Happy Chinese New Year

Public transit planning and scheduling based on AVL data in China

Prof. Yindong Shen

Huazhong University of Science and Technology

Email: **yindong@hust.edu.cn**

Global Scheduling Seminar on Zoom on Wednesday February 2, 2022

OUTLINE

1. Background – Public transport in China
2. Major Problems related to transit planning
3. Comprehensive framework of transit planning
4. An integrated solution for public transport scheduling (iPTS)
5. Vehicle scheduling based on AVL data

yindong@hust.edu.cn

China

- Population:
  1.328 billion by the end of 2008
- Area:
  9.6 million km^2
- Provinces (23) & autonomous regions (5+2) & Municipality (4): 34
- Capital: Beijing

Severe challenges to urban transportation

Urbanization

Motorization

Challenges

- traffic jams
- accidents
- pollution
- ……

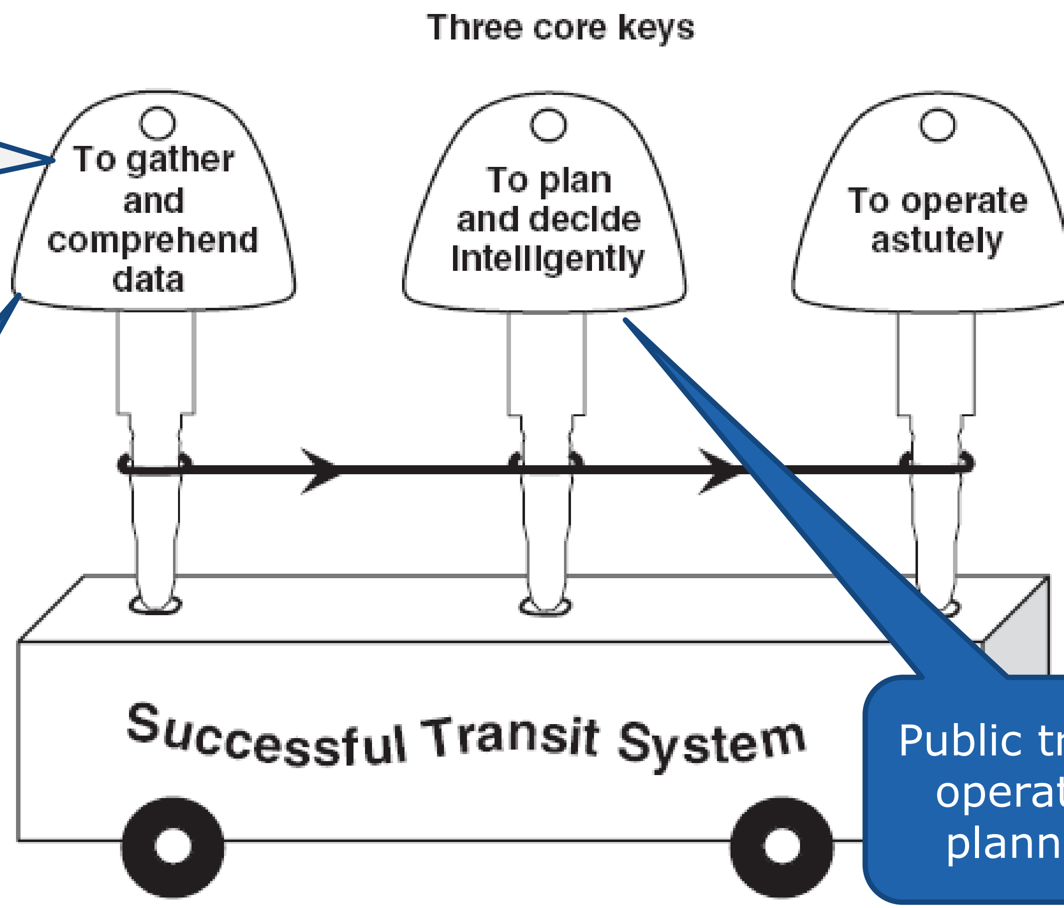
Solutions

improving public transport is a fundamental way to tackle urban traffic problems

How to achieve it?

Components of successful transit system

It forms the foundation of the other two functions: planning and operation.

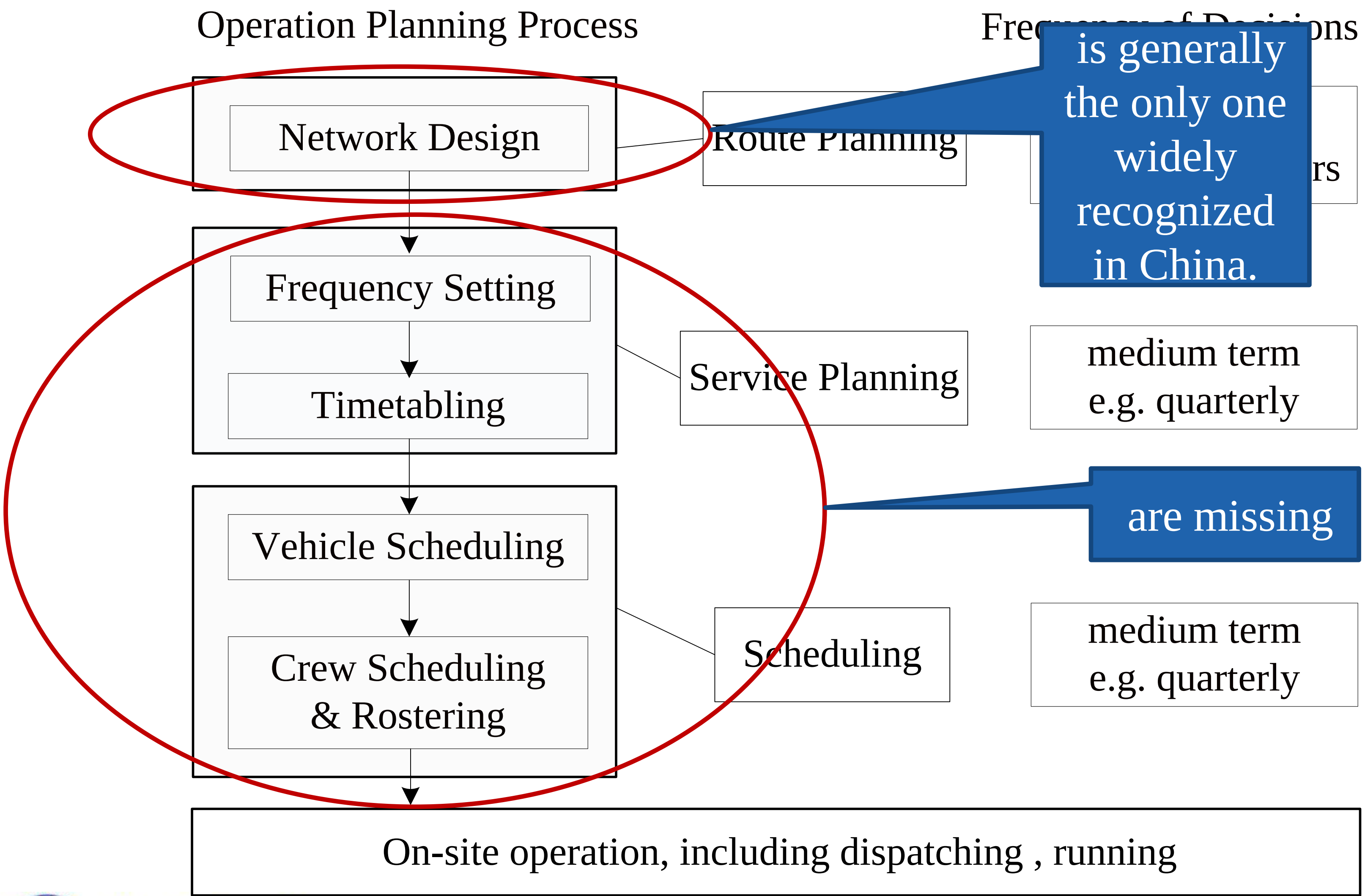


Collected by AVL, APC, AFC systems

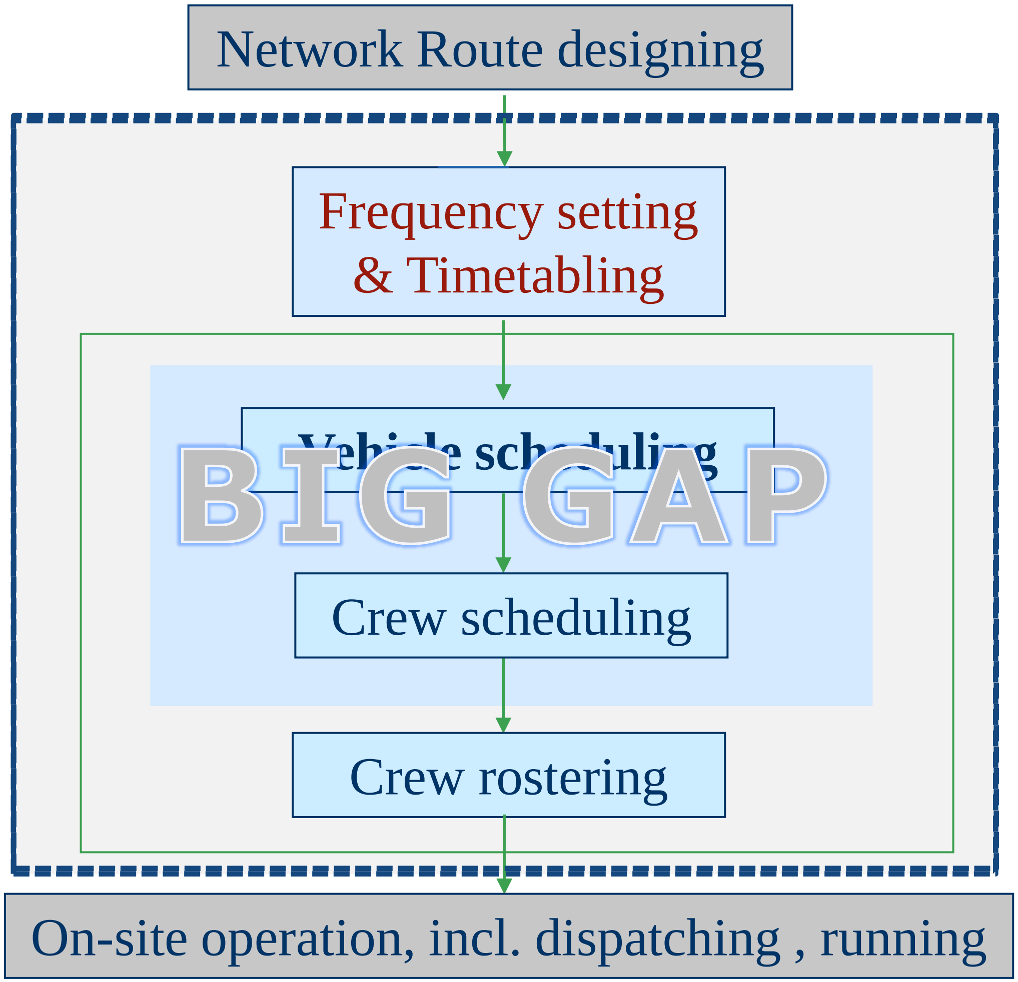
Public transit operation planning

Ceder A (2007). Public transit planning and operation: theory, modeling and practice. Elsevier, Butterworth-Heinemann

Public transit operation planning process



Gap between route design and operation

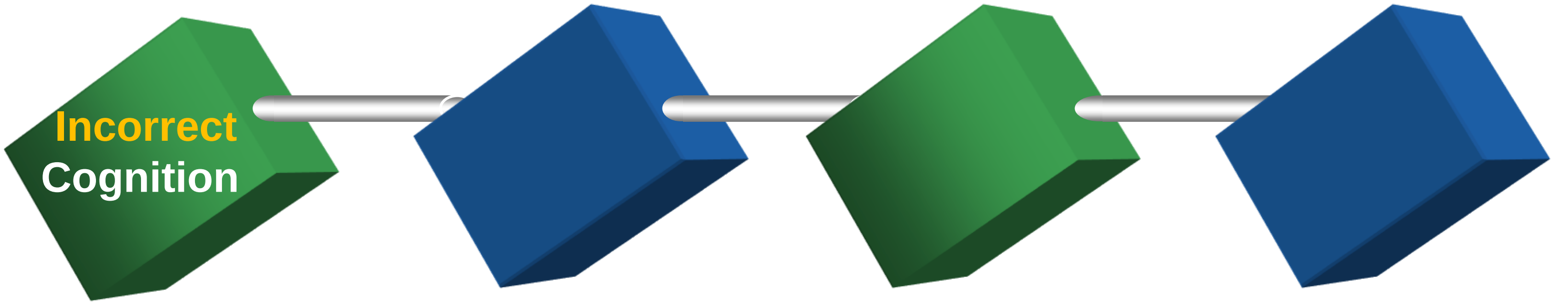


Why ?

- **Dispatching** is generally paid more attention than **scheduling** in China

yindong@hust.edu.cn

Major Problems related to transit planning



Misunderstanding the public transport planning as network route design.

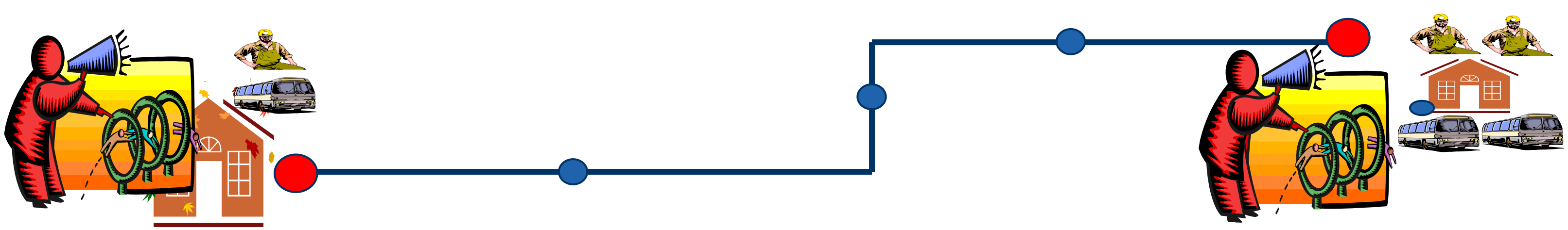
Scheduling is often confused with **dispatching**.

