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

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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

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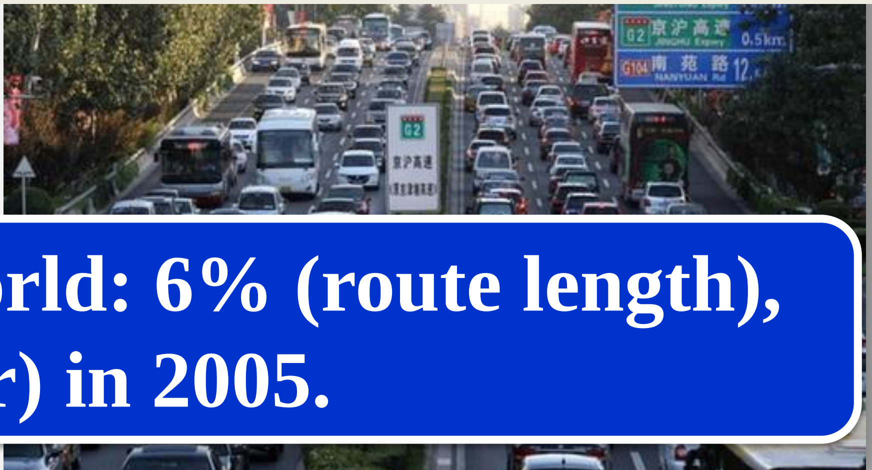
Goods by Railway (2006-2010)

- Wood: 85%
- Crude oil: 85%
- Coal: 60%
- Steel etc.: 80%

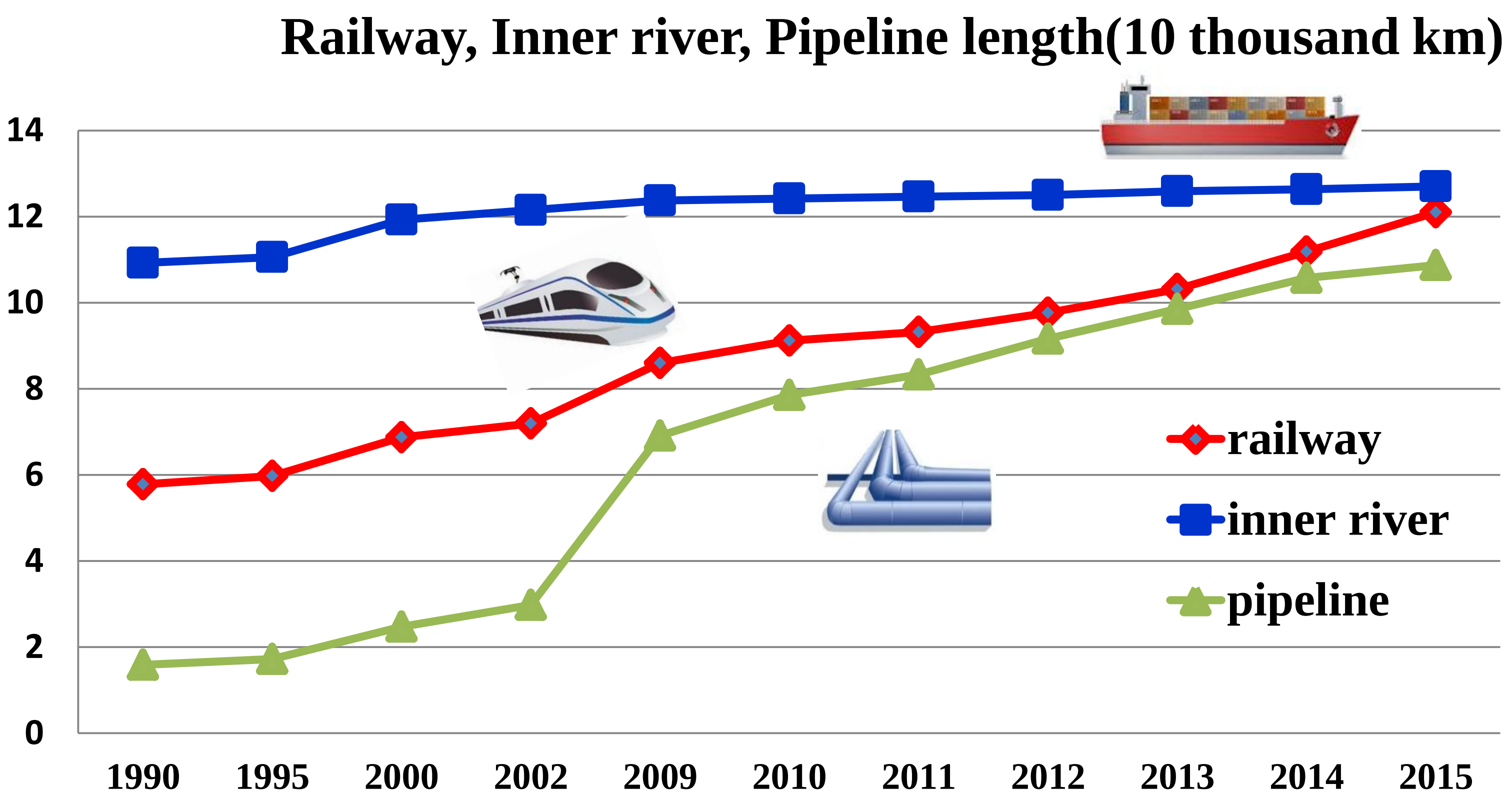

Passenger in Railway Station

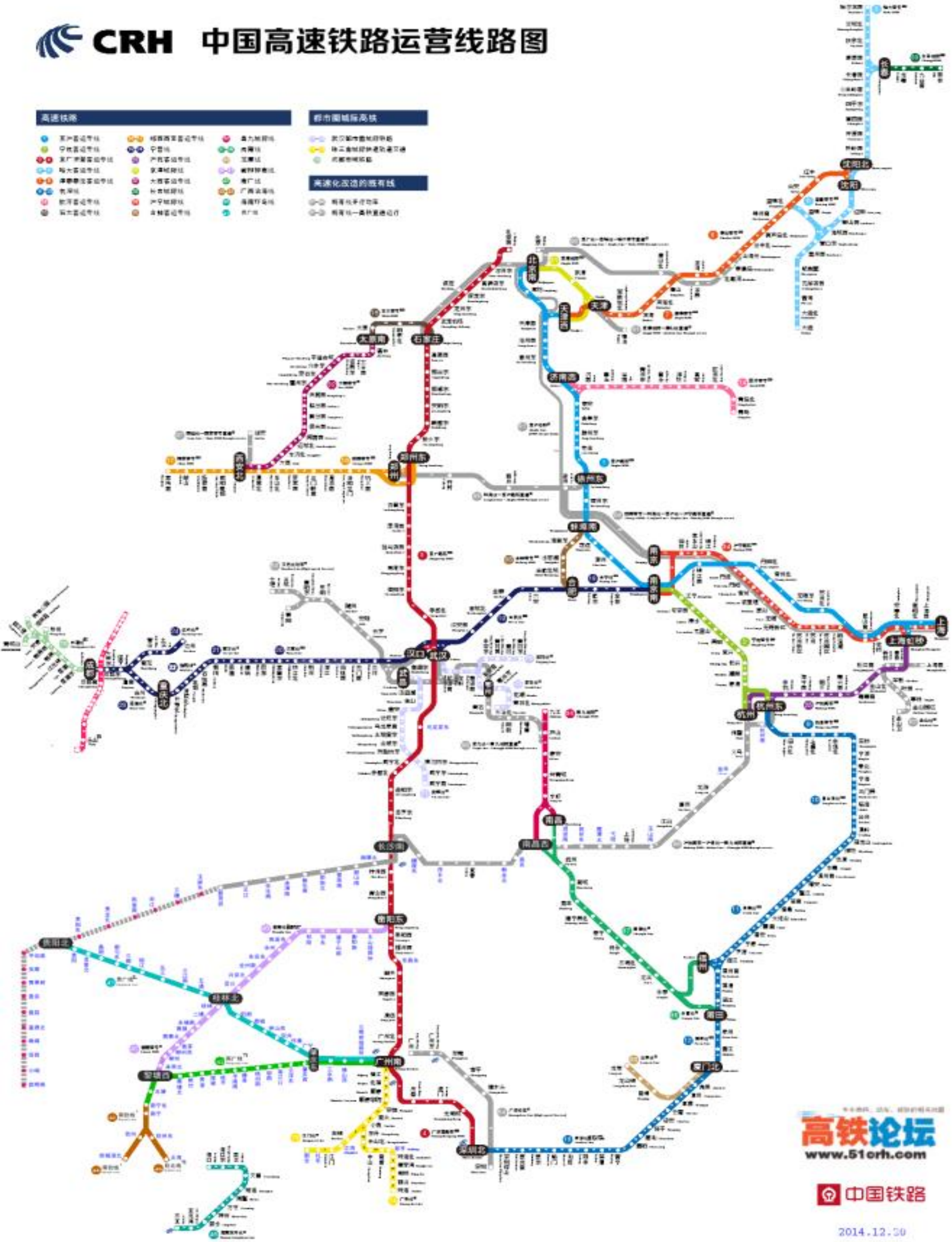

Coal Truck on highway


Traffic jam in city, almost no subway

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

The Development of Network





- 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.

