Passenger perspectives in railway operations research

Mining, analysis and modelling of passenger flow data, time and route choice in railway networks

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Rail Norrköping

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DTU Management, Transport Division
Department of Technology, Management and Economics
About me

• Professor in transport modelling, and head of the transport research division at DTU Management
• PhD in transport modelling, 1994
• 1998-2000 Manager of Research and Development, Railnet Denmark
• 2006-2007. Visiting Professor at TU Delft, Netherlands
• Leader of the national transport model
• Leader of the IPTOP project on Integrated Public Transport Optimisation and Planning
Overview of the lecture

- Motivation
- Measurement of passenger flows
- Transport modelling
- Experienced punctuality
- Integrated Public Transport Optimisation and Planning
Interview of central decision makers related to train timetabling

• Quantitative Methods for Assessment of Railway Timetables, PhD-afhandling, Bernd Schittenhelm, 2014

1. List the most important timetable evaluation criteria for your company.

   1. Describe/explain each criterion thus making it operational in a timetable context.

   2. How can each criterion be recognized in the timetable?

   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
<table>
<thead>
<tr>
<th>Timetable evaluation criterion</th>
<th>Rail Net Denmark</th>
<th>DSB</th>
<th>Arriva Denmark</th>
<th>DB Schenker</th>
<th>National Transport Authority</th>
<th>Prioritization points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robustness of timetable</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>18</td>
</tr>
<tr>
<td>- Complexity of traffic in/around stations</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>- Reserve freight train timetable timeslots</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Efficient use of infrastructure</td>
<td>4</td>
<td>4</td>
<td>-</td>
<td>4</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>- Low level of scheduled waiting time</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>- Capacity consumption of infrastructure</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>- Attractive transfer options for trains and busses</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>- Fast, high frequent and direct connections</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Periodic timetable is preferable</td>
<td>-</td>
<td>-</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>9</td>
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<tr>
<td>Compliance with traffic tender demands</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>Coordinated international timetable timeslots</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>Timetable timeslots give flexibility to where change of train driver can take place</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>Train service for smaller stations</td>
<td>-</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Servicing starting hours of schools and larger workplaces</td>
<td>-</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>Scalability of timetable</td>
<td>-</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Timetable is prepared within given deadline</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
</tbody>
</table>
What is missing?
Out of 75 mentioned priorities in timetabling, passenger considerations was not mentioned once!!!

DSB’ only happy costumer has become sour
Two perspectives

1) Train and system performance

New delays at "West Funen"

2) Passenger experience

DSB to delayed passengers; “Enjoy the view”
MEASUREMENT OF PASSENGER FLOWS

• What we need is the door to door travel
• What we often get is tap-in tap-out or point measurements
Type of data sources, “old school”

• "Postal card surveys (entering/exit)
  – Typically only one-day sample (not so representative)
• Onboard counts
  – Often “guestimates” by staff
• Ticket sale
  – Maybe only subcomponent of journey
  – Problems with monthly cards, etc.
• Transport surveys
  – Telephone, internet, on-board
  – Small samples, but often rich in background information
Type of data sources, automated

- Platform-based or on-board based counts
  - Video, infrared beans, weighing systems
- Travel card/smart card
  - Tap-in/Tap-out
  - Not always representative (when other types of tickets as well)
- WIFI
- Smartphone-based surveys

- Common; Large samples, maybe not representative, no background information on travellers
How travel behaviour is revealed (1)

• General questions
  – E.g. customer surveys

• Experiments with “hypothetical” questions
  – E.g. Value of Time studies
  – Stated preference/choice experiments

• Observation of routes/behaviour and estimation of statistical model (revealed data)
  – E.g. the national transport survey (TU)

• Calibration of model on aggregated data (typical counts)
  – E.g. the national transport model
How travel behaviour is revealed (2)

• Difference whether existing users are asked – or the entire population
• Difference on sample sizes
  – Detailed small samples
  – Aggregated large samples
• Question related to representatively (sample corrections)
  – E.g. internet panels
  – Travel card (“Rejsekortet”)
• Not whole journey is measured (Travel Card)
Arrival distribution as function of frequency – smart card data

Importance of schedules

- Fully random arrivals for metro passengers (6-min)
- 57% random for S-train passengers (5-min)

Importance of schedules

- Fully random arrivals for frequency-based independent of headway
- Decreasing share of random arrivals when published

Importance of schedules

- Fully random arrivals for frequency-based independent of headway
- Decreasing share of random arrivals when published