- The **schedule compilation** is generally underrated, but
- **dispatching**, by contrast, plays a much more important role in bus operation.

yindong@hust.edu.cn

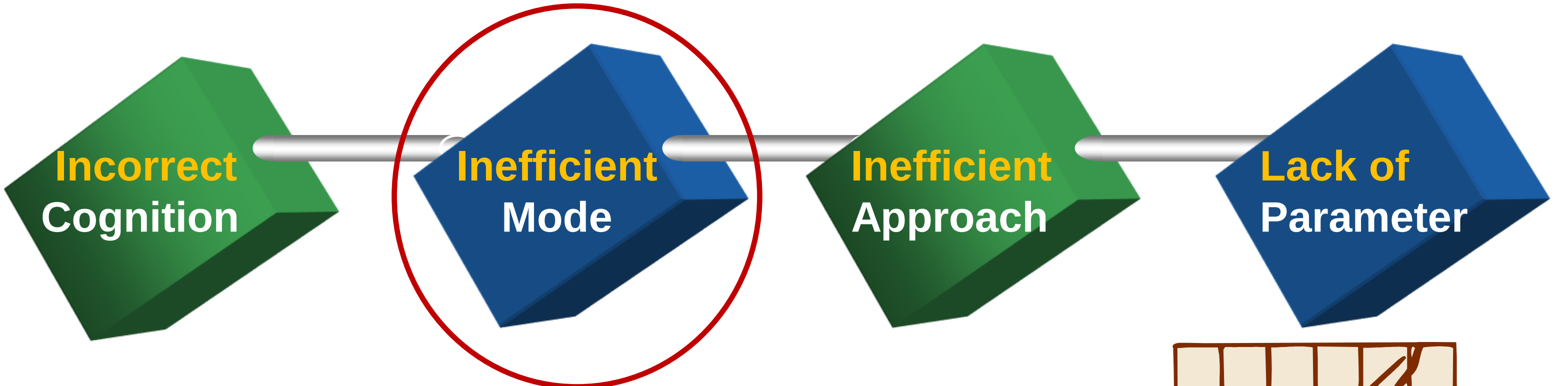
Pay more attention on dispatching

- **Each terminus is usually equipped with at least a dispatcher, who plays part of the roles of schedulers by deciding the departure time of each service trip according to experiences.**
- The efficiency of dispatching depends greatly on the experience, responsibility and personal authority over drivers of an individual dispatcher.

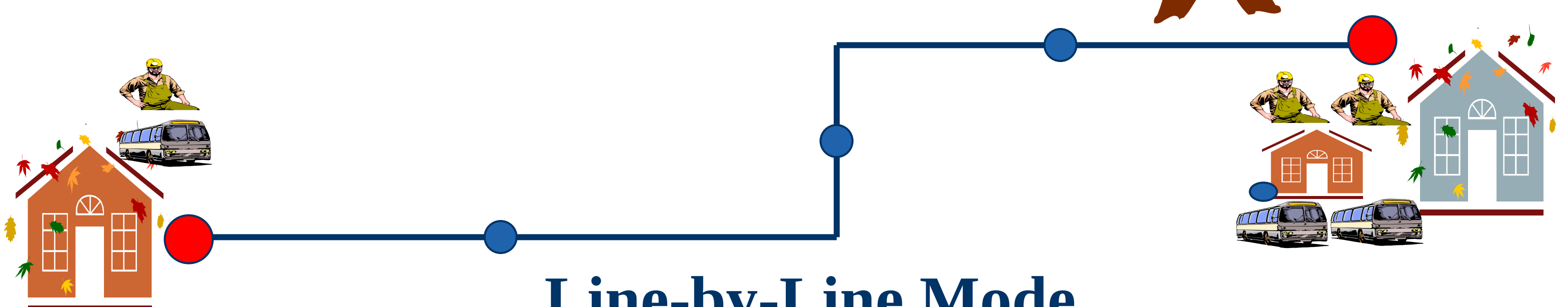


Line-by-Line Mode

Major Problems related to transit planning

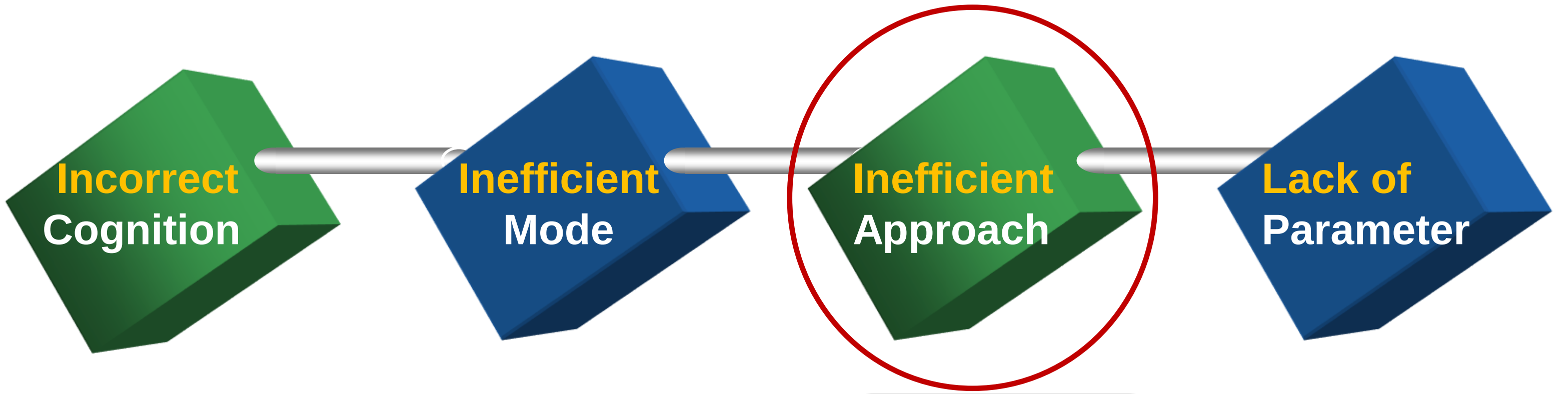


- Schedules are compiled **manually** on a **line-by-line** basis.



Line-by-Line Mode

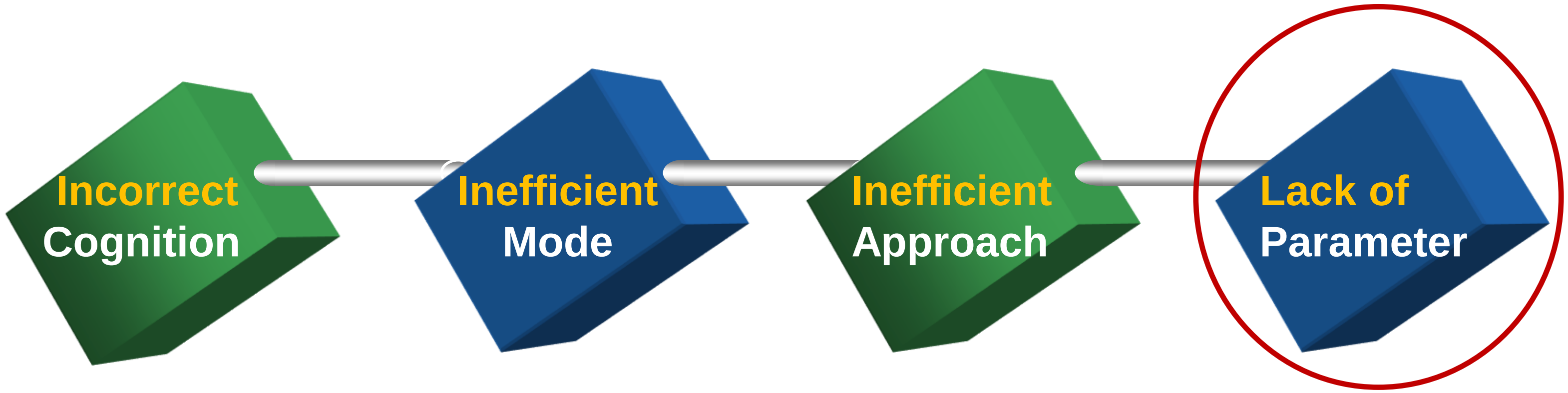
Major Problems related to transit planning



❖The scheduling approaches successful in developed countries cannot be directly applied in China due to **some Chinese specific rules**.

The practical scheduling approach or system is missing.

Major Problems related to transit planning



The service planning and scheduling are missing, or carried out roughly and arbitrarily

Lack of data or parameters has acted as a disincentive to the widespread use of scheduling systems.

Our major efforts

Major means

Foundation

To build a **comprehensive framework** for public transit planning in China

Core technique

To develop practical **scheduling approaches** based on AVL data

How to fulfil them?

yindong@hust.edu.cn

Shortcut to achieve the goal

To achieve the goal

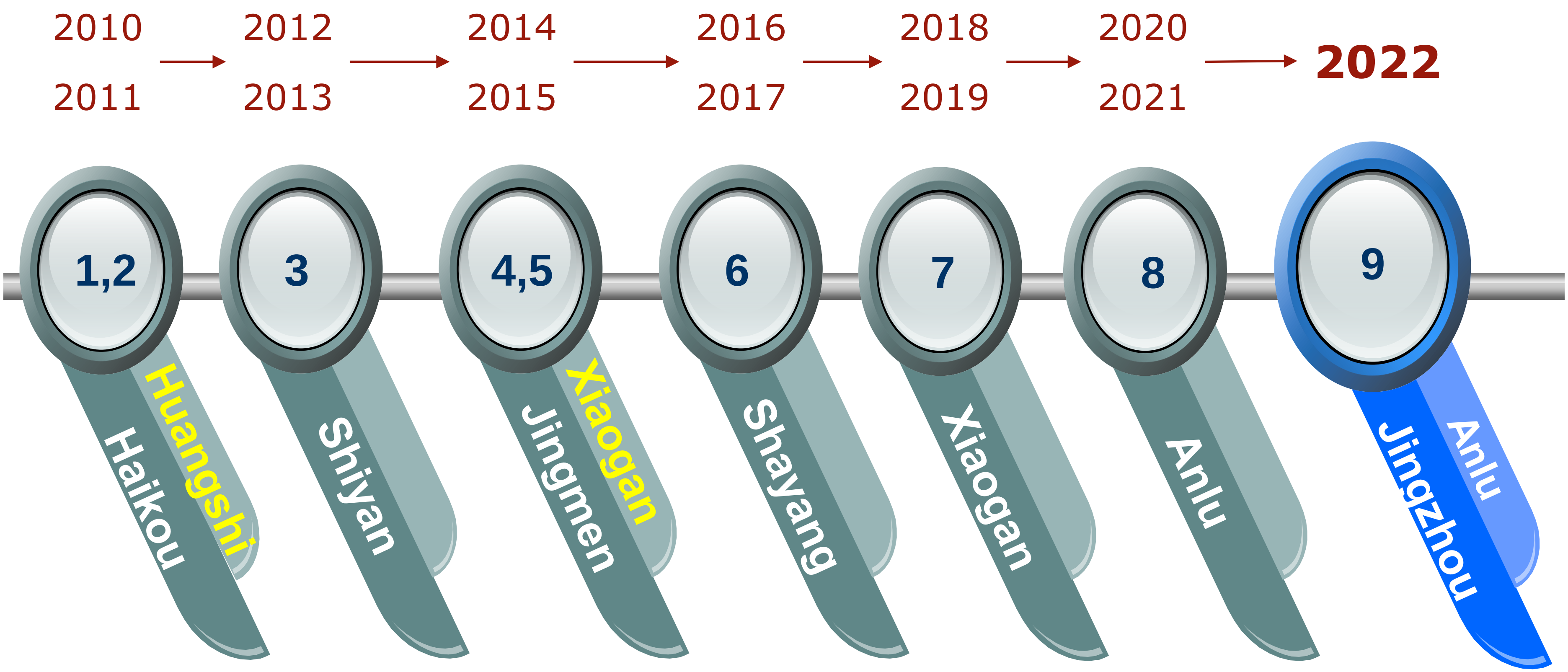
First of all ↓ we should let transit authority and operators

have a comprehensive understanding of public transit operation planning.

↓ We believe

being involved in traditional transit planning projects would be a shortcut.