Mid-term and Long-term Railway Network Plan (2017)

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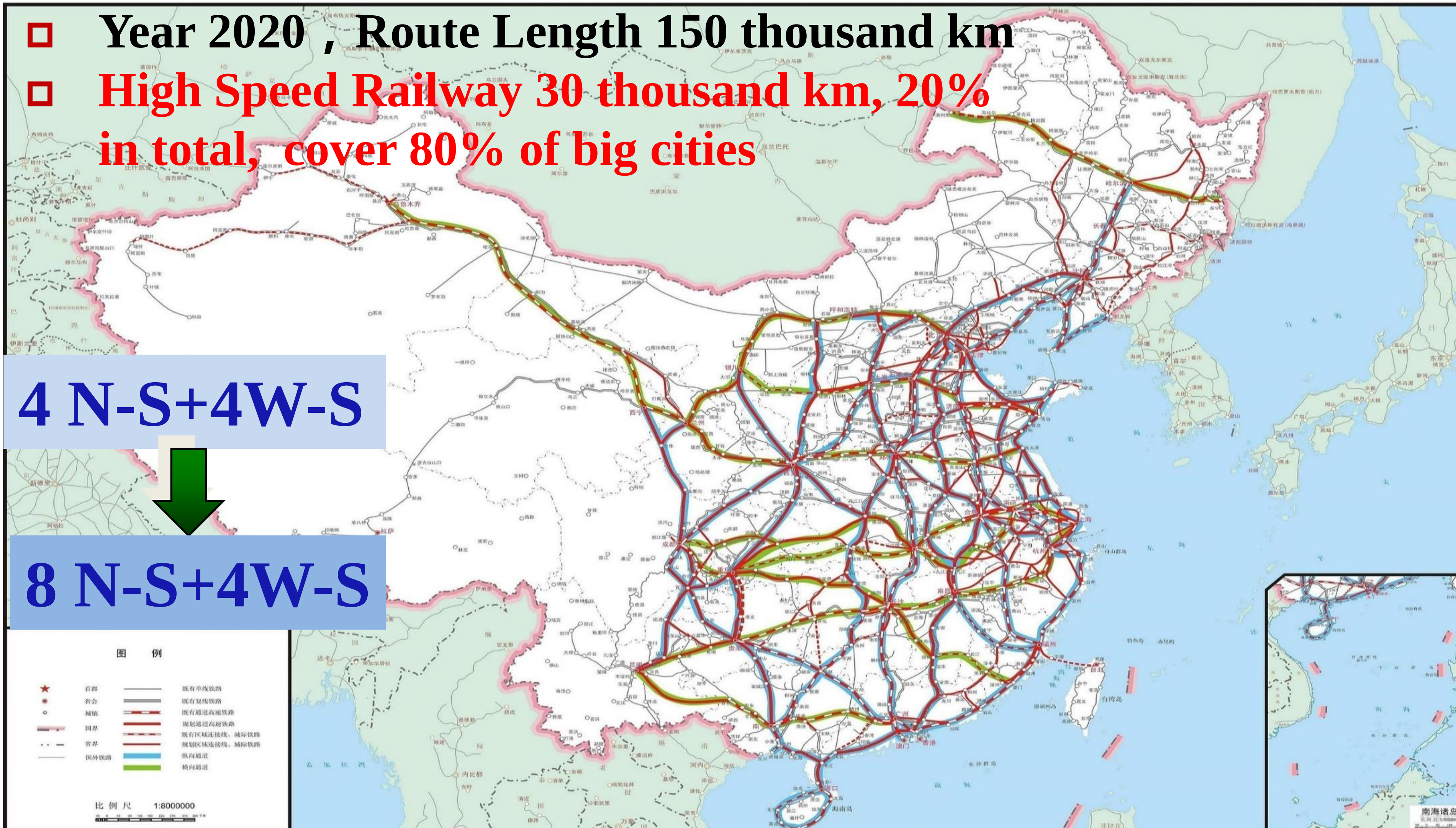
中长期高速铁路网规划图



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

4 N-S+4W-S

8 N-S+4W-S

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Shorten the Time-space Gap

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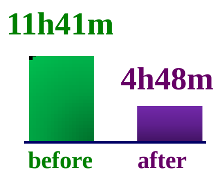
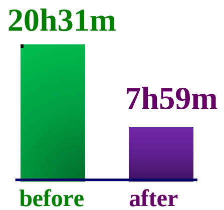
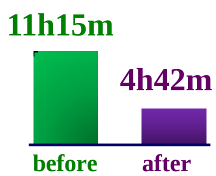


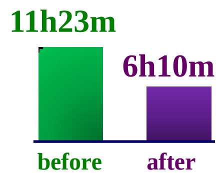
Beijing—Shanghai



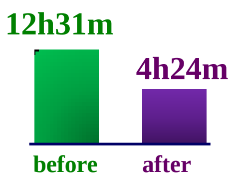
Beijing—Guangzhou



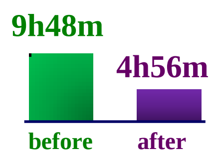
Beijing—Xi'an



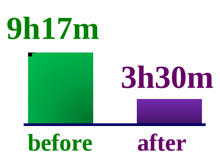
Beijing—Dalian



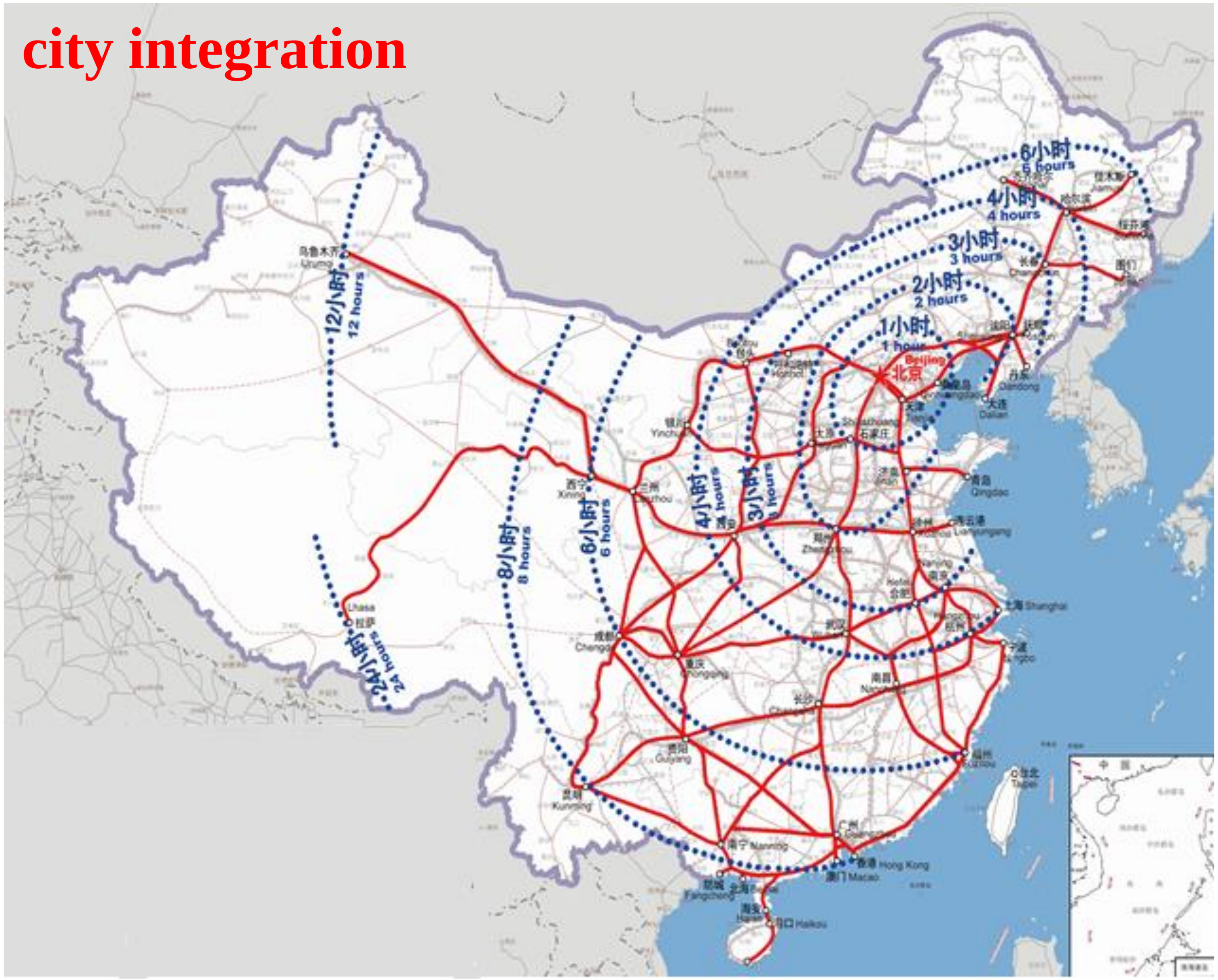
Shanghai—Changsha



Shanghai—Wuhan



Harbin—Dalian



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 , 1443million, 52%

30% increasing

Market Share of Passenger Transportation

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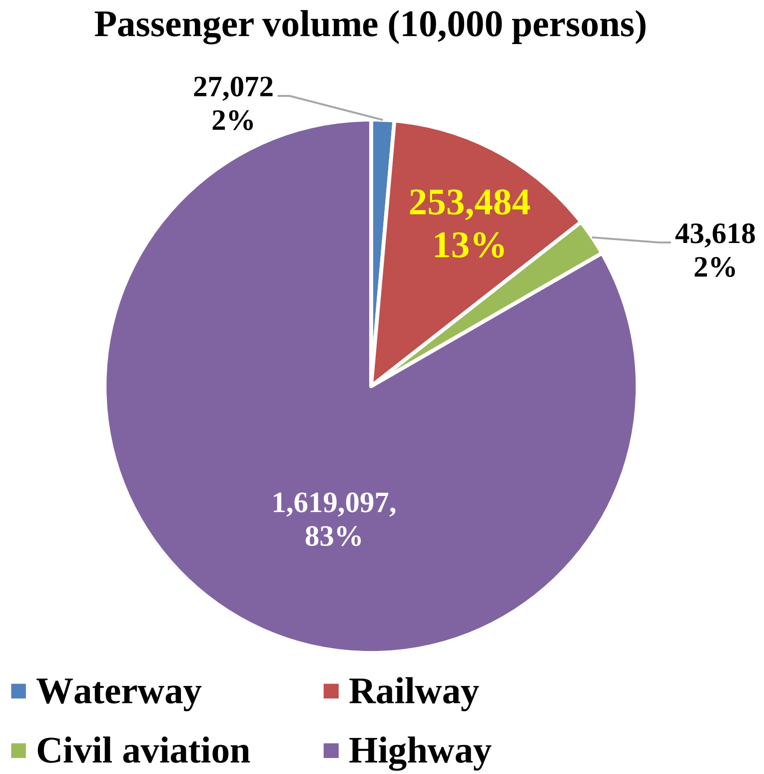
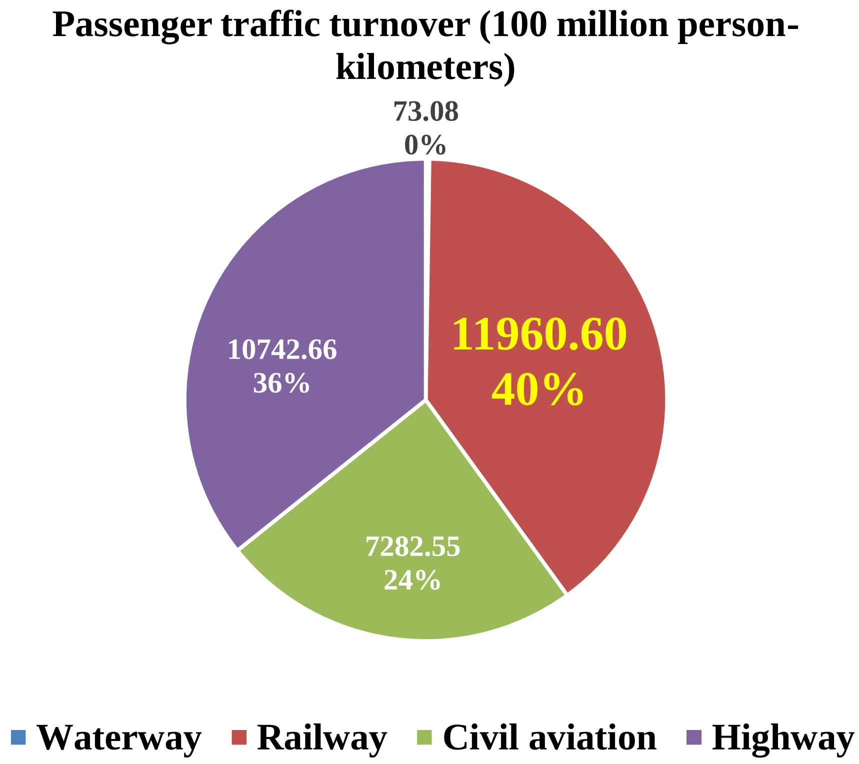
(Year 2015)	Total volume	Waterway	Railway	Civil aviation	Highway
Passenger volume (10,000 persons)	1,943,271	27,072	253,484	43,618	1,619,097
Passenger traffic turnover (100 million person-kilometers)	30,058.89	73.08	11960.60	7282.55	10,742.66