Railway transport versus busses

- Public transports market share
  - Radial S-train lines
  - Versus busses going between suburbs
## Share using public transport
(National Transport Survey)

<table>
<thead>
<tr>
<th>Distance from work to nearest station</th>
<th>Distance from home to nearest station</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;400 m</td>
</tr>
<tr>
<td>&lt;400 m</td>
<td>31%</td>
</tr>
<tr>
<td>400-800 m</td>
<td>25%</td>
</tr>
<tr>
<td>800-2000 m</td>
<td>27%</td>
</tr>
</tbody>
</table>
Relationship between nearness to station, household income and car ownership

\[ y = -1 \times 10^{-7}x^2 + 0.0004x + 1.03 \]
\[ R^2 = 0.8662 \]

\[ y = -3 \times 10^{-8}x^2 + 0.0002x + 0.79 \]
\[ R^2 = 0.9447 \]

\[ y = 5 \times 10^{-8}x^2 + 7 \times 10^{-5}x + 0.59 \]
\[ R^2 = 0.7989 \]

\[ y = 1 \times 10^{-7}x^2 + 9 \times 10^{-6}x + 0.37 \]
\[ R^2 = 0.705 \]
Meta study across 48 European cities


- Metro network, connectivity and urban density
- Suburban rail network and terminals
- Light rail network
“Observed” public transport routes in the national transport survey (TU)

- Standard question after pilot in PhD-project (Marie Karen Anderson)
Example of visualisation of a trip
Reasonable paths
Table 6. Estimated parameter coefficients, t-tests and values scaled to bus in-vehicle time for PSC model for each trip purpose.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Work</th>
<th>Leisure</th>
<th>Scaled to Bus IVT</th>
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</thead>
<tbody>
<tr>
<td><strong>In-vehicle time:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bus</td>
<td>-0.192</td>
<td>-0.143</td>
<td>1.00</td>
</tr>
<tr>
<td>Local train</td>
<td>-0.180</td>
<td>-0.116</td>
<td>0.94</td>
</tr>
<tr>
<td>Metro</td>
<td>-0.083</td>
<td>-0.045</td>
<td>0.43</td>
</tr>
<tr>
<td>%reg. train, length &gt; 20 km</td>
<td>-0.143</td>
<td>-0.126</td>
<td>0.74</td>
</tr>
<tr>
<td>%reg. train, length &lt; 20 km</td>
<td>-0.312</td>
<td>-0.279</td>
<td>1.63</td>
</tr>
<tr>
<td>S-train</td>
<td>-0.177</td>
<td>-0.127</td>
<td>0.92</td>
</tr>
<tr>
<td>Access/Egress</td>
<td>-0.394</td>
<td>-0.346</td>
<td>2.05</td>
</tr>
<tr>
<td><strong>Transfer attributes:</strong></td>
<td>Work</td>
<td>Leisure</td>
<td></td>
</tr>
<tr>
<td>Walk time</td>
<td>-0.125</td>
<td>-0.155</td>
<td>0.65</td>
</tr>
<tr>
<td><strong>Path Size Correction:</strong></td>
<td>PSC</td>
<td>0.123</td>
<td>0.64</td>
</tr>
<tr>
<td><strong>Frequency:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Headway &gt; 6 minutes</td>
<td>-0.079</td>
<td>-0.076</td>
<td>0.41</td>
</tr>
<tr>
<td>Headway &lt; 6 minutes</td>
<td>-0.131</td>
<td>-0.084</td>
<td>0.68</td>
</tr>
<tr>
<td><strong>Ease of wayfinding:</strong></td>
<td>Easy</td>
<td>-1.02</td>
<td>5.31</td>
</tr>
<tr>
<td>Little difficulty</td>
<td>-1.17</td>
<td>-1.24</td>
<td>6.09</td>
</tr>
<tr>
<td>Moderate difficulty</td>
<td>-1.49</td>
<td>-1.37</td>
<td>7.76</td>
</tr>
<tr>
<td>Difficulty</td>
<td>-2.35</td>
<td>-1.61</td>
<td>12.24</td>
</tr>
<tr>
<td><strong>Shop level:</strong></td>
<td>No shop</td>
<td>-0.424</td>
<td>2.21</td>
</tr>
<tr>
<td><strong>Wait time, leg level:</strong></td>
<td>Bus, no shelter</td>
<td>-0.035</td>
<td>0.18</td>
</tr>
<tr>
<td>Bus, small shelter</td>
<td>-0.023</td>
<td>-0.028</td>
<td>0.12</td>
</tr>
<tr>
<td>Bus, large a</td>
<td>-0.019</td>
<td>-0.008</td>
<td>0.10</td>
</tr>
<tr>
<td>Metro, overground</td>
<td>-0.226</td>
<td>-0.388</td>
<td>1.18</td>
</tr>
<tr>
<td>Metro, underground</td>
<td>-0.216</td>
<td>-0.198</td>
<td>1.13</td>
</tr>
<tr>
<td>Train, all</td>
<td>-0.053</td>
<td>-0.033</td>
<td>0.28</td>
</tr>
<tr>
<td><strong>Level changes:</strong></td>
<td>Ascending</td>
<td>-0.220</td>
<td>1.15</td>
</tr>
<tr>
<td>Descending, escalator</td>
<td>0.332</td>
<td>2.18</td>
<td></td>
</tr>
<tr>
<td>No level change</td>
<td>-0.855</td>
<td>-0.819</td>
<td>4.45</td>
</tr>
<tr>
<td><strong>No. of est. parameters:</strong></td>
<td>25</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td><strong>Number of observations:</strong></td>
<td>2,667</td>
<td>2,454</td>
<td></td>
</tr>
<tr>
<td>Null log-likelihood:</td>
<td>-13,063</td>
<td>-11,659</td>
<td></td>
</tr>
<tr>
<td>Final log-likelihood:</td>
<td>-5,895</td>
<td>-6,064</td>
<td></td>
</tr>
<tr>
<td>Likelihood ratio test:</td>
<td>14,337</td>
<td>11,191</td>
<td></td>
</tr>
<tr>
<td>Adjusted rho-square:</td>
<td>0.547</td>
<td>0.478</td>
<td></td>
</tr>
</tbody>
</table>
12 Danish Value of Time studies (normalized to bus VoT)