Projects on public transit planning



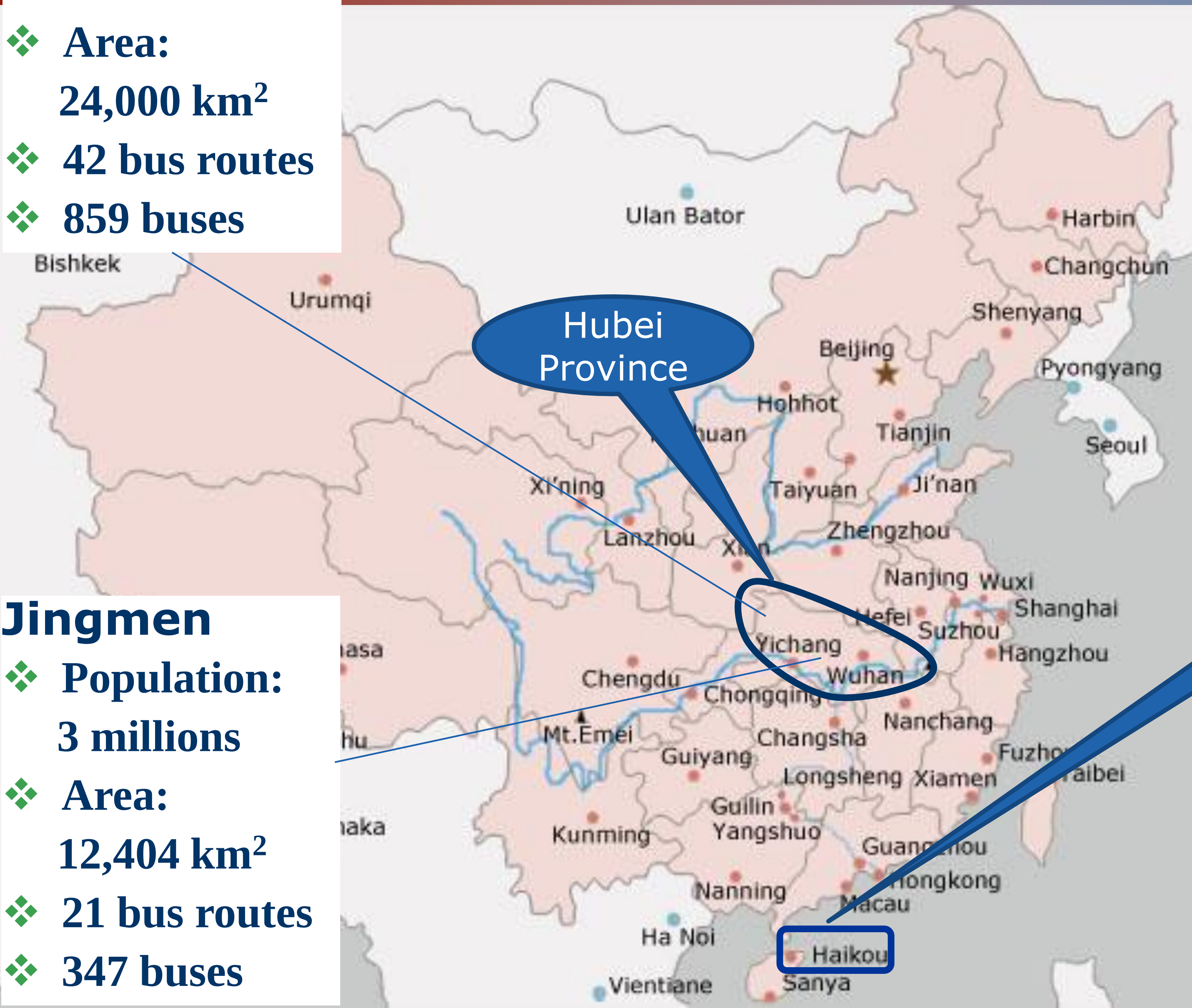
yindong@hust.edu.cn

Some projects

sponsored by transit authorities in the cities and provinces.

Shiyan

- Population: 3.5 millions
- Area: 24,000 km²
- 42 bus routes
- 859 buses



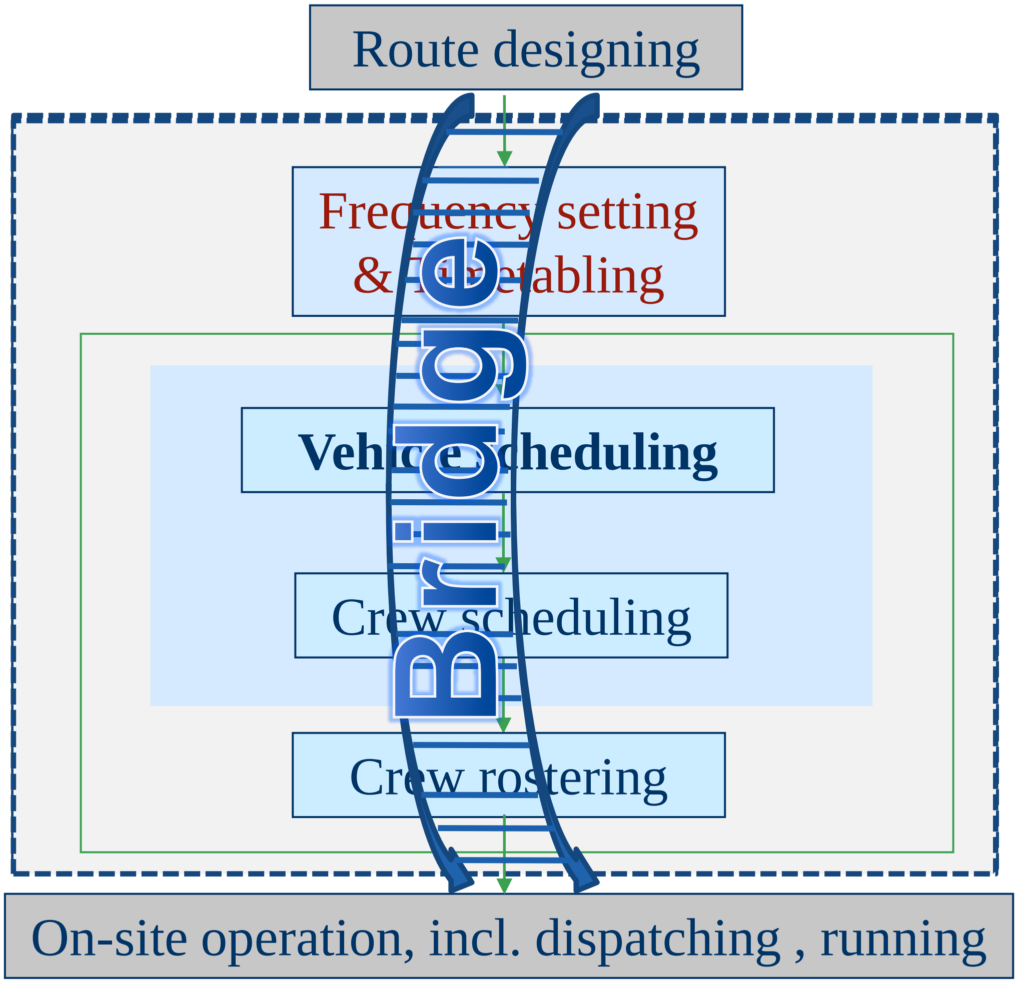
Jingmen

- Population: 3 millions
- Area: 12,404 km²
- 21 bus routes
- 347 buses

Haikou

- Population: 2.05 millions
- Area: 2304.84 km²
- 60 bus routes
- 1135 buses

Bridge between route design and operation

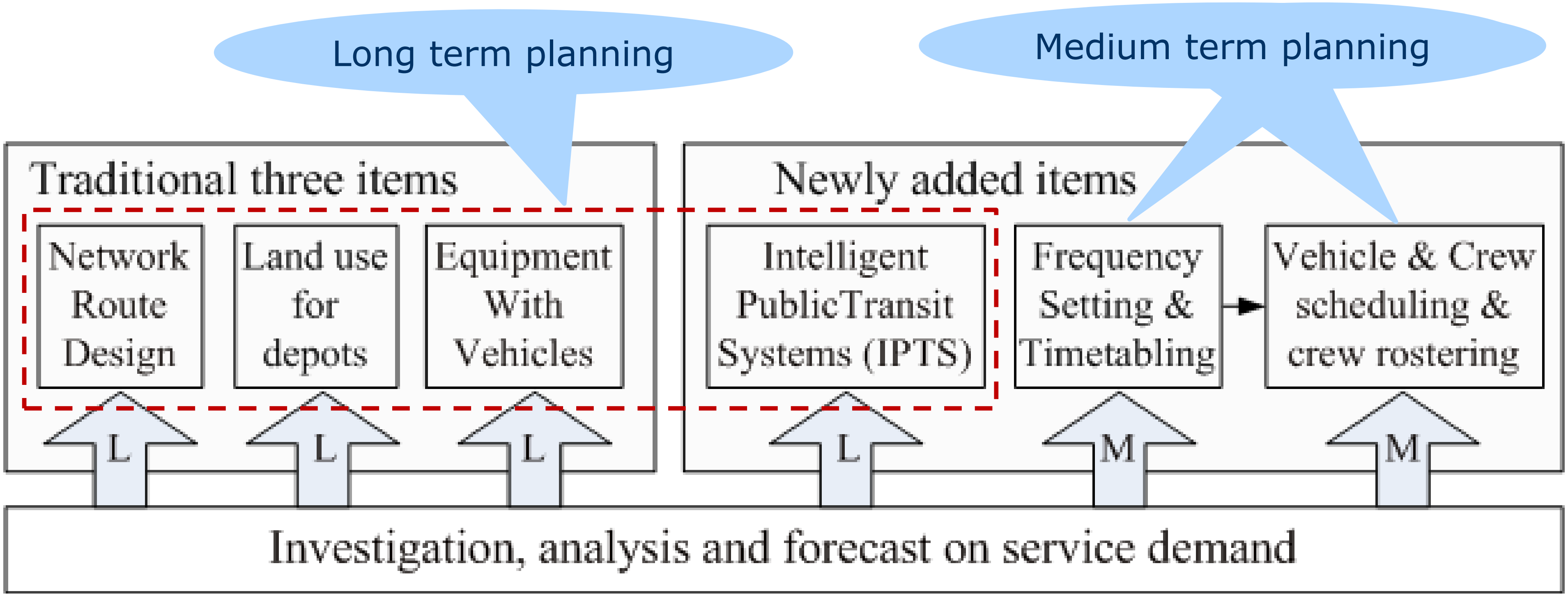


Structure design

- Set up a comprehensive framework of transit operation planning

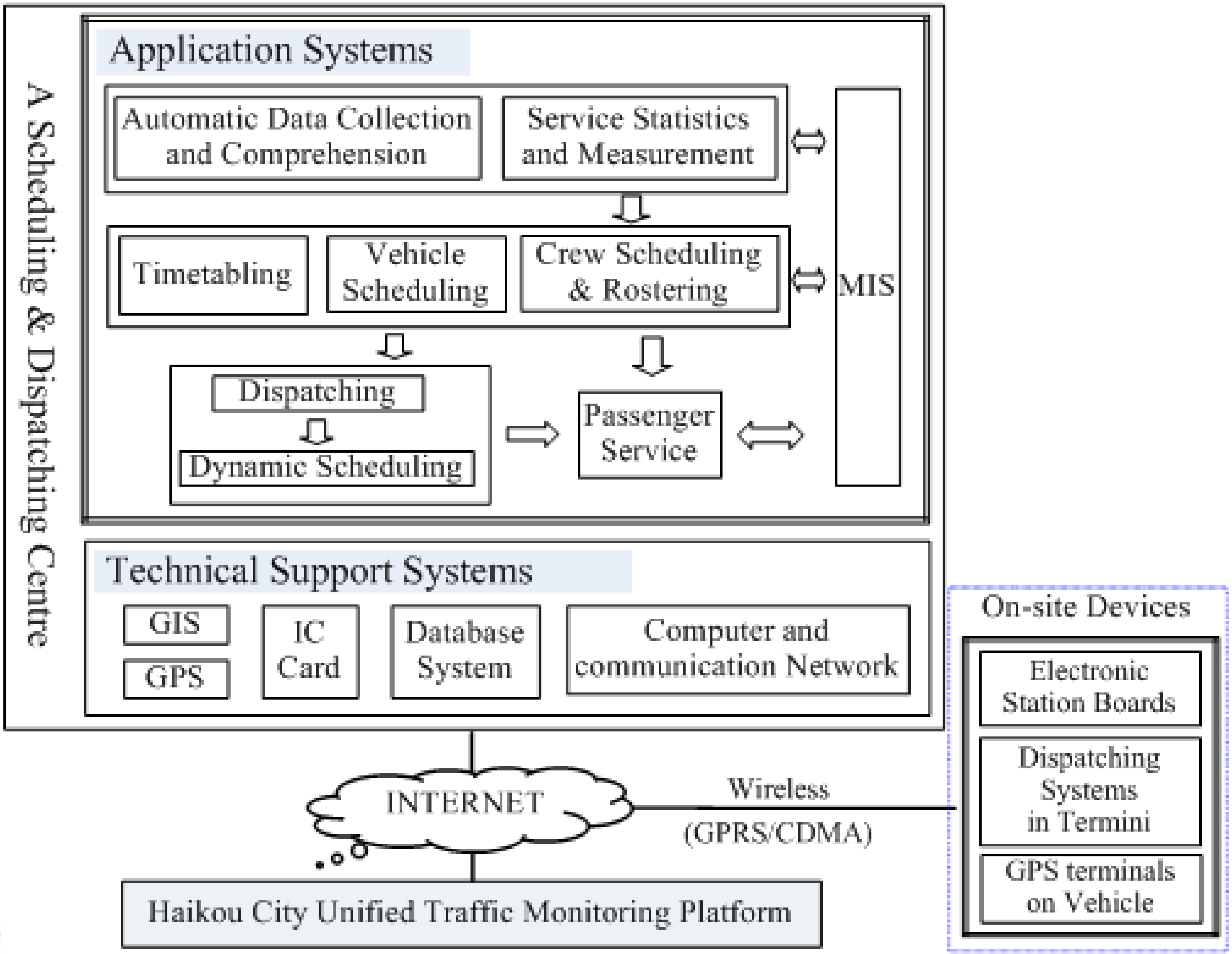
- **Dispatching** is generally paid more attention than **scheduling** is in China

Our proposed comprehensive framework

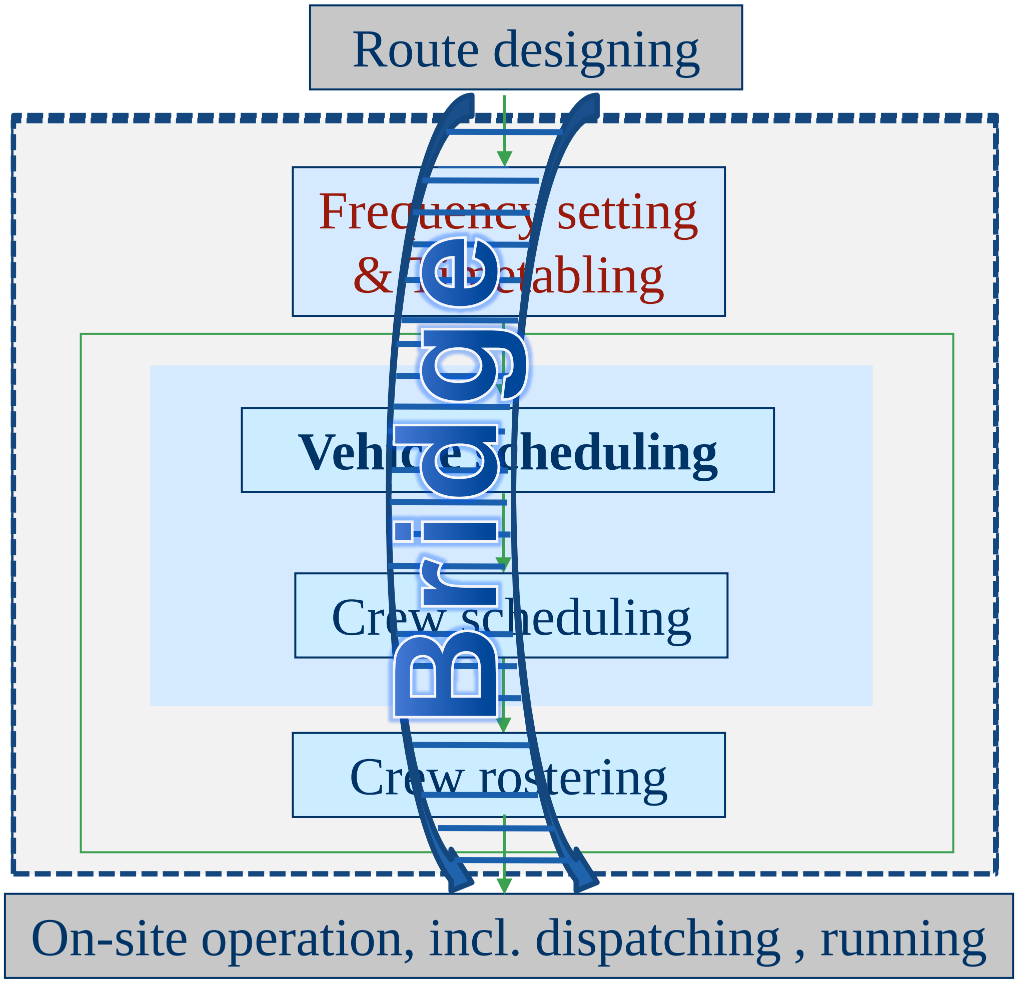


- The comprehensive framework of public transit planning in China **encompasses** all the contents in the public transit planning.

