance between pattern X and Y
CTS_{X-Y} = Common Train Services in timetable pattern X and Y
NTS_Y = Number of Train Services in timetable pattern Y

If a high degree of timetable pattern resemblance is recognized, the use of the STI_t methodology (Equation 9.7) is recommendable. In the case of a low level of difference the STI_c-index approach is preferable (Equation 9.8). This thesis recommends that values higher than 0.5 indicate a high level of timetable pattern resemblance.

For example 2 the degree of timetable pattern resemblance between pattern 1 and 2 is:

$$DTPR_{1-2} = \frac{2 \times 6_{1-2}}{6_1 + 9_2} = \frac{12}{15} = 0.8$$

Therefore the STI_t-index of 92% is recommendable.

The equations presented in section 9.1.1 can be used to measure the level of structure in a timetable. Looking from a railway customer perspective, passenger and freight, a timetable structure index should be calculated for any given travel relation. This can become a very cumbersome task, depending on both the size and structural features of the examined railway network and on the traffic complexity of the given timetable variant.

From a railway timetable planner's point of view, working for an infrastructure manager (IM) or train operating company (TOC), it is interesting to know the level of structure in the timetable, on the entire railway network or on a selected part of it. To get a picture of how apportioned the structure is in a given railway timetable, this thesis recommends applying the preferred timetable structure index methodology on all partial railway network sections as used by the IM for the UIC (International Union of Railways / Union Internationale des Chemins de fer) 406 methodology for capacity analyses. A standard analysis area average can be calculated based on these railway line section values.

Example 3: Travel relation Østerport → Helsingør (Elsinore) on The Coast line (Kystbanen): The public timetable for the railway line between Østerport and Elsinore stations is shown in Figure 9.3. An overview of identified timetable patterns can be seen in Table 9.2.

	dagtimer					aftentimer			nattetimer	
køredage	ma-fr	ma-sø	ma-sø	ma-fr: 6.22-9.02	ma-fr	ma-sø	ma-sø	ma-sø	ma-sø	nat efter
tidsinterval	6.09-7.09	4.13-18.53	4.42-19.22	15.42-18.22 lø: 11.02-12.02	15.09-17.49	19.42-22.42	19.13-23.33		0.33-3.33	fr og lø 0.33-3.33
Malmö C		13 33 53		22 42 02			13 33 53		33	33
Triangeln		17 37 57		26 46 06			17 37 57		37	37
Hyllie		22 42 02		31 51 11			22 42 02		42	42
Kbh./Kastrup ✈		34 54 14	42 02 22	42 02 22		42 02 22	34 54 14		54	54
Tårnby		38 58 18	46 06 26	46 06 26		46 06 26	38 58 18		58	58
Ørestad		40 00 20	48 08 28	48 08 28		48 08 28	40 00 20		00	00
København H ank.		47 07 27	55 15 35	55 15 35		55 15 35	47 07 27		07	07
København H	09 29 49	56 16 36	59 19 39	59 19 39	09 29 49	58 18 38	49 09 29	0.29 0.49	09	09
Nørreport	13 33 53	00 20 40	03 23 43	03 23 43	13 33 53	02 22 42	53 13 33	0.33 0.53	13	13
Østerport	16 36 56	03 23 43	06 26 46	06 26 46	16 36 56	05 25 45	56 16 36	0.36 0.56	16	16
Hellerup	│ │ │	08 28 48	11 31 51	11 31 51	│ │ │		01 21 41	0.41 1.01		21
Klampenborg	│ │ │	│ │ │	17 37 57	17 37 57	│ │ │		05 25 45	0.45 1.05		25
Skodsborg	│ │ │	│ │ │	21 41 01	21 41 01	│ │ │		10 30 50	0.50 1.10		30
Vedbæk	│ │ │	│ │ │	25 45 05	25 45 05	│ │ │		13 33 53	0.53 1.13		33
Rungsted Kyst	33 53 13	│ │ │	29 49 09	29 49 09	34 54 14		17 37 57	0.57 1.17		37
Kokkedal	37 57 17	22 42 02	33 53 13	33 53 13	│ │ │		20 40 00	1.00 1.20		40
Nivå	│ │ │	26 46 06	36 56 16	36 56 16	│ │ │		24 44 04	1.04 1.24		44
Humlebæk	43 03 23	29 49 09			43 03 23		27 47 07	1.07 1.27		47
Espergærde	46 06 26	33 53 13			46 06 26		31 51 11	1.11 1.31		51
Snekkersten	50 10 30	36 56 16			50 10 30		34 54 14	1.14 1.34		54
Helsingør ank.	54 14 34	41 01 21			54 14 34		38 58 18	1.18 1.38		58

Figure 9.3: Public timetable for the Coastal Line, driving direction Østerport → Helsingør (Elsinore) (DSB First 2011)

Timetable pattern ID	Time period [hours]	Departure times from Østerport station [min]					
1	05 - 06	03	-	23	-	43	-
2	06 - 07	03	16	23	36	43	56
1	07 - 15	03	-	23	-	43	-
2	15 - 18	03	16	23	36	43	56
1	18 - 20	03	-	23	-	43	-
3	20 - 01	-	16	-	36	-	56

Table 9.2: Overview of timetable patterns for the travel relation Østerport → Helsingør (Elsinore) (DSB Øresund 2011)

The difference between timetable patterns 1 and 2 is the additional rush hour trains with departure in minute 16, 36 and 56 at Østerport station. The stopping pattern for the rush hour trains is not the same as the regular train service but the travel time is 38 minutes for both train services. In timetable pattern 3 there is only one train service running on the line, calling at all stations thereby increasing travel time to 42 minutes. There are bigger differences between timetable pattern 1 and 3 than between timetable patterns 1 and 2.

For this example, the earlier presented timetable structure indexes in sections 9.1.2 and 9.1.3 are calculated and compared with the new indexes presented by this thesis in Table 9.3. The English CI-index and the Swiss RI-index both indicate a structure level of the example timetable about 60%. Achieving a value of 66 % for the degree of timetable pattern resemblance between timetable pattern 1 and 2 recommends applying the STI_t-index using the sum of hours for the most used timetable pattern. Timetable pattern 1 and 3 have nothing in common and the degree of resemblance would therefore be 0%. The result with the STI_t-index is 55%. This value is lower than both the English and Swiss approach. Generally the calculated values are too low for a timetable example that contains a very high level of structure.

The English approach	$CI = \frac{\left\lceil \frac{NT-1}{SS} \right\rceil}{NDDT} = \frac{\frac{72-1}{20}}{6} = 0.59$
The revised English approach by this thesis	$CI_{rev} = \frac{\frac{NT}{SS}}{NDDT} \times \frac{1}{NTP} \times \frac{1}{NSTP+1} = \frac{\frac{72}{20}}{6} \times \frac{1}{3} \times \frac{1}{6} = 0.03$
The Swiss approach	$RI = \frac{A}{A+B} \times 100\% = \frac{72}{72+48} \times 100\% = 60\%$
	$SI = \frac{A+C}{A+C+D} \times 100\% = \frac{72}{72} = 100\%$
Newly developed approaches in this thesis	$DTPR_{1-2} = \frac{2 \times CTSX_{1-2}}{NTS_1 + NTS_2} \times 100\% = \frac{2 \times 1}{1+2} = \frac{2}{3} = 66\%$
	$STI_t = \frac{\sum TS_{mtp}}{TS_{inv}} \times 100\% = \frac{1+8+2}{20} \times 100\% = 55\%$
	$STI_c = \frac{TS_{ctp}}{TS_{inv}} \times 100\% = \frac{8}{20} \times 100\% = 40\%$

Table 9.3: Overview of calculated timetable structure indexes for example 3

It is noticeable in this example that timetable pattern 2 contains the entire timetable pattern 1. Therefore it can be discussed if timetable pattern 1 is present in 15 of the investigated 20 timetable hours. If this approach is accepted the timetable achieves a STI_t-index value of 75%. The value of 75% is more reasonable than the earlier value of 55%. This specific circumstance with entire timetable patterns contained inside other timetable patterns must be considered when using the STI_t-index methodology. This thesis recommends using the approach where the time span of a contained timetable pattern is added to the sum of time span in the calculation of the STI_t-index.

In the following two sections calculation examples of the STI KPI are presented. Section 9.1.6 shows how the STI is calculated for a travel relation whereas section 9.1.7 calculates the STI for a railway line section. Both examples use The Coastal Railway Line (in Danish: Kystbanen) between Copenhagen and Elsinore (in Danish: Helsingør). The calculations apply Equation 9.3 to measure how systematic the timetable for The Coastal Railway Line is.

9.1.6 Calculation of Systematic Timetable Index for a travel relation

The public timetable for The Coastal Line between Copenhagen and Elsinore is shown in Figure 9.4. An overview of identified timetable patterns for the travel relation between Østerport and Helsingør (Elsinore) stations can be seen in Table 9.4.

Dag / Myldretid / Aften		alle dage 4.13-18.53	alle dage 4.42-19.02	ma-fr 6.22- 8.42 15.42-17.02 1	ma-fr 6.18- 7.18 15.18-17.58 2	alle dage 19.13-23.33 3	alle dage 19.22-0.22 4
Malmö C		13 33 53		22 42 02		13 33 53	
Triangeln		16 36 56		25 45 05		16 36 56	
Hyllie		21 41 01		30 50 10		21 41 01	
CPH Lufthavn ✈		34 54 14	42 02 22	42 02 22		34 54 14	22 42 02
Tårnby		38 58 18	45 05 25	45 05 25		38 58 18	25 45 05
Ørestad		40 00 20	48 08 28	48 08 28		40 00 20	28 48 08
København H	ank.	48 08 28	56 16 36	56 16 36		48 08 28	36 56 16
København H		52 12 32	01 21 41	01 21 41	18 38 58		41 01 21
Nørreport		55 15 35	04 24 44	04 24 44	21 41 01		│ │ │
Østerport		59 19 39	08 28 48	08 28 48	25 45 05		48 08 28
Hellerup		04 24 44	13 33 53	13 33 53	│ │ │		53 13 33
Klampenborg		│ │ │	18 38 58	18 38 58	│ │ │		58 18 38
Skodsborg		│ │ │	23 43 03	23 43 03	│ │ │		03 23 43
Vedbæk		│ │ │	26 46 06	26 46 06	│ │ │		06 26 46
Rungsted Kyst		│ │ │	30 50 10	30 50 10	41 01 21		10 30 50
Kokkedal		18 38 58	34 54 14	34 54 14	45 05 25		14 34 54
Nivå		21 41 01	37 57 17	37 57 17	│ │ │		17 37 57
Humlebæk		25 45 05			50 10 30		21 41 01
Espergærde		29 49 09			54 14 34		26 46 06
Snekkersten		32 52 12			57 17 37		29 49 09
Helsingør	ank.	36 56 16			01 21 41		34 54 14

Figure 9.4: Public timetable for the Coastal Line, travel relation Østerport → Helsingør (Elsinore). The investigated train departures from Østerport are marked with the red box (DSB Øresund 2012)

The difference between timetable patterns 1 and 2 is the additional rush hour trains with departure in minute 16, 36 and 56 at Østerport station. The stopping pattern for the rush hour trains is not the same as the regular train service but the travel time is 38 minutes for both train services. In timetable pattern 3 there is only one train service running on the line calling at all stations thereby increasing travel time to 42 minutes. There are bigger differences between timetable pattern 3 and timetable patterns 1 and 2.

Timetable pattern ID	Time span [hour]	Departure times from Østerport station [min]					
1	05:00 – 06:30	-	19	-	39	-	59
2	06:30 – 07:30	05	19	25	39	45	59
1	07:30 – 15:30	-	19	-	39	-	59
2	15:30 – 18:00	05	19	25	39	45	59
1	18:00 – 20:00	-	19	-	39	-	59
3	20:00 – 01:00	08	-	28	-	48	-

Table 9.4: Overview of timetable patterns for the travel relation Østerport → Helsingør (Elsinore)

The regularity index for the timetable can be calculated by Equation 9.3.

$$RI = \frac{A}{A+B} \; X \; 100\% = \frac{84 \; departures}{84 + 124 \; departures} \; X \; 100\% = \mathbf{40}\%$$

Where A = 55 train departures in minute 19, 39 and 59 and 13 in minute 05, 25 and 45. In the late evening there are 16 departures in minute 08, 28 and 48.
Where B = 5 hours without departures in minute 19, 39 = 16 plus 16 hours and 20 minutes without departures in minute 05, 25 and 45 = 50 plus 19 hours without departures in minute 08, 28 and 48 = 58. This adds up to in total 124 missing departures.

$$STI = \frac{\sum TS_{mtp}}{TS_{inv}} \; x \; 100\% = \frac{11.5 \; hours}{20 \; hours} \; X \; 100\% = \mathbf{57.5}\%$$

Where TS_{mtp} is 11 hours since timetable pattern 1 is time wise the most used. It is in use from hour 05:00-06:30, 07:30-15:30 and 18:00-20:00 = 11.5 hours
TS_{inv} = 20 hours since the investigation time span is from hour 05 to 01 = 20 hours

The Swiss RI-index indicates a regularity of the example timetable of 40%. The systematic timetable index using the sum of hours for the most used timetable pattern gives 57.5%. A STI-value is more reasonable than the rather low RI-index. It can be argued for that the index values are too low since the train service with departure times in minute 19 39 and 59 is present in 15 of the 20 hours that the timetable covers and therefore should be closer to 75%. It is noticeable that timetable pattern 2 contains the entire timetable pattern 1. Therefore it can be discussed if timetable pattern 1 is present in 15 of the 20 investigated hours and the result should be 75% instead of 57.5%. Differences between timetable patterns can be very big even though one pattern is contained in the other. Therefore this thesis recommends using the STI as KPI.

This KPI can be calculated for any given travel relation on a railway network but is most interesting to prepare for travel relations with the biggest passenger and/or freight flows.

9.1.7 Calculation of Systematic Timetable Index for a railway line section

A different approach in applying this KPI is looking at investigation railway line sections as defined by the UIC 406 leaflet for capacity consumption analysis (UIC 2004). The railway line section from the terminus station Helsingør to the junction Snekkersten has been investigated. At Snekkersten a train service from the TOC Lokalbanen between Helsingør and Hillerød leaves The Coastal Railway Line and continues towards Hillerød. Figure 9.5 shows the public timetables for the TOC DSB (Danish State Railways) and TOC Lokalbanen train services.