Transportation during the Spring Festival:
The world's largest migration

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Year	Start and finish date	Total passengers（100 million）	Raiway（100 million）	Highway（100 million）	Waterway（10 thousand ）	Civil Aviation（10 thousand ）
2002	1.28—3.08	17.4	1.3	15.9	2430	725
2003	1.17—2.25	18.2	1.3	16.6	2400	870
2004	1.07—2.15	18.9	1.4	17.2	2600	1050
2005	1.25—3.05	19.5	1.4	17.7	2760	1248
2006	1.14—2.22	20.4	1.5	18.8	2800	1760
2007	2.03—3.14	22.5	1.6	20.5	2850	2000
2008	1.24—3.02	22.6	2.0	20.2	2878	2100
2009	1.11—2.19	23.6	1.9	21.1	3089	2572
2010	1.30—3.10	25.6	2.0	22.9	3357	2902
2011	1.19—2.27	28.6	2.2	26.4		
2012	1.08—2.16	31.1	2.2	28.5	4245	3374
2013	1.26—3.06	34	2.4	31.0	4380	3810
2014	1.16—2.24	33.2	2.7	30.5		
2015	2.04—3.16	28.1	2.9	24.2	4286	4920
2016	1.24-3.3	29.1	3.3	24.9	4260	5309
2017	1.13-2.21	29.8	3.6	25.2	4350	5830

Revenue of Chinese HSR

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

From: Huaxia Times

- **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: web information

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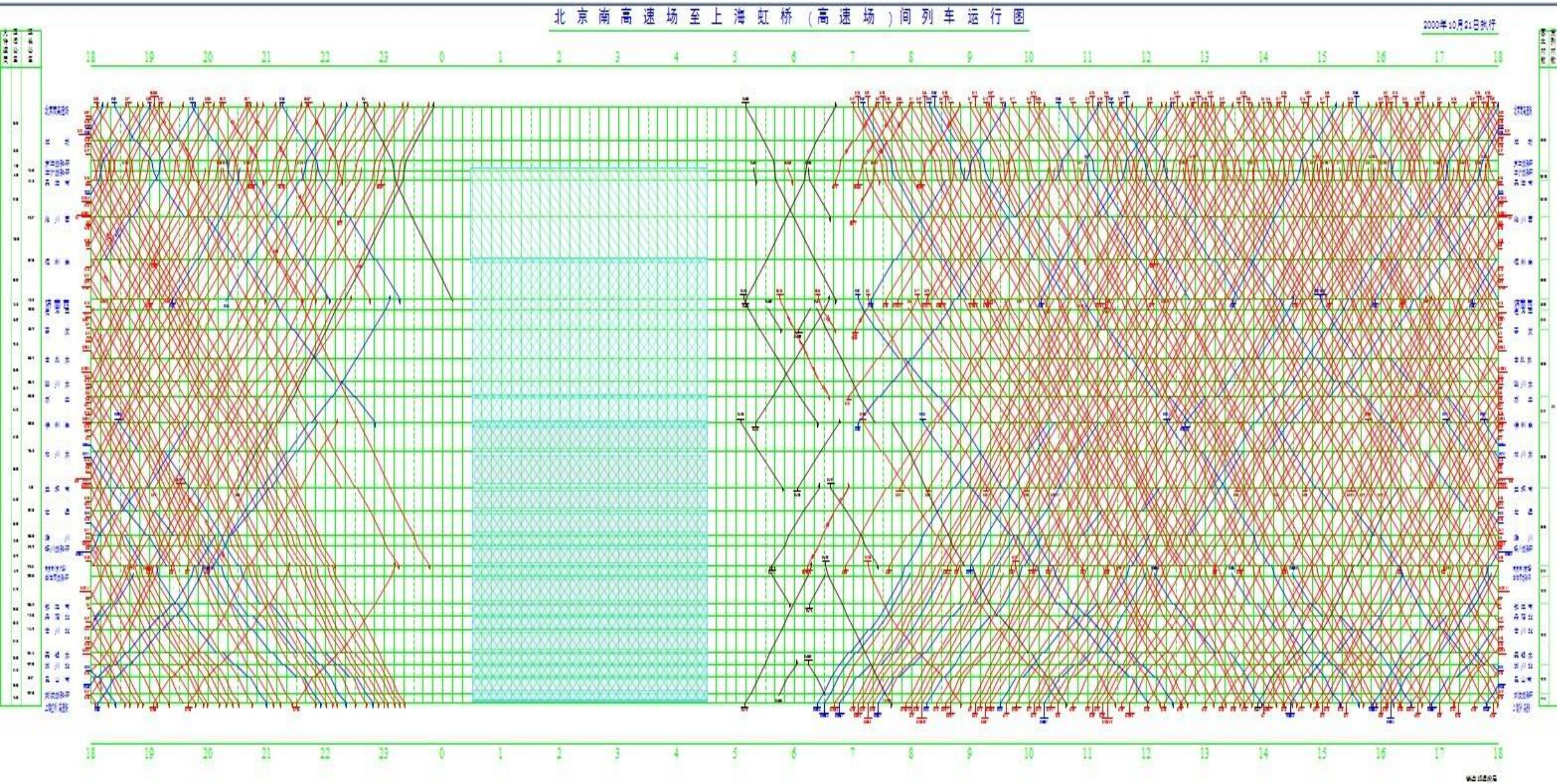
0:00-6:00 Maintenance time