A general framework of IPTS plan of Haikou



Bridge between route design and operation



Structure design

- Set up a comprehensive framework of transit operation planning, in which,
- IPTS plans were successfully accepted in China.

Technical design

An Integrated Solution for Public Transport Scheduling

SCHEDULING

- Vehicle scheduling
- Crew scheduling
- Crew rostering

GOVERNMENT SERVICE

- Subsidies Accounting
- Service Policy Setting

DATA ANALYSIS

- Running Time Analysis
- Ridership Analysis
- Timetable Development
- Comparison of Schedules

INTEGRATED TOOLS

- Interfaces
- External Systems

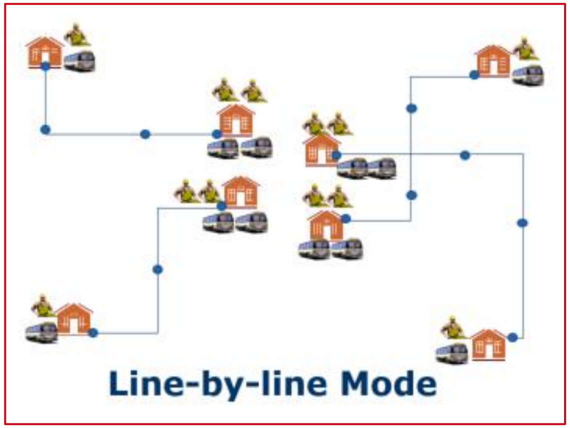
ERP

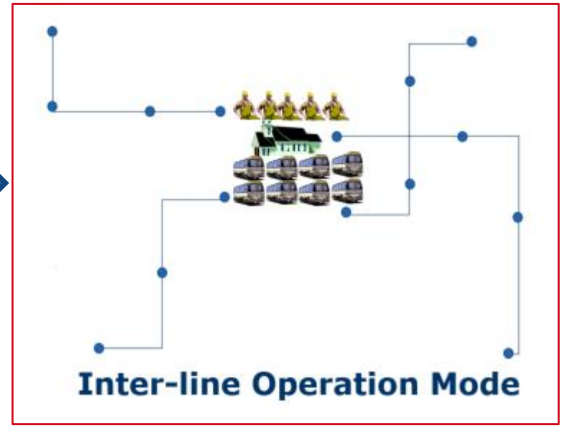
- Infrastructure and Equipment Management
- Operations and Safety Management
- Logistics and Maintenance Management
- Party Affairs and Administration
- Financial Management

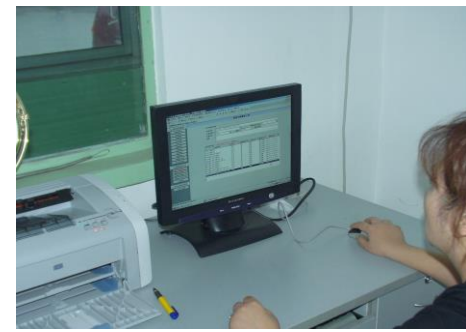
RELATED SERVICES

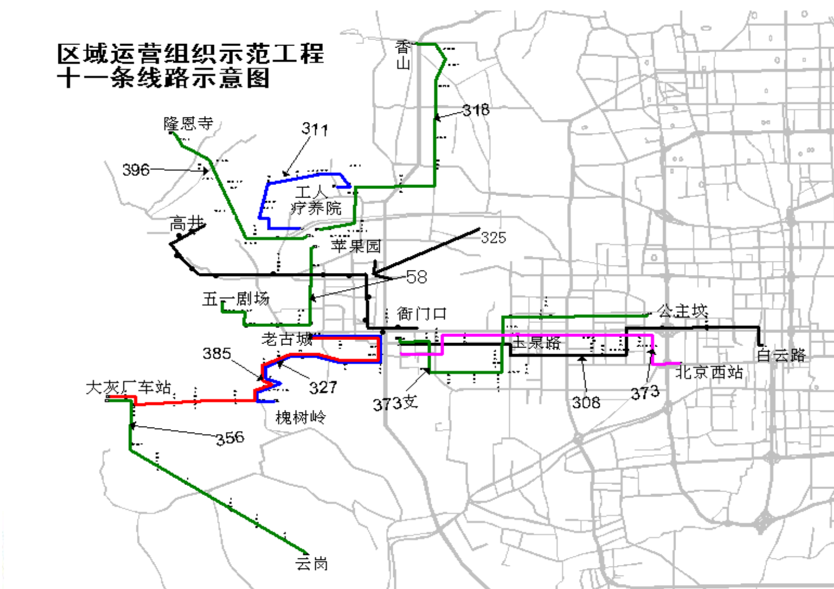
- Network Route Planning
- Feasibility Consultation

Case Study: in Beijing Bus Group(BJBUS)









	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	客六示范区域行车方案总站行车计划表									苹果园站							第1页共10页
2	到达车辆									开出车辆							
3	线路名称	本路车次	车号	到达时间	实际行驶时间	准点情况			不准点原因	线路名称	本路车次	车号	开出时间	停站时间	间隔时间	停站过久及间隔不准的原因	附注及报告事项
4						准	早	晚									
5																	
6									苹果园场发	B311路(上行)	6		5:10		0		
7									苹果园场发	B58路(上行)	8		5:10		8		
8									苹果园场发	B58路(上行)	12		5:18		4		
9									苹果园场发	B311路(上行)	14		5:22		4		
10									苹果园场发	B58路(上行)	17		5:26		8		
11									苹果园场发	B311路(上行)	27		5:34		0		
12									苹果园场发	B58路(上行)	28		5:34		8		
13									苹果园场发	B58路(上行)	37		5:42		2		
14									苹果园场发	B311路(上行)	38		5:44		6		
15									苹果园场发	B58路(上行)	50		5:50		4		
16	B58路(下行)	8		5:50						B311路(上行)	8		5:54	4	4		
17	B311路(下行)	6		5:50						B58路(上行)	6		5:58	8	6		
18	B58路(下行)	12		6:00						B311路(上行)	12		6:04	4	1		
19									苹果园场发	B58路(上行)	86		6:05		6		
20	B58路(下行)	17		6:08						B58路(上行)	17		6:11	3	3		
21	B311路(下行)	14		6:10						B311路(上行)	14		6:14	4	4		
22									苹果园场发	B58路(上行)	67		6:18		6		
23	B58路(下行)	28		6:16						B58路(上行)	28		6:24	8	0		
24									苹果园场发	B311路(上行)	31		6:24		7		
25	B311路(下行)	27		6:22						B58路(上行)	27		6:31	9	2		
26									苹果园场发	B311路(上行)	77		6:33		4		
27	B311路(下行)	38		6:32						B58路(上行)	38		6:37	5	5		
28	客六示范区域行车方案总站行车计划表									苹果园站							第2页共10页
29	到达车辆									开出车辆							

苹果园 / 槐树岭东站 / 隆恩寺 / 大灰厂 / 衙门口 / 丁字口 / 工人疗养院 / 老古城 / 东口 / 香山 / 北京西站 / 西黄村 / 公主坟 / 五一剧场 / 高井 / 白云路 / 云岗

yindong@mit.edu

Case Study: in Beijing Bus Group(BJBUS)

Items	Manual Schedule	iPTS System	PRD
Num of Trips	1971	1971	0
Num of Buses	116	105	9.5%
Ratio (%)	16.99 trips/bus	18.77 trips/bus	10.4%
Num of Crews	182	166	8.8%

- The iPTS system produced a better solution by saving 11 from 116 buses and 16 from 182 crews.
- The computational time was very short (the elapsed time less than 4 minutes on a Pentium III 1gHz PC).
- The schedules generated have meet all the requirements, especially the particular ones of BJBUS .

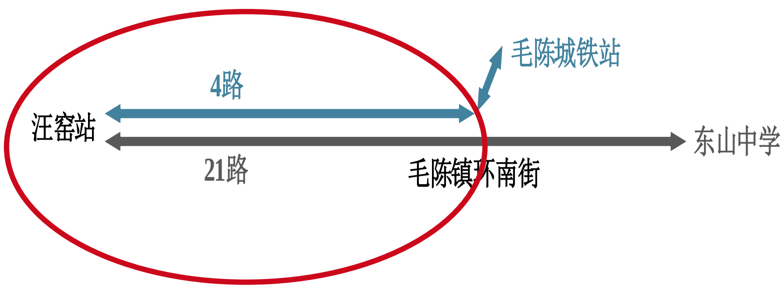
AWARDS

International Federation of Operational Research Societies (IFORS) “IFORS Prize for Operational Research in Development ”, Runner-up

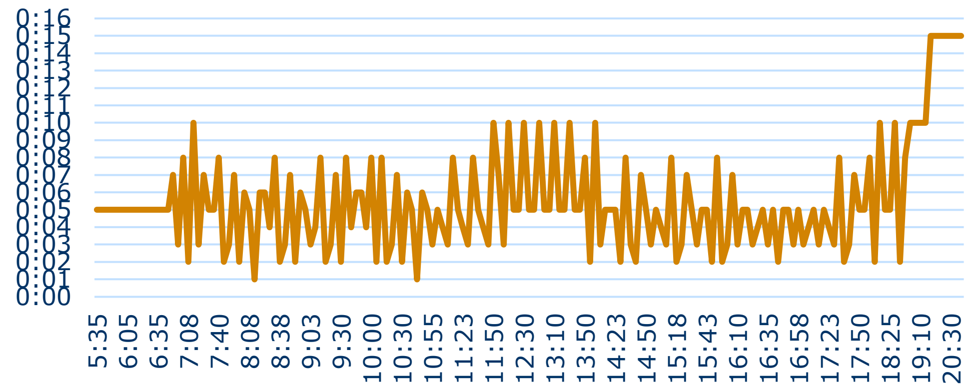
Case Study: in Xiaogan Bus Group

Even Headways

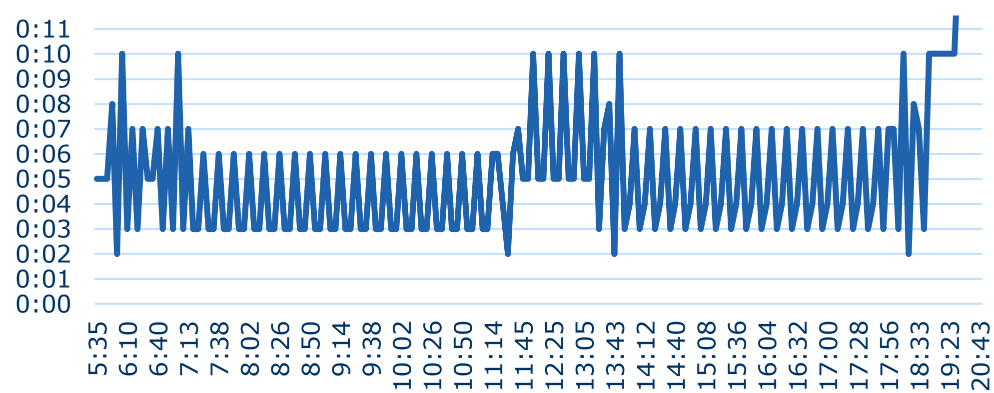
For the common route segment



Headways in Wangyao Terminal (Ori)



Headways in Wangyao Terminal (Ori)