Dag Myldretid Aften	alle dage 4.30-5.10	alle dage 4.38-5.16	alle dage 5.43-19.03	alle dage 6.01-19.21	ma-fr 6.01- 7.21 14.21-17.21 1	ma-fr 6.36- 8.16 16.16-16.56 2	alle dage 19.25-0.05
Helsingør		38 58 16	43 03 23			36 56 16	25 45 05
Snekkersten		42 02 22	47 07 27			39 59 19	29 49 09
Espergærde		45 05 25	50 10 30			42 02 22	32 52 12
Humlebæk		48 08 28	53 13 33			46 06 26	36 56 16
Nivå		52 12 32	57 17 37	01 21 41	01 21 41	| | |	41 01 21
Kokkedal		55 15 35	00 20 40	04 24 44	04 24 44	51 11 31	44 04 24
Rungsted Kyst		58 18 38	| | |	07 27 47	07 27 47	55 15 35	47 07 27
Vedbæk		02 22 42	| | |	11 31 51	11 31 51	| | |	51 11 31
Skodsborg		06 26 46	| | |	15 35 55	15 35 55	| | |	55 15 35
Klampenborg		10 30 50	| | |	19 39 59	19 39 59	| | |	59 19 39
Hellerup		15 35 55	15 35 55	24 44 04	24 44 04	| | |	04 24 44
Østerport	30 50 10	21 41 01	21 41 01	30 50 10	30 50 10	13 33 53	10 30 50
Nørreport	| 53 13	24 44 04	24 44 04	33 53 13	33 53 13	16 36 56	| | |
København H ank.	35 57 17	28 48 08	28 48 08	37 57 17	37 57 17	20 40 00	15 35 55
København H	40 00 20	32 52 12	32 52 12	40 00 20	40 00 20		20 40 00
Ørestad	46 06 26	38 58 18	38 58 18	46 06 26	46 06 26		26 46 06
Tårnby	49 09 29	41 01 21	41 01 21	49 09 29	49 09 29		29 49 09
CPH Lufthavn ✈	52 12 32	46 06 26	46 06 26	52 12 32	54 14 34		32 52 12
Hyllie		59 19 39	59 19 39		09 29 49		
Triangeln		02 22 42	02 22 42		12 32 52		
Malmö C ank.		06 26 46	06 26 46		16 36 56		

Hverdage	5.09	5.18–19.48	20.39–21.39	20.48–21.48	23.00 & 0.00
Helsingør		18 48		48	00
Snekkersten		23 53		53	05
Mørdrup		26 56		56	08
Kvistgård		30 00		00	11
Langerød		33 03		03	14
Fredensborg	09	39 09	39	09	18
Kratbjerg	–	– 10	–	10	–
Grønholt	12	42 –	42	–	21
Hillerød	18	48 18	49	18	27
Hillerød	22	A 52 22	02	22	23.42
København H	02	32 02	42	02	0.22

Figure 9.5: Public timetables for The Coastal Railway Line between Helsingør (Elsinore) and Snekkersten. Investigated DSB train departures are marked with red boxes (left) and Lokalbanen train departures are marked green (right) (DSB Øresund 2012, Lokalbanen 2012b)

Table 9.5 gives an overview of the identified timetable patterns based on the public timetables shown in Figure 9.5. Train departure minutes from TOC DSB are shown with red numbers and TOC Lokalbanen with green. The timetable Regularity Index is calculated below:

$$RI = \frac{A}{A+B} X\ 100\% = \frac{108\ departures}{108 + 190\ departures} X\ 100\% = \mathbf{36}\%$$

Where A = TOC Lokalbanen: 34 timetabled train paths + TOC DSB: 74 planned trains paths = 108 departures in total
Where B = TOC Lokalbanen: 24 missing regular train paths + TOC DSB: 166 missing regular train paths = 190 missing departures in total

This is 4% lower than the RI calculated for the travel relation Østerport – Helsingør. This can be explained by the higher number of identified timetable patterns in this example. There have been identified six different timetable patterns during the investigation time span of 20 hours. The timetable pattern with the longest overall time span is pattern number 2 with 11 hours. This gives an STI-value of:

$$STI = \frac{\sum TS_{mtp}}{TS_{inv}} \; x \; 100\% = \frac{11 \; hours}{20 \; hours} \; X \; 100\% = 55\%$$

This is only 2.5% lower than the STI-value for the travel relation between Østerport and Helsingør. The reason for this is that the additional train service from Lokalbanen, has a very systematic timetable from 05:00 to 20:00. It does therefore not reduce the overall time span of timetable pattern 2 covering the basic 20 minutes frequency train service between Helsingør and Copenhagen during the day time hours.

Timetable pattern ID	Time span [hour:min]	Departure times from Helsingør (Elsinore) station [min]								
1	04:30 – 05:30	-	-	16	18	-	38	-	48	58
2	05:30 – 06:30	-	03	-	18	23	-	43	48	-
3	06:30 – 08:15	-	03	16	18	23	36	43	48	56
2	08:15 – 16:15	-	03	-	18	23	-	43	48	-
3	16:15 – 17:00	-	03	16	18	23	36	43	48	56
2	17:00 – 19:00	-	03	-	18	23	-	43	48	-
4	19:00 – 20:00	-	05	-	18	25	-	45	48	-
5	20:00 – 22:00	-	05	-	-	25	-	45	48	-
6	22:00 – 00:30	00	05	-	-	25	-	45	-	-

Table 9.5: Overview of identified timetable patterns for the railway line section Helsingør → Snekkersten. DSB departure minutes from Helsingør (Elsinore) station are shown with red and Lokalbanen with green

Also in this example the STI value with 55% is considerably higher than the RI-value of 36%. The STI value is more realistic and again it can be discussed if the time span of timetable pattern 2 should be extended with timetable pattern 3 since pattern 2 is totally included in pattern 3. This would lead to a STI-value of 67.5%.

9.2 Capacity consumption on railway line sections

The International Union of Railways (UIC) recommends performing railway capacity analyses according to the method described in their leaflet UIC 406 (UIC 2004). This approach, also called the UIC 406 methodology, has gained acceptance in most of Europe (Landex 2008). Based on the time that a train occupies a block section in the investigation area, a percentage of used and available minutes is calculated. Strengths and weaknesses of this methodology are described in detail by Landex (Landex 2008). This thesis recommends investigating the consumption of railway capacity on railway line sections by using the UIC 406 methodology and using the results as KPI for this timetable evaluation criterion. The methodology provides guidelines based on current practices of IMs for capacity consumption levels (UIC 2004). An example of a network capacity analysis at IM Rail Net Denmark can be seen in section 9.2.1.

Presently stations, including switch zones and platform tracks, are included in the sections of analysis that begin/end here. An approach where stations are considered separately has been investigated but has not yet been introduced in Denmark (Jensen 2009, Landex 2011, Schittenhelm 2011a).

9.2.1 Calculation of capacity consumption on railway line sections

Figure 9.6 shows a map illustrating the division of the railway network of Rail Net Denmark into line sections based on the guidelines given in UIC leaflet 406. The division of the network depends on the route structure of the train services and is therefore not static. The map is from the year 2008 but is still valid today. When dividing the railway network into analysis line sections, IM Rail Net Denmark focuses on changes in number of running trains and major changes in the infrastructure. This results in a division of the network at junctions and terminus stations for train services plus stations where the number of line tracks change, e.g. from single to double track, and where the interlocking system changes, e.g. going from automatic train control to manual train control. The railway network is not divided at stations with timetabled train overtakings and crossings.

An overview of the percent wise capacity consumption for a peak hour in the yearly timetable for 2010 is given in Figure 9.7. Lines with single track are marked brown, with double track blue and with quadruple track purple. Double track railway lines are analyzed according to the UIC 406 methodology using the blocking stair case theory and compressed timetables. The UIC recommends a maximum capacity consumption of 75% for double track lines (UIC 2004). Single tracked railway lines are investigated by looking at the number of available standard train paths per hour that are used. The number of standard train paths is based on the longest travel time between two neighboring crossing stations on a single tracked railway line section. This approach can be used since train traffic is mostly homogenous, trains stop at all stations, on single tracked lines. Rail Net Denmark accepts higher capacity consumption levels for single track railway lines since the network is not divided at stations with timetabled train crossings.

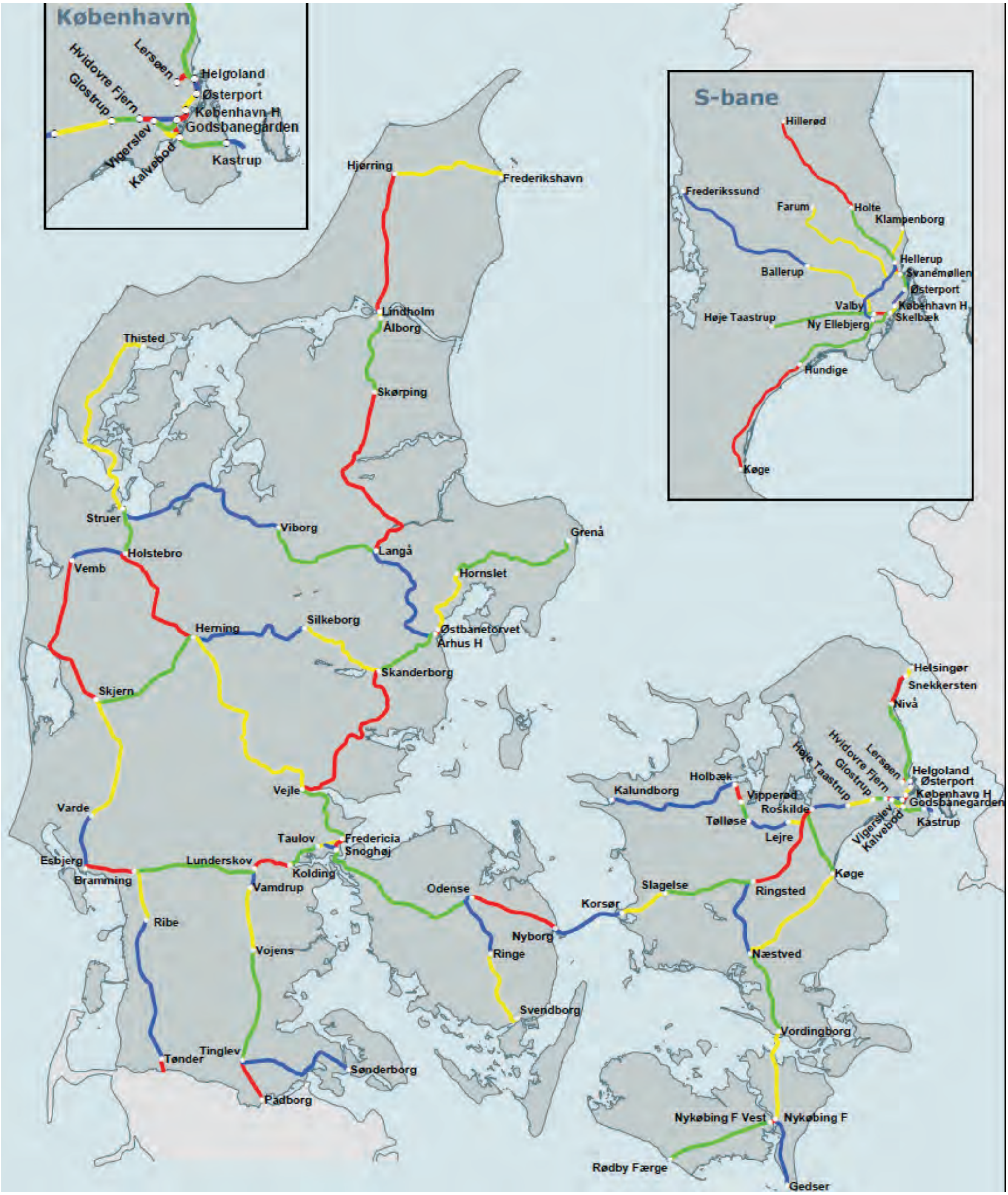


Figure 9.6: Division of the railway network of Rail Net Denmark into line sections for capacity analysis (Landex et al 2008)

Figure 9.7: Peak hour capacity consumption in percent [%] of railway line sections for the yearly timetable in 2010. Double track lines are marked with blue, single track lines with brown and quadruple track lines with purple. Recommended maximum capacity consumption is 75% for double track lines (RND 2011b)

9.3 Robustness of the timetable

This timetable evaluation criterion has many aspects and therefore several approaches of analysis with their own KPIs are needed. In the following sections, aspects that affect the robustness of the timetable are addressed. Each aspect can require one or several KPIs to make a thorough analysis.

9.3.1 Time supplements

The primary method used by the Danish railway sector to ensure the robustness of the timetable towards stochastic delays up to a certain magnitude is to add time reserves to both running times and stopping times of trains. In Denmark the running time supplements are a speed dependent fixed percentage. Table 9.6 gives an overview of the time supplements for passenger trains used by IM Rail Net Denmark and the recommendations from the UIC. The UIC recommendations are for trains consisting of multiple units (Schittenhelm 2011c).

Speed interval [km/h]	Time supplements used by IM Rail Net Denmark [%]	UIC recommendations [%]
0-75	3	3 (+ fixed supplement: 1 or1.5min/100km)
76-100	4	3 (+ fixed supplement: 1 or1.5min/100km)
101-120	5	3 (+ fixed supplement: 1 or1.5min/100km)
121-140	7	3 (+ fixed supplement: 1 or1.5min/100km)
141-160	9	4 (+ fixed supplement: 1 or1.5min/100km)
161-180	11	5 (+ fixed supplement: 1 or1.5min/100km)
181-200	13	5 (+ fixed supplement: 1 or1.5min/100km)
201-250	13	6 (+ fixed supplement: 1 or1.5min/100km)
251-300	13	7 (+ fixed supplement: 1 or1.5min/100km)

Table 9.6: Comparison of percentage of running time supplements for passenger trains as used by IM Rail Net Denmark and as recommended by the UIC (Johansson 2011, Schittenhelm 2011c, UIC 2000)

An overview of applied running time supplements for freight trains is given in Table 9.7. The UIC recommendation for high speed freight trains are based on locomotive hauled passenger trains with a weight higher than 700 tons.

<table>
<tr><th>Speed interval [km/h]</th><th>Time supplements used by IM Rail Net Denmark [%]</th><th colspan="2">UIC recommendations [%]</th></tr>
<tr><td>0-120</td><td>3</td><td colspan="2">4</td></tr>
<tr><td rowspan="3">121-200</td><td rowspan="3">3</td><td><160 km/h:</td><td>5 (+1.5min/100km)</td></tr>
<tr><td>161-200 km/h:</td><td>6 (+1.5min/100km)</td></tr>
<tr><td>>201 km/h:</td><td>7 (+1.5min/100km)</td></tr>
</table>

Table 9.7: Comparison of percentage of running time supplements for freight trains as used by IM Rail Net Denmark and as recommended by the UIC (Johansson 2011, Schittenhelm 2011c, UIC 2000)

A detailed description of running time calculations at the IM Rail Net Denmark is given in the paper “Planning with time supplements in railway timetables” (Schittenhelm 2011c).

Each timetabled train paths must be checked to see if it contains time supplements according to the IM timetable planning rules used or if deviations occur. The following KPI “Degree of deviation from planning rule running time” is recommended by this thesis. See Equation 9.10.

The currently used timetabling tools at Rail Net Denmark, TPS and RailSys, calculate train running times with an accuracy of seconds and therefore the times should be entered in seconds. If the result of Equation

9.10 is 0.0 then timetabled running times are in accordance with planning rule times. If the timetabled time is 25% larger than the planning rule time, then the degree would be 0.25. If the timetabled time was less than the planning rule time the result would be negative. This calculation can be made for a single train path, a train service, a train class or all timetabled train paths (Schittenhelm & Landex 2010).

$$Degree\ of\ deviation\ from\ planning\ rules, running\ time =$$

$$\frac{Timetable\ running\ time\ [sec] - Planning\ rule\ running\ time\ [sec]}{Planning\ rule\ running\ time\ [sec]} \quad \text{(Equation 9.10)}$$

Geographically the analysis can be made for a specific investigated railway line section, a region of the railway network or the entire railway network. See section 9.3.3 for an application of this KPI for a single train path. The example train path has a degree of deviation from planning rules between 0.04 and 0.47.