High speed railway（Beijing South-Shanghai Hongqiao）

The characteristics of train line plan

non-cyclic timetable

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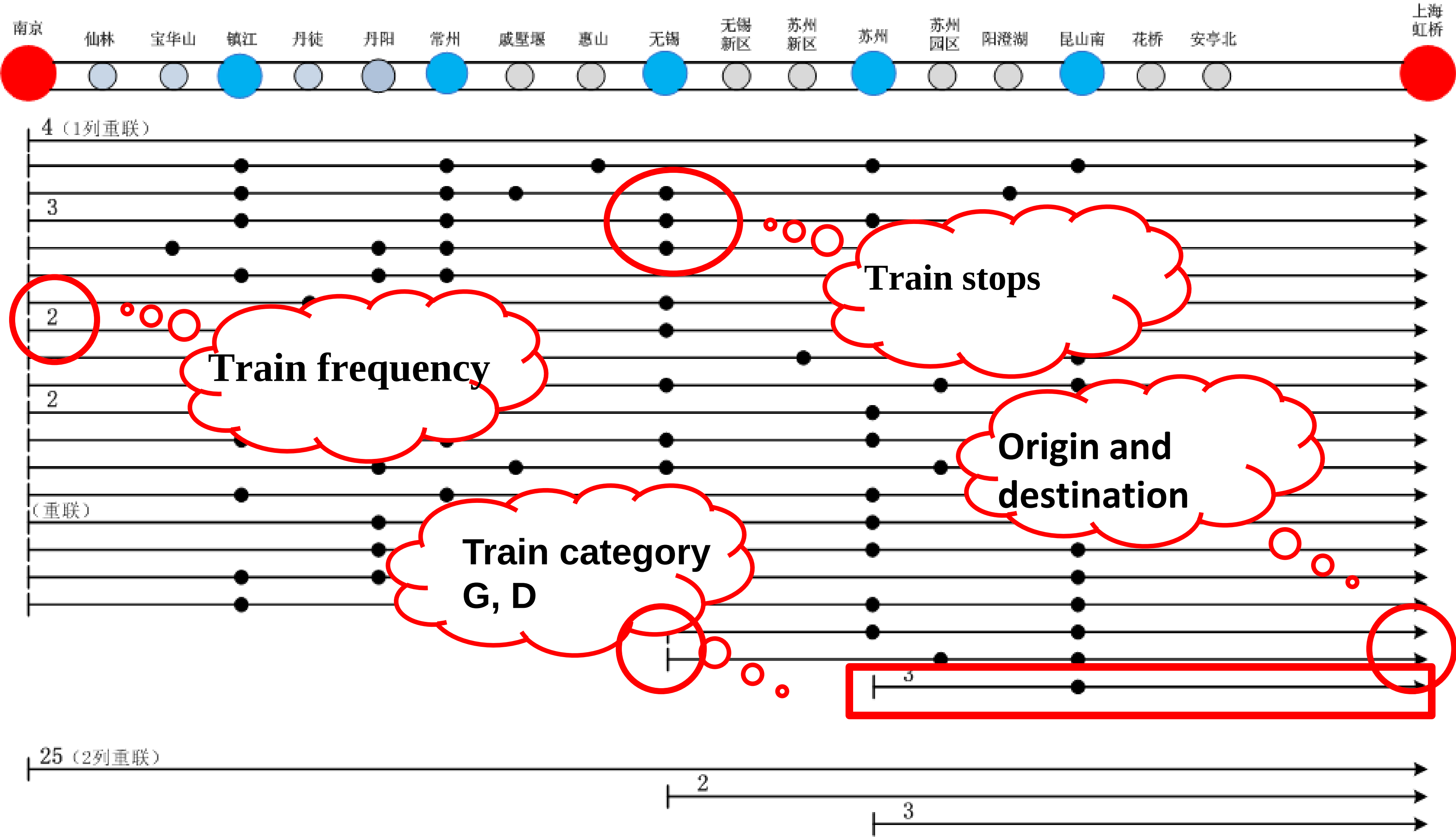
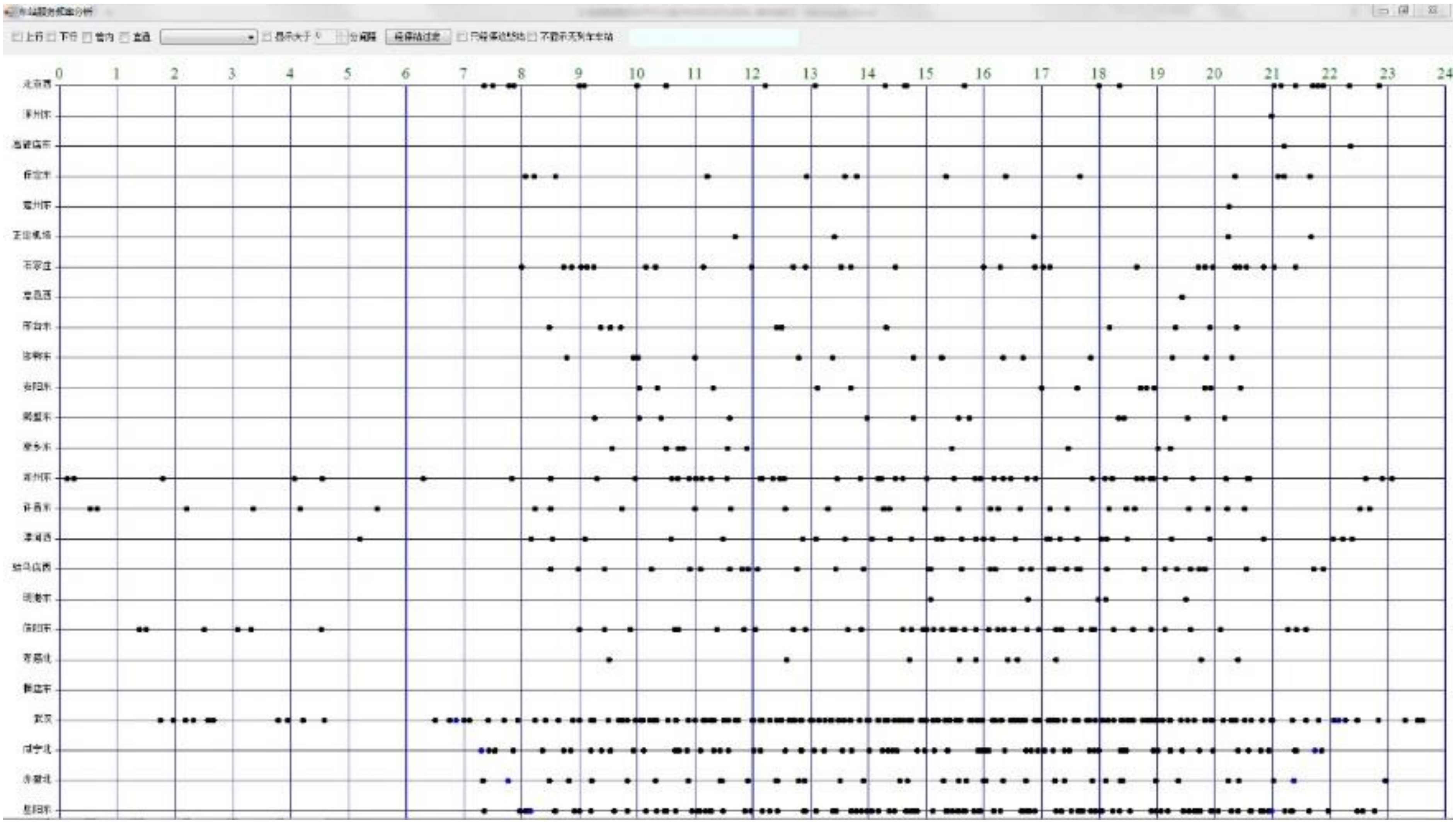


Train frequency between two stations

	武汉	咸宁北	赤壁北	岳阳东	汨罗东	长沙南	株洲西	衡山西	衡阳东	耒阳西	韶关	英德西	清远	广州北	广州南	庆盛	虎门	光明城	深圳北
武汉		23	14	36	13	65	19	12	30	14	31	9	9	11	57	0	10	0	15
咸宁北	19		6	12	6	23	8	4	12	4	13	4	4	4	18	0	2	0	4
赤壁北	16	4		4	6	14	6	2	10	5	8	4	3	4	13	0	1	0	2
岳阳东	43	14	7		6	38	9	10	17	10	18	7	8	5	32	0	7	0	9
汨罗东	16	6	6	8		14	5	4	4	4	9	2	3	4	12	0	0	0	1
长沙南	64	19	16	45	18		25	21	41	20	46	12	15	17	79	1	19	0	25
株洲西	22	5	6	18	4	27		5	14	9	19	4	8	9	25	1	5	0	6
衡山西	12	4	3	10	5	21	5		6	11	17	4	6	7	21	0	5	0	6
衡阳东	30	11	10	20	8	40	14	6		6	22	12	9	9	41	1	10	0	12
耒阳西	11	3	4	11	5	21	12	10	5		17	4	5	8	20	0	4	0	6
郴州西	32	8	9	23	7	43	12	12	29	4	22	12	12	10	49	1	13	0	16
韶关	31	9	8	25	8	42	20	10	22	16		4	9	10	46	1	11	0	12
英德西	7	4	3	6	6	14	5	8	9	6	6		4	4	12	0	4	0	5
清远	9	4	4	6	5	17	8	7	11	8	8	4		5	15	0	3	0	4
广州北	7	2	3	6	3	11	6	6	8	6	6	4	4		17	0	1	0	1
广州南	56	14	14	39	15	78	27	21	40	21	42	14	17	11		1	19	0	25
庆盛	0	0	0	0	0	1	0	1	0	0	1	0	0	0	1		1	0	1
虎门	12	4	2	8	1	21	6	6	12	5	11	3	2	2	21	1		0	19
光明城	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
深圳北	15	5	3	9	1	25	7	7	13	6	12	3	2	2	25	1	21	0	

Train departure time distribution at stations



Complex operation

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BeiJing JiaoTong University

- 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


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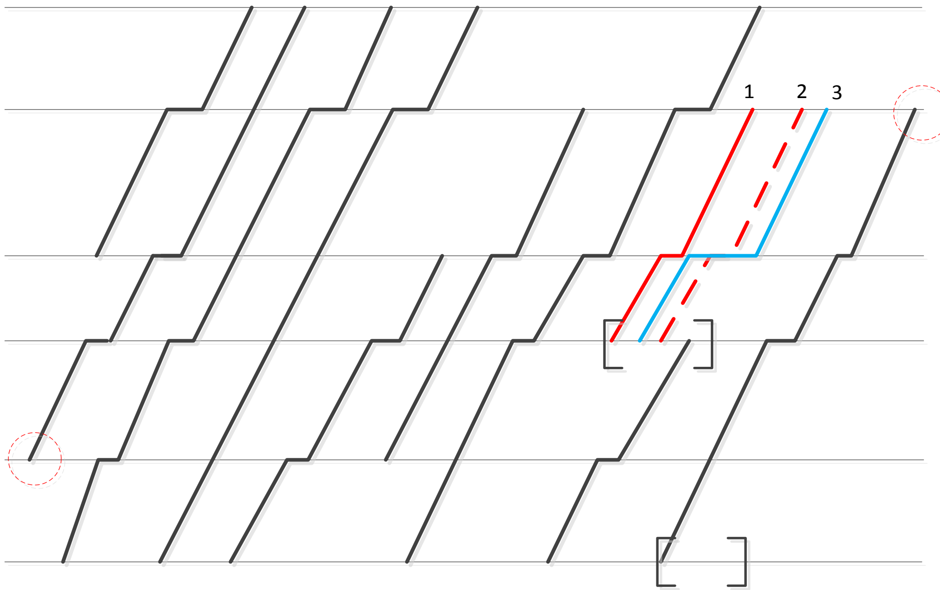
Case 1

Non-cyclic operation

Non-cyclic timetable:

A mixed integer programming model



Objective

- The minimum occupied time: train path compression

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

⬇

$$\min \quad Z=\sum_{i=1}^{I} a_{i,des_i}$$

Model

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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

$$d_{is} - a_{is} \geq w_{is} x_{is}$$

$$d_{is} - a_{is} \leq \overline{w}_{is} x_{is}$$

- Headways

$$d_{js} - d_{is} + M\left(1 - O_{ij}^{s}\right) \geq HD_{s}$$

$$d_{is} - d_{js} + MO_{ij}^{s} \geq HD_{s}$$

$$a_{js+1} - a_{is+1} + M\left(1 - O_{ij}^{s}\right) \geq HA_{s+1}$$

$$a_{is+1} - a_{js+1} + MO_{ij}^{s} \geq HA_{s+1}$$

- Overtaking

$$\left| \sum_{j=1,\, j \neq i}^{N} \left(O_{ij}^{s-1} - O_{ij}^{s}\right) \right| \leq 1$$