Case Study: in Jingmen – timetable

8 周一至周五

热电厂 —— 李宁工业园（每4-7分钟一班）

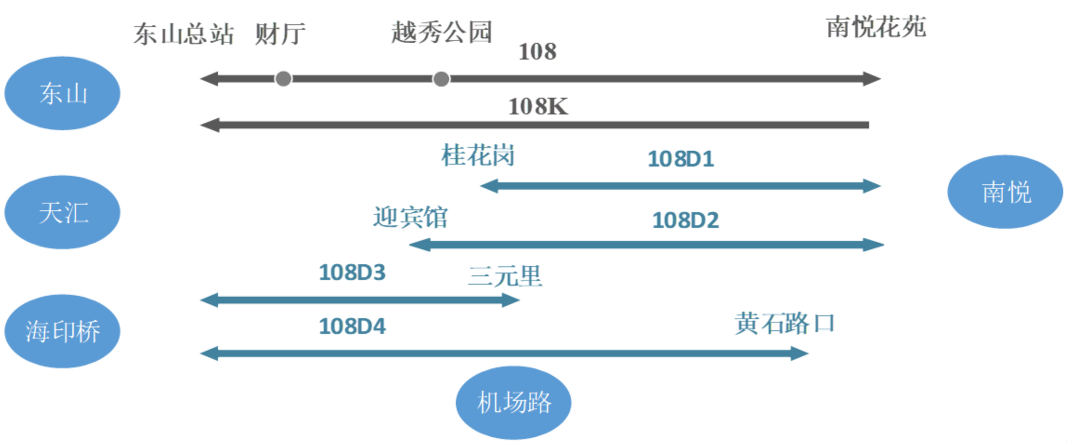
往"热电厂"： 首班：6:00； 末班：20:50

往"李宁工业园"： 首班：6:00； 末班：20:50

工作日（周一至周五）	热电厂 1	洪源市场 2	客运中心 3	职教集团 4	交通小学 5	李宁工业园 6	李宁工业园 6	交通小学 5	职教集团 4	客运中心 3	洪源市场 2	热电厂 1
	上行：热电厂—李宁工业园 单程时间：0:56:26						下行：李宁工业园—热电厂 单程时间：0:56:18					
	6:00	6:09	6:15	6:31	6:45	6:52	6:00	6:07	6:12	6:26	6:39	6:45
	6:05	6:14	6:20	6:36	6:51	7:00	6:05	6:12	6:17	6:31	6:44	6:50
	6:10	6:19	6:25	6:41	6:56	7:05	6:10	6:17	6:22	6:36	6:49	6:55
	6:15	6:24	6:30	6:46	7:01	7:10	6:15	6:22	6:27	6:41	6:54	7:01
	6:20	6:29	6:35	6:51	7:09	7:18	6:20	6:27	6:32	6:46	6:59	7:06
	6:25	6:34	6:40	6:56	7:14	7:23	6:25	6:32	6:37	6:51	7:07	7:13
	6:30	6:39	6:45	7:01	7:19	7:28	6:30	6:37	6:42	6:56	7:12	7:18
	6:35	6:44	6:51	7:10	7:29	7:37	6:35	6:42	6:47	7:01	7:17	7:23
	6:40	6:49	6:56	7:15	7:34	7:42	6:40	6:47	6:52	7:09	7:25	7:32
	6:45	6:54	7:04	7:23	7:41	7:50	6:45	6:52	6:59	7:16	7:32	7:39
	6:49	6:58	7:08	7:27	7:45	7:54	6:49	6:56	7:03	7:20	7:36	7:43
	6:53	7:04	7:14	7:33	7:51	7:59	6:53	7:01	7:08	7:25	7:41	7:48
	6:57	7:08	7:18	7:37	7:55	8:03	6:57	7:05	7:12	7:29	7:45	7:52
	7:01	7:12	7:22	7:41	7:59	8:07	7:01	7:09	7:16	7:33	7:49	7:56
	7:05	7:16	7:26	7:45	8:03	8:11	7:05	7:13	7:20	7:37	7:53	7:59
	7:09	7:20	7:30	7:49	8:07	8:15	7:09	7:17	7:24	7:41	7:57	8:03
	7:13	7:24	7:34	7:53	8:09	8:17	7:13	7:21	7:28	7:45	8:01	8:07
	7:17	7:28	7:38	7:57	8:13	8:21	7:17	7:25	7:32	7:49	8:05	8:11
	7:21	7:32	7:42	8:01	8:17	8:25	7:21	7:29	7:36	7:53	8:08	8:14
	7:25	7:36	7:46	8:05	8:21	8:29	7:25	7:33	7:40	7:57	8:12	8:18
	7:29	7:40	7:50	8:07	8:23	8:31	7:29	7:37	7:44	8:01	8:16	8:22

Case Study: in Guangzhou

A complicated bus route (108) with several short lines



Case Study: in Guangzhou

Running time analysis

To increase the on-time performance

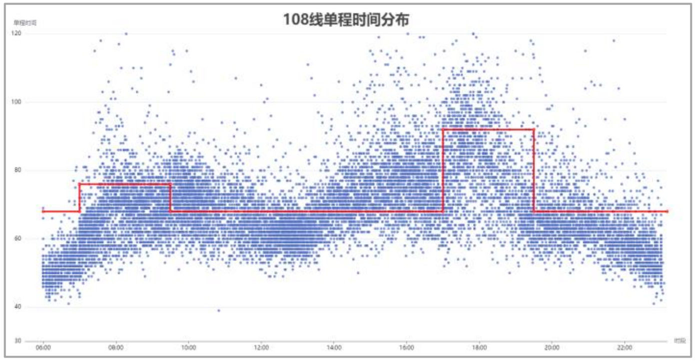


Fig. 1 Running time (in the manual schedule)

Improved

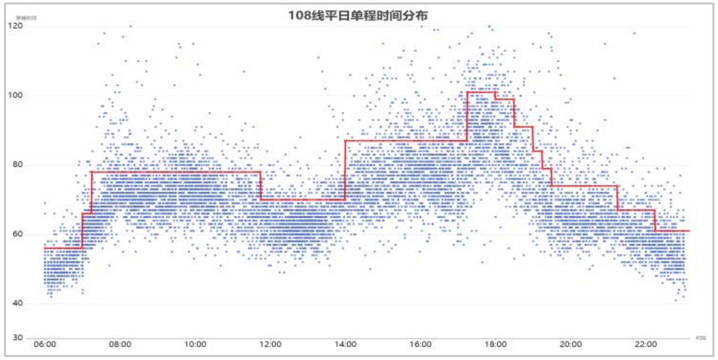


Fig. 2 Running time（Weekdays）

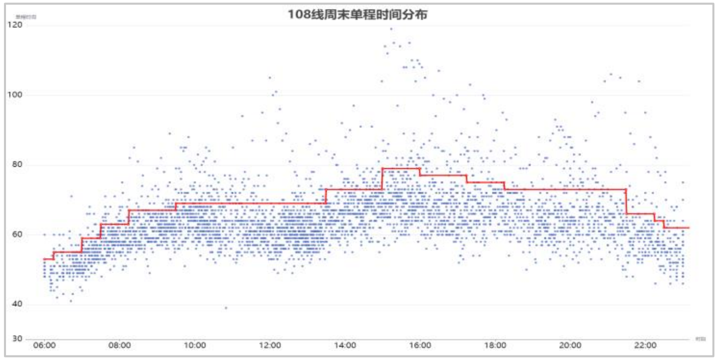


Fig. 3 Running time（Weekends）

Case Study: in Guangzhou

Headway optimization

To meet passenger demands

& even headways

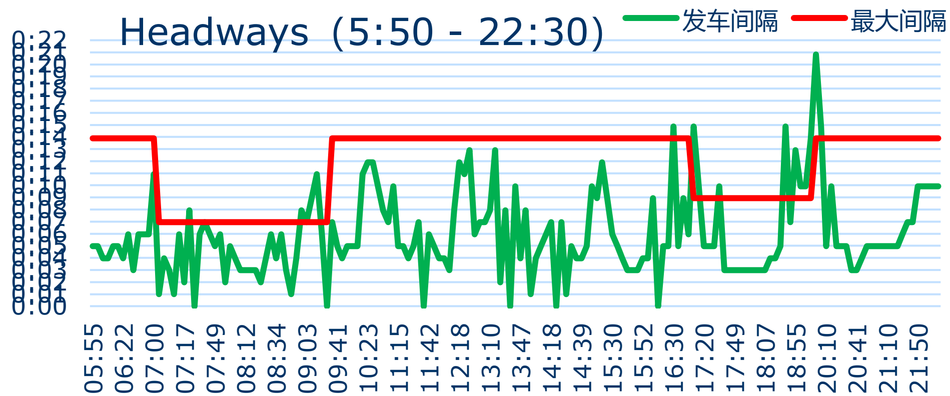


Fig. 1 Headways in 108 (NY-DS) in the manual schedule

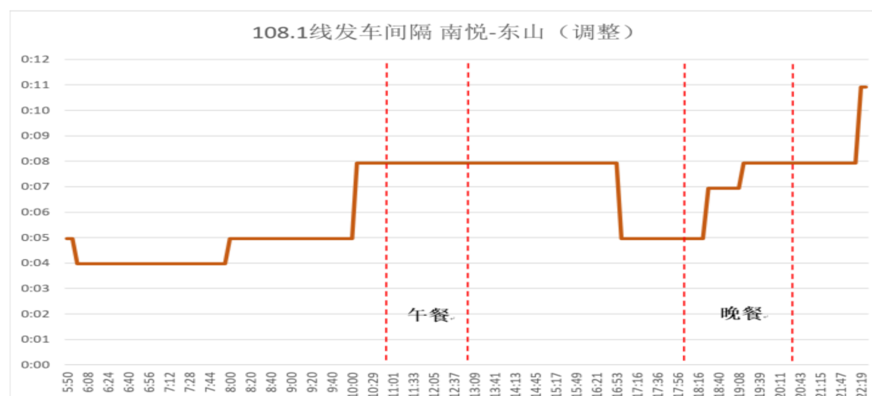
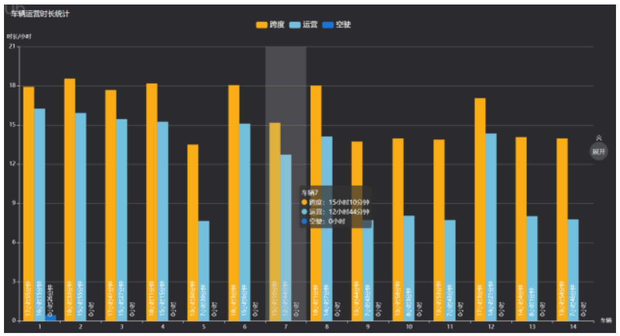


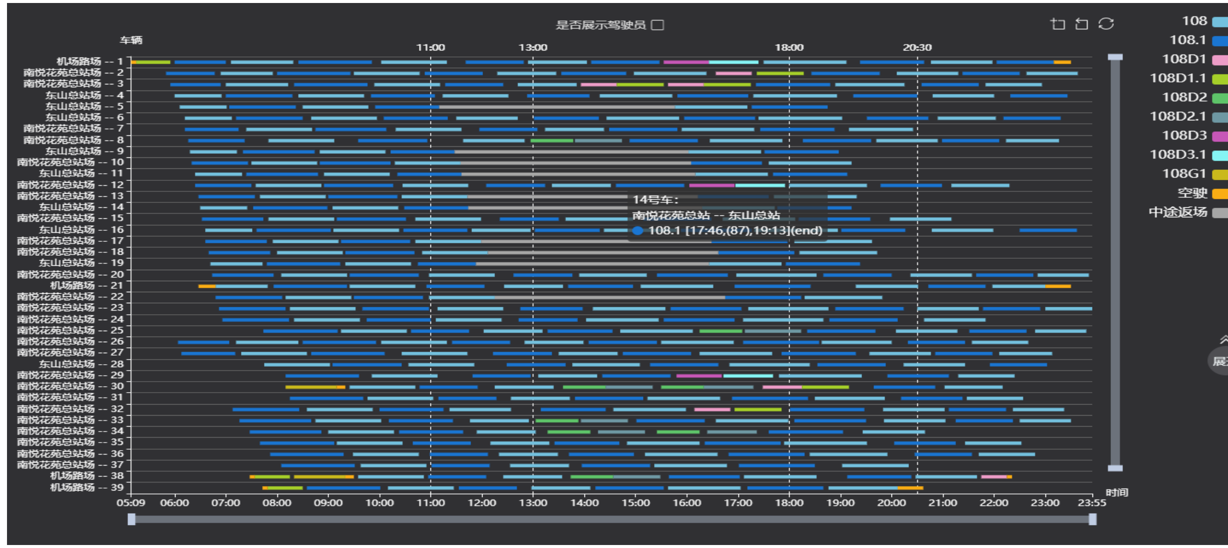
Fig. 2 Optimized headways in 108 (NY-DS)

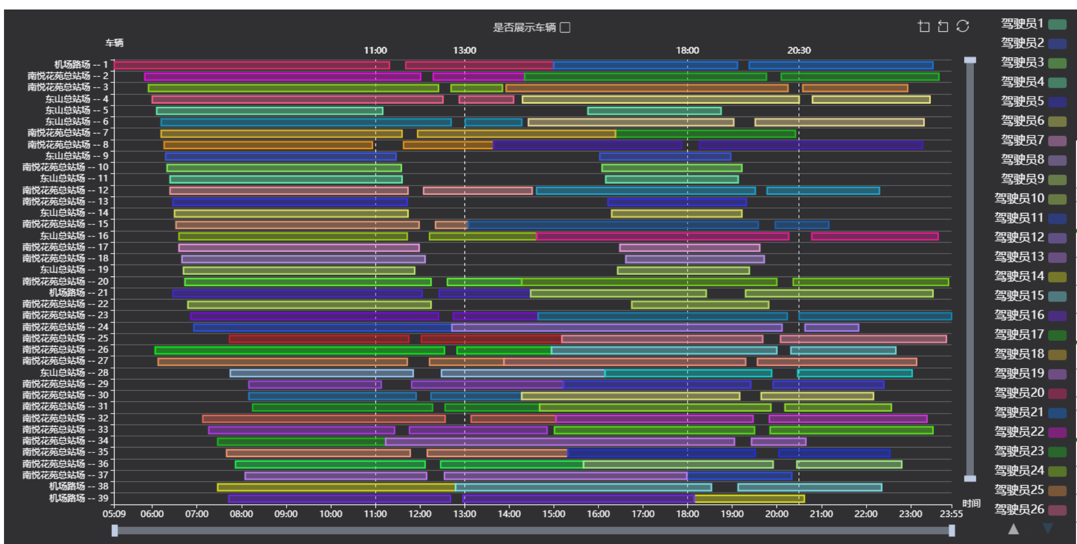
華中科技大學
Huazhong University Of Science & Technology