- Access egress time
- Hidden waiting time
- Bus
- Metro
- Urban train (S-train)
- Walk when transferring
- Waiting time at transfers
- Delay at the destination

Number of transfers (in min) vs. Penalty when no seat

- Open
- Max
- Min
- Close
Differences in passenger preferences

• Distributed on sub-modes
Flow in unified network

Overall cost: 10.97
Description of transfers – Frequency versus schedule-based services
DTU – Brønshøj – more frequency-based lines

Modification of network
DTU – Brønshøj – flow changes

Change of flow

Overall cost: 11.25 (Base 10.97)
## Overall results

<table>
<thead>
<tr>
<th>Network design</th>
<th>Overall cost for pax [Abs(utility)]</th>
<th>Diff. from schedule-based network</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schedule-based network</td>
<td>10.82</td>
<td>0%</td>
</tr>
<tr>
<td>Frequency-based network</td>
<td>11.49</td>
<td>+6.2%</td>
</tr>
<tr>
<td>Unified network</td>
<td>10.97</td>
<td>+1.4%</td>
</tr>
</tbody>
</table>

Parameters adapted from the Danish National Transport Model
EXPERIENCED PUNCTUALITY
Passenger delays equal train delays?

- Trains tend to be more delayed during peak hour (larger capacity utilization)
- Peak hour delays normally affects more passengers per train
- Delays tends to accumulate during a train run, i.e. more and more delayed e.g. when approaching Copenhagen in the morning peak
- Passenger are hit by the delay when they exit the train. Whether the train is on-time during the run matters less, if it is delayed at the destination
- If a connection is missed, then the passenger delay is much larger than the train delay

Are passengers delayed if this train is not on time?

Are delays of this train affecting more passengers?
Full scale calculations on the Copenhagen Urban Rail network

- 104 “zones”, 80 trains
- 1.8 million inhabitants in Copenhagen,
- 330,000 trips made each day by the urban rail
- 42 main time intervals with 1-5 min. Launches
- 60,000 OD-elements (sparse matrix)
- 1,200 train runs per day
- Diachronic graph with 200,000 links and 120,000 nodes
- A calculation of an entire day takes between 10 and 20 minutes with 5 min. launches
Alternative route options?
## Comparing train and passenger delays