- 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

$$\underline{k}_{is} \leq d_{is} \leq \overline{k}_{is}$$

- Departure time control

$$\underline{t}_{is} \leq d_{is} \leq \overline{t}_{is}$$

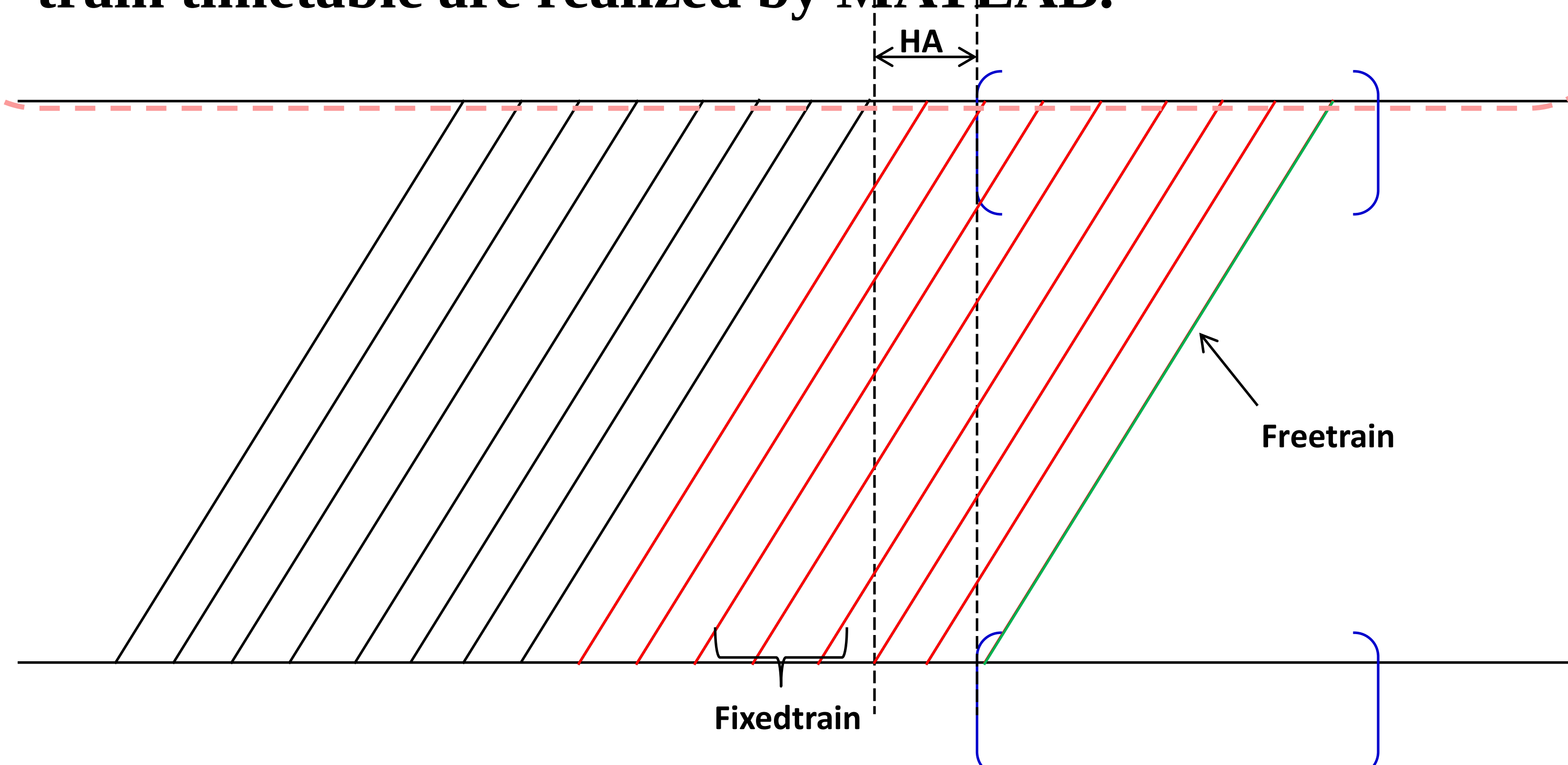
- Maintenance time window

$$d_{is} \geq SL_{e}$$

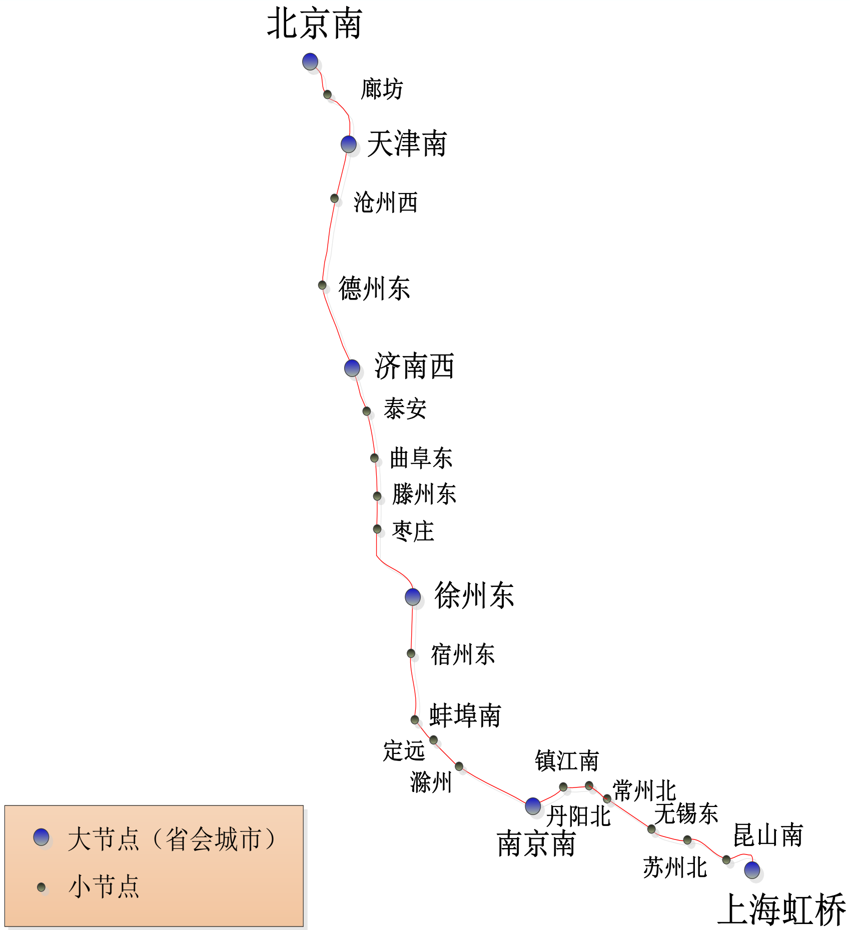
$$a_{is} \leq SL_{b}$$

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

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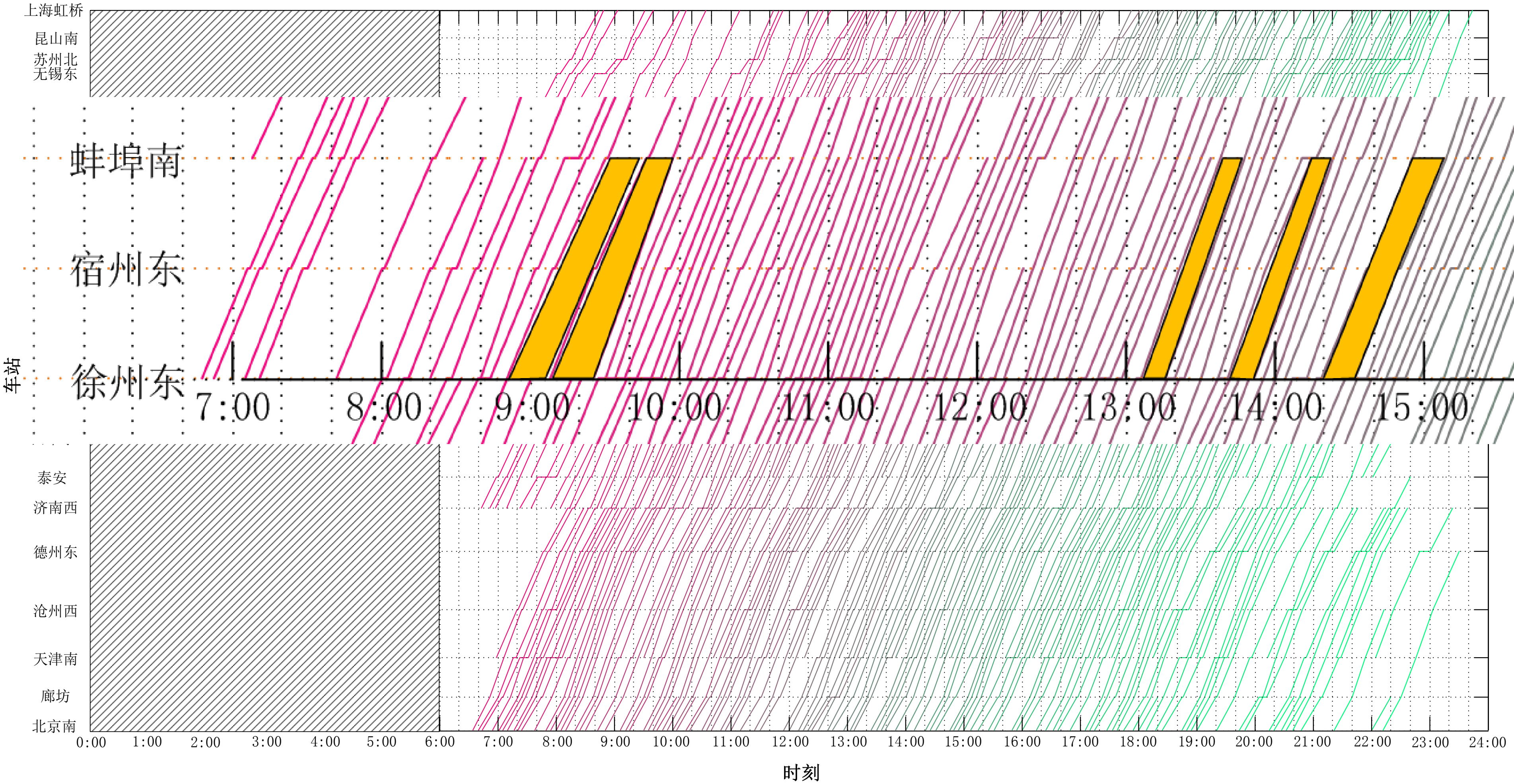
2017. 01 timetable at Xuzhou-Bengbu



Case study: Non-cyclic timetable

Reduce occupation time by 21min

2017- 01 timetable at Xuzhou-Bengbu

	Earliest departure	Latest arrived	Occupation time/min
real world	6:40	23:22	1002
optimized	6:48	23:01	973

	Travel time/min	Travel speed /(km/h)	Technical speed /(km/h)
real world	42543	219	228.7
optimized	41811	223.5	240.0

train	Travel /min		Travel speed /(km/h)		Technical speed/(km/h)	
	RW	Opt	RW	Opt	RW	Opt
G	41821	41198	221.4	225.1	230.8	241.2
D	722	613	141	162.3	194	180.1

Case 2

Cyclic operation

Analysis on section capacity for cyclic timetable (TR. Part C 2016)

BeiJing JiaoTong University

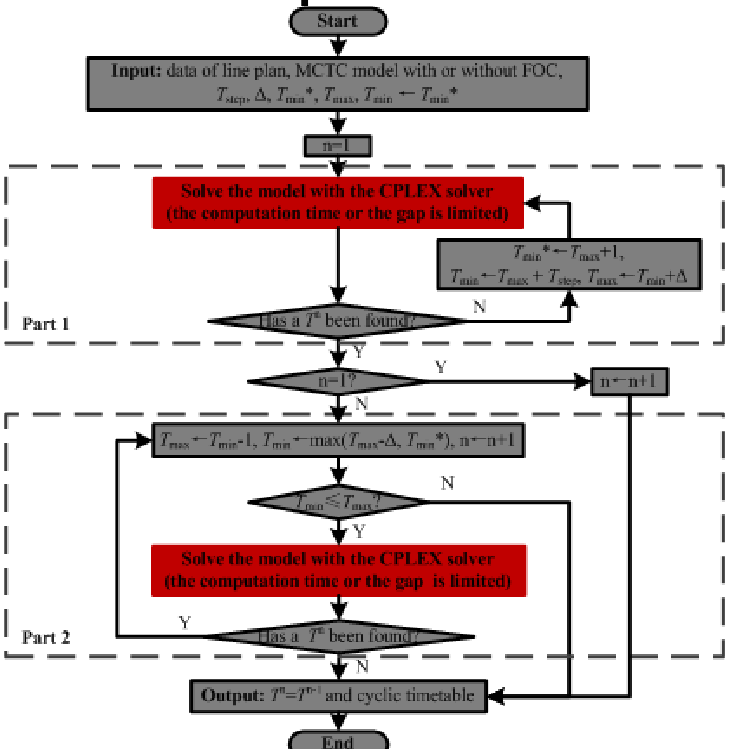
- **Integrating capacity analysis with timetabling** can reveal the influence of the structure of train line plans and operating on improving capacity utilization .
- For most capacity analyses and cyclic timetabling methods, **the cycle time is a constant.**
- **A minimum cycle time calculation (MCTC) 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.