Case Study: in Guangzhou

A vehicle schedule





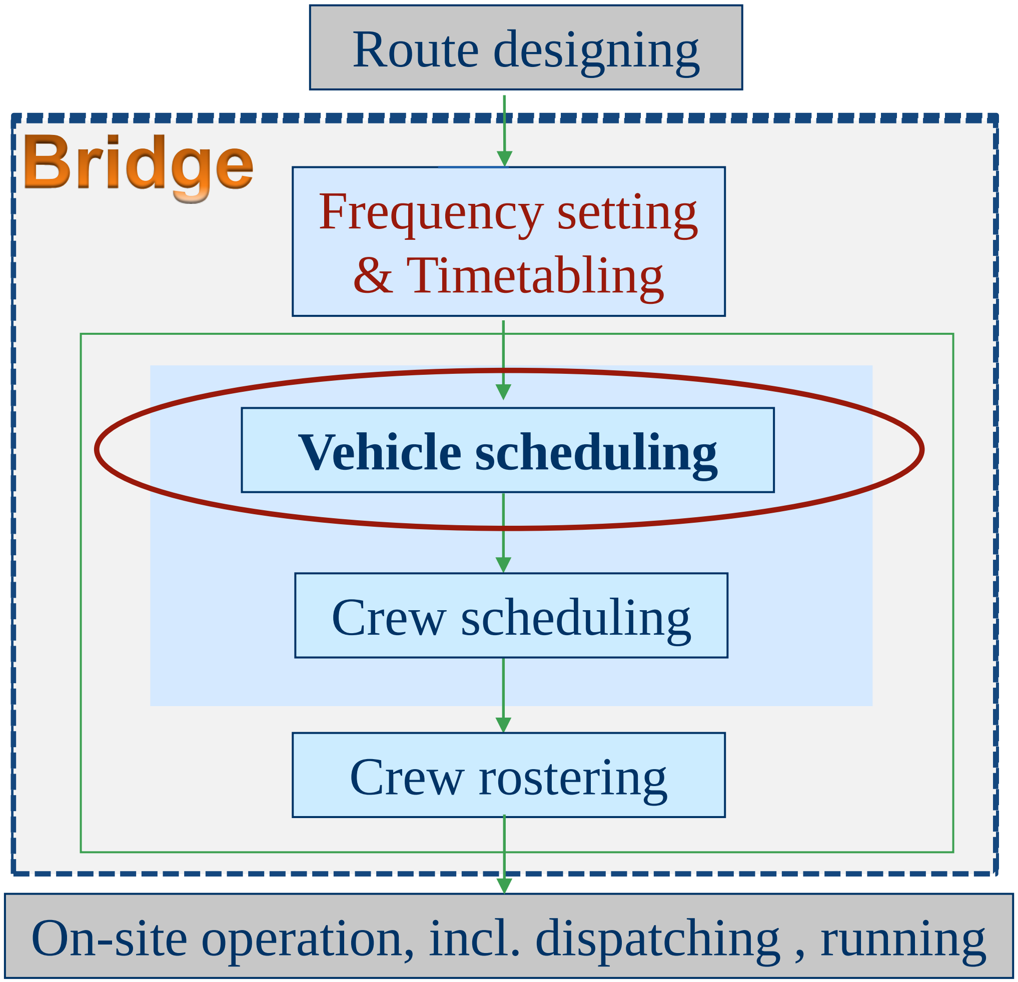


A driver schedule

广州108线驾驶员调度平日劳动配班方案

本方案班次数:65							编制人：hqGuest						编制日期：2021-11-08 14:51:32.0		
车位	班次序号	签到时间	出发		到达		签出时间	停车用餐	分段有效工时	分段工时	总跨度	总有效工时	总工时	班次类型	签到地
			时间	地点	时间	地点									
1	20	04:54	05:09	机场路场	11:19	南悦花苑总站		00:22	05:42	06:10					
	20		11:41	南悦花苑总站	15:00	越秀公园	15:00		03:09	03:19	10:06	08:51	10:06	整班（早）	机场路场
	21	15:00	15:00	越秀公园	19:07	南悦花苑总站		00:16	03:56	04:07					
	21		19:23	南悦花苑总站	23:30	机场路场	23:45		03:54	04:07	08:45	07:50	08:45	整班（晚）	机场路场
2	22	05:35	05:50	南悦花苑总站场	12:01	东山总站		00:17	05:49	06:11					
	22		12:18	东山总站	14:21	越秀公园	14:21		01:57	02:03	08:46	07:46	08:46	整班（早）	南悦花苑总站场
	23	14:21	14:21	越秀公园	19:46	东山总站		00:20	04:50	05:25					
	23		20:06	东山总站	23:38	南悦花苑总站场	23:53		03:19	03:32	09:32	08:09	09:32	整班（晚）	南悦花苑总站场
3	24	05:40	05:55	南悦花苑总站场	12:25	东山总站		00:17	06:03	06:30					
	24		12:42	东山总站	13:51	南悦花苑总站	13:51		01:09	01:09	08:11	07:12	08:11	整班（早）	南悦花苑总站场
	25	13:56	13:56	南悦花苑总站	20:15	南悦花苑总站		00:20	06:02	06:19					
	25		20:35	南悦花苑总站	22:56	南悦花苑总站场	23:11		02:13	02:21	09:15	08:15	09:15	整班（晚）	南悦花苑总站场

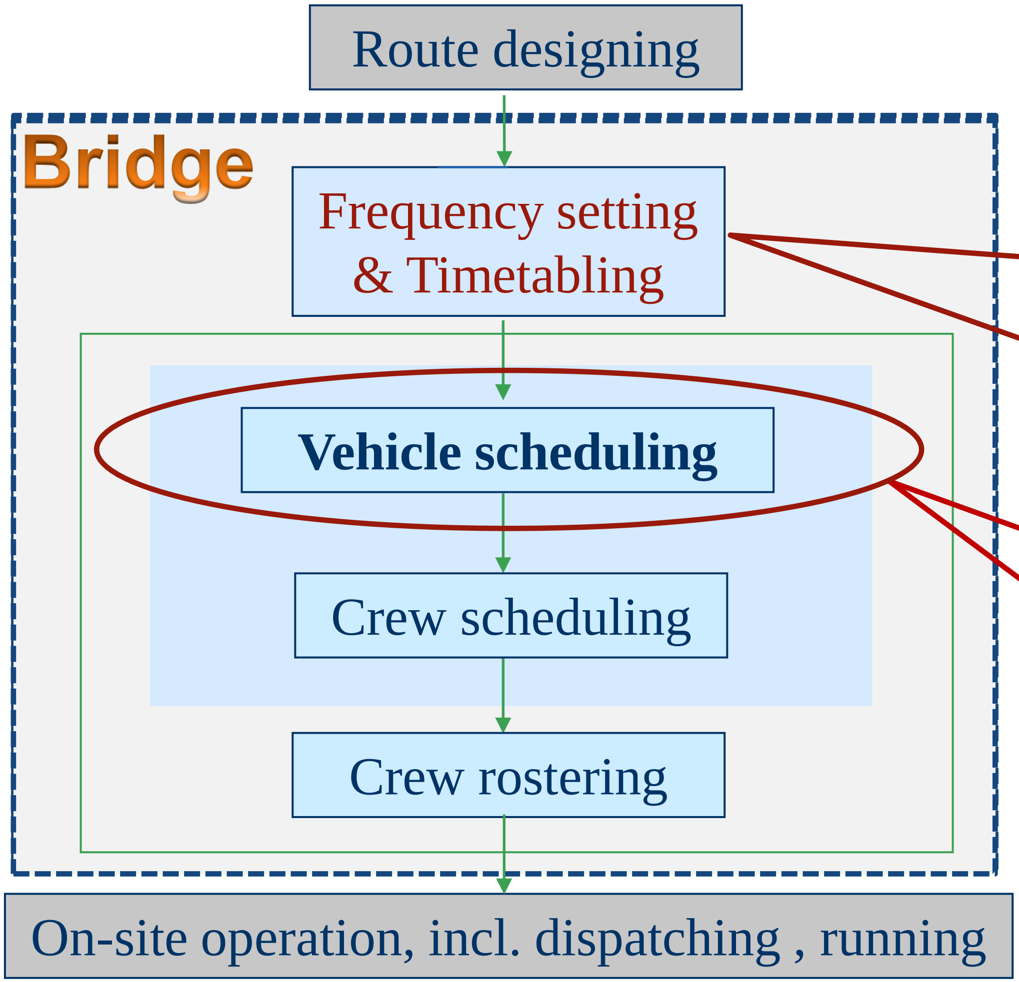
Vehicle scheduling based on AVL data



- Each sub-problem in the 'bridge' is individually hard,
- it is infeasible to develop a global solution approach.
- A simple but applicable bridge is more acceptable in China.

- **Dispatching** is generally paid more attention than **scheduling** is in China

Vehicle scheduling based on AVL data

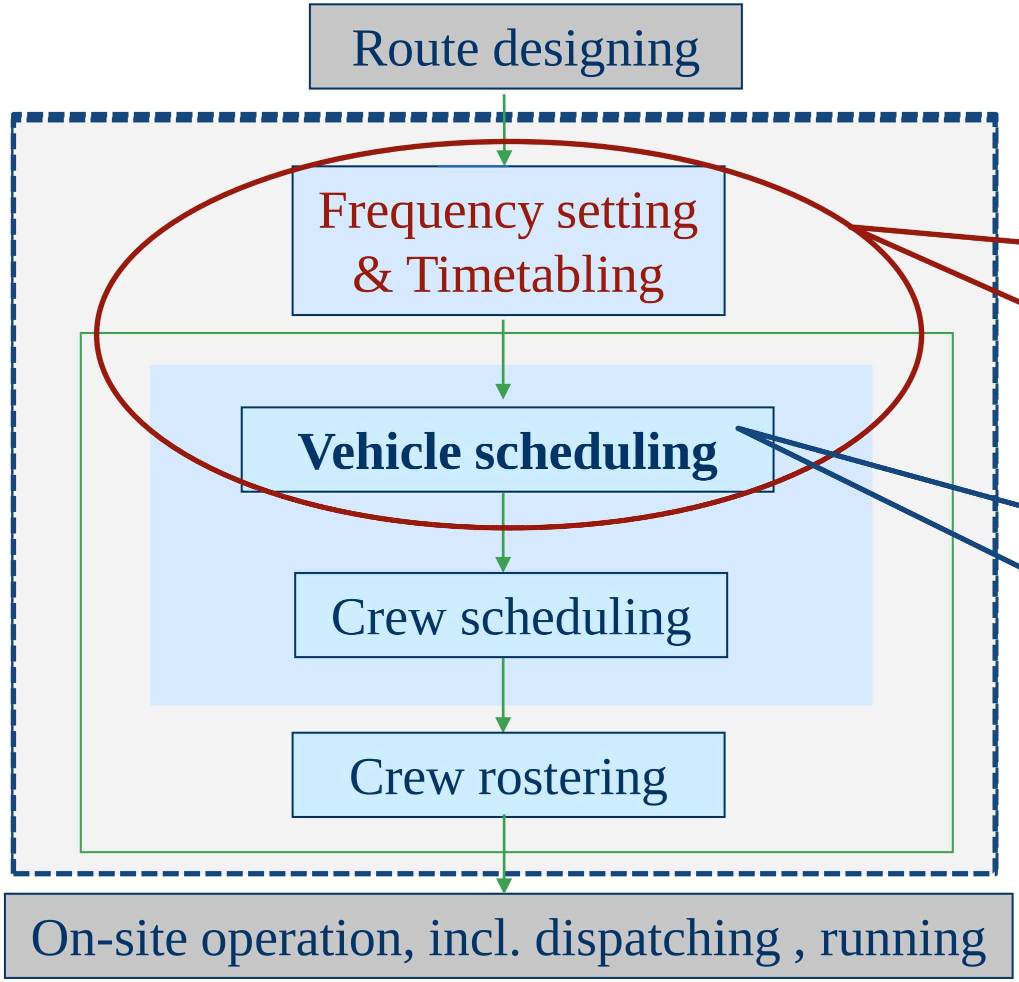


In China (lack of scheduling parameters -- trips)

- No precompiled timetables
- No well-designated trip times and headways

Traditional Vehicle scheduling is based on a given timetable, which consists of a set of timetabled trips.

Vehicle scheduling based on AVL data



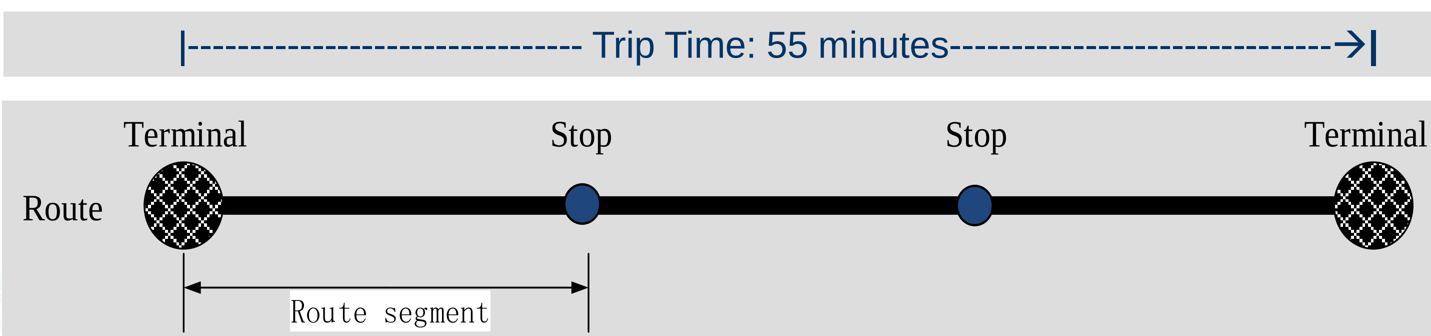
The proposed vehicle scheduling is based on AVL data, which integrates the service planning and vehicle scheduling.

Traditional Vehicle scheduling is based on a given timetable, which consists of a set of timetabled trips.