9.3.2 Timetable complexity

The complexity of the timetable can be subdivided into several topics (Schittenhelm & Landex 2013):

- Complexity of train traffic at a station or junction – potential for conflicting train paths
- Complexity of a timetabled train path – for the entire train path or a section of it
- Complexity of rostering plans for rolling stock – for the TOC overall, a given train service or a single piece of rolling stock
- Complexity of rostering plans for train staff – for the TOC overall, a given train service or a single train staff member

Complexity of train traffic at a station or junction

This topic has been investigated several times in Denmark (Landex 2008, Landex 2011, Jensen 2009, Schittenhelm 2011a). A high level of traffic complexity at a station or junction indicates that the potential for conflicting train paths is high. In Denmark the traffic complexity is defined as the conflict potential between timetabled train paths at a given station. The conflict potential depends on the number of planned train paths that can potentially be in conflict with each other and how much buffer time there has been allocated between these train paths. Based on (Landex 2011), a risk index for train conflicts at a given station or junction has been developed by this thesis, based on the infrastructure layout, minimum headway times given by the interlocking system and a detailed timetable. A conflict risk index can be calculated with a value between 0 and 1 as shown in Equation 9.11:

$$CRI_s = \frac{NHRC_s}{PC_s} \quad \text{(Equation 9.11)}$$

Where:
CRI_s = Conflict Risk Index for a given station
$NHRC_s$ = Number of High Risk Conflicts at a given station
PC_s = Number of Potential Conflicts at a given station

If there is no buffer time or only up to 50% of the possible minimum headway time as buffer time between two potentially conflicting train paths, this thesis recommends this as a high risk conflict. This is based on empiric experience. A low CRI_s-value indicates a low conflict risk at a given station. This thesis proposes to use this as KPI for measuring the complexity of train traffic at stations and junctions (Schittenhelm 2011a).

Complexity of a timetabled train path

In the timetable, a train path is surrounded by other planned train paths. Regarding the same driving direction only train paths in front of the analyzed train path can potentially become conflicting train paths. Looking at the opposite driving direction both earlier and later scheduled train paths can become potential conflicts. This potential is especially high at train path fix points. Train path fix points for traffic complexity are (based on Andersen 2012, Schittenhelm & Landex 2013):

- Crossing stations on single tracked railway lines where the analyzed train path is scheduled to cross with another timetabled train path
- Transition stations between single and double track railway line sections. The analyzed train path goes from a double track to single track line section and is scheduled to cross a train path in the opposite direction.
- Stations where the analyzed train path is planned to overtake another train path
- Level railway junctions where the analyzed train path has potential conflicts with other train paths
- Stations where the order of departing trains due to their travel speed must be kept
- Stations where the analyzed train path is scheduled to catch up with a slower train path

A second category of fix points for train paths are transfers. Transfer fix points are:

- Stations where there is one or more planned transfer options to other trains that must be kept
- Stations with transfer options to other means of transportation e.g. ferries that must be kept

A third category of train path fix points are rolling stock and train staff fix points:

- Stations where rolling stock and/or train staff is handed over to/received from a different train service
- Starting/terminus stations with turn-around times for rolling stock and/or train staff

The higher the number of train path fix points is in a timetable, the higher is the level of complexity of the timetable. A high level of timetable complexity generally leads to a lower level of timetable robustness. See section 9.3.3 for the identification of fix points for a single train path.

This thesis proposes using the following KPI approach for measuring train path complexity (Schittenhelm & Landex 2013):

- **Number of fix points for a given train path**
  - A number of fix points per analysis railway line section according to the UIC 406
  - To get a more varied picture this can be normalized to a number of fix points according to the length of the train path: Fix points per train path kilometer or to the train path running time: Fix points per train path running time minute

- **Number of fix points for a group of train paths**
  - A train path group can be a train class such as InterCity-trains or train paths that are within a selected geographical area within a selected time span
  - An overall train path group average of fix points can be calculated

- This can be normalized to a number of fix points per train path group kilometer or per train path running time minute to get a more varied picture

- **Risk profile for a train path**
  - Amount of time supplements (both running time and dwell time) between individual identified train path fix points
  - An average of time supplements between one train path's fix points

- **Risk profile for a group of train paths**
  - The average amount of time supplements between fix points for a group of train paths

Generally the more fix points a train path has the higher is the potential for being delayed by another train path. A simple KPI approach is to calculate a train path average of fix points for the investigation area which can be anything from a single train path, a railway line section to the entire railway network. A time span for such an investigation must also be applied, e.g. rush hours. No previous data of this kind exists for Danish railway timetables and therefore no history of a given fix point average for train paths in a given timetable exists. This category of data can become more and more available for future timetable variant evaluation and thereby over time become more and more useful for timetable planners (Schittenhelm & Landex 2013).

In case train path fix points are geographically situated closely together, the quantity of timetabled time supplements between them is most likely not big, if the general Rail Net Denmark timetable planning rules are followed. This increases the risk of transferring a given train delay from one fix point to the next and thereby potentially creating new conflicts between train paths, delaying even more trains. See section 9.3.3 for an example of this approach (Schittenhelm & Landex 2013).

Some timetable classes may require more transfers between trains to get through a given railway network, e.g. such as an integrated fixed interval timetable with selected station hubs (Schittenhelm 2008). Planned transfer options between trains are easy recognizable in a modern software timetabling tool since a data connection can be created between the relevant means of transport, e.g. two trains. Some transfer times include a buffer time to ensure the transfer option in case of minor delays. Other planned train to train transfers are just feasible. If there is issued a traffic dispatching rule saying that trains do not wait for delayed transfer feeder trains, timetable complexity wise it means that there are no planned transfer possibilities. Hereby no delays can be transferred from delayed trains to on time trains. If trains have to wait for delayed transfer trains, the risk of transferring delays increases with the number of planned transfers to a train path at a given station. The risk further increases if there are no buffer times included in the scheduled transfer times (Schittenhelm & Landex 2013).

Complexity of rostering plans for rolling stock

Train services can be operated with dedicated rolling stock for only one service or the rolling stock can be shared amongst several train services. The first can be found within subway systems e.g. some lines of the London underground and the latter is the normal situation in railway traffic, since a higher utilization level of rolling stock can be achieved (Maróti 2006).

Due to the basic tree like structure of the Danish railway network most long distance passenger train services are running in combined train runs on the main railway line between Copenhagen and Jutland. Here the train runs are split up into individual train services that run on different railway lines. Furthermore the length of trains is changed during their runs to adapt the available seating capacity to the passenger demand along the railway line. This intricate use of rolling stock increase the complexity of the rolling stock rostering plans drastically (Schittenhelm & Landex 2013).

Sharing rolling stock covers both receiving and handing over rolling stock. Receiving rolling stock is critical in regards to carrying through a given train service. The rostering of rolling stock can be a very intricate issue, why it is not necessarily all timetabled train paths that are run with shared rolling stock. This thesis proposes the KPI "Degree of train paths with shared rolling stock" that takes this into account by looking at the fraction of train paths that are run with shared rolling stock out of the total number of train paths. If no train paths are run with shared rolling stock, there are no rolling stock interdependencies between trains. Rolling stock wise the timetable is then as simple as possible. See Equation 9.12 (Schittenhelm 2008, Schittenhelm & Landex 2009, Schittenhelm & Landex 2010, Schittenhelm & Landex 2013):

$$Degree\ of\ train\ paths\ with\ shared\ rolling\ stock = \frac{Number\ of\ total\ train\ paths - Number\ of\ train\ paths\ with\ not\ shared\ rolling\ stock}{Number\ of\ total\ train\ paths} \qquad \text{(Equation 9.12)}$$

This KPI can be calculated for a single station, a single railway line section, a region of the railway network or the entire network for a defined time span. Additionally this KPI can be calculated for one single TOC, a group of TOCs or all TOCs running trains on the network. Unfortunate the needed data to calculate this KPI is most often not available. This is due to missing interfaces between the timetabling software and the software tools used to create rostering plans for rolling stock. Detailed rostering plans are often prepared very shortly before the day of operation they are meant for. This means that this KPI will become available very shortly before the timetable is put into service and thereby only make a reduced contribution in the yearly timetabling process. Furthermore, a TOC might consider this information as classified, since rostering plans for rolling stock is an important competition parameter when entering a bid for operating public service train traffic (Schittenhelm & Landex 2013).

When a train reaches its terminus station a turnaround time for the rolling stock is planned. The turnaround time depends on the class of rolling stock and what operations have to be done to the rolling stock at the terminus station, e.g. cleaning and/or refueling. If there is no buffer time included in this turnaround time, then the risk increases of transferring delays from one train service to another or from one driving direction to another if the rolling stock stays with the same train service. This thesis introduced a new KPI: "Degree of buffer time for turnaround times for rolling stock". The calculation of this KPI can be seen in Equation 9.13 (Schittenhelm & Landex 2013):

$$Degree\ of\ buffer\ time\ in\ turnaround\ time\ for\ rolling\ stock = \frac{Turnaround\ time\ for\ rolling\ stock[min] - minimum\ turnaround\ time\ for\ rolling\ stock\ [min]}{minimum\ turnaround\ time\ for\ rolling\ stock[min]} \qquad \text{(Equation 9.13)}$$

This KPI can be calculated for a single train service, a single terminus station and up to all train services and the entire railway network. For long distance train services the needed data to calculate this KPI is likely not available due to the same reasons as mentioned in regards to Equation 9.12. If looking at bounded suburban or metro railway systems, such as the Copenhagen suburban trains (S-tog), it can be possible to calculate this KPI based on the public timetable (Schittenhelm & Landex 2013).

Complexity of rostering plans for train staff

As for rolling stock, train services can be manned with dedicated train crews or the crew members can be shared with other train services. The latter is most common in railway crew rostering. On long distance train services the crew can change several times en route. It is not necessarily the entire crew that is shared with other train services (Maróti 2006). This thesis proposes to use the KPI: Degree of train paths with shared train staff. It can be calculated as show in Equation 9.14 (Schittenhelm 2008, Schittenhelm & Landex 2009, Schittenhelm & Landex 2010, Schittenhelm & Landex 2013):

$$Degree\ of\ train\ paths\ with\ shared\ train\ staff\ = \frac{Number\ of\ total\ train\ paths - Number\ of\ train\ paths\ with\ not\ shared\ train\ staff}{Number\ of\ total\ train\ paths} \qquad \text{(Equation 9.14)}$$

Similar to rolling stock the scheduled turnaround times for train staff at terminus stations for train services can contain more or less buffer time and thereby decreasing or increasing the risk of transferring a delay from one train service to another. The minimum turnaround time for train staff can differ from the minimum turnaround time for rolling stock due to the collective agreements between labor unions and TOCs. This thesis proposes to use the KPI: Degree of buffer time in turnaround times for train staff. It is calculated as shown in Equation 9.15 (Schittenhelm & Landex 2013):

$$Degree\ of\ buffer\ time\ in\ turnaround\ time\ for\ train\ staff = \frac{Timetabled\ turnaround\ time\ for\ train\ staff[min] - minimum\ turnaround\ time\ for\ train\ staff\ [min]}{minimum\ turnaround\ time\ for\ train\ staff[min]} \qquad \text{(Equation 9.15)}$$

Calculation of these train staff rostering plan complexity KPIs is again made difficult due to the unavailability of this category of timetable data. Rostering plans for train staff is also an important parameter for TOCs when competing with other TOCs to win bids to operate public service railway traffic. Furthermore, the detailed rostering plans for train staff are made in separate software systems which most often do not have an interface to timetabling software tools (Schittenhelm & Landex 2013).

9.3.3 Analysis of timetable robustness for train RØ 4111

As an example for the use of some of the presented KPIs in this thesis, a single train path has been selected for investigation. Regional train RØ 4111 running between Copenhagen and Ringsted with stop at all immediate stations has been selected for a first analysis of timetable robustness (Schittenhelm & Landex 2013).

Figure 9.8 shows the train graph for the railway line between Ringsted station (Rg) and Copenhagen central station (Kh). The train path to be analyzed, train RØ 4111, is marked with red circles. The train graph is a screenshot from Rail Net Denmark's train production database software "P-base" (Schittenhelm & Landex 2013).

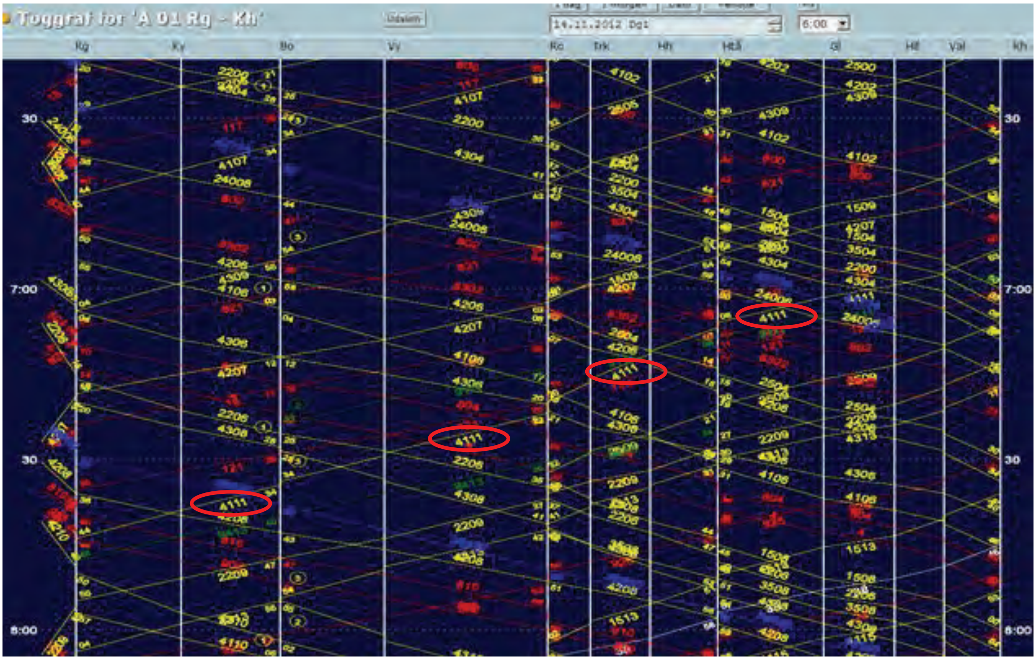


Figure 9.8: Train graph for the railway line Ringsted (Rg) and Copenhagen central station (Kh). Train RØ 4111 is marked with red circles. Screenshot from Rail Net Denmark's train production database sofware: P-base (Schittenhelm & Landex 2013)

The detailed timetable for train RØ 4111 can be seen in Table 9.8. Data are taken from Rail Net Denmark's TPS timetabling system. From the two columns to the right, it becomes clear that this train only has positive deviations from the timetable planning rules used at Rail Net Denmark. It has been planned with substantial running time reserves. Considering the complex traffic pattern around this train, this makes sense from a timetable robustness point of view (Schittenhelm & Landex 2013).