Problem and Model

- 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

Methods and Algorithms

- 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



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Case study: Cyclic timetable

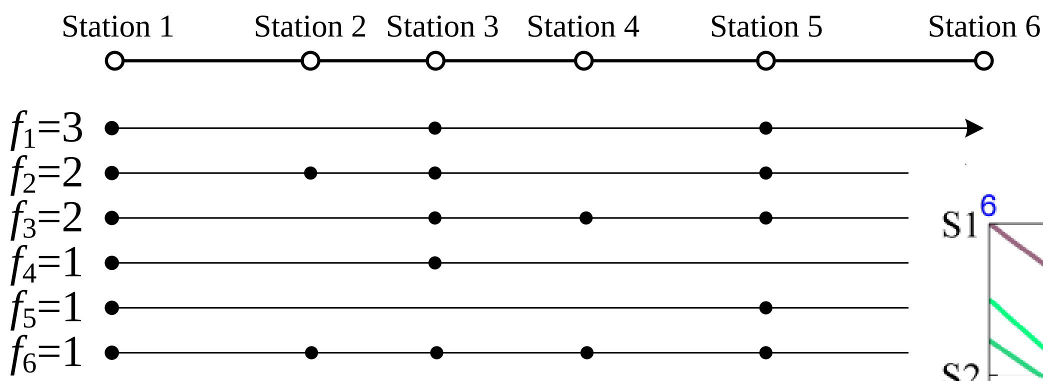

Fig. 12. Hypothetical case : Line plans

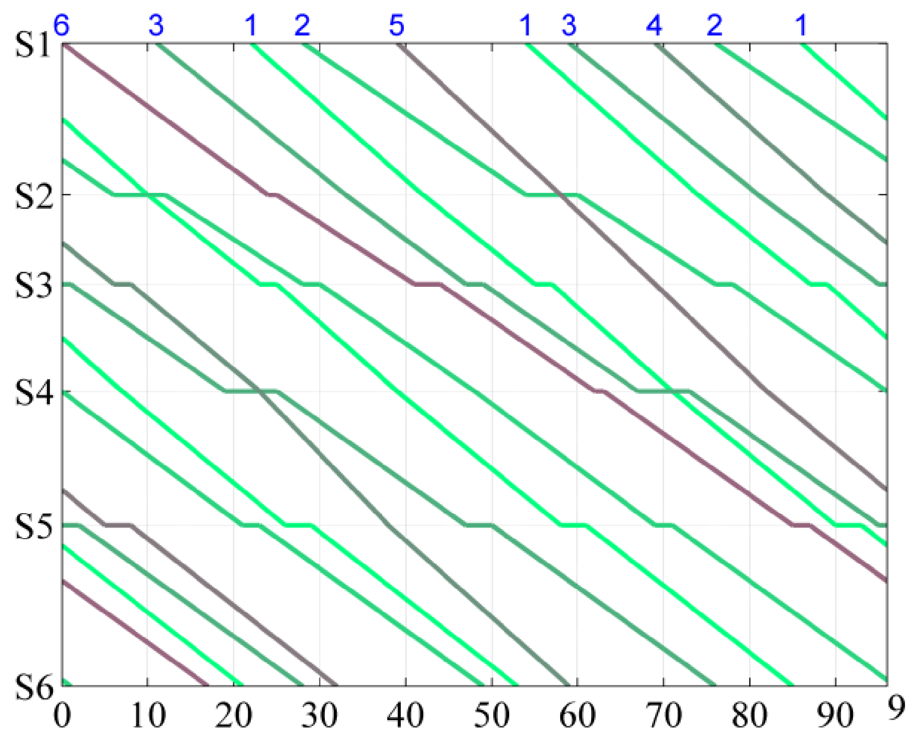

Fig. 14. Examples of timetables

different colors represent different train lines; the blue numbers indicate the numbers of the lines; *K* = 0;

Case study: Cyclic timetable

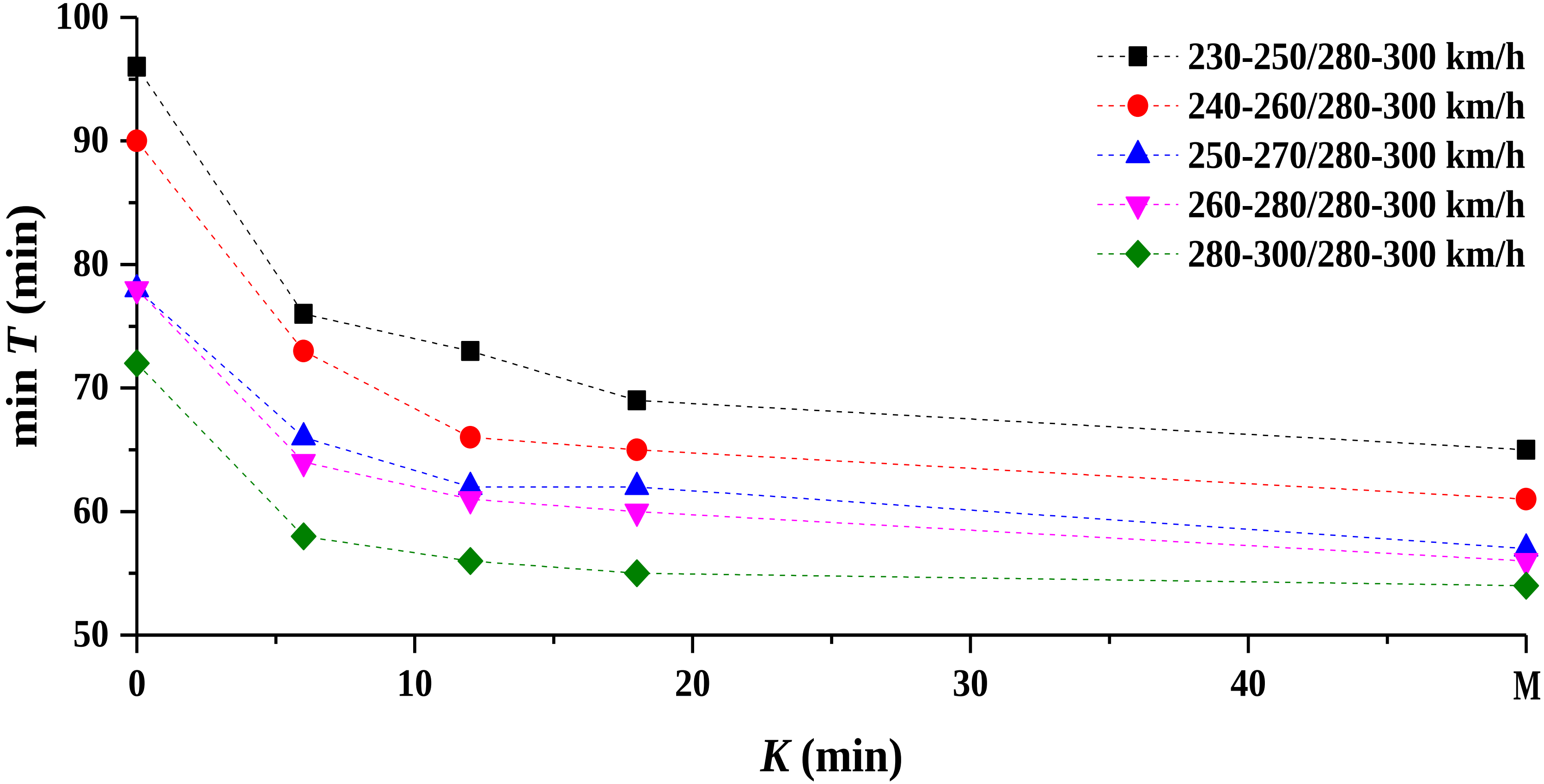

Fig. Influence of the regularity constraint and the train speed gap on the minimum *T* (the MCTC model *with* the FOCs; the average computation time for all cases is 4,420 seconds).

