Optimizing the structure of train line plan to improve the capacity of High Speed Railway

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2017-11-17
OUTLINE

- High speed railway network in China
- Operation performance of HSR in China
- The characteristics of train line plan
- Capacity improvement
Capacity Shortage of Railway Transport

Goods by Railway (2006-2010)
- Wood: 85%
- Crude oil: 85%
- Coal: 60%
- Steel etc.: 80%

The busiest railway in the world: 6% (route length), 25% (converted ton-kilometer) in 2005.
The Development of Network

Railway, Inner river, Pipeline length (10 thousand km)

- railway
- inner river
- pipeline
- 2014, over 16,000 km high-speed railway in operation, 14.3% in total length
- 2015, over 19,000 km high-speed railway in operation, 15.8% in total length of 120000km
- 2016, the operational route lengths of high speed railway has reached 22,000 km, the longest operational route in the world.

- Year 2020, Route Length 150 thousand km
- High Speed Railway 30 thousand km, 20% in total, cover 80% of big cities
OUTLINE

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Shorten the Time-space Gap

Beijing—Shanghai before 11h41m, after 4h48m
Beijing—Guangzhou before 20h31m, after 7h59m
Beijing—Xi'an before 11h15m, after 4h42m
Beijing—Dalian before 11h23m, after 6h10m
Shanghai—Changsha before 12h31m, after 4h24m
Shanghai—Wuhan before 9h48m, after 4h56m
Harbin—Dalian before 9h17m, after 3h30m

City integration
Passenger Flow Volume

- 2016, 4300 EMU train/day
- Rapid increase of EMU train passenger
  - Year 2013, 670 million, 32.4%
  - Year 2014, 908 million, 40.0%
  - Year 2015, 1106 million, 46.5%
  - Year 2016, 1443 million, 52%

30% increasing
## Market Share of Passenger Transportation

<table>
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<tr>
<th>(Year 2015)</th>
<th>Total volume</th>
<th>Waterway</th>
<th>Railway</th>
<th>Civil aviation</th>
<th>Highway</th>
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<td><strong>Passenger volume</strong> (10,000 persons)</td>
<td>1,943,271</td>
<td>27,072</td>
<td>253,484</td>
<td>43,618</td>
<td>1,619,097</td>
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<td><strong>Passenger traffic turnover</strong> (100 million person-kilometers)</td>
<td>30,058.89</td>
<td>73.08</td>
<td>11960.60</td>
<td>7282.55</td>
<td>10,742.66</td>
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### Passenger volume (10,000 persons)
- Waterway: 27,072 (2%)
- Railway: 253,484 (13%)
- Civil aviation: 43,618 (2%)
- Highway: 1,619,097 (83%)

### Passenger traffic turnover (100 million person-kilometers)
- Waterway: 73.08 (0%)
- Railway: 11960.60 (40%)
- Civil aviation: 7282.55 (24%)
- Highway: 10742.66 (36%)
Transportation during the Spring Festival: The world's largest migration

<table>
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<th>Year</th>
<th>Start and finish date</th>
<th>Total passengers (100 million)</th>
<th>Railway (100 million)</th>
<th>Highway (100 million)</th>
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Revenue of Chinese HSR

- **Beijing-Shanghai high speed railway:**
  - First year: 11 billion RMB
  - Second year: 17 billion RMB
  - Third year: 25 billion RMB

- Without considering depreciation, 6 HSRs revenue and expenditure can be balanced:
  - **Beijing-Tianjing:** 120 km, 2008-8-1
  - **Beijing-Nanjing:** 301 km, 2010-7-1
  - **Beijing-Shanghai:** 1318 km, 2011-6-30
  - **Shanghai-Hangzhou:** 202km, 2010-10-26
  - **Nanjing-Hangzhou:** 249km, 2013-7-1
  - **Guangzhou-Shenzhen:** 126km, 2011-12-26

From: Huaxia Times

From: web information
0:00-6:00 Maintenance time

High speed railway (Beijing South-Shanghai Hongqiao)
The characteristics of train line plan
non-cyclic timetable

Train category: G, D

Train frequency

Train stops

Origin and destination
## Train frequency between two stations

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<th>咸宁北</th>
<th>赤壁北</th>
<th>长沙南</th>
<th>株洲西</th>
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<th>衡阳东</th>
<th>耒阳西</th>
<th>韶关</th>
<th>英德西</th>
<th>清远</th>
<th>广州北</th>
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Note: The frequency values are not directly translatable into a simple text format. They likely represent the number of trains or the time intervals between trains.
Train departure time distribution at stations
Complex operation