<table>
<thead>
<tr>
<th>Threshold (sec)</th>
<th>Train regularity and punctuality</th>
<th>Morning</th>
<th>Day hours</th>
<th>Afternoon</th>
<th>Other hours</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>99,6</td>
<td>95,4</td>
<td>94,5</td>
<td>90,6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Base OD launches (min)</td>
<td>10</td>
<td>5</td>
<td>20</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>Regularity</td>
<td>100,0</td>
<td>100,0</td>
<td>100,0</td>
<td>100,0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Punctuality (no delays)</td>
<td>84,0</td>
<td>84,3</td>
<td>80,5</td>
<td>80,6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>of this before time</td>
<td>15,7</td>
<td>14,1</td>
<td>17,3</td>
<td>15,3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Average delay (min)</td>
<td>8,2</td>
<td>7,9</td>
<td>9,0</td>
<td>7,7</td>
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<td>98,1</td>
<td>98,1</td>
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<td>Punctuality (no delays)</td>
<td>85,0</td>
<td>84,3</td>
<td>80,5</td>
<td>82,7</td>
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<td>of this before time</td>
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<td></td>
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<td>7,5</td>
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<tr>
<td>150</td>
<td>Regularity</td>
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<td>100,0</td>
<td>100,0</td>
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<td></td>
<td>Punctuality (no delays)</td>
<td>82,7</td>
<td>83,4</td>
<td>79,8</td>
<td>79,2</td>
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<td>248</td>
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<td>Punctuality (no delays)</td>
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<td>8,3</td>
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<td>9,0</td>
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<tr>
<td>400</td>
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<td>100,0</td>
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<tr>
<td></td>
<td>Punctuality (no delays)</td>
<td>80,1</td>
<td>80,7</td>
<td>78,8</td>
<td>76,6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>of this before time</td>
<td>14,6</td>
<td>13,4</td>
<td>16,2</td>
<td>14,5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Average delay (min)</td>
<td>9,4</td>
<td>8,6</td>
<td>10,1</td>
<td>8,6</td>
<td></td>
</tr>
</tbody>
</table>

### Trains
- Base OD launches (min): 5/10
- Regularity: 100.0
- Punctuality (no delays): 85.0
- Average delay (min): 7.5

### Passengers
- Regularity: 100.0
- Punctuality (no delays): 82.7
- Average delay (min): 7.7

### With fast information
- Regularity: 100.0
- Punctuality (no delays): 80.1
- Average delay (min): 8.6

### Note
- The table above compares train and passenger delays across different thresholds (50, 150, 248, 400 seconds). The data includes regularity (percentage of trains on time) and punctuality (percentage of trains with no delays), along with average delays for different times of the day (morning, day hours, afternoon, other hours).
Delays, examples of measurements

- Optimistic passenger punctuality
- Passenger punctuality
- Train punctuality

Old service contract
New service contract
Passengers are more delayed than the trains.

Complete simulation day for day for all weeks 2010-2014.
Measurements (KPI’s) and service contract – Focus on sub-components in the journey

% delayed more than x minutes

Old service contract

New service contract
KPI’s – you get what you measure!
S-train delays in the Copenhagen Region (recent MATSIM analyses, Mads Paulsen)

Passenger delays at the destination may become much larger than train delays.

Full information can reduce passenger delays.
Timetable supplements

Passenger travel time

Risk of delay propagation

Unused time supplements

Optimal

Time supplement
Example of simulation of robustness

- Depart 10 min too late
  Catch up 5 min
  Arrive 5 min too late

- Alternative
  Depart on time
  5 min. faster time-table
  Arrive on time
INTEGRATED PLANNING AND OPTIMISATION OF PUBLIC TRANSPORT (IPTOP)

5-year project funded by the Danish Innovation Fund and co-funded by the participants

Diagram:
- Network design → Stopping pattern → Frequency setting → Timetable setting → Vehicles scheduling → Crew scheduling

Detailed description:
www.iptop.transport.dtu.dk

Research partners
• DTU
• Other Universities;
  • MIT
  • Univ. of Auckland & Technion
  • North Eastern
    (Erasmus Univ.)
  • Univ. Of Bologna
  • Hong Kong Tech
Sector partners

- Rapidis (software)
- MOVIA (busses, local rails)
- DSB (Train operator)
- Railnet Denmark (rail infrastructure)
- Trafikstyrelsen (national transport authority)
A lot of real-life large-scale data

- Entire east Denmark, rail and bus
- Rail in west-Denmark

- Timetables, planned and realised (both trains and busses), over the year(s)
- Delay course descriptions (trains)
- Rolling stock and cost of operations
- Traffic counts, trip matrices, smart card data (“Rejsekortet”)
- Transport surveys, attitude surveys
- Fare structures
- Detailed infrastructure data
Competing design principles – Models can help evaluating the options