Station	Arrival [hr:min:sec]	Departure [hr:min:sec]	Deviation from planning rules [min:sec]	Degree of deviation from planning rules
Copenhagen central station (Kh)	-	06:53:00	-	-
Valby (Val)	06:57:00	06:57:30	+ 00:27	0.13
Høje Taastrup (Htå)	07:06:00	07:07:00	+ 00:18	0.04
Hedehusene (Hh)	07:11:00	07:11:30	+ 00:42	0.20
Trekroner (Trk)	07:16:00	07:16:30	+ 01:24	0.47
Roskilde (Ro)	07:20:00	07:22:00	+ 00:58	0.39
Viby Sjælland (Vy)	07:29:00	07:29:30	+ 00:45	0.12
Borup (Bo)	07:34:00	07:34:30	+ 00:14	0.06
Ringsted (Rg)	07:44:00	-	+ 00:59	0.12

Table 9.8: Detailed timetable data for train RØ 4111 - including deviation and degree of deviation from planning rules (DSB 2011e)

The train path of train 4111 has three identified timetable fix points on the route between Copenhagen central station and Ringsted station. These are (Schittenhelm & Landex 2013):

1. **Copenhagen central station (km 0.0)** – the order of departing trains must be kept. Fast passenger train InterCity-Express train L 19 is departing at 06:50 and slow regional train RØ

4111 at 06:53. This is the minimum planning headway time between two following trains out of Copenhagen central station (Johansson 2011).

2. **Roskilde station (km 31.3)** – change of train order. Train RØ 4111 is overtaken between Høje Taastrup station and Roskilde station (4 track line section) by empty train M 9111 and InterCity-train IC 121.

3. **Ringsted station (km 63.9)** – this is a level junction and train RØ 4111 must cross the train path of InterCity-train IC 810 and morning rush hour InterCity-Express train L 902 both trains going towards Copenhagen (opposite driving direction).

This gives an average of a timetable fix point every 21.3km or every 17 minutes of running time for train RØ 4111. There are unfortunately no available data with which these values can be compared. It is therefore difficult to evaluate the found average values for timetable fix points for the train path of train RØ 4111 (Schittenhelm & Landex 2013).

Table 9.9 gives an overview of the potential train path conflicts that train RØ 4111 may experience on its run between Copenhagen central station and Ringsted station. Train paths surrounding train RØ 4111 are listed at the relevant fix point and the conflict category stated and evaluated according to its risk level. This thesis proposes to use the following risk levels: Low, medium, high and critical. The latter is used in this example since the arrival minute of train RØ 4111and departure minute of train L 902 at Ringsted station is the same (Schittenhelm & Landex 2013).

Train number	Fix point	Arrival Departure	Conflicting train number	Arrival Departure	Conflict category	Risk level of conflict
RØ 4111	Copenhagen central station	- 06:53	L 19	- 06:50	Train order	High
			M 9111	- 06:57	Train order	-
			IC 121	- 07:00	Train order	-
	Roskilde	07:20 07:22	M 9111	- 07:14	Overtaking / train order	Low
			IC 121	07:18 07:20	Overtaking / train order	High
	Ringsted	07:44 -	IC 810	07:39 07:40	Crossing train paths	Medium
			L 902	07:43 07:44	Crossing train paths	Critical

Table 9.9: Overview of potential conflicts at identified fix points for the train path of regional train RØ 4111 (DSB 2011c, DSB 2011d, DSB 2011e)

When looking at the far right column in Table 9.9, a first impression would be that the risk of train RØ 4111 getting delayed is rather high. However one must remember the positive running time deviations from the timetable planning rules as shown in Table 9.8. From the timetable data alone it is not possible to deduce if the timetable planner added the extra running time reserves to train RØ 4111 because of the complexity in the timetable concerning train RØ 4111 and the neighboring train paths or if it was simply to make the timetable feasible. This thesis estimates that the planned train path of train RØ 4111 has an adequate timetable robustness level (Schittenhelm & Landex 2013).

9.4 Societal acceptance of the timetable

To achieve success with a railway timetable it must be acceptable to society, both to political decision makers and normal customers of the railway transportation system. Measuring the societal acceptance level of a timetable is difficult. This thesis recommends conducting regular satisfaction surveys amongst railway customers (both passengers and freight clients) and parliamentarian transportation politicians as a KPI for societal acceptance of the timetable. The timetable must obtain a minimum agreed upon score in these surveys to achieve the label “accepted by society”.

Key timetable aspects that must be covered in the satisfaction survey include (Schittenhelm & Landex 2013):

- **Punctuality levels of train services** – is the punctuality satisfactory to customers and politicians?
- **Travel time of train services** – are travel times attractive for customers and society?
- **Frequency of train services** – is the number of departures per hour at a given time of day suitable?
- **Connections with other train services** – does the timetable provide attractive transfer options?

Inspiration for such a satisfaction survey could be taken from Great Britain, where an independent non-departmental public body named “Passenger Focus” since 2005 has performed half yearly satisfaction surveys. Here train passengers are asked to evaluate several railway transport issues covering everything from train comfort to the attractiveness of the timetable. Passengers are faced with a number of statements and must give one of the following grades: Good ☺☺ – satisfied ☺ – neither nor 😐 – dissatisfied ☹ – poor ☹☹. These surveys are conducted to ensure that passengers and the government get high value for their money spend on railway transportation. The results are drawn up per TOC, train service/route, per region and a national total. Survey data are also drawn up according to journey purpose, age and gender. All survey results are made public in a report twice a year – spring and autumn (Passenger Focus 2012, http://www.passengerfocus.org.uk/about/history (05.07.2012), Schittenhelm & Landex 2013).

In Denmark the TOCs are requested to make satisfaction surveys according to their public service traffic contracts with the Danish Ministry of Transport. Doubt can arise about the objectivity of results from these surveys since the TOCs evaluate their own train services. This thesis therefore recommends introducing the British model in Denmark by creating a non-departmental body to carry out satisfaction surveys for the entire railway system but also for other means of public transport such as busses and ferries. Hereby objectivity is ensured and it is possible to compare different TOCs on an objective basis. Section 9.4.1 shows a few examples of the presented results from the British rail passenger satisfaction survey from spring 2012 (Schittenhelm & Landex 2013).

9.4.1 Evaluating the societal acceptance of the timetable

On the following three pages some examples from the railway passenger satisfaction survey conducted in spring 2012 by the British Passenger Focus organization are presented. Such surveys give a better understanding about the societal acceptance level of the investigated timetable. Figure 9.9 gives a national total overview of the most important evaluated railway issues. Please notice the railway issues that are evaluated by passengers in the red box. These are particularly interesting from a timetable attractiveness point of view and should therefore be included in a future Danish railway customer survey about societal acceptance of the timetable. From the survey it can be noted that the passengers feel they get less railway transport value for their ticket money.

The customer satisfaction with punctuality and reliability levels of the different TOCs in the UK is presented in Figure 9.10. The summative issue “value for money” is presented on a railway route level in Figure 9.11.

Such customer satisfaction surveys should be extended to cover both passenger and freight railway transport, but should also be sent to potential future railway customers. Input from potential customers would give valuable insights to train operating companies about what services they must provide to attract new clients and therefore which investments to make. The government could likewise get guidelines for how and where to invest money in the national railway sector.

National total

Improved ↑
Unchanged ⊖
Declined ↓

Overall sample size 28832	Spring 2012 sample size	Spring 2012 % satisfied or good	Spring 2012 % neither/nor	Spring 2012 % dissatisfied or poor	Improvement/decline in % satisfied or good since Autumn 2011: % change	Improvement/decline in % satisfied or good since Autumn 2011: significant change	Improvement/decline in % satisfied or good since Spring 2011: % change	Improvement/decline in % satisfied or good since Spring 2011: significant change
Overall satisfaction	28407	83	10	7	-1	↓	-1	⊖
STATION FACILITIES								
Overall satisfaction with the station	28128	77	16	7	-1	↓	1	↑
Ticket buying facilities	14973	73	14	12	0	⊖	1	⊖
Provision of information about train times/platforms	27092	81	11	8	0	⊖	2	↑
The upkeep/repair of the station buildings/platforms	27081	67	20	13	0	⊖	2	↑
Cleanliness	26930	71	19	10	-1	⊖	1	⊖
The facilities and services	23377	50	22	29	-1	⊖	0	⊖
The attitudes and helpfulness of the staff	20520	71	19	10	0	⊖	1	⊖
Connections with other forms of public transport	20037	73	16	12	0	⊖	0	⊖
Facilities for car parking	10934	49	19	33	-2	↓	0	⊖
Overall environment	27564	67	22	11	-1	⊖	2	↑
Your personal security whilst using	24544	68	26	6	1	⊖	2	↑
The availability of staff	23542	60	23	18	1	⊖	2	↑
How request to station staff was handled	4348	83	6	10	-3	↓	0	⊖
TRAIN FACILITIES								
The frequency of the trains on that route	27722	78	8	13	0	⊖	1	⊖
Punctuality/reliability (i.e. the train arriving/departing on time)	27651	81	8	11	0	⊖	1	⊖
The length of time the journey was scheduled to take (speed)	27325	85	9	6	0	⊖	0	⊖
Connections with other train services	16111	77	16	7	1	⊖	1	⊖
The value for money for the price of your ticket	26437	42	21	37	-4	↓	-2	↓
Upkeep and repair of the train	27927	75	15	10	0	⊖	2	↑
The provision of information during the journey	25330	70	19	10	1	⊖	1	⊖
The helpfulness and attitude of staff on train	16867	64	26	9	0	⊖	0	⊖
The space for luggage	21958	55	22	24	1	⊖	2	↑
The toilet facilities	12008	37	23	40	-1	⊖	1	⊖
Sufficient room for all passengers to sit/stand	27441	69	13	18	1	⊖	2	↑
The comfort of the seating area	27346	72	17	11	0	⊖	2	↑
The ease of being able to get on and off	27764	80	13	7	0	⊖	0	⊖
Your personal security on board	26147	77	19	4	0	⊖	1	↑
The cleanliness of the inside	28044	75	15	11	0	⊖	2	↑
The cleanliness of the outside	24032	71	20	9	-3	↓	3	↑
The availability of staff	20768	47	29	25	1	⊖	1	⊖
How well train company deals with delays	4517	37	37	26	-2	⊖	1	⊖

Figure 9.9: Example of results on a national level from Passenger Focus satisfaction survey in Great Britain (Passenger Focus 2012)

Punctuality/reliability (i.e. the train arriving/departing on time)

Improved ↑
Unchanged ⊖
Declined ↓

% of passengers satisfied/good by sector:
London and South East - 79%
Long Distance - 87%
Regional - 85%

	Spring 2012				Improvement/decline in % satisfied or good since Autumn 2011		Improvement/decline in % satisfied or good since Spring 2011	
	sample size	% satisfied or good	% neither/nor	% dissatisfied or poor	% change	significant change	% change	significant change
Arriva Trains Wales	1133	87	5	8	0	⊖	3	⊖
c2c	1072	92	5	3	0	⊖	0	⊖
Chiltern Railways	1148	86	6	8	5	↑	-2	⊖
CrossCountry	1131	85	5	10	6	↑	1	⊖
East Coast	1178	88	5	7	9	↑	3	⊖
East Midlands Trains	1178	88	5	7	0	⊖	1	⊖
First Capital Connect	1927	76	9	15	-1	⊖	1	⊖
First Great Western	2911	78	8	14	-1	⊖	1	⊖
First Hull Trains	550	93	4	3	8	↑	4	⊖
First TransPennine Express	1122	88	5	7	4	↑	1	⊖
Greater Anglia*	2341	70	9	22	-7	↓	-5	↓
Heathrow Connect	578	91	7	2	1	⊖	4	⊖
Heathrow Express	529	93	5	2	-1	⊖	-3	⊖
London Midland	1142	81	8	10	3	⊖	6	↑
London Overground	1145	88	8	5	4	↑	9	↑
Merseyrail	606	94	3	3	-1	⊖	1	⊖
Northern Rail	1222	78	9	13	-2	⊖	0	⊖
ScotRail	1192	87	6	7	1	⊖	6	↑
South West Trains	2240	82	8	10	-2	⊖	-4	↓
Southeastern	1651	79	9	12	-1	⊖	1	⊖
Southern	2228	78	8	14	0	⊖	0	⊖
Virgin Trains	1084	89	4	7	4	↑	-3	⊖

Figure 9.10: Passenger experienced punctuality and reliability levels of different train operating companies from Passenger Focus' satisfaction survey in Great Britain, spring 2012 (Passenger Focus 2012)

Figure 9.10 shows the passenger evaluation of experienced punctuality and reliability of train services from different train operating companies. Such an overview makes it possible to see if a specific company experiences problems in fulfilling passenger expectations, e.g. TOC Greater Anglia, or has created new initiatives and/or developed new approaches that are appreciated by passengers, e.g. TOC London Overground. These results are made public and therefore train operating companies get an insight into how they are perceived by their customers and how they perform compared to other TOCs.

The value for money for the price of your ticket

Improved ⊕
Unchanged ⊖
Declined ↓

% of passengers satisfied/good by sector:
London and South East - 38%
Long Distance - 54%
Regional - 54%

	Spring 2012				Improvement/decline in % satisfied or good since Autumn 2011		Improvement/decline in % satisfied or good since Spring 2011	
	sample size	% satisfied or good	% neither/ nor	% dissatisfied or poor	% change	significant change	% change	significant change
Arriva Trains Wales	1114	56	18	25	-3	⊖	-4	⊖
c2c	1030	42	22	36	-1	⊖	-1	⊖
Chiltern Railways	1108	48	21	31	-2	⊖	0	⊖
CrossCountry	1117	49	22	29	-4	⊖	-5	⊖
East Coast	1167	56	18	26	-1	⊖	-1	⊖
East Midlands Trains	1155	52	18	31	-1	⊖	0	⊖
First Capital Connect	1824	34	22	44	-4	↓	2	⊖
First Great Western	2867	48	20	33	-5	↓	-2	⊖
First Hull Trains	543	56	19	25	-5	⊖	-6	⊖
First TransPennine Express	1098	56	18	25	-2	⊖	-4	⊖
Greater Anglia*	2251	30	21	49	-3	⊖	-5	↓
Heathrow Connect	530	56	21	23	-2	⊖	1	⊖
Heathrow Express	526	33	27	40	-4	⊖	-4	⊖
London Midland	1052	53	21	27	1	⊖	0	⊖
London Overground	1018	49	23	29	-5	⊖	-4	⊖
Merseyrail	461	67	12	20	1	⊖	4	⊖
Northern Rail	1156	50	21	28	-10	↓	-7	↓
ScotRail	1158	51	18	31	-8	↓	-4	⊖
South West Trains	2143	36	21	43	-2	⊖	0	⊖
Southeastern	1534	32	21	47	-4	⊖	0	⊖
Southern	2128	38	21	41	-4	↓	-2	⊖
Virgin Trains	1056	59	15	26	0	⊖	0	⊖

Figure 9.11: Example of results on a train service/railway route level from Passenger Focus satisfaction survey in Great Britain (Passenger Focus 2012)

One of the most important parameters for societal acceptance of a given timetable is if the railway customers feel that they get good value for their money. This aspect has been analyzed in the satisfaction survey and is presented on a railway route level in Figure 9.11.

