Train and Bus Timetable Design to Ensure Smooth Transfer in Areas with Low-Frequency Public Transportation Services

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Special thanks to
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Norimitsu Ishii (Building Research Institute)
Tomoyoshi Kosaka (Central Consultant Inc.)

March 25, 2015
Transportation service in Japan

Urban areas: 20 to 30 trains are running per hour per direction on a double track.

How about rural areas?

http://railtokyo2015.cs.it-chiba.ac.jp/
Target area in this talk: Rural areas

Urban areas: 20 to 30 trains per hour
Rural areas: about 10 trains per day
Current situation

areas with low traffic demand

low-frequency public transportation services

Problems in rural areas

- Train and bus services are scheduled within each railway/bus company, so that their timetables are not designed for smooth transfer among different companies
- We sometimes have no choice but to wait for an unexpected long time

Timetables are very inconvenient for passengers
This talk: Timetable design in rural areas

- areas with low traffic demand
  - low-frequency public transportation services

This talk
- presents a mathematical optimization model to generate a train and bus timetable which ensures smooth transfer among buses and trains
- no drastic changes such as increase of the number of services and the number of crews

Timetables are very inconvenient for passengers
  - convenient
Railway optimization

- min. total passenger waiting time

- max. the number of passengers on direct connections
  Bussiecka, Kreuzerb, and Zimmermann (1997)

- real-time conflict resolution problem
  D’Ariano, Pacciarelli, Pranzo (2007)

- and so on

Most previous papers focus on urban areas

What should be optimized in rural areas?
Why is the current timetable inconvenient?  
because waiting time for transfer is very long

- hospital at 9 o’clock
- waiting time
- : hospital
- : bus stop
- 9:00 time axis
- position coordinate
Why is the current timetable inconvenient? because waiting time for transfer is very long

Japanese timetable permits only one-way transfer

Next bus will arrive after a few hours!

low-frequency services + one-way transfer substantially inconvenient transfer
Introduce “mutual transfers”

**Objective:**
Increase the number of mutual transfers with a little negative effect on standing time.

**Variables:**
Arrival time and departure time for trains and buses with at most 5 services in a day.

Bus stands for 7 minutes!

 matière shorter transfer time / matière longer standing time
Train and bus network

Time-space network

Vertex: train station/bus stop
- X bus stop
- X bus stop at 6:54
- X bus stop at 6:42
- X bus stop at 6:31

Vertex: arrival/departure time of each train and bus

About 60,000 vertices
About 90,000 arcs

10 vertices
Time-space network (details)

- Stand at train station/bus stop
- Travel between train stations/bus stops
- Passengers’ waiting behavior
Time-space network (details)

→: stand at train station/bus stop
→: travel between train stations/bus stops
↑: passengers’ waiting behavior
↑: transfer

Train X

Bus A-2

Bus A-1

time axis

bus stop

position coordinate
Passengers’ behavior corresponds to a path:

- : stand at train station/bus stop
- : travel between train stations/bus stops
- : passengers’ waiting behavior
- : transfer

Train X: 11:46
Bus A-2: 11:46

11:55
12:05

TS network = vehicle services + feasible transfer (timetable)

Each vertex has time corresponding to arr. time or dep. time
Mutual transfer in TS network

one-way transfer

mutual transfer

To activate the blue arc (transfer from train to bus), change arrival time and departure time of vertices to satisfy

departure time of $D \geq$ arrival time of $A$
TS network design

current train and bus timetable

TS network

revised timetable

new TS network

add blue arcs
impossible transfer
in current timetable

activate some blue arcs
feasible transfer
in revised timetable

variables in MIP

\( \tau(v) \): arrival/departure time of vertex \( v \)

\( z_{uv} \): 0-1 variable which determines to activate blue arc \((u,v)\) or not
Mathematical optimization model

(1) If we activate blue arc, then \((\text{time of } D) \geq (\text{time of } A)\)

**big-M type constraint**

\[
\tau(v) - \tau(u) + M (1 - z_{uv}) \geq 0 \\
(u,v): \text{ blue arc}
\]

\((M: \text{ large constant})\)