• Many different direct low-frequent lines with many stops
  – Good area coverage, few transfers, small walk distances
  – Example; traditional bus systems

• Few high-frequent lines with many stops
  – Medium area coverage, many transfers, small walking distances
  – Example; A-busses in Copenhagen

• Few medium frequent lines with few stops
  – Fast service between main points, more transfers, longer walk distances
  – Example; S-busses in Copenhagen

• Different principles of operation
  – Skip-stop service
  – “metro style” service
Public transport – a bit provocative

• Drives from a place, where you are not located
• To a place, where you are not going
• At another time than you need
IPTOP – Activities, Work Packages

WP1b Revealing passenger flow patterns

WP3a Understanding Passenger Preferences

WP4a Understanding delays

WP2 Organisational Context and planning constraints

WP3b Modelling of passenger responses

Consumer surplus

Schedule

Simulated Timetable flows

Passenger flows

Simulated Timetable delays

WP5 Optimisation of schedules

Constraints

Schedule

Operating costs

WP6 Optimisation of operations

WP4b Simulation of operations

Simulated Timetables

WP7 Modelling system and software

WP1a Common data foundation
Train optimisation - tactical level

Example of pair wise problem solving

WP3b Schedule-based Modelling of passenger responses

Consumer surplus → Schedule

WP5 Optimisation of schedules (timetabling)

Schedule → Operating costs

WP6 Rolling Stock Allocation

WP4b Simulation of operations

Simulated Timetable delays

WP? Train path allocation

Simulated Timetable delays

WP7 Modelling system and software

Depot planning

Crew scheduling
Bus optimisation, tactical level

- WP3b Schedule-based Modelling of passenger responses
  - Consumer surplus
  - Schedule

- WP5 Optimisation of schedules (timetabling)
  - Schedule
  - Operating costs

- WP4b Simulation of operations
  - Simulated Timetable delays
  - Passenger flows

- WP6 Rolling Stock Allocation – draft evaluation
  - Crew scheduling

- WP3 Car Traffic Modelling
  - Simulated Timetable delays

- WP7 Modelling system and software
Strategic planning level

WP3b Frequency-based modelling of passenger responses

Consumer surplus

Line plan

WP5 Line planning, frequency setting, stopping pattern

Schedule

Operating costs

WP6 Rough Rolling Stock Allocation

Simulated Timetable delays

Passenger flows

WP4b Meso-level simulation of operations

Simulated Timetable delays

WP7 Modelling system and software
Timetable optimisation

• "translated" to a mathematical program

\[
\min_T \sum_{i=1}^{M} \sum_{j=1}^{N} \omega_{ij}(T) w_{ij}^s
\]

Where

\[
w_{ij}^s = \min_j [\pi_j + a_j^s + \beta_j^s - (\pi_i + a_i^s + \delta^s)] + a_i^s + \beta_j^s \geq \pi_l + a_i^s + \delta^s
\]

Subject to

\[
\begin{align*}
\alpha_{i-1}^s & \leq H_{k,l-1,t} + a_i^s, \quad \forall k, i, s \in K, M, N \\
\pi_K & \geq 0, \quad \forall k \in K \\
H_{k,l-1,t} & \geq 0, \quad \forall k, i \in K, M \\
\alpha_i^s & \geq 0, \quad \forall i, s \in M, N \\
\beta_i^s & \geq 0, \quad \forall i, s \in M, N \\
\delta_s & \geq 0, \quad \forall s \in N
\end{align*}
\]

Set of LineVariants: [1, ..., K], Set of Runs: [1, ..., M], Set of Stops: [1, ..., N]

• NP-hard -> solved by some meta heuristic
• Simplified -> solved by exact methods
Mathematical model

**Input and Output**

- Allowed shifts
- Allowed dwells
- Maximum deadhead distance
- Maximum Turnaround time