9.5 Train travel time

Based on infrastructure characteristics (e.g. maximum line speeds and signaling system), rolling stock characteristics (e.g. maximum speed, acceleration and breaking performance) and agreed upon timetabling planning rules between TOCs and IMs (e.g. running time supplements), a minimum travel time for a direct non-stop train service between two given stations can be calculated in today's timetable planning systems (Schittenhelm 2011c), e.g. TPS (Barber 2007, Kaas & Gossmann 2004, http://www.hacon.de/tps (05.07.2012)), Roman D (Barber 2007, http://www.siemens.at/roman/ (05.07.2012)), RailSys (Barber 2007, Sewcyk 2007, http://www.rmcon.de/de/produkte/railsys.html (05.07.2012)) and Open Track (Barber 2007, Nash & Hürlimann 2004, http://www.opentrack.ch (05.07.2012)). The theoretical possible minimum timetable travel time can then be compared to the timetabled train travel time in a given timetable variant. This thesis proposes using the degree of prolonged timetable travel time as a timetable evaluation KPI. See Equation 9.16 (Schittenhelm & Landex 2010, Schittenhelm & Landex 2013):

$$Degree\ of\ timetable\ travel\ time\ prolongation =$$

$$\frac{Shortest\ timetable\ travel\ time\ [min] - Shortest\ possible\ direct\ non-stop\ travel\ time [min]}{shortest\ possible\ direct\ non-stop\ travel\ time\ [min]} \quad \text{(Equation 9.16)}$$

A degree of timetabled travel time prolongation can be calculated for every travel relation or a group of selected travel relations covering the biggest passenger and freight flows. Furthermore it can be calculated for a single train service, a group of train services or all train services running on a railway line section, an entire railway line, a part of the railway network or the entire railway network. The degree of timetable travel time prolongation can be weighted by e.g. passenger and/or freight volumes (Schittenhelm & Landex 2013).

In section 9.5.1 the degree of timetable travel time prolongation has been calculated between the six biggest Danish cities: Copenhagen, Odense, Esbjerg, Aarhus, Randers and Aalborg. The degrees of timetable travel time prolongation vary between 0.12 and 0.54. A non-weighted average can be calculated to be 0.22.

Timetable travel times can be prolonged due to several reasons: Homogenization of travel speed for rail traffic is needed due to capacity restrictions. If TOCs want to run both more fast and slow trains on the same railway track a solution is to reduce the travel speed of the fast trains so they do not catch up with the slower trains. On single tracked railway lines, travel time prolongation can occur due to the location of crossing stations, e.g. trains of one driving direction have to wait for trains from the opposite driving direction. Travel time prolongation can be present in a timetable train path in the following three ways (Landex 2008):

- Not wanted stops (this needs full knowledge about the original TOC capacity application)
- Prolonged running times (planning trains with a lower speed than possible)
- Prolonged stopping times (applying longer stopping times than necessary)

When investigating a timetable variant, it is impossible to detect if a scheduled stop in a given timetable train path is wished or not by the TOC. Full knowledge about the original TOC capacity application for the given train service to the IM in the timetabling process is needed. A large necessary prolongation of running time can be converted into an extra stop (Landex 2008).

If a transfer is unavoidable on a travel relation then a possibility arises to experience a longer than necessary transfer time at the given transfer station. The Rail Net Denmark railway timetable planning rules hold a minimum required transfer time for all transfer stations. This transfer time is valid for all possible transfers at the given station, e.g. train - train, train – bus and train – ferry. Timetable travel time prolongation due to prolonged transfer times must also be taken into consideration when calculating minimum and scheduled travel times for Equation 9.16.

9.5.1 Train travel time calculations

An overview of train travel times between the biggest cities in Denmark is given in Table 9.10. First row in each cell is the shortest possible timetable travel time from the yearly timetable for 2012. Second row is the fastest possible theoretical travel time with direct non-stop train scheduled according to the agreed upon planning rules between IM and TOC. Third row is the calculated degree of timetable travel time prolongation in the yearly timetable for 2012. The degree of prolongation is calculated according to Equation 9.16.

The timetabled travel times were collected from the online travel planner service: www.rejseplanen.dk (05.07.2012) and from Rail Net Denmark's timetable production software system TPS. Here the valid timetable and infrastructure data for the year 2012 were used. A non-weighted average can be calculated to be 0.22.

Destination / Origin	Copenhagen	Odense	Esbjerg	Aarhus	Randers	Aalborg
Copenhagen		01:15:00 01:07:00 **0.12**	02:53:00 02:17:00 **0.26**	02:43:00 02:26:00 **0.12**	03:29:00 02:59:00 **0.17**	04:19:00 03:42:00 **0.17**
Odense	-		01:20:00 01:08:00 **0.18**	01:23:00 01:17:00 **0.08**	02:12:00 01:50:00 **0.20**	03:02:00 02:33:30 **0.19**
Esbjerg	-	-		02:29:00 01:37:00 **0.54**	03:08:00 02:10:00 **0.45**	04:03:00 02:53:30 **0.40**
Aarhus	-	-	-		00:31:00 00:28:00 **0.11**	01:21:00 01:11:30 **0.13**
Randers	-	-	-	-		00:49:00 00:42:30 **0.15**
Aalborg	-	-	-	-	-	

Table 9.10: Overview of train travel times for selected travel relations. First row: Shortest timetable travel time [hour:min:sec]. Second row: Shortest possible travel time with non-stop train following planning rules [hour:min:sec]. Third row: Degree of travel time prolongation in the 2012 timetable (www.rejseplanen.dk (05.07.2012))

In the yearly timetable for 2012 there were planned direct InterCity-Express (almost) non-stop trains between Copenhagen and Aarhus via Odense. Normal InterCity-Express trains continue on to Randers and Aalborg. These travel relations show the smallest degree of travel time prolongation in the timetable.

An hourly InterCity-train service is running between Copenhagen and Esbjerg via Odense. These trains have several stops en route and the degree of travel time prolongation therefore is higher than for the Copenhagen – Odense/Aarhus travel relations.
There is only a direct regional train service between Esbjerg and Aarhus that stops at all intermediate stops. Continuing on to Randers and Aalborg requires a train to train transfer in Aarhus. Travel relations between Esbjerg and Randers/Aalborg result in the highest levels of timetable travel time prolongation.

9.6 Attractive transfer options

The needed number of transfers is an important attractiveness parameter for a railway journey. For passengers with heavy luggage it is not convenient to change trains. Each transfer can furthermore have the risk of extending the travel time compared to a direct train service. In most cases the passengers will experience a scheduled waiting time in connection with transfers. The minimum train to train transfer time can be calculated by Equation 9.17 (Engelhardt-Funke & Kolonko 2000, Tyler 2003, Wardman et al. 2004):

$$p = h + d \qquad \text{(Equation 9.17)}$$

Where:

p = Minimum train to train transfer time
h = Necessary infrastructure dependent headway between the two trains entering the station
d = Planned dwell time of trains

If the connecting train uses the same track or platform, the planned transfer time can be down to a few minutes. In case the transferring passengers have to go to a different platform, then the necessary transfer time depends on the station's platform and platform track layout.

Assigning platform tracks to trains depends on the following (based on Tyler 2003):

- The same platform is used by connecting train services
- The TOC always uses the same track or platform
- The platform length must match the length of the train
- The platform track has the necessary power supply, e.g. third rail or overhead contact wire
- The track is close to ticket sale facilities, station entrances, parking lot, shops or other public transport modes
- The train can be catered when using the given track

In the timetable planning rules used by IM Rail Net Denmark a minimum transfer time for train to train transfers has been defined for all potential transfer stations. This minimum transfer time is based on the basic station layout and assumes a necessary change of platforms and that passengers travel with luggage. The time difference between the arrival of the first train and departure of the second train must be equal to or larger than the minimum transfer time. If this is not the case the transfer cannot be regarded as a timetable planned transfer and cannot be used when planning a journey with e.g. online Danish journey planner www.rejseplanen.dk. Minimum transfer times for Danish railway stations are between 4-6 minutes. Larger stations such as Copenhagen central station and Aarhus central station need the longest minimum transfer times (DSB 2011c, DSB 2011d, Schittenhelm & Landex 2013).

Timetabled transfers hold the possibility for prolongation of travel time. It happens if the timetabled transfer time is longer than the predefined minimum station dependent transfer time. This thesis recommends the KPI: Degree of timetable transfer time prolongation. This can be calculated according to Equation 9.18 (Schittenhelm & Landex 2010, Schittenhelm & Landex 2013):

$$Degree\ of\ timetable\ transfer\ time\ prolongation = \qquad \text{(Equation 9.18)}$$

$$\frac{Timetabled\ transfer\ time\ [min] - \ Minimum\ transfer\ time\ [min]}{Minimum\ transfer\ time\ [min]}$$

The necessary input data for calculating the degree of timetable transfer time prolongation can be found in both public and working timetables. This KPI can be calculated for a single transfer at a single station. An average value can be calculated for a group of or all transfers taking place at a given station, for a group of stations or for all stations in the network. To get a more varied picture a passenger number weighted average can be calculated. A necessary train to train transfer often prolongs the total travel time. This can be caused by limitations in the railway infrastructure within and around the transfer station and by the time needed to get from one train to the other. The latter is much influenced by the station layout (Schittenhelm & Landex 2010, Schittenhelm & Landex 2013).

The Danish Transport Authority (in Danish: Trafikstyrelsen) has prepared a national traffic plan for the state owned railway for the years 2008-2018. In this report transfer times from trains to busses at the largest stations in each administrative region have been investigated. Figure 9.12 gives an example of such an investigation for the region Northern Jutland (DTA 2009b). The transfer times take into consideration the minimum physically needed transfer time and show the timetabled transfer time. Transfer times have been divided into time intervals and their share of the traffic volume is shown in percentage. Time intervals are: <2, 2-5, 6-10, 11-20, 21-30 and >30 minutes. See section 9.6.1 for a calculation example from Elsinore station. At Elsinore station the degree of transfer time prolongation varies between 0.00 and up to 7.0, resulting in a total non-weighted average of 1.67.

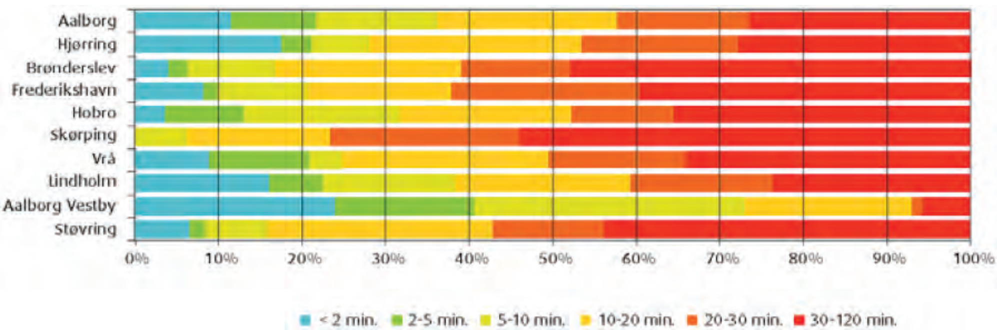


Figure 9.12: Transfer times in minutes and their traffic volume share in percentage at selected stations in Northern Jutland from regional and long distance trains to busses (DTA 2009b).

A train to train transfer can be more or less optimal in regards to travel time prolongation. There are some key aspects that have a high influence on the degree of timetable transfer time prolongation. If the connecting train uses the opposite track at the same platform, the prolongation of transfer time can be kept on a minimum and even create no overall travel time prolongation. If the connecting train uses the same track, travel time prolongation can be down to a few minutes, depending on the possible train headway times. If transferring passengers have to go to a different platform, the degree of transfer time prolongation depends on station layout and station facilities such as escalators and elevators. This thesis proposes introducing the KPI: Degree of optimal transfer conditions for a given timetable variant. See Equation 9.19 (Schittenhelm & Landex 2013).

$$Degree\ of\ optimal\ transfer\ conditions =$$ (Equation 9.19)

$$\frac{Number\ of\ timetabled\ train\ to\ train\ transfers\ taking\ place\ at\ the\ same\ platform}{Total\ number\ of\ timetabled\ train\ to\ train\ tranfers}$$

Current timetabling software tools based on microscopic infrastructure models take the use of specific platform tracks into account when preparing a timetable variant. The needed data to calculate the degree of optimal transfer options at a given station can be made available from these systems. This KPI can be calculated for the same groups of transfers as Equation 9.18: For a single transfer at a single station. An average value can be calculated for a group of or all transfers taking place at a given station, for a group of stations or for all stations in the network. Calculation of the degree of optimal transfer options for Elsinore station can be seen in section 9.6.1. Elsinore station achieves a degree of optimal train to train transfers of 0.40.

9.6.1 Attractive transfer options at Elsinore station

Table 9.12 shows transfer waiting times (timetabled transfer time – minimum transfer time) and the matching degree of transfer time prolongation for Elsinore (Helsingør) station. The predefined minimum transfer time at this station is 4 minutes for train to train transfers and 15 minutes for transfers between trains and ferries to/from Helsingborg, Sweden. Not all transfer combinations are calculated since they are not relevant due to e.g. an earlier departure servicing the same stations. Please be aware of that the trains from/to Copenhagen/Malmö run on the same railway line (The Coastal Railway Line) but with different stopping patterns.

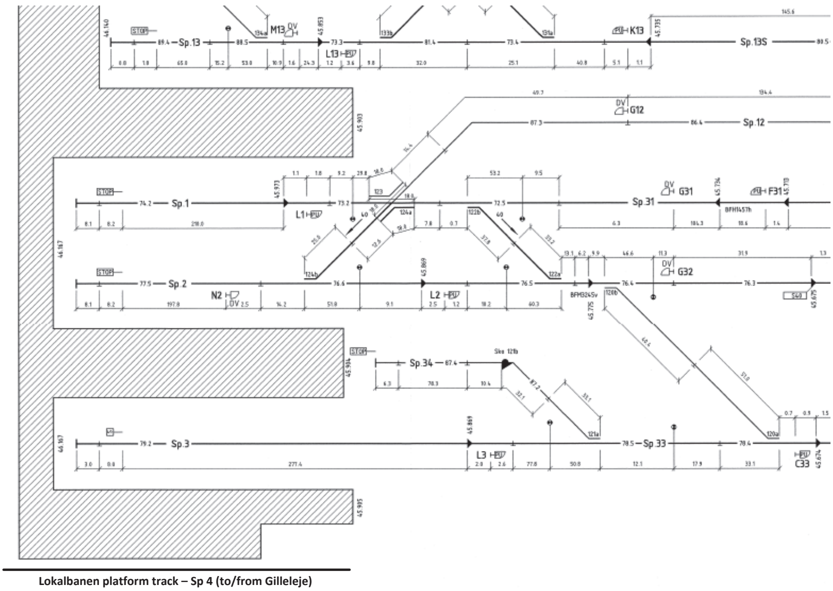


Figure 9.13: Schematic platform track plan for Elsinore (Helsingør) station. The platform tracks (Sp) are numbered 13, 1, 2, 3 and 4. The platform area is marked with the grey hatching (RND 2013a)

Figure 9.13 shows a schematic platform track plan for Elsinore (Helsingør) station. Elsinore is the terminus station for train services coming from Copenhagen (TOC DSB), Malmö (TOC DSB), Hillerød (TOC Lokalbanen) and Gilleleje (TOC Lokalbanen). Elsinore is a dead-end station, meaning that trains must leave the station in the same direction from which they entered it. The track occupation plan for Helsingør station is shown in Figure 9.14. Platform tracks 1 and 2 are used for the Oresund (in Danish: Øresund) train services

(ØR) to/from Malmö. These trains use train numbers 20xx. Rush hour trains to/from Copenhagen central station (RØ) have train numbers 44xx and use track 3. Lokalbanen trains (LB) to/from Hillerød have train numbers 2100xx and use track 13. The Lokalbanen trains to/from Gilleleje use platform track 4. They are not displayed in Figure 9.14 since this track is owned by Lokalbanen and not IM Rail Net Denmark.

