What’s the value of capacity?

Connecting transport economics and railway operations research

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Linköping University
<table>
<thead>
<tr>
<th>Transport economics</th>
<th>Railway operations research</th>
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<tbody>
<tr>
<td>Valuing things</td>
<td>Analysing and quantifying capacity</td>
</tr>
<tr>
<td>Analyzing markets and decision processes</td>
<td>Optimizing timetables and real-time control</td>
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</tbody>
</table>

**Valuing capacity** useful e.g. for

- prioritizing among competing projects
- resolving train path conflicts
- pricing capacity (track charges)
What does “railway capacity” mean?

• “The maximum number of trains which can be scheduled in a fixed period of time” (RailNetEurope)

• Silly.

• When we say “capacity” we also think of robustness, flexibility, possibility to mix speeds etc etc
The “capacity” of a railway network is the *feasible set of timetables*

- The universe of timetables is a high-dimensional space
- Network characteristics constrain which timetables are feasible
Simple illustration (2 dimensions so it can be drawn)

• Consider a single-track stretch with a few meeting stations
• Assume identical passenger trains running in alternating directions
• Trade-off: high frequencies vs. short travel times
Defining the (societal) value of capacity requires specifying:

1) A way to calculate the net (societal) benefits of a timetable
   - Analogous to an objective function
   - Not just "the maximal possible number of trains"
   - Can be probabilistic
   - Whose value? Could also be the operator’s value, if relevant

2) The timetable selection process (e.g. profit or welfare maximization)
   - Analogous to an "algorithm" determining which "solution" is obtained
   - Can be probabilistic
A brutal generalization (sorry)

• Economists know and care a LOT about valuations, efficient allocation processes and market structures
  • ... but seldom understand the complexities of capacity constraints

• Railway engineers/OR:s know and care a LOT about optimizing timetables and operations
  • ... but often use ridiculously simplified objective functions
  • ... and tend to assume that efficient timetables will magically self-organize
The value (social benefits) of a timetable (simplified)

• Consumer (passenger) surplus
  • Total generalized travel costs = travel times + fares + waiting/headways + interchanges + delays + ...
  • Lots of research on relative weights of components (e.g. value of travel time)

• Producer surplus:
  • Fare revenues minus operations costs
  • Negative for subsidized traffic

• Infrastructure costs: wear & tear etc.
• Second-order effects: reduced road traffic emissions etc.
• Wider economic impacts: economic growth etc.
How is the timetable determined?

In reality, a combination of:

- Profit maximization (commercial train operators)
  - Monopolistic or oligopolistic
- Welfare maximization and political considerations (public operators)
- Capacity allocation rules (conflict resolution processes)
  - E.g. priority rules, first-come, pricing, auctions...
- No guarantee that this results in the “best” timetable (highest social benefits)!
The value of increased capacity may be zero
- Single track stretch with meeting stations
- Identical trains in alternating directions
- Currently 3 trains/hour
- Wants to increase to 6 trains/hour
- Investment in capacity (more meeting stations) needed to keep travel time constant
- Calculate social benefit of the investment

Illustration (based on true story)

The value of increased capacity?

<table>
<thead>
<tr>
<th></th>
<th>No investment</th>
<th>Investment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trains/hour</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Travel time</td>
<td>46</td>
<td>40</td>
</tr>
<tr>
<td>Passengers</td>
<td>1015</td>
<td>1104</td>
</tr>
<tr>
<td>Consumer surplus</td>
<td>7 400</td>
<td></td>
</tr>
<tr>
<td>Producer surplus</td>
<td>16 300</td>
<td></td>
</tr>
<tr>
<td>Total social benefits</td>
<td>23 700</td>
<td></td>
</tr>
</tbody>
</table>

**Version A**

<table>
<thead>
<tr>
<th></th>
<th>No investment</th>
<th>Investment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trains/hour</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Travel time</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Passengers</td>
<td>1000</td>
<td>1104</td>
</tr>
<tr>
<td>Consumer surplus</td>
<td>8 800</td>
<td></td>
</tr>
<tr>
<td>Producer surplus</td>
<td>2 700</td>
<td></td>
</tr>
<tr>
<td>Total social benefits</td>
<td>11 500</td>
<td></td>
</tr>
</tbody>
</table>

**Version B**
The investment shifts the benefits functions
The value of the capacity increase is determined by the timetables before vs. after.
Without a principle for how timetables are determined, *the value of capacity is not defined*

Max social benefits? Max monopolistic profits?
Oligopolistic competition?
Welfare max AND profit max, with decision order?
Include crowding penalties in CS calculations
(also based on true story)

Common paradox:
• Consider a crowded PT service with capacity constraints prevents increasing frequency
• But: increased frequency is calculated to give negative benefits!
• According to the calculation, frequency should in fact decrease!