Huazhong University Of Science & Technology

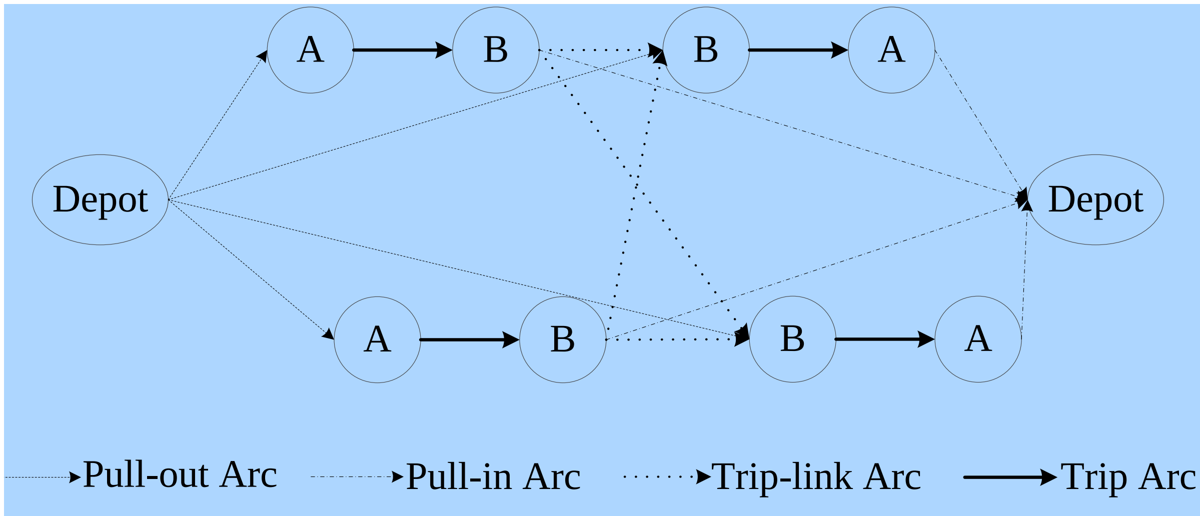
Vehicle Scheduling Problem (VSP)

- **Vehicle Scheduling Problem (VSP)** is concerned with the allocation of a set of trips in a predetermined timetable to a fleet of vehicles, in such a way that
  - the total number of vehicles and operating cost are minimized .
- An efficient schedule can bring transit operators a considerable saving on property and operating cost.
- **Each trip** contains a start time at its departure point and an end time at its arrival point.

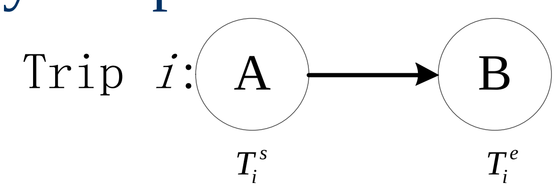


The network flow representation of VSP

❖ The VSP can be represented as a network flow

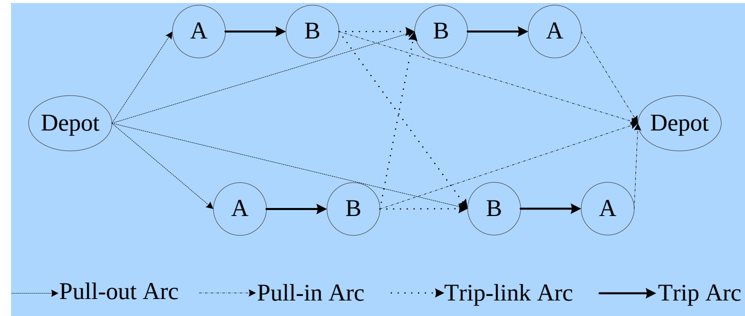


❖ Each trip is represented as a departure node and an arrival node, connected by a trip arc:



The objectives of VSP

1. To minimize the fleet size
2. To minimize the total operating cost



Operating cost

- idle time
- deadhead
- depot-return

idle time: waiting time between any two consecutive trips.

deadhead time: empty movement between any two consecutive trips

depot-return: when the gap between two consecutive trips is large enough (e.g. more than 3 h), a vehicle is enforced to return to a depot temporarily

Formulations of traditional VSPs

- Let P denotes the set of pull-out arcs, Q denotes the set of pull-out arcs,
  R denotes the set of trip-link arcs,
  $A = P \cup Q \cup R$ denotes the set of all arcs

- Given a depot d and a set of trips T, the **VSP with single depot** can be modelled as follows.

$$\min \sum_{(i,j)\in A} c_{ij} x_{ij} \quad (1)$$

$$st. \ \sum_{i:(i,j)\in A} x_{ij} - \sum_{i:(j,i)\in A} x_{ji} = 0, \quad \forall j \in T \quad (2)$$

$$\sum_{j:(d,j)\in P} x_{dj} - \sum_{i:(i,d)\in Q} x_{id} = 0 \quad (3)$$

$$\sum_{i:(i,j)\in A} x_{ij} = 1, \quad \forall j \in T \quad (4)$$

$$x_{ij} \in \{0,1\}, \quad \forall (i,j) \in A \quad (5)$$

- Given a set of depots D and a set of trips T, the **VSP with multi depots** (MDVSP) can be modelled as follows.

$$\min \sum_{d\in D} \sum_{(i,j)\in A^d} c_{ij}^d \cdot x_{ij}^d \quad (1)$$

$$st. \ \sum_{i:(i,j)\in A^d} x_{ij} - \sum_{i:(j,i)\in A^d} x_{ji} = 0, \quad \forall j \in T, \forall d \in D \quad (2)$$

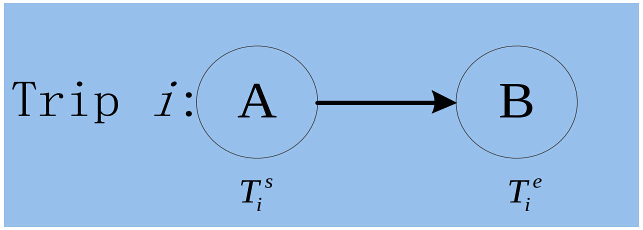
$$\sum_{j:(d,j)\in P} x_{dj} - \sum_{i:(i,d)\in Q} x_{id} = 0, \quad \forall d \in D \quad (3)$$

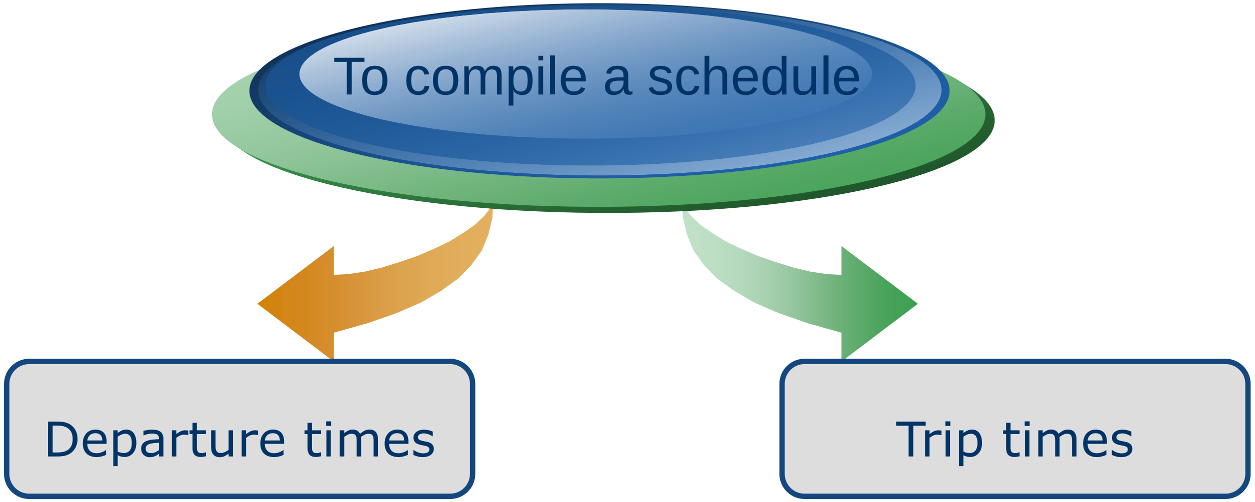
$$\sum_{d\in D} \sum_{i:(i,j)\in A^d} x_{ij} = 1, \quad \forall j \in T \quad (4)$$

$$x_{ij} \in \{0,1\}, \quad \forall (i,j) \in A \quad (5)$$

VSP based on fixed trip times

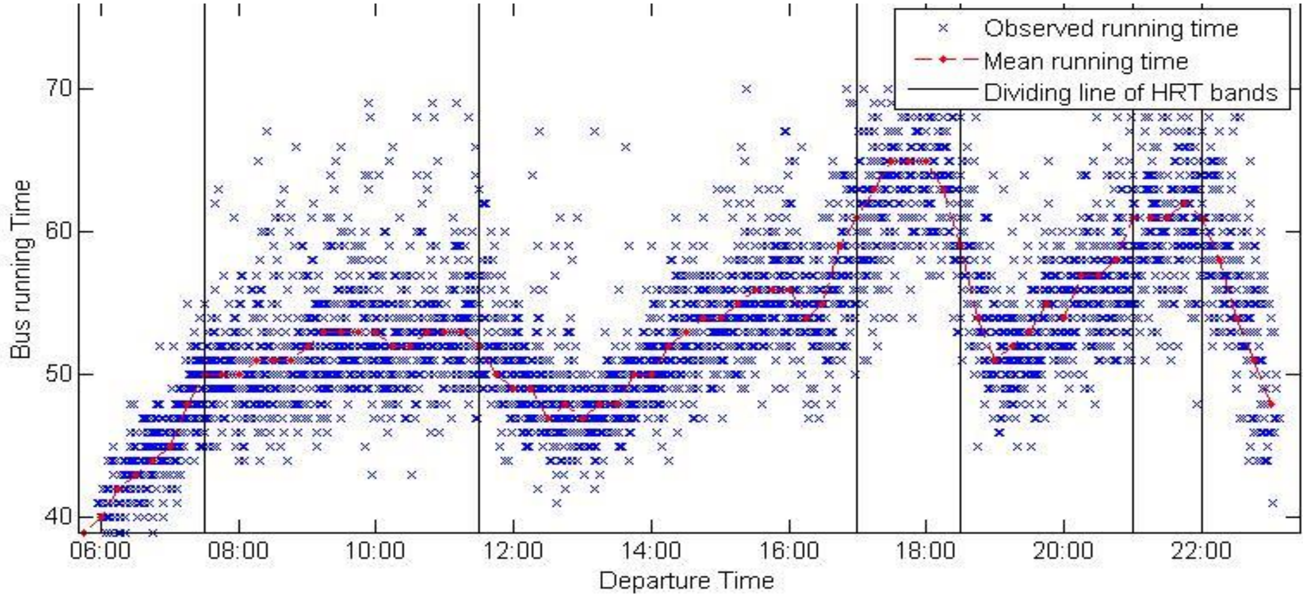
- Each trip in the timetable has
  - a fixed departure time
  - a fixed trip time –
    called scheduled trip time (ST)





Variation of trip times

- The travel time at each route segment usually varies dramatically in different (e.g. peak- or off-peak) periods through a day due to fickle traffic, uncertain passenger demands and vehicle malfunction, etc.
- It is well known that the travel time is hard to be precisely measured and predicted (Chakroborty and Kikuchi, 2004; Vu and Khan, 2010; Ng et al., 2011).



Trip times abstracted from the AVL data of Bus Line 4 in the city of Haikou (11585 samples)

Two main problems raised in the traditional VSP

- Due to trips times vary dramatically during a day, therefore, **based on fixed scheduled trip times (STs),**

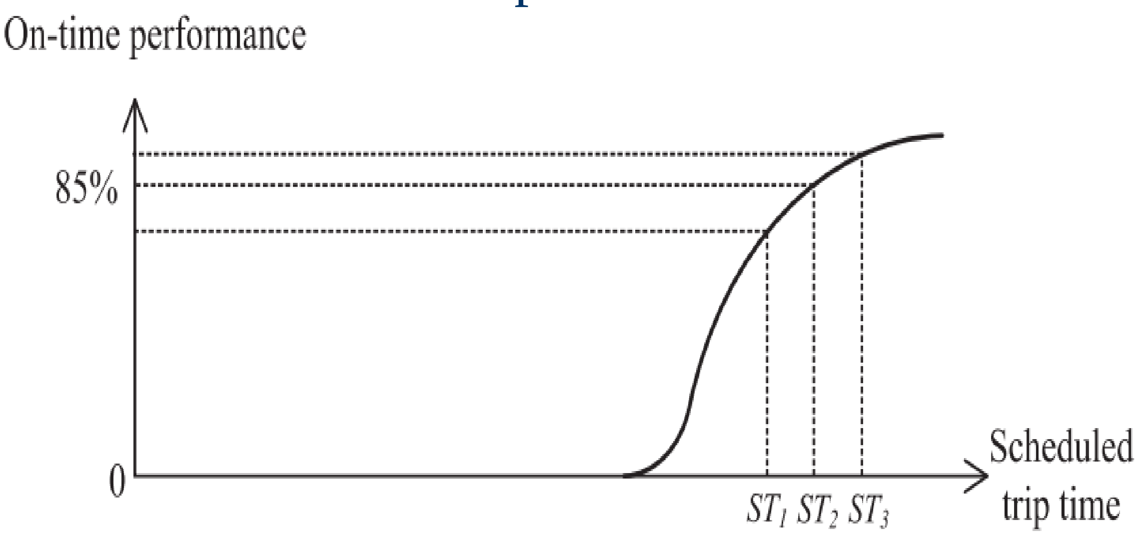
(1) on-time performance:
The resulting schedule is hard to comply with in practice

(2) parameters setting:
Setting STs is very time-consuming and often frustrates schedulers

- To increase the on-time performance of a schedule, the common practice is to increase the scheduled trip times(STs).

The influnece of increasing STs

- With enlarged scheduled trip times, the on-time performance of the resulting schedule will increase.