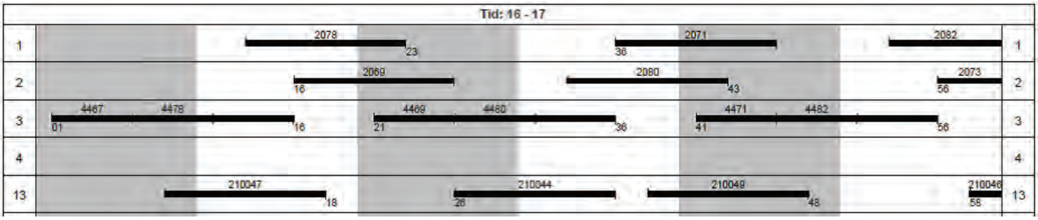


Figure 9.14: Track occupation plan for Elsinore station in the time interval from 16-17 on a weekday (Screenshot from Rail Net Denmark's timetable production database software: P-base (03.01.2013))

An attempt has been made to give an overview of the transfer time prolongation at Elsinore station in Table 9.11. This is inspired by the Danish Transport Authority's (Trafikstyrelsen) national traffic plan for the state owned railways (DTA 2009b). The transfer time prolongations have been put into the recommended time intervals by the Danish Transport Authority (DTA) and a number of transfers have been calculated. An accumulated percentage is shown to the most right column. Three different average degrees of transfer time prolongation have been calculated at the bottom of Table 9.11. An overall non-weighted average degree of transfer time prolongation results in a value of 1.64 for Elsinore station. Train to train transfers have an average degree of transfer time prolongation of 2.64 (10.6 minutes), whereas transfers including the ferry to/from Helsingborg achieve a value of 0.72 (10.8 minutes). When comparing the average degrees of transfer time prolongation, it must be kept in mind that the minimum transfer time for train to train transfers is 4 minutes and 15 minutes for transfers including the ferry.

Transfer time prolongation interval [min:sec]	Number of transfers	Accumulated percentage [%]
<2:00	6	12
2:00 - 4:59	9	30
5:00 - 9:59	9	48
10:00 - 19:59	18	84
20:00 – 29:59	8	100
30:00 ≥	0	100
Overall non-weighted average degree of transfer time prolongation		**1.64**
Non-weighted average degree of transfer time prolongation (train - train)		**2,64**
Non-weighted average degree of transfer time prolongation (train - ferry)		**0,72**

Table 9.11: Overview of transfer waiting times at Odense station (inspired by DTA 2009b)

Departure / Arrival		Train / Ferry	LB	ØR	Ferry	RØ	LB	ØR	Ferry	LB	RØ	Ferry	ØR	LB	RØ	Ferry
Arrival		Destination	Gilleleje	Malmö	Helsing-borg	Copen-hagen	Hillerød	Malmö	Helsing-borg	Gilleleje	Copen-hagen	Helsing-borg	Malmö	Hillerød	Copen-hagen	Helsing-borg
Train/ Ferry	**Origin**	**Minute**	**00**	**03**	**13**	**16**	**18**	**23**	**28**	**30**	**36**	**43**	**43**	**48**	**56**	**58**
RØ	**Copenhagen**	**01**	-		-		13/3.25		12/0.80	**25/6.25**		-		-		-
Ferry	**Helsingborg**	**05**	-	-		-	-	3/0.20		10/0.67	16/1.07		-	28/1.87	-	
LB	**Gilleleje**	**10**		-	-	2/0.500	4/1.00	9/2.25	3/0.20		-	-	-	-	-	-
ØR	**Malmö**	**16**	-		-		-		-	10/2.50		12/0.80		**28/7.00**		-
Ferry	**Helsingborg**	**20**	25/1.66	-		-	-	-		-	1/0.07		8/0.53	13/0.87	-	
RØ	**Copenhagen**	**21**	-		-		-		-	5/1.25		7/0.47		13/3.25		-
LB	**Hillerød**	**26**	-	-	-	-		-	-	**0/0.00**	6/1.50	2/0.13	13/3.25		-	-
Ferry	**Helsingborg**	**35**	10/0.67	13/0.87		-	28/1.87	-		-	-		-	-	6/0.40	
ØR	**Malmö**	**36**	**20/5.00**		-		-		-	-		-		8/2.00		7/0.47
LB	**Gilleleje**	**39**		-	-	-	-	-	-		-	-	**0/0.00**	5/1.25	13/3.25	4/0.27
RØ	**Copenhagen**	**41**	15/3.75		-		-		-	-		-		3/0.75		2/0.13
Ferry	**Helsingborg**	**50**	-	-		11/0.73	13/0.87	18/1.20		25/1.67	-		-	-	-	
ØR	**Malmö**	**56**	**0/0.00**		2/0.13		18/4.50		-	-		-		-		-
LB	**Hillerød**	**58**	-	1/0.25	**0/0.00**	14/3.50		-	-	**28/7.00**	-	-	-		-	-

Table 9.12: Prolongation of transfer times and degree of timetable transfer time prolongation at Elsinore (Helsingør) station for the yearly timetable 2013, weekdays 16-17. [transfer time prolongation / degree of timetable transfer time prolongation]. For Elsinore station: Defined minimum train to train transfer time = 4 minutes, minimum transfer time between ferry and train = 15 minutes (DSB Øresund 2012, Lokalbanen 2012a, Lokalbanen 2012b, Scandlines 2012)

When looking at the degree of optimal transfer conditions, one most know the specific station layout and the timetabled platform track utilization for train services. Figure 9.13 shows the schematic track plan including platforms of Elsinore station. Optimal train to train transfers take place at the same platform and can therefore take place at the following track combinations: 13 - 1, 2 - 3 and 3 – 4. Transfers between the train service to/from Hillerød (2 train/hour, track 13) and half of the train services to/from Malmö (3 trains/hour, track 1) are optimal. Similar are transfers between the train service to/from Gilleleje (2 trains/hour, track 4) and the rush hour trains to/from Copenhagen (3 trains/hour, track 3) optimal. Transfers between the trains from Malmö to rush hour trains to Copenhagen and from rush hour trains from Copenhagen to trains to Malmö are not relevant since they run on the same railway line. Therefore the potential optimal transfers between track 2 and 3 are not utilized. Based on the track occupation plan presented in Figure 9.14the number of optimal transfers can be summed up to be 10 out of 24 relevant train to train transfers at Elsinore station. This gives the following degree of optimal transfer conditions:

$$Degree\ of\ optimal\ transfer\ conditions = \frac{Number\ of\ timetabled\ train\ to\ train\ transfers\ taking\ place\ at\ the\ same\ platform}{Total\ number\ of\ timetabled\ train\ to\ train\ tranfers}$$

➔ $\frac{9.5}{24} = \mathbf{0.40}$

9.7 Discussion

The calculation of the proposed timetable evaluation KPIs by this thesis is generally a work heavy process, if done manually. Only the calculation of the capacity consumption percentage on railway line sections with the UIC 406 methodology has already been automated in railway timetabling and simulation software, such as TPS, RailSys and OpenTrack. Since there are several different opinions about how to apply the UIC 406 methodology, calculation results for a given railway line section can potentially vary from analyst to analyst and from country to country.

The application of the UIC 406 methodology to measuring the capacity consumption levels on railway line sections is almost inevitable since it by now is used all over the world and has achieved a very high level of general acceptance. This makes it easy to “communicate capacity” between different timetable stakeholders. Being able to conduct UIC 406 methodology investigations automatically in software timetabling systems makes this approach even more attractive. A weakness of the methodology is that it contains a set of potential paradoxes. These have been described in detail by Landex (Landex 2008). If looking at the presentation of results using the UIC 406 approach, as shown in Figure 9.7, another weakness is exposed: The overall result does not show which block section of the investigated railway line section has the highest level of capacity consumption. It could be within a station area. Displaying the compressed timetable graphs for every analyzed railway line section is not an attractive option. Additional information in form of an indicator showing the block section with the highest capacity consumption level or a text box with similar information could be useful. A future improvement of the UIC 406 methodology should be to handle stations bordering to railway line sections of analysis separately and not as being a part of the analyzed railway line section.

Analyzing timetable data to recognize a series of timetable patterns during an operational day for line sections of a railway network or the entire network demands a high work effort. It is further complicated by that a high level of background knowledge on timetable data is needed from the analyst. The developed KPI for systematic timetables by this thesis has though proven to give a good and varied picture of how systematic a given timetable variant is by looking at the length of the time span of the most used timetable pattern. Creating an automated tool for timetable pattern recognition in commonly used timetabling tools presents a complicated task.

Robustness of the railway timetable depends on many aspects. Therefore, several KPIs are needed to cover this topic. Making sure that the agreed upon timetable planning rules between TOCs and IM are complied with in regards to train running times between stations is an essential approach and much needed. The developed KPIs by this thesis: Degree of deviation from planning rules, running times; gives an insight into the robustness of the individual train path or an entire train service if the single train runs are identical. An automated calculation of this KPI is estimated to be easy and it should be possible to integrate quickly into timetable software tools such as TPS, RailSys and OpenTrack. A further development of this KPI could be to have two separate approaches: One for big differences between timetable patterns and one for small differences.

Analysis of the traffic complexity level in a given railway timetable will indicate a risk level for, if the basic timetable structures are supporting timetable robustness or make it easily receptive towards secondary delays. Introducing the Conflict Risk Index (CRI) for a station or junction can help to get a better understanding of the risk level a timetable contains to create secondary delays from an initial train delay. Detailed data about the infrastructure and timetable are necessary for KPI calculations and this can be a hindrance. This can also make an automated calculation approach of this KPI difficult to implement. The threshold values for high risk conflicts must be based on experiences made with the application of this KPI and not empiric experience as is the case now.

The recommended concept of timetable fix points by this thesis has proven to be a fruitful approach to measuring the traffic complexity level in a railway timetable. Unfortunately today there exist no available data to compare different timetables according to their timetable fix point statistics. Timetable fix points give a very high level of flexibility when preparing analyses for e.g. an individual train path, train paths following a railway line section during the morning rush hour or the entire railway network for the entire day. The level of difficulty for implementing automated identification of fix points in timetable data must depend on the track layout. Large stations with big switch zones and large level junctions can make it difficult to identify fix points, whereas at crossing stations on single track lines and transition stations from double to single track a simple headway check between trains is needed to identify a fix point. An automated identification of timetable fix points will be a great improvement for the quality control of a given timetable variant.

Investigating the complexity levels of rostering plans for both rolling stock and train staff is difficult since rostering plans are either generated manually or in different advanced software tools than timetables are. Most often there are no interfaces between timetabling and rostering plan systems. Detailed rostering plans for rolling stock and train crews are often created very shortly before they are put into use. This reduces the usefulness of these KPIs when preparing the yearly timetable. The timetable planner can make a qualified guess in regards to general used rostering concepts. Furthermore, rostering plan data is considered to be classified by most TOCs, since it is a very important competiveness parameter in todays liberalized railway sector. The developed KPIs by this thesis: Degree of train paths with shared rolling stock/train staff and Degree of buffer time in turnaround time for rolling stock/train staff have therefore not been tested yet. An automation of KPI calculation is very difficult due to the missing interfaces and the confidentiality of rostering plan data.

Determining if a given railway timetable is acceptable to society can only be done by asking the customers of the railway system, both passengers and freight, and traffic political decision makers. Satisfaction surveys are being carried out today by TOCs themselves in Denmark. But this does not ensure an objective approach and presentation of the found results. In the United Kingdom the task of carrying out satisfaction surveys for railway passengers is done by an independent non-departmental organization called “Passenger

Focus”. A similar approach is recommendable to be made in Denmark. Such a future organization should not only cover passenger train transport but also the freight transport part of the Danish railway sector. Furthermore both present and potential future customers should get a chance to evaluate the railway sector. The results of these satisfaction surveys should be part of the data foundation on which future railway timetables are based. Setting up a Danish counterpart to the British Passenger Focus organization can be difficult, as this topic is not on the present or near future political agenda. A first step could be to give the responsibility of carrying out satisfaction surveys to the Danish Transport Authority (in Danish: Trafikstyrelsen).

To measure the attractiveness of the timetabled travel time this thesis proposes the KPI: The degree of timetabled travel time prolongation. When comparing the shortest possible timetabled travel time to a theoretical direct non-stop train, an insight into which travel relations suffer the most from travel time prolongation in a given timetable variant is gained. From a socio-economic perspective there should be a correlation between the size of passenger and freight volumes on a given travel relation and the degree of travel time prolongation in the timetable. High numbers of passengers and large quantities of freight should entail low degrees of timetabled travel time prolongation. It is assumed that the automated calculation of this KPI easily can be implemented in timetabling software systems.

The need for attractive train to train transfer options depends on how heavily the railway timetable is based on necessary transfers to get through the railway network. In most standard situations a train to train transfer will prolong the travel time. This thesis introduces the KPI: Degree of timetabled transfer time prolongation. This gives an insight into how much the travel time will be prolonged compared to a physical minimum feasible transfer time at a given station. A minimum transfer time for each potential transfer station must be predefined in the timetabling process. Developing an automated calculation of this KPI in existing timetabling software tool is evaluated to be easy. This is due to the fact that detailed arrival and departure times for all trains are available and that transfer connections between trains can already be defined today. The only new development is the minimum transfer time for a given station.

Optimal transfer conditions are achieved if passengers do not have to move to a different platform to make a train to train transfer. This thesis introduces the KPI: Degree of optimal transfer conditions. It measures the degree of transfers that take place at the same platform out of the total number of planned transfers at a given station. A transfer taking place at the same platform demands the minimum transfer time. Creating an automated calculation method for this KPI is possible. The difficulties are that it demands knowledge of the predefined minimum transfer time for all stations, the timetabled train to train transfers and the track occupation data for all stations. For the latter it must furthermore be defined which platform tracks use the same platform.

In Denmark each relevant transfer station has been given one predefined minimum transfer time. This transfer time must ensure that all possible transfers are physical feasible at the given station and therefore it is defined by the worst case scenario. An improvement of this approach is to have minimum two minimum transfer times per station: One transfer time for optimal transfer conditions (same platform) and one for other transfers. Depending on the station layout it can be relevant to have a minimum transfer time for groups of platforms that are situated closely to each other.