<table>
<thead>
<tr>
<th>Mathematical model</th>
<th>Input and Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^* = \min \sum \sum a_i x_{ik} + \sum (M_i + f_i)$</td>
<td><strong>•</strong> Allowed shifts</td>
</tr>
<tr>
<td>s.t. $\sum x_{ik} = 1, i \in T$</td>
<td><strong>•</strong> Allowed dwells</td>
</tr>
<tr>
<td>$\sum x_{ik} = \sum x_{ij}, k \in K, i \in T$</td>
<td><strong>•</strong> Maximum deadhead distance</td>
</tr>
<tr>
<td>$\sum x_{jk} = \sum x_{ij}, k \in K, i \in T$</td>
<td><strong>•</strong> Maximum Turnaround time</td>
</tr>
<tr>
<td>$\sum x_{ij} \leq n_i, i \in T$</td>
<td><strong>•</strong> Modified timetables</td>
</tr>
<tr>
<td>$\sum x_{ij} \leq n_j, j \in W$</td>
<td><strong>•</strong> Vehicle schedules</td>
</tr>
<tr>
<td>$0 \leq \tau_i - \tau_i^{(0)} - (M_{ij} - M_{ji}) \leq M_{ij} - M_{ji}$</td>
<td><strong>•</strong> Operational costs</td>
</tr>
<tr>
<td>$\tau_i \geq \tau_i^{(0)} + M_{ij} - M_{ji}$</td>
<td><strong>•</strong> Transfer costs</td>
</tr>
<tr>
<td>$n_i \in \mathbb{Z}^+$</td>
<td><strong>•</strong> Too large to compute for one day (optimal solution)</td>
</tr>
<tr>
<td>$n_j \in \mathbb{Z}^+$</td>
<td><strong>•</strong> Heuristically decompose (slice) into smaller problems</td>
</tr>
<tr>
<td>$a_i \in [0,1]$</td>
<td><strong>•</strong> Solve iteratively</td>
</tr>
</tbody>
</table>

- $i, j \in T$ 
- $\tau_i$ is the start time of operation $i$, and $\tau_i^{(0)}$ is the start time of the same operation without any operation time.
- $M_{ij}$ is the minimum time required to travel from node $i$ to node $j$, and $M_{ji}$ is the minimum time required to travel from node $j$ to node $i$.
- $n_i$ is the number of passengers at node $i$ for operation $i$.
- $f_i$ is a fixed cost associated with operation $i$.
- $a_i$ is a binary variable indicating whether operation $i$ is performed (1) or not (0).
- $T$ is the set of all operations.
Investigation of initial solutions

Example – the importance of considering passengers’ travel behaviour

![Diagram showing two routes A to B with times and passenger flows.]

<table>
<thead>
<tr>
<th></th>
<th>Base</th>
<th>Optimised</th>
<th>Optimised (demand responsive)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Route</td>
<td>Flow</td>
<td>Transfer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 pax</td>
<td>15 min.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90 pax</td>
<td>5 min.</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>40,5 min.</td>
<td></td>
</tr>
</tbody>
</table>
Real example
Optimisation of timetables with focus on passenger preferences

- Smaller transfer times (adjustment of time of departure of each run/line)
  - 1-16% improvement in different Danish studies
- More drastic optimisation
  - Line patterns
  - Frequency
  - Stop pattern (3-4% improvements)
- Optimisation of operations
  - Rolling stock (2-8%), staff, design of tender packages
  - Savings that can be utilised for the benefit of passengers
Challenges concerning timetable optimisation

- Lack of knowledge on door-to-door passenger flows
- Missing software and methods
- Organisation in many companies/organisations leads to sub-optimisation
- Train schedules are released too late for the bus-companies to renegotiate contracts and schedules
- Tendering of packages of bus-route, may hinder optimisation
- Municipal funding focus not on the entire journey and only a subset of customers
Organisations and mechanisms for coordination, East Denmark

The commuter network

45 municipalities
2 regions

Bus
Railway
Metro

Bus operators

Other freight operators

Lokaltog

DSB

Granskningsmøder

Rettidighedsprogrammet

banedanmark

Metro

Metro

Coordination via ownership and instruction
Coordination via contract
Coordination via partnership

The commuter network

45 municipalities
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Rettidighedsprogrammet

banedanmark

Metro

Metro

Coordination via ownership and instruction
Coordination via contract
Coordination via partnership
Ongoing research topics

• Demand & route choice
  – Characteristics by transfers
  – Mixed schedule- and frequency based networks
  – Capacity constraints
    • Seating, or even missed boarding options
  – Modelling door-to-door demand
  – Links to last-mile-transport, including flexible public transport

• Further improvements on optimization
  – Attempts to include route choice in optimization

• Further empirical knowledge and modelling of delays
Questions?
Some key references, system perspectives


Some key references, modelling

Some key references, optimisation


Some key references, measurement