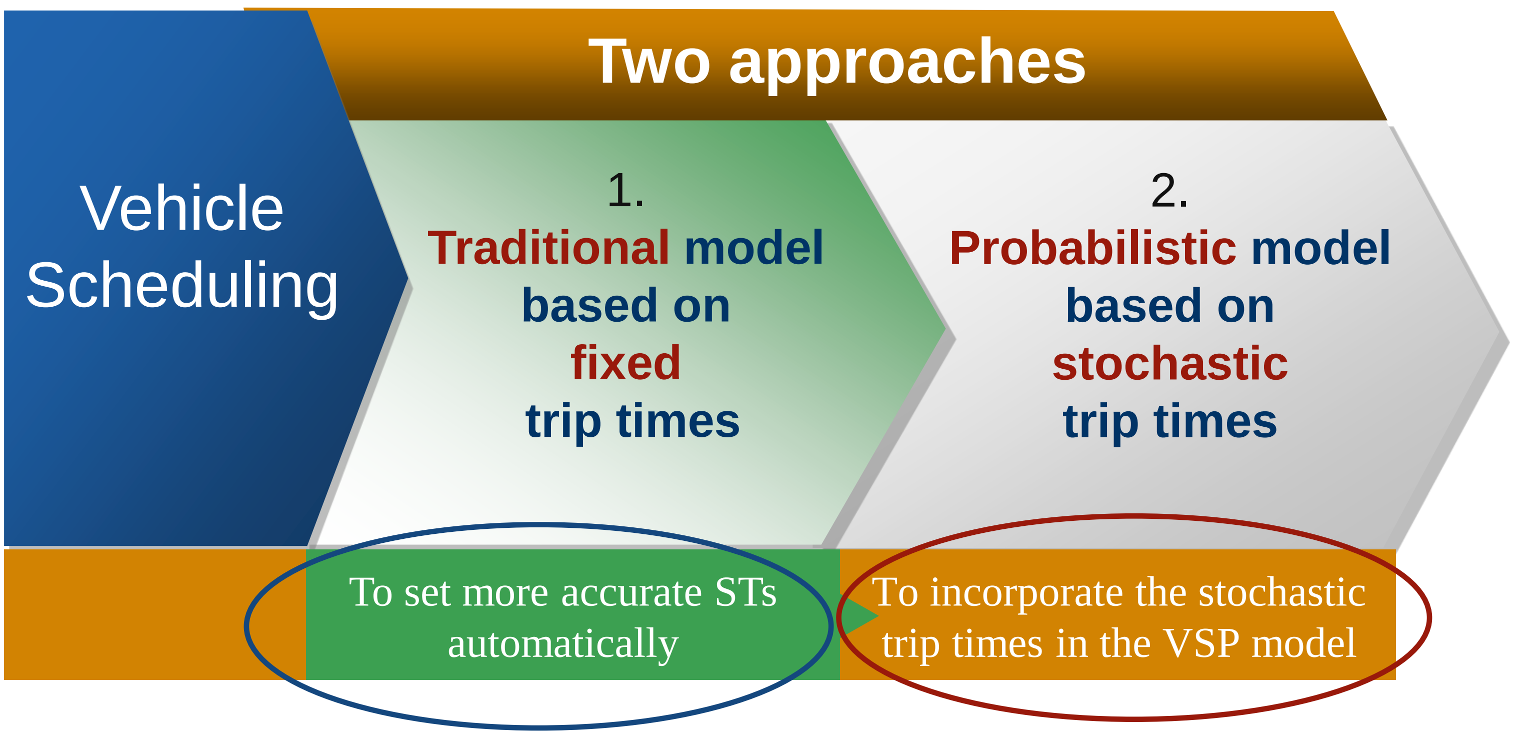
However, enlarged STs may lead to the increase of the schedule's operating cost, even more vehicles are needed.

- STs affect service reliability
  - Longer STs: high cost
  - Shorter STs: low on-time performance

- Therefore, it is non-trivial to set suitable scheduled trip times.

Vehicle scheduling based on AVL data

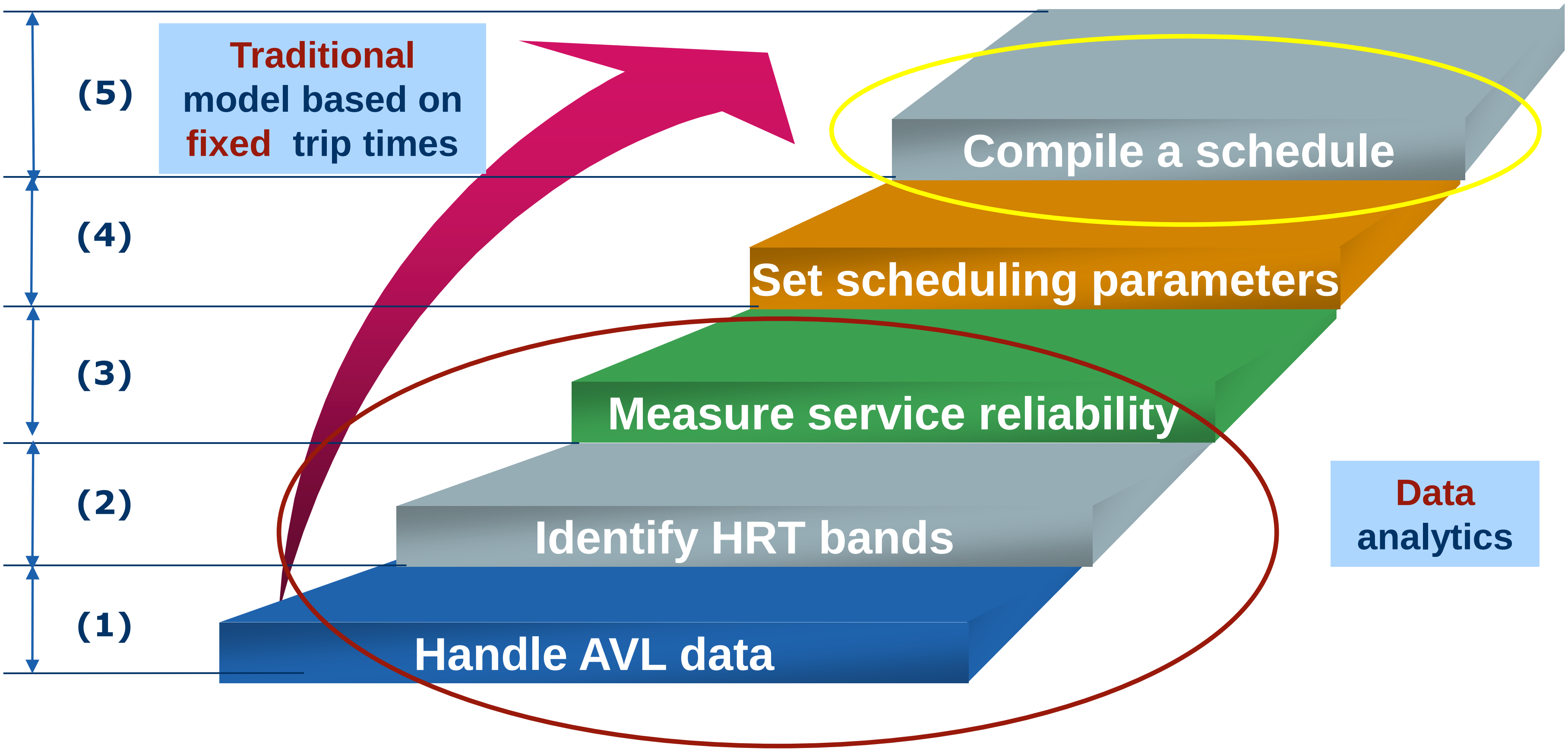
- **Vehicle scheduling approaches based on AVL data**, which aim to
  - increase the on-time performance of compiled schedules
  - reduce the pressure of human schedulers



yindong@hust.edu.cn

Vehicle scheduling based on AVL data

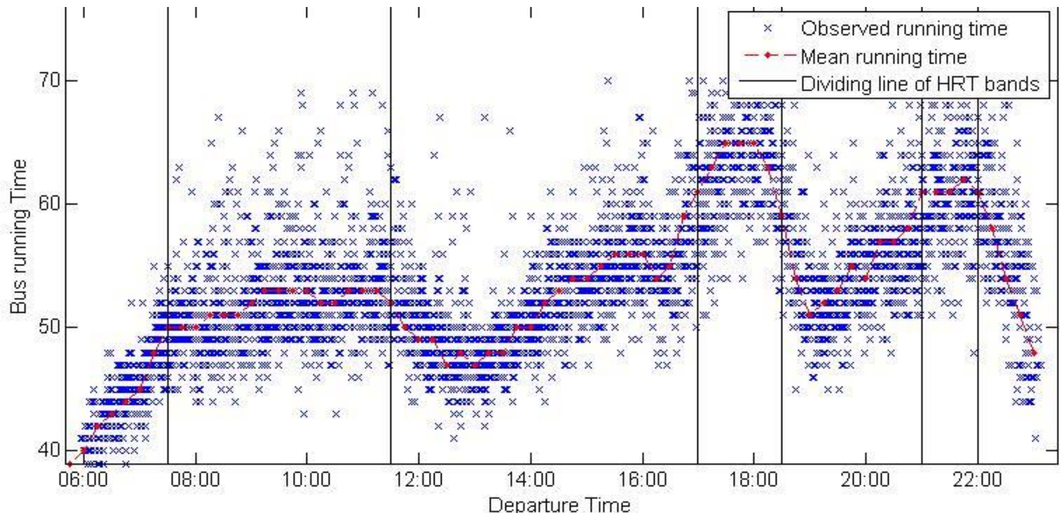
❖ The approach is composed of the following steps:

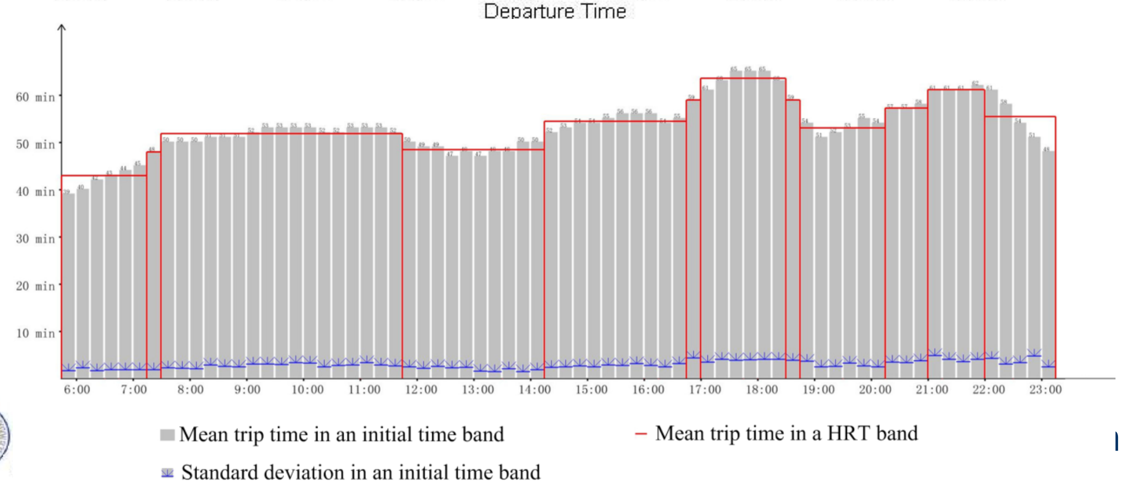


❖ **To set more accurate STs automatically**

Vehicle scheduling with stochastic trip times

❖ Handling AVL data, partitioning service span into HRT periods based on observed travel times

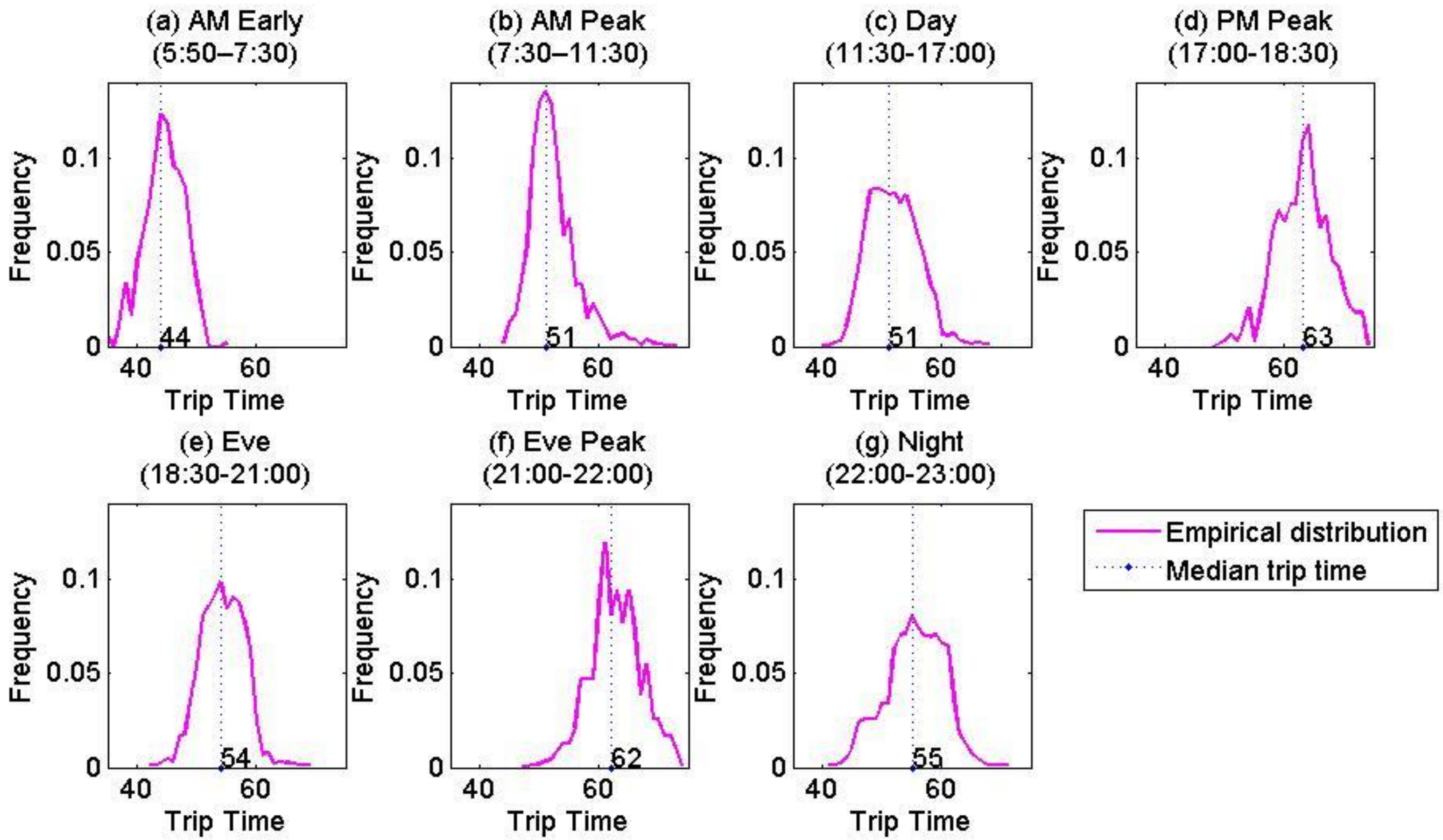