- Large-scale network: 22000km → 45000km
- EMU train station: 770
- EMU train, 4632 train paths
- Train operation distance: <100km → >2500km
  - >2000km, about 108 train paths
  - 2760km, from Beijing to Kunming
  - 16h24min, from Chengdu East to Fuzhou
OUTLINE

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- Operation performance of HSR in China
- The characteristics of train line plan
- Capacity improvement
Case 1

Non-cyclic operation
A model for analyzing the influence of train line structure on section capacity

Non-cyclic timetable:
A mixed integer programming model

Objective

- The minimum occupied time: train path compression

\[ \min \ Z = \max \{ a_{i,d_i} \mid i \in I \} - \min \{ d_{j,o_i} \mid j \in I \} \]

\[ \min \ Z = \sum_{i=1}^{I} a_{i,des_i} \]
Model

Constraints

• Running time
  \[ a_{is+1} - d_{is} \geq r_{is} + \beta_{is} x_{is} + \gamma_{is+1} x_{is+1} \]
  \[ a_{is+1} - d_{is} \leq r_{is} + \beta_{is} x_{is} + \gamma_{is+1} x_{is+1} + y_{is} \]

• Dwell time
  \[ d_{is} - a_{is} \geq w_{is} x_{is} \]
  \[ d_{is} - a_{is} \leq w_{is} x_{is} \]

• Headways
  \[ d_{js} - d_{is} + M \left(1 - O_{ij}^s\right) \geq H_{Ds} \]
  \[ d_{is} - d_{js} + MO_{ij}^s \geq H_{Ds} \]
  \[ a_{js+1} - a_{is+1} + M \left(1 - O_{ij}^s\right) \geq H_{As+1} \]
  \[ a_{is+1} - a_{js+1} + MO_{ij}^s \geq H_{As+1} \]

• Overtaking
  \[ \left| \sum_{j=1}^{N} (O_{ij}^{s-1} - O_{ij}^s) \right| \leq 1 \]

• Train order 列车前后行关系
  \[ O_{ij}^s + O_{ji}^s = 1 \]

• Cross-line train 跨线车的固定到发
  \[ k_{is} \leq d_{is} \leq k_{is} \]

• Departure time control
  \[ t_{is} \leq d_{is} \leq t_{is} \]

• Maintenance time window
  \[ d_{is} \geq SL_{e} \]
  \[ a_{is} \leq SL_{b} \]
Algorithm

- The Branch and Bound based on the optimal estimation
- To solve the large-scale problem: The Segmentation and Scroll strategy used to draw train timetable piecewised
- CPLEX solver, and the visualization and index statistics of train timetable are realized by MATLAB.
Case study: Non-cyclic timetable

1318km, 23 stations
G, D
Headway: 4min
Dwell time at big station: 2min
the other station: 1min

Beijing-Shanghai
Case study: Non-cyclic timetable

2017. 01 timetable at Xuzhou-Bengbu
**Case study: Non-cyclic timetable**

### 2017-01 timetable at Xuzhou-Bengbu

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<th>Technical speed/(km/h)</th>
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Reduce occupation time by 21 min
Case 2

Cyclic operation
Integrating capacity analysis with timetabling can reveal the influence of the structure of train line plans and operating on improving capacity utilization.

For most capacity analyses and cyclic timetabling methods, the cycle time is a constant.

A minimum cycle time calculation (MCTC) model based on the periodic event scheduling problem (PESP) for a given train line plan. A non-collision constraint and a series of flexible overtaking constraints (FOCs) are constructed based on variations of the original binary variables in the PESP.

Because of the complexity of the PESP, an iterative approximation (IA) method for integration with the CPLEX solver is proposed.
Our model

- based on the PESP and the model in *Sparing and Goverde (2013)*
- further ongoing study of our previous paper (*Zhang and Nie (2016) on Transportation Part C*)

- **Objective**: minimize the cycle time $T$
- **Input**: periodic line plan, operation parameters and service requirements
- **Output**: minimum cycle time $T$ (important), periodic timetable
The (ILP) model was coded by MATLAB R2012a and solved by Cplex 12.3

Our extended iterative approximation methods can help Cplex solver reducing the computation time
Case study: Cyclic timetable

Fig. 12. Hypothetical case: Line plans

Fig. 14. Examples of timetables

different colors represent different train lines; the blue numbers indicate the numbers of the lines; $K = 0$;
Case study: Cyclic timetable

Fig. Influence of the regularity constraint and the train speed gap on the minimum $T$ (the MCTC model with the FOCs; the average computation time for all cases is 4,420 seconds).
Case study: Cyclic timetable

Fig. Influence of $K$ and the proportion of fast trains on the minimum $T$ (MCTC model with the FOCs).