Case study: Cyclic timetable

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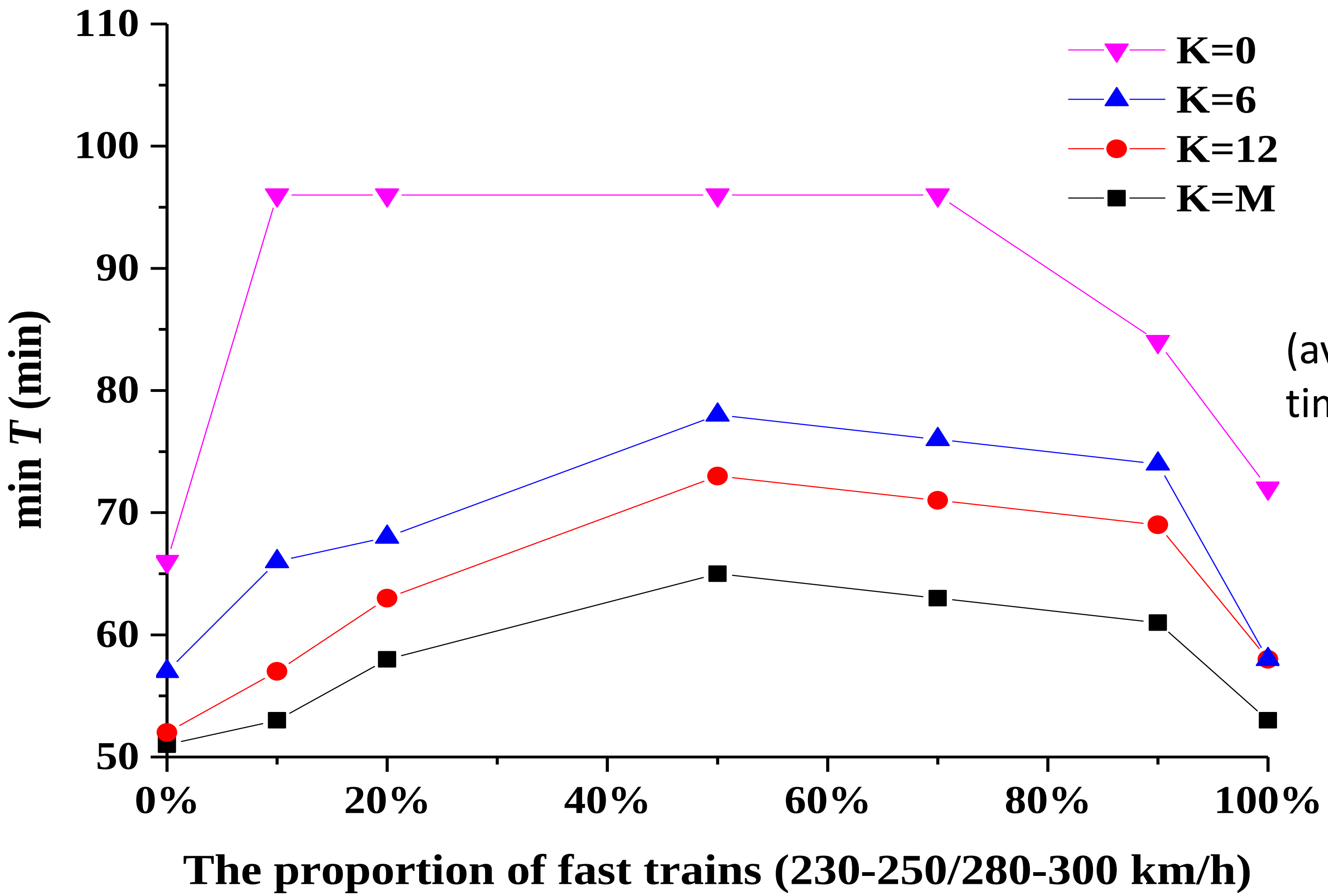

(average computation time is 3,798 seconds).

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

Real world Case: Cyclic timetable

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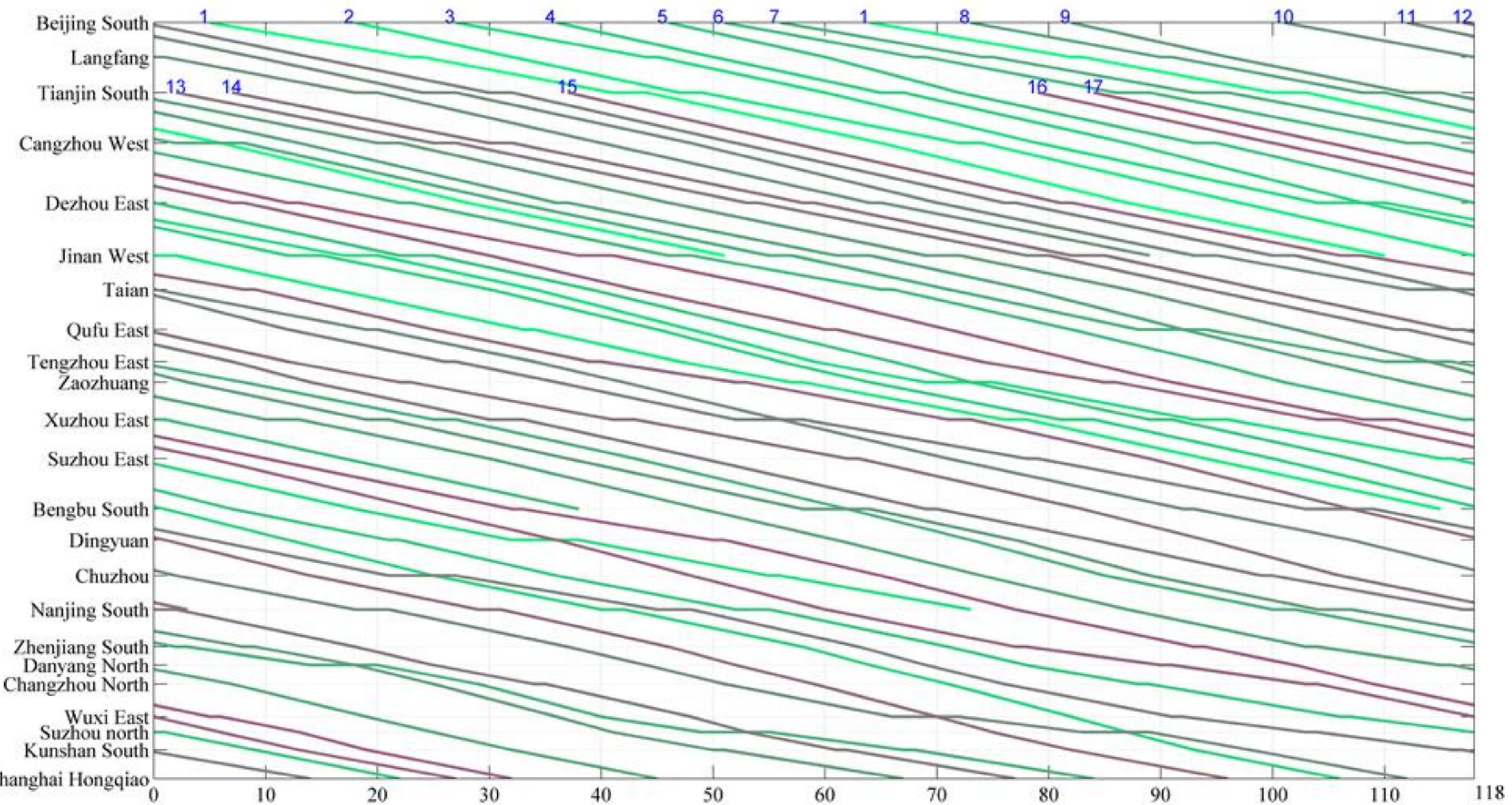
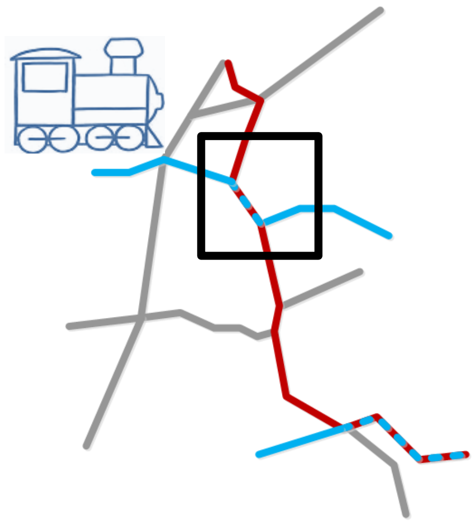
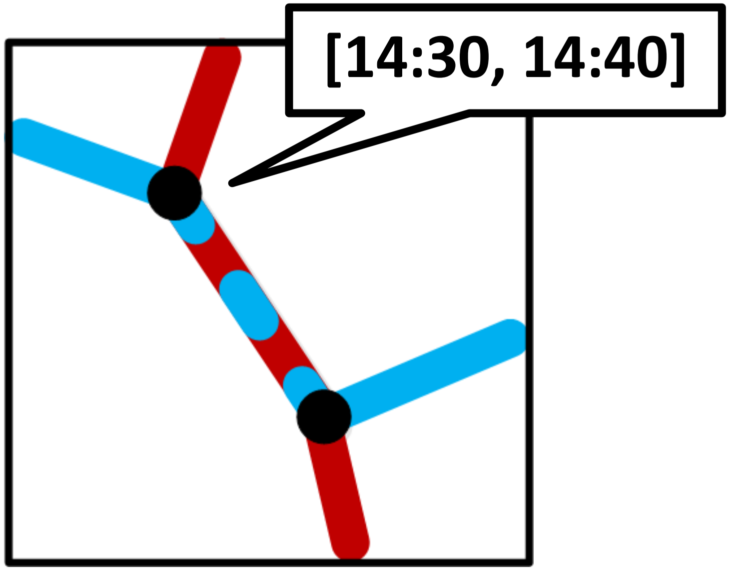


Fig. 19. Time-space diagram of the solution for the real-world test case *with* the FOCs

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)





A train time window for cross-line train

- Naming rules of the experiments: four factors of train time window are included

s – 2 – 0 – 1

Stations | **Number** | **Span** | **Regularity**

-s(origin)
-m(intermediate)

-one time window for one cross-line train

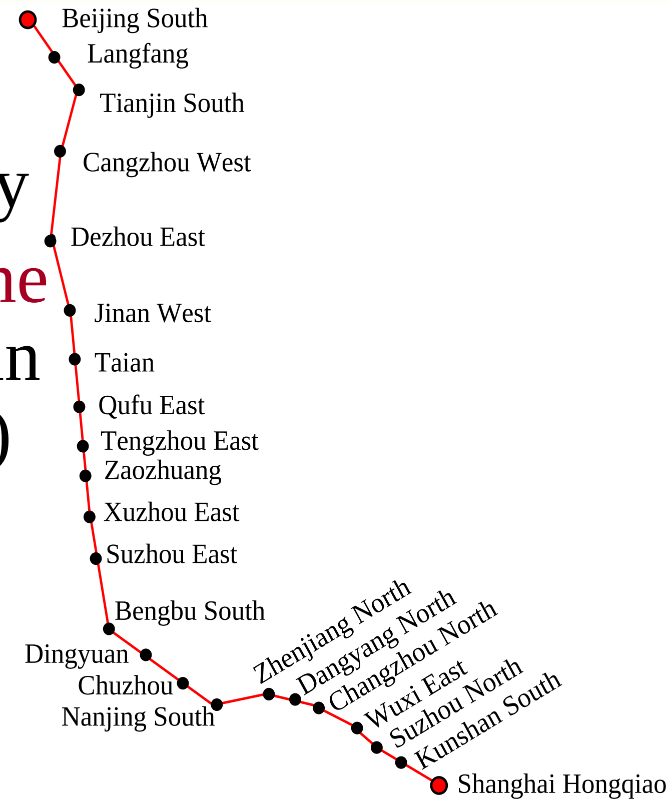
-δ in regularity constraint

$$\frac{T}{f_{ij}} - \delta \leq x_{ij} \leq \frac{T}{f_{ij}} + \delta,$$
$$\forall (i,j) \in A_{regular}$$