Some of the stated timetabling criteria in the interviews with the railway timetable stakeholder interviews, see section 7.2.1 to 7.2.5 and section 7.6.1 to 7.6.5, did not make it to the final common Danish list of prioritized timetable evaluation and optimization criteria. However, the presented KPIs by this thesis can to some degree be used to evaluate and measure the presence of some of these timetabling criteria in a given timetable variant. The stated timetable evaluation and optimization criteria that cannot be covered by the presented KPIs are (13 in total):

- Coordinated international train timetable train paths (DB Schenker)
- Train paths give flexibility to where a change of train driver can take place (DB Schenker)
- A reserve of freight train timetable train paths (Danish Transport Authority)
- The timetable is prepared within the given deadline (Rail Net Denmark)
- Transportation capacity of the timetable (Danish Ministry of Transport)
- Average waiting time a stations (Danish Ministry of Transport)
- A socio-economic approach to timetable train path conflict resolution between TOCs (Danish Ministry of Transport)
- The timetable fulfills the business demands given by the customers of the TOC (Hector Rail)
- Train path capacity (Hector Rail)
- Day to day planning stability of the timetable (Hector Rail)
- Coupling/decoupling of trains at stations (The Danish Rail Punctuality Task Force)
- Efficient use of prepared dispatching plans in case of disruptions (The Danish Rail Punctuality Task Force)
- Modular timetable (The Danish Rail Punctuality Task Force)

Table 9.13 gives an overview of how the remaining stated timetabling criteria can be covered more or less by the presented KPIs. Three more overall timetabling criteria have been added. These were present in all stakeholder interviews and they are:

- Operational costs
- Socio-economy
- Railway customer preferences

The to some degree flexible application of the developed railway timetable KPIs by this thesis can be seen in Table 9.13. Each timetable evaluation and optimization criterion is minimum covered by three out of 13 different KPIs. Every KPI covers minimum four out of eight different timetable evaluation criteria.

KPI	Operational costs	Socio-economy	Customer preferences	Efficient use of the infrastructure	Scalability of the timetable	Compliance with tender documents	Realistic timetable	Low level of scheduled waiting time
Systematic timetable index	• Experience shows improved utilization levels of rolling stock and train staff in systematic timetables • Potential for optimizing operating costs with non-periodic timetables	• Systematic timetables makes travel-planning easier and less time consuming • IFIT-timetables provide optimal transfer options within the public transport system	• Systematic timetables are seen as more attractive than non-systematic timetables both by passengers (DTA interview) and freight shippers (DB Schenker interview)	• Using railway infrastructure in a systematic way has been seen as more efficient than with non-periodic timetables. A high systematic timetable index indicates efficiency	-	-	-	-
UIC 406 methodology	• A high level of capacity consumption can result in prolonged travel times to homogenize traffic travel speeds which can increase the need for rolling stock and train staff (units and time)	• High levels of capacity consumption lead to a lower train service punctuality • Low levels of capacity consumption indicate a to high performance level of the infrastructure	• Customers request a high level of train service punctuality resulting in a recommended maximum level of capacity consumption	• Capacity consumption levels compared with the heterogeneity/ homogeneity level of train traffic can give a picture of the efficient use of the available infrastructure	• High levels of capacity consumption, specially caused by heterogeneous train travel speeds, can make it difficult to add train services to a timetable	• If the traffic tender documents entail maximum capacity consumption levels	• Very high capacity consumption levels make the timetable prone to delays and therefore not realistic	• A high level of capacity consumption can result in prolonged travel times to homogenize traffic travel speeds which can be considered as scheduled waiting time
Degree of deviation from timetable planning rules	• Positive deviations result in prolonged travel times which can increase the need for rolling stock and train staff • Negative deviations can reduce the need for rolling stock and train staff (units and time)	• A positive deviation prolongs travel times but improves punctuality levels • Negative deviations reduces travel times but makes train services more susceptible to delays	• A positive deviation prolongs travel times but improves punctuality levels • Negative deviations reduces travel times but makes train services more susceptible to delay	• Positive deviations can indicate steps made to make room for more trains • Minor negative deviations can indicate an efficient use of the infrastructure, e.g. making it in time to a crossing station	-	• Larger deviations from stated train running times or proposed timetables in tender documents can make a bid incompliant with tender documents	• Large negative deviations from the planning rules can result in physical impossible train running times between two stations • To large positive deviations make travel times unattractive	• Positive deviations result in prolonged travel times which can be considered as scheduled waiting time

KPI	Operational costs	Socio-economy	Customer preferences	Efficient use of the infrastructure	Scalability of the timetable	Compliance with tender documents	Realistic timetable	Low level of scheduled waiting time
Conflict risk index	• If a traffic tender entails a fine/bonus arrangement it can cause increased costs with a high conflict risk index (train services are prone to delays) and reduced costs with a low index	• A high conflict risk index indicates that trains services are susceptible to delays. Delays are costly to society	• Customers prefer punctual trains. A high conflict risk index indicates an increased risk of delayed trains	• A to efficient use of infrastructure can result in trains running to close and thereby create a high conflict risk index • Very low levels of conflict risk indexes can show an inefficient use of infrastructure	-	-	• A general high level of conflict risk indexes points to that the timetable is prone to train delays and therefore not realistic • Low levels of conflict risk indexes suggest that the timetable is realistic	-
Timetable train path fix points	• A high number of or concentration of train path fix points increases the risk for transferring delays between trains. With a fine/bonus arrangement it can cause increased costs	• A high number of or concentration of train path fix points increases the risk for transferring train delays. Delays are a socio-economic cost	• Customers prefer punctual trains. A high number of/concentration of train path fix points indicates an increased risk for transferring train delays	• A high number of trains on the infrastructure can result in a high number of/concentration of train path fix points. This can indicate a to efficient use of infrastructure • A low number of/concentration of train path fix points can show an inefficient use of infrastructure	-	-	• A general high number of/concentration of train path fix points shows that the timetable is prone to train delays and therefore not realistic • Low numbers of and concentration of train path fix points suggest that the timetable is realistic	-
Degree of train paths with shared rolling stock	• Shared rolling stock increases flexibility in planning and thereby the optimization	• Shared rolling stock increases flexibility in planning and thereby the optimization	• Punctuality levels can be increased with dedicated train service rolling stock since the risk of	-	• Shared rolling stock increases flexibility in planning and thereby potentially the scalability of the	• If the tender documents contain requirements or guide lines in regards to shared or	• A complicated planning with shared rolling stock can result in a timetable prone to	-

KPI	Operational costs	Socio-economy	Customer preferences	Efficient use of the infrastructure	Scalability of the timetable	Compliance with tender documents	Realistic timetable	Low level of scheduled waiting time
	potential to reduce costs • Dedicated rolling stock reduces the risk of transferring train delays and thereby increases the punctuality level which can result in a bonus	potential to reduce costs • Train service dedicated rolling stock reduces the risk of transferring train delays	transferring train delays is reduced		timetable	dedicated rolling stock then it can be checked	transferring delays and thereby maybe less realistic • Low degrees of shared rolling stock point to that the timetable is robust and thereby realistic	
Degree of train paths with shared train staff	• Shared train staff increases flexibility in planning and thereby the optimization potential to reduce costs • Dedicated train staff reduces the risk of transferring train delays and thereby increases the punctuality level which can result in a bonus	• Shared train staff increases flexibility in planning and thereby the optimization potential to reduce costs • Train service dedicated train staff reduces the risk of transferring train delays	• Punctuality levels can be increased with dedicated train service train staff since the risk of transferring train delays is reduced	-	• Shared train staff increases flexibility in planning and thereby potentially the scalability of the timetable	• If the tender documents contain requirements or guide lines in regards to shared or dedicated train staff then it can be checked	• A complicated planning with shared train staff can result in a timetable prone to transferring delays and thereby maybe less realistic • Low degrees of shared train staff point to that the timetable is robust and thereby realistic	-
Degree of buffer time in turnaround times for rolling stock	• High degrees of buffer time in turnaround times for rolling stock can increase the need for rolling stock and thereby the costs • Buffer times make it	• Buffer times ensure a higher level of train punctuality • High degrees of buffer time in turnaround times for rolling stock can increase the need for rolling stock and	• Train service punctuality levels can be increased with turnaround buffer times for rolling stock	• Occupying the limited source of platform tracks for a prolonged time due to large buffer times can reduce the efficient use of the infrastructure	-	• If the tender documents contain requirements or guide lines in regards to turnaround buffer times for rolling stock then it can be	• Buffer times in the turnaround times for rolling stock makes the timetable more robust and thereby more realistic • No buffer times in turnaround times make the timetable	-

KPI	Operational costs	Socio-economy	Customer preferences	Efficient use of the infrastructure	Scalability of the timetable	Compliance with tender documents	Realistic timetable	Low level of scheduled waiting time
	possible to absorb train delays and thereby achieve higher punctuality levels which can trigger a bonus	thereby the costs				checked	prone to transferring train delays and thereby less stable and therefore less realistic	
Degree of buffer time in turnaround times for train staff	• High degrees of buffer time in turnaround times for train staff can increase the need for train staff and thereby the costs • Buffer times make it possible to absorb train delays and thereby achieve higher punctuality levels which can trigger a bonus	• Buffer times ensure a higher level of train punctuality • High degrees of buffer time in turnaround times for train staff can increase the need for train staff and thereby the costs	• Train service punctuality levels can be increased with turnaround buffer times for train staff	-	-	• If the tender documents contain requirements or guide lines in regards to turnaround buffer times for train staff then it can be checked	• Buffer times in the turnaround times for train staff makes the timetable more robust and thereby more realistic • No buffer times in turnaround times make the timetable prone to transferring train delays and thereby less stable and therefore less realistic	-
Independent organization carrying out customer satisfaction surveys	• If the train traffic tender documents contain a fine/bonus agreement in regards to passenger satisfaction then an independent survey can ensure the right payment	• Satisfaction or dissatisfaction of railway customers can be taken into account in socio-economic calculations. An independent organization ensure the objectivity of the used data	• Customer satisfaction surveys provide valuable information about customer preferences. An independent organization ensures an objective handling of data	• If railway customers demand a higher frequency of train services then this could point to an inefficient use of the railway infrastructure	-	• Present traffic tender documents contain an agreement about conducting customer satisfaction surveys in regular intervals. An independent organization can	• Customer satisfaction surveys provide valuable information about if customers perceive the present timetable as realistic. This can be used as input for future timetables	• Customer satisfaction surveys provide valuable information about if customers perceive the present timetabled travel times as too long. This can indicate the use of scheduled waiting

KPI	Operational costs	Socio-economy	Customer preferences	Efficient use of the infrastructure	Scalability of the timetable	Compliance with tender documents	Realistic timetable	Low level of scheduled waiting time
						ensure that these agreements are fulfilled		time
Degree of timetable transfer time prolongation	-	• Prolonged travel times are considered as a cost in socio-economic calculations. High degrees of transfer time prolongation also prolong the travel time	• Customer want shortest possible travel times and that includes short transfer times. High degrees of transfer time prolongation is not a customer preference	• Dependent on infrastructure characteristics a high level of transfer time prolongation can point to an inefficient use of the infrastructure in and near transfer stations	-	• Most traffic tender documents will ask bidders to make an attractive timetable, including short transfer times. Timetable evaluation considers transfer times	• Prolonged transfer times contain a buffer time. This ensures that train delays are not transferred to other trains by transferring passengers or goods. This makes the timetable more robust and thereby more realistic	• Prolonged transfer times can be considered as scheduled waiting time. High degrees of transfer time prolongation suggests the presence of scheduled waiting time in the timetable variant
Degree of optimal transfer conditions	-	• The hassle with non-optimal transfers can be taken into account in socio-economic calculations. A high degree of optimal transfer conditions indicates a good socio-economic evaluation	• Customers prefer easy transfers at the same platform. A high degree of optimal transfer conditions points to that customer preferences are applied	• A high degree of optimal transfer conditions can indicate an optimized use of platform tracks at transfer stations and thereby also an efficient use of the infrastructure	-	-	-	• A high degree of optimal transfer conditions creates the basis for using the minimum necessary transfer time at a station thereby avoiding scheduled waiting time
Degree of timetable travel time prolongation	• Prolonged travel times can increase the number of needed rolling stock units and train staff. These extra	• Prolonged travel times contain buffer times and help to improve punctuality levels • Travel times longer than necessary are	• On one side customers want reliable timetables and prolonged travel times with their time buffer ensure that	• Prolonged travel time is achieved by reducing the travel speed of trains. This can increase the time that the train occupies the	-	• Traffic tender documents contain minimum travel times between stations. Prolonged travel times	• Prolonged travel times contain buffer times and these help to improve the robustness of the timetable and thereby making it	• Prolonged travel times are considered as scheduled waiting time. A high degree of prolonged travel time points to a high

KPI	Operational costs	Socio-economy	Customer preferences	Efficient use of the infrastructure	Scalability of the timetable	Compliance with tender documents	Realistic timetable	Low level of scheduled waiting time
	resources increase operational costs	considered a cost in socio-economic calculations	• On the other hand customers want short travel times. It is a balance.	infrastructure and thereby decreases the efficient use of infrastructure		guarantee that the proposed timetable more than complies with the tender documents	realistic • If the degree of travel time prolongation is to high the timetable becomes too unattractive and thereby unrealistic	level of scheduled waiting time in the timetable

Table 9.13: Presented timetable attractiveness KPIs and their usefulness in regards to other stated timetabling criteria in this thesis. Boxes marked with "-" indicate that the KPI is not useful for evaluating/measuring the given timetable variant in regards to the stated timetabling criteria

9.8 Conclusions

This chapter has presented a series of newly developed and existing railway timetable evaluation KPIs. Each KPI is attached to one of the six railway timetabling criteria from the first version of a common Danish list of railway timetable evaluation and optimization criteria.

This thesis has developed the concept of timetable patterns to measure how systematic a given timetable variant is. It has been proven to be a very useful approach. Based on a Swiss regularity index for train services, a refinement is presented that uses the time span of the most used timetable pattern during an operational day to measure how systematic a timetable is.

The suggested use of the widely accepted UIC 406 methodology for measuring the capacity consumption makes cooperation and communication easier between IMs and TOCs, also on an international level. Strengths and weaknesses of the methodology are well known and tested. Automatic UIC 406 methodology capacity analysis modules are already available in today's timetabling software tools and therefore the use of this KPI is already widely implemented in the European railway sector.

Development of the Conflict Risk Index for railway stations and junction can give a better insight into a given timetable's potential for creating secondary delays from a minor initial delay. It is based on detailed infrastructure and timetable data and can therefore be difficult to calculate. The recommend policy in regards to threshold values for high risk conflicts is based on empiric experiences and can be improved over time with the implementation of this KPI.

Applying the concept of timetable train path fix points for measuring the level of traffic complexity in regards to timetable robustness is very promising. This form of analysis contains a high level of flexibility since the area of analysis can go from a single train path to the entire railway network and time wise from one hour to an entire operational day. The identification of timetable fix points had to be made manually and was therefore time consuming. To identify fix points, one needs a high level of knowledge about railway timetabling and the railway infrastructure characteristics. If an automated approach is developed for the identification of timetable train path fix points, it can greatly improve the overall quality control of the entire given timetable variant.

To measure the societal acceptance level of an implemented railway timetable, one must ask the railway customers and the traffic political decision makers. Good inspiration can be taken from the United Kingdom, where an independent non-departmental organization named "Passenger Focus" conducts half yearly satisfaction surveys amongst train passengers.

Measuring the degree of travel time prolongation in a railway timetable as a KPI is very useful in a socio-economic context. There should be a correlation between the number of passengers plus the freight volumes and the degree of travel time prolongation for a travel relation. Big traffic flows should require a low degree of travel time prolongation.