(average computation time is 3,798 seconds).
Real world Case: Cyclic timetable

Fig. 19. Time-space diagram of the solution for the real-world test case with the FOCs
Cross-line train

- Trains which pass/across at least two different railway lines at connection/border stations
- A train time window is the time span that the train can depart or arrive in, and depends on the requirements of timetabling (usually for passenger transfers in stations)
• Naming rules of the experiments: four factors of train time window are included

- **Stations**
  - s(origin)
  - m(intermediate)

- **Number**
  - one time window for one cross-line train

- **Span**

- **Regularity**
  - $\delta$ in regularity constraint
  
  \[
  \frac{TF_{ij}}{f_{ij}} - \delta \leq x_{ij} \leq \frac{TF_{ij}}{f_{ij}} + \delta,
  \forall (i, j) \in A_{\text{regular}}
  \]

— “0-0-0-∗” means the case without time windows, i.e. the basic case
Case study

- Beijing-Shanghai High Speed Railway
- Only the impacts of the number of time windows are analysed (time window in origin stations, ten minutes span, $\delta=0$)
- Time period of line plan is two hours

<table>
<thead>
<tr>
<th>Property</th>
<th>Real-world case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of stations</td>
<td>23</td>
</tr>
<tr>
<td>Number of trains</td>
<td>18</td>
</tr>
<tr>
<td>Number of lines (train stop schedules)</td>
<td>17</td>
</tr>
<tr>
<td>Line plan</td>
<td>17 types of train stop schedule</td>
</tr>
</tbody>
</table>
### The structure of train line plan

**Cross-line train: 69.7%**

<table>
<thead>
<tr>
<th>Section</th>
<th>Total trains</th>
<th>Cross-line</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>北京南-廊坊</td>
<td>109</td>
<td>50</td>
<td>45.9%</td>
</tr>
<tr>
<td>廊坊-天津南</td>
<td>103</td>
<td>47</td>
<td>45.6%</td>
</tr>
<tr>
<td>天津南-沧州西</td>
<td>128</td>
<td>69</td>
<td>53.9%</td>
</tr>
<tr>
<td>沧州西-德州东</td>
<td>126</td>
<td>68</td>
<td>54.0%</td>
</tr>
<tr>
<td>德州东-济南西</td>
<td>125</td>
<td>68</td>
<td>54.4%</td>
</tr>
<tr>
<td>济南西-枣庄</td>
<td>123</td>
<td>73</td>
<td>59.3%</td>
</tr>
<tr>
<td>枣庄-徐州东</td>
<td>121</td>
<td>71</td>
<td>58.7%</td>
</tr>
<tr>
<td>徐州东-宿州东</td>
<td>142</td>
<td>90</td>
<td>63.4%</td>
</tr>
<tr>
<td>宿州东-蚌埠南</td>
<td>141</td>
<td>89</td>
<td>63.1%</td>
</tr>
<tr>
<td>蚌埠南-南京南</td>
<td>125</td>
<td>70</td>
<td>56.0%</td>
</tr>
<tr>
<td>南京南-上海虹桥</td>
<td>109</td>
<td>57</td>
<td>52.3%</td>
</tr>
</tbody>
</table>
In sum, the minimum $T$ increases as the number of time window (the cross-line trains) increases. The uptrend is higher at first and when eight cross-line trains are considered, but relatively stable for other values.

Case study

– Box-plot: number of time windows

In fact, the proportion of the number of the cross-line trains is more than 50% (for B-S HSR)!

nearly half of all trains!
Case study

– Box-plot: number of time windows

The overlaps show that even the number of time windows increases, they still have a chance to obtain low minimum cycle time. Therefore, the significance of the time window location is highlighted.
Optimize the structure of Train line plan

- Reduce Cross-line train
- Regularize Stop Pattern
- Utilize Triangle area
- Reduce Train Stops
- Categorize G,D train speed
Future huge traffic demand

- **Year 2016**
  - Passenger: 2.75 billion, 2.0 times/person

- **Year 2020**
  - Demand: $1.45 \times 4 = 5.8$ billion persons?

**Objective:** 4 billion

(National Railway Cooperation)
Thanks!

❓ Question