  – "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, δ=0)
- Time period of line plan is two hours



Property	Real-world case
Number of stations	23
Number of trains	18
Number of lines (train stop schedules)	17
Line plan	17 types of train stop schedule

The structure of train line plan

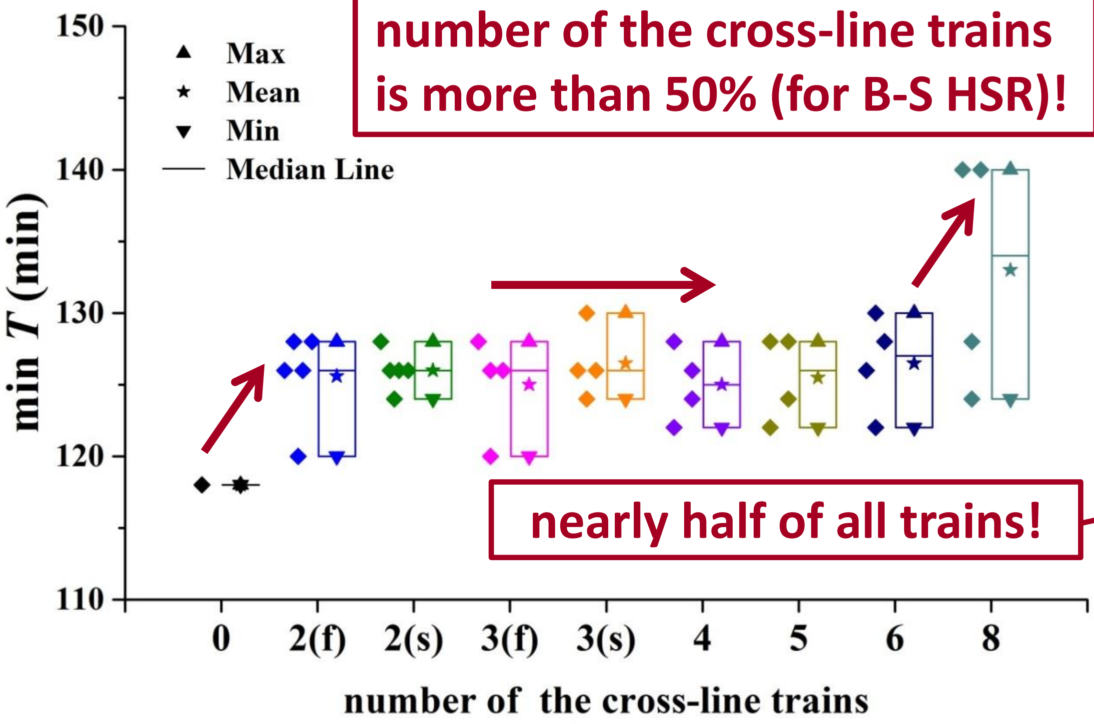
➢Cross-line train: 69.7%

Section	Total trains	Cross-line	%
北京南-廊坊	109	50	45.9%
廊坊-天津南	103	47	45.6%
天津南-沧州西	128	69	53.9%
沧州西-德州东	126	68	54.0%
德州东-济南西	125	68	54.4%
济南西-枣庄	123	73	59.3%
枣庄-徐州东	121	71	58.7%
徐州东-宿州东	142	90	63.4%
宿州东-蚌埠南	141	89	63.1%
蚌埠南-南京南	125	70	56.0%
南京南-上海虹桥	109	57	52.3%

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)!

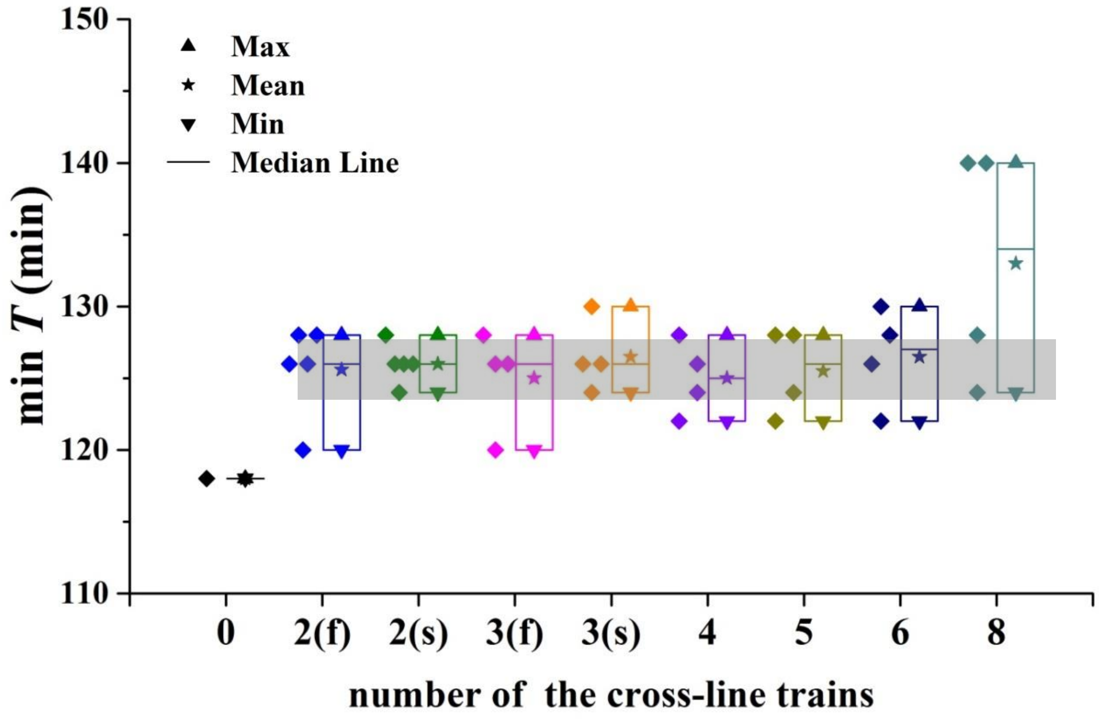


nearly half of all trains!

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.

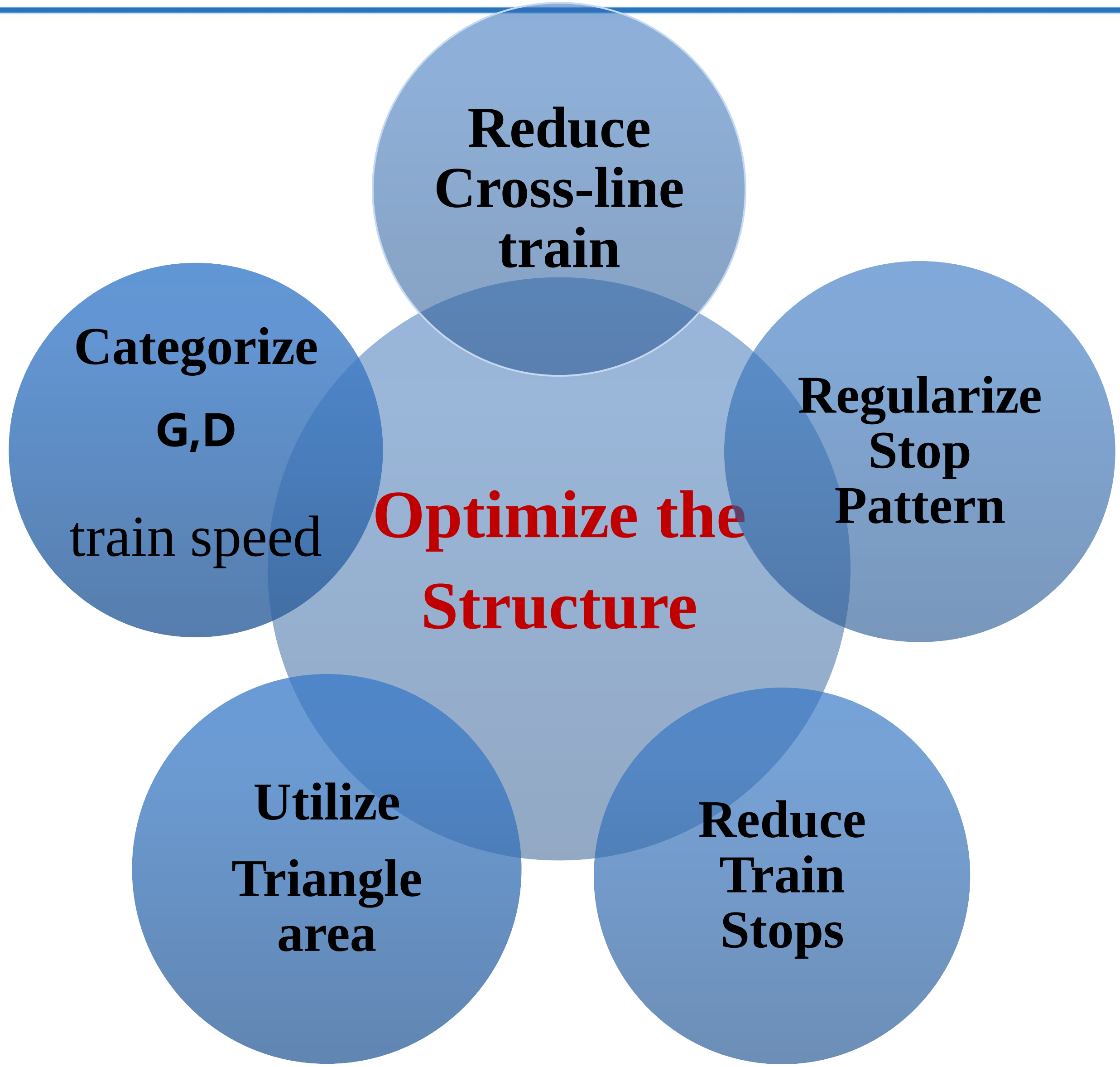
Case study

– Box-plot: number of time windows



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



Future huge traffic demand

- **Year 2016**

  Passenger：2.75 billion, 2.0 times/person

- **Year 2020**

Demand：1.45 billion people×4 times

=5.8 billion persons？

Objective：4 billion

(National Railway Cooperation)

Thanks!

? Question