(2) keep existing arcs in the original time-space network

\[
\tau(v) - \tau(u) = (\text{travel time}) \\
(u,v): \text{ travel between train stations/bus stops}
\]

\[
\tau(v) - \tau(u) \leq 10 \text{ [min.]} \\
(u,v): \text{ standing at train stations/bus stops}
\]

\[
\tau(v) - \tau(u) \geq 0 \\
(u,v): \text{ other arcs}
\]

(3) constraints for vertices

\[
\tau(v): \text{ fixed} \\
0 \leq \tau(v) \leq 24 \times 60 \text{ [min.]} \\
v: \text{ vertices on railway lines with more than 5 services in a day}
\]

\[
v: \text{ other vertices}
\]
Objective function

represents trade-off between

😊 transfer passengers: shorter transfer time --- mutual transfer
😊 on-board passengers: longer waiting time --- standing time

If $z_{uv} = 1$, transfer passengers do not need to wait for the next train/bus for a long time

$$\text{max.} \sum_{(u,v)} (\text{weight}) z_{uv} \quad (\text{waiting time in the current timetable})$$

$$- \sum_{x: \text{train, bus}} (\text{weight}) \times (\text{total travel time})$$

corresponds to the amount of change in the sum of standing time at bus stops.
Target area

803 bus stops
168 bus lines
88 train stations

Kamaishi
Ichinoseki
Rikuzentakata
Kesennuma
Ofunato
Tono
Rikuzentakata
Kesennuma
Numerical results

- Scale of TS network
  - # vertices: 59,558
  - # arcs: 91,103
  - # blue arcs: 3,129
  - # activated blue arcs: 447

- Computational time
  - 170.1 seconds

Most stations have at least one mutual transfers

IP solver ILOG CPLEX 12.4
Windows 7 (CPU: Intel(R) Core(TM) i7, 3.4GHz, RAM: 8.00GB)
Comparison of travel time

- Imagine that we want to arrive at a hospital before 9:00
- Which timetable allows us to start later?

The number of bus stops at which the latest departure time belongs to each time slot

<table>
<thead>
<tr>
<th></th>
<th>8:30-9:00</th>
<th>8:00-8:30</th>
<th>7:30-8:00</th>
<th>7:00-7:30</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>current</td>
<td>98</td>
<td>114</td>
<td>196</td>
<td>244</td>
<td>652</td>
</tr>
<tr>
<td>revised</td>
<td>117</td>
<td>124</td>
<td>188</td>
<td>311</td>
<td>740</td>
</tr>
<tr>
<td></td>
<td>+19</td>
<td>+10</td>
<td>-8</td>
<td>+67</td>
<td>+88</td>
</tr>
</tbody>
</table>

The objective function of the MIP does not contain any direct term to reduce travel time for trips to hospitals.

However, smooth transfer improves travel time!
A little negative effect on standing time

Distribution of standing time for trains

<table>
<thead>
<tr>
<th>standing time [min.]</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>current</td>
<td>4,834</td>
<td>5,602</td>
<td>188</td>
<td>156</td>
<td>160</td>
<td>95</td>
<td>69</td>
<td>38</td>
<td>24</td>
<td>28</td>
<td>19</td>
</tr>
<tr>
<td>revised</td>
<td>6,247</td>
<td>4,236</td>
<td>147</td>
<td>143</td>
<td>144</td>
<td>93</td>
<td>62</td>
<td>39</td>
<td>38</td>
<td>28</td>
<td>46</td>
</tr>
</tbody>
</table>

- We have 17,110 stops
- Standing time at 499 of them (2.9%) increases in the revised timetable
- The average amount of increase is 4.6 minutes

There is a little negative effect on standing time

$$\tau(v) - \tau(u) \leq 10 \text{ [min.] }$$

$(u,v)$: standing at train stations/bus stops
Summary

- presented a mathematical optimization model to generate a train and bus timetable which ensures smooth transfer in areas with low-frequency public transportation services.
- showed that mutual transfers are essential to smooth transfer in rural areas.
- can establish a lot of mutual transfers if we can change timetables for railway lines with low-frequency services (even if we do not change those with high-frequency services).

Another result (Bus timetable design)

- also designed a bus timetable under the assumption that the current train timetable is fixed.
- improved not only connections between a train and a bus but also connections between buses.