• Reason: crowding not included in generalized travel cost. Should be:

\[ GTC = fare + \alpha(N) \times time + \beta(wait) \ldots \]
Optimal frequencies with and without crowding

WITH CROWDING

WITHOUT CROWDING

Opt. freq. 1

Opt. freq. 2

Opt. freq. 1

Opt. freq. 2
Comparing metro and bus: example

Optimal frequency = minimize sum of operations costs and passengers’ GTC (with and w/o crowding costs)

\[ GTC = \alpha(N) \times \text{traveltime} + \beta(\text{wait}) + \ldots \]

\[ \alpha(N) = \alpha_0 \left(1 + \gamma \left(\frac{N}{\text{seats}}\right)^2\right) \]

<table>
<thead>
<tr>
<th>Frequency (dep./h)</th>
<th>Bus, ignore crowding</th>
<th>Metro, ignore crowding</th>
<th>Bus, consider crowding</th>
<th>Metro, consider crowding</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>9</td>
<td>150</td>
<td>18</td>
<td></td>
</tr>
</tbody>
</table>
Calculating benefits – some more notes

• Value of headway (frequency) is non-linear
  • Partly scheduling time, partly waiting time
  • Can assume constant for high frequencies (<15 min.) - simplifies

• Assuming constant demand (O-D matrix) is often OK, simplifies
  • Fare revenues become constant: ΔPS is only change in operations costs
  • Only need total travel times, waiting times (if const.), interchanges etc – not by O-D pair

• Valuing delays: expected delay (in minutes) seems to work OK

• The future is uncertain: use probabilistic approaches if possible
  • E.g. check robustness by evaluating a set of realistic timetables, weighted by probability
Robustness of benefit/cost ratios

• ~500 investment projects with different benefit/cost ratios
• Budget constraint: ~100 projects
• How sensitive is the selection to parameter changes?

Changes in top 150 projects

<table>
<thead>
<tr>
<th></th>
<th>Freight benefits +100%</th>
<th>Safety benefits +100%</th>
<th>Emission benefits +100%</th>
<th>Person travel time benefits +100%</th>
<th>New values of time (diff. wrt mode, purpose)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Changes in Top 150</td>
<td>14</td>
<td>22</td>
<td>5</td>
<td>11</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Higher oil price</th>
<th>Slower technological development</th>
<th>Higher car ownership</th>
<th>No carbon reduction measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Changes in Top 150</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

Achieved total benefits change much less
Oligopolistic competition and slot trading in open-access railway markets

Stylized open-access market:

- Operators request train paths from Infrastructure Manager
- IM constructs draft of timetable
  - = decides exact paths based on requests
- (Operators negotiate the details of the timetable between them) - ?
- Operators set fares to maximize profits

- Operator timetable negotiations very common, incl. slot trading (open or informal)
- What are the consequences?

### Competition vs. monopoly

<table>
<thead>
<tr>
<th></th>
<th>Monopolist</th>
<th>Two competing operators</th>
<th>Welfare max. (w/o subsidy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of departures</td>
<td>16</td>
<td>18 + 7</td>
<td>22</td>
</tr>
<tr>
<td>Average fare</td>
<td>703</td>
<td>317</td>
<td>104</td>
</tr>
<tr>
<td>No. of passengers</td>
<td>7,100</td>
<td>11,100</td>
<td>13,300</td>
</tr>
<tr>
<td>Consumer surplus</td>
<td>2,430,000</td>
<td>6,190,000</td>
<td>8,840,000</td>
</tr>
<tr>
<td>Producer surplus</td>
<td>3,800,000</td>
<td>1,520,000</td>
<td>0</td>
</tr>
<tr>
<td>Total welfare</td>
<td>6,230,000</td>
<td>7,720,000</td>
<td>8,840,000</td>
</tr>
</tbody>
</table>

- With slot trading, competitive situation **isn’t stable**
- One operator will buy the other out to become a monopolist
- **General** problem: monopolist profits are higher than combined profits under competition
- Competitive railway markets must be regulated (somehow) – otherwise they become monopolies
Summary

• Think of “capacity” as the feasible set of timetables

• To put a value on a capacity increase, you need
  • A method for valuing timetables (economists’ home turf)
  • A principle to determine what timetable(s) will result (e.g. profit max.)

• Without this, the value of a capacity investment isn’t defined

• Crowding costs needs to be included in local public transport CBA

• Open-access, oligopolistic competition better than monopoly (concessions, competition-for-the-market)

• ... but will tend to revert to monopolies without regulation