Calculation of the degree of timetabled transfer time prolongation is also important for a socio-economic evaluation of a given timetable variant. The calculations are made complicated since it is manual work to identify which train to train transfer possibilities are relevant and which are feasible. In Denmark, each station has one predefined minimum needed transfer time between two trains. This time covers the worst case scenario where a slow walking passenger must cover the longest possible distance to make a transfer.

Finally the developed railway timetable KPIs by this thesis are applied to as many as possible of the stated timetabling criteria in the earlier stakeholder interviews. Five additional criteria can be covered. Three new criteria are added in this exercise: Operational costs, socio-economy and railway customer preferences. Unfortunately there are 13 of the stated criteria that cannot be evaluated/measured with the presented KPIs.

9.9 Summary

Based on the first common list of Danish railway timetable evaluation and optimization criteria this chapter presents a series of newly developed and existing key performance indicators (KPIs) for the evaluation of Danish railway timetables. Each KPI is attached to a timetable evaluation criterion. See Table 9.14 for an overview. A calculation example is presented for each timetable KPI, where data was available.

Timetable evaluation criteria	Key Performance Indicator (KPI)
Systematic timetable	1. Systematic Timetable Index (based on timetable patterns) (developed by this thesis)
Capacity consumption	2. UIC 406 methodology (existing KPI)
Robustness of the timetable	3. Degree of deviation from timetable planning rules, running time (developed by this thesis) 4. Conflict Risk Index (developed by this thesis) 5. Timetable train path fix points (existing KPI) 6. Degree of train paths with shared rolling stock (developed by this thesis) 7. Degree of train paths with train staff (developed by this thesis) 8. Degree of buffer time in turnaround time for rolling stock (developed by this thesis) 9. Degree of buffer time in turnaround time for train staff (developed by this thesis)
Social acceptance of the timetable	10. Independent organization carrying out customer satisfaction surveys (inspiration from British “Passenger Focus”)
Attractive transfer options	11. Degree of timetable transfer time prolongation (proposed by this thesis) 12. Degree of optimal transfer conditions (developed by this thesis)
Travel time	13. Degree of timetable travel time prolongation (proposed by this thesis)

Table 9.14: An overview of timetable evaluation criteria and the attached key performance indicators (KPIs)

The thesis introduces the concept of timetable patterns to measure how systematic a given timetable variant is. The time span of the most used timetable pattern in the investigation time span determines the systematic level. Measuring the level of timetable capacity consumption of railway line section is recommended to be done with the well-known UIC 406 methodology.
Robustness of the timetable depends much on the complexity of the planned railway traffic. The thesis has developed a new conflict risk index for railway infrastructure. This is based on detailed timetable data and predefined train headway thresholds. With the application of timetable train path fix points a new flexible tool becomes available to measure the robustness potential of a timetable. The higher the number of fix points, the higher the risk for secondary delays. Societal acceptance of an implemented timetable is crucial for its success. It can be measured with satisfaction surveys. These must be conducted by an independent non-departmental organization to ensure objectivity, as it is done by “Passenger Focus” in the United Kingdom.

Short travel and transfer times make the railway competitive. The degree of deviation from the shortest possible travel and transfer time gives an overview of the socio-economic attractiveness of a given timetable. Optimal transfer conditions exist if the train to train transfer takes place at the same platform. Big passenger and freight traffic flows should require low degrees of travel time prolongation.

The presented railway timetable KPIs have proven useful in their first trial. Most of the KPIs have been calculated manually but have a high potential to be automated and integrated into future versions of timetabling software packages. Some of the KPIs demand a high level of knowledge about railway infrastructure characteristics and timetable train path structures. This can make a future automation more difficult. The first trial of the recommended timetable KPIs has shown further development possibilities by e.g. looking separately at railway stations when applying the UIC 406 methodology and considering timetable pattern differences when calculating how systematic a timetable is.

To test the flexibility of the application of the developed KPIs, they are tested on all stated timetabling criteria form the performed stakeholder interviews. Five additional timetable evaluation criteria can be covered.

10 Conclusions

The research for this thesis has created the basis for making future railway timetables more attractive. The first step was the achievement of a common agreement in the Danish railway sector about what makes a railway timetable attractive. This resulted in a common Danish list of prioritized railway timetable evaluation and optimization criteria. The second step was to make timetable attractiveness quantifiable through the development of 13 railway timetable key performance indicators (KPIs). These KPIs are based on the common list. Their practical applicability has been successfully tested on real-life timetable examples. A recommended revised timetabling process has been presented for the responsible timetable creator: the Danish railway infrastructure manager Rail Net Denmark (in Danish: Banedanmark). The process takes the KPIs developed into consideration, when preparing the annual timetable. With the help of the recommended KPIs, it is possible to measure the attractiveness level of future railway timetable variants. And this gives the timetable planners insight into the timetable variants that are most attractive and what can be done to make them even more attractive.

The introductory investigation of railway timetables revealed the need for an improved European timetable definition due to the liberalization of the European railway sector. This thesis proposes two new definitions: one for a liberalized railway sector where the timetable is an agreement between an infrastructure manager and one or more train operating companies, and a second for a state-owned or completely privatized railway sector monopoly, in which the timetable is an internal agreement, since the railway company is both infrastructure manager and train operating company.

Seven commonly used types of railway timetables have been recognized in this thesis. Railway customers have access to the public timetable and the remaining six are used internally in the railway sector. Each of them provides insight into one aspect of railway traffic operation. The timetable types identified are the working timetable, the graphical timetable, track occupation diagrams for stations, and the rolling stock and train staff roster plans.

This thesis identified seven existing basic timetable classes. They can be categorized based on their structural features, such as repeating traffic patterns, symmetry for both driving directions, and station hubs with train meetings. The timetable classes identified are:

- The non-periodic timetable
    - The non-periodic symmetric timetable
    - The non-periodic integrated interval timetable
- The high-frequency timetable
- The periodic/systematic timetable
    - The systematic symmetric timetable
    - The integrated fixed interval timetable (IFIT)

To measure how systematic a given timetable is, the thesis introduces a new concept of “timetable patterns”. This new measuring tool improves the calculation of how systematic a timetable is and has proved itself in practical calculation examples with real-life timetables.

It is difficult to identify all the potentially different timetable classes contained in a timetable covering a large railway network. Currently, this is a manual and potentially labour-intensive process. The thesis proposes an overall railway timetable class analysis. The share of timetable classes identified in a network timetable can be weighted by a set of statistical factors, such as the number of train runs, train-kilometres, and passenger and freight ton-kilometres. Using these weighting factors gives a more differentiated picture of the composition of the overall network timetable.

To measure timetable attractiveness quantitatively, it is necessary for all railway timetable stakeholders to agree on what makes a timetable attractive. The research for this thesis developed and initiated a process to reach such agreement and this resulted in the first common Danish list of six prioritized railway timetable evaluation and optimization criteria. Beginning with a series of individual interviews with the most important railway timetable stakeholders and ending with a joint timetabling criteria workshop, an agreement was achieved. The Danish timetable evaluation criteria selected using this development process are:

- High priority: Systematic timetable & Capacity consumption of railway line sections
- Middle priority: Robustness of the timetable & Societal acceptance of the timetable
- Low priority: Attractive transfer options & Travel time

The robustness of such a list is not necessarily very high since the Danish railway sector is very much affected by the ever-changing political climate. So this thesis recommends repeating this process at reasonable intervals, e.g. every two to five years.

Stakeholder interviews have also revealed a lack of focus on railway customer preferences from both TOCs, due to too few available resources, and the public, represented by the Ministry of Transport and the Danish Transport Authority.

Based on the timetable evaluation criteria identified, the thesis proposes a revised timetabling process at the Danish infrastructure manager, Rail Net Denmark. The options for major changes in the overall timetabling process structure are limited by the basic process structure required by European Union (EU) railway legislation. New features include a formal learning loop for the annual timetabling process and the introduction of new tasks in some working steps in the timetabling process. These new tasks are recommended analyses based on the timetable evaluation criteria.

This thesis proposes a set of 13 Danish railway timetable KPIs. Of these, nine are newly developed and four are already in use today. Each is allocated to one of the six timetable evaluation criteria. The proposed KPIs for railway timetables are:

- **Systematic timetable**
  1. Systematic timetable index, based on the most used timetable pattern timewise

- **Capacity consumption of railway line sections**
  2. The UIC (International Union of Railways / Union Internationale des Chemins de fer) 406 methodology

- **Robustness of the timetable**
  3. Degree of deviation from planning rules with regard to time supplements (comparing the timetabled running times with the ideal running times according to the planning rules)
  4. Conflict risk index for a given station (the number of high risk train conflicts at a given station within a time period)
  5. Complexity of a train path (number and distribution of timetable fix points for a train path)

6. Proportion of train paths with shared rolling stock (comparing the number of train paths with shared rolling stock to the total number of train paths)
7. Proportion of buffer time in turn-around or hand-over time for rolling stock (comparing timetabled times with predefined minimum times)
8. Proportion of train paths with shared train staff (comparing the number of train paths with shared train staff to the total number of train paths)
9. Proportion of buffer time in turn-around or hand-over time for train staff (comparing timetabled times with predefined minimum times)

- **Societal acceptance of the timetable**
10. Regular satisfaction surveys for existing and potential railway customers and political decision makers. This work must be done by an independent organization.

- **Attractive transfer options**
11. Proportion of transfer time prolongation (comparing the timetabled extra transfer time transfer time with the predefined minimum feasible)
12. Proportion of optimal transfer conditions (the number of transfer options available on the same platform out of the total number of transfer options at a given station)

- **Travel time**
13. Proportion of travel time prolongation for a travel relation (comparing the timetabled extra travel time to a theoretical direct non-stop train)

The research for this thesis tested these key performance indicators on real-life timetable examples to assess their practical applicability and the calculations were successful. It is therefore believed that an automated adaption of the key performance indicators could be implemented in future versions of timetabling software.

10.1 Main contributions of the thesis

To improve the attractiveness of future railway timetables, the research for this PhD thesis made an initial comprehensive study of railway timetables; both types and classes with their different characteristics. A process resulting in a common Danish understanding of railway timetable attractiveness was conducted. Based on this, a set of railway timetable KPIs was developed and successfully applied to real-life timetable examples. By making the qualitative term “timetable attractiveness” quantifiable, the basis has been created for more attractive railway timetables in the future. During this process the research contributed to the subjects listed in Table 10.1.

Subject	Main contributions in the thesis	Described in
Railway timetable characteristics	The definition of a railway timetable prepared for a state-controlled liberalized railway sector and a new definition of a railway timetable valid in a state or private monopoly of the railway sector	Section 2.1
Railway timetable types	An overview of the railway timetable types commonly used in the European railway sector	Section 3.1 to Section 3.7
Railway timetable classes	The identification of seven existing basic timetable classes and their categorization according to their structural features The comparison of all the timetable classes identified according to their strengths and weaknesses The introduction of the concept of "timetable patterns" to calculate how systematic a timetable is	Section 4.1 Section 4.11 Section 9.1.1
Railway timetable class analysis	The presentation of a new approach to carrying out railway timetable analysis in order to identify contained timetable classes and the recommendation of a set of statistical weights to give a more differentiated picture	Section 5.1
The Danish timetabling process	The first mapping of the timetabling processes in the liberalized Danish railway sector. At the Danish Transport Authority, the passenger train operating company DSB (Danish State Railways), and the infrastructure manager Rail Net Denmark	Section 6.3 Section 6.4 Section 6.5
A common Danish list of prioritized railway timetable evaluation and optimization criteria	The development and initiation of a process that led to a common Danish list of six prioritized timetable evaluation criteria. Through individual interviews with the most important Danish railway timetable stakeholders followed by a joint timetabling criteria workshop, an agreement was achieved	Section 7.2 Section 7.4
A revised timetabling process	The presentation of a revised timetabling process for the Danish railway infrastructure manager, Rail Net Denmark	Section 8.2
Danish railway timetable key performance indicators	The development of 13 Danish railway timetable key performance indicators. Their practical applicability was tested on real-life timetable examples	Section 9.1 to Section 9.6

Table 10.1: Overview of the main contributions of this PhD thesis

10.2 Recommendations for future research and implementations

To make future railway timetables more attractive for both the railway sector and its customers, it is necessary to improve our knowledge about the success criteria for a railway timetable. In this thesis, the evaluation and optimization criteria were: systematic timetables, capacity consumption on railway line sections, robustness of the timetable, societal acceptance of the timetable, attractive transfer options, and travel time. This short-list of criteria and their prioritization is not final, so further research is needed in the field of railway timetable attractiveness. Research is also needed on how to keep such a list up to date and ensuring that it is applied in the railway sector.

Today's timetable planners are assisted by timetabling software tools that help with the practical daily work. It is still the task of the timetable planner to create a feasible timetable with its structures of train services. This means that during the annual timetabling process the timetable planners only work with one timetable variant. If the timetabling software tools were able to help create a timetable – or even create it entirely – it would be possible to work on several timetable variants during most of the phases in the timetabling process. Experimenting with several timetable solutions during the timetabling process would improve the quality and attractiveness of the final annual timetable. To do so, a "timetable generator" is needed. Research that could result in such an operations research-based tool is therefore highly desirable. This would lead to a big improvement to timetable planning efficiency, as well as timetable attractiveness and quality.

Railway simulation tools have been used for many years to carry out timetable robustness analysis in Denmark. The handling of train traffic during simulated disruptions cannot be done very intelligently due to the algorithms currently implemented. Rescheduling actions like a train skipping stations, short-turning a train or cancelling an entire train run are not possible, even though they are used in the daily traffic management. If the usefulness and trustworthiness of this kind of timetable robustness analysis is to improve, it is necessary to develop more intelligent railway simulation software that can act more like real-life traffic dispatchers.

Railway customers – both passengers and freight shippers have not played a major role in this PhD study. It was assumed that their interests would be represented by the Danish Ministry of Transport, the Danish Transport Authority (buyer of public train service traffic) and the train operating companies (TOCs). But if we look at the prioritization of the timetable evaluation criteria that was made, it can be questioned as to whether the railway customers have really been represented. A focused study on railway timetable attractiveness seen from the passengers' point of view is needed and recommended for future research.

When looking at timetable robustness, one of the most critical issues is network effects. How fast does a primary delay create secondary delays, and how quickly do those spread throughout the network? Improved methods to measure the potential of network effects contained in a given timetable variant and proposals for counter measures can improve the robustness of future railway timetables. So it is recommended that further research within this field should be conducted.

Better integration of railway customer preferences, both passengers and freight, in the timetabling process can make a big contribution to improving timetable attractiveness. To do so, further research is needed in the field of railway customer preferences and in the field of future timetabling processes. The timetabling process must take customer preferences into consideration and thereby a need for a new key performance indicator about inclusion of customer preferences in a given timetabling process arises.

Timetable attractiveness could be greatly improved if a railway timetable optimization approach could be developed that takes into account both the train service line structures and the robustness of the timetable. Optimal train service line structures should provide minimum travel times and the smallest number of necessary transfers. Optimal timetable robustness should ensure that the timetable is able to regenerate quickly from train delays up to a certain magnitude. Such a new combined optimization approach has a big potential for improving timetable attractiveness and is therefore recommended as a future research topic.

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List of figures

List of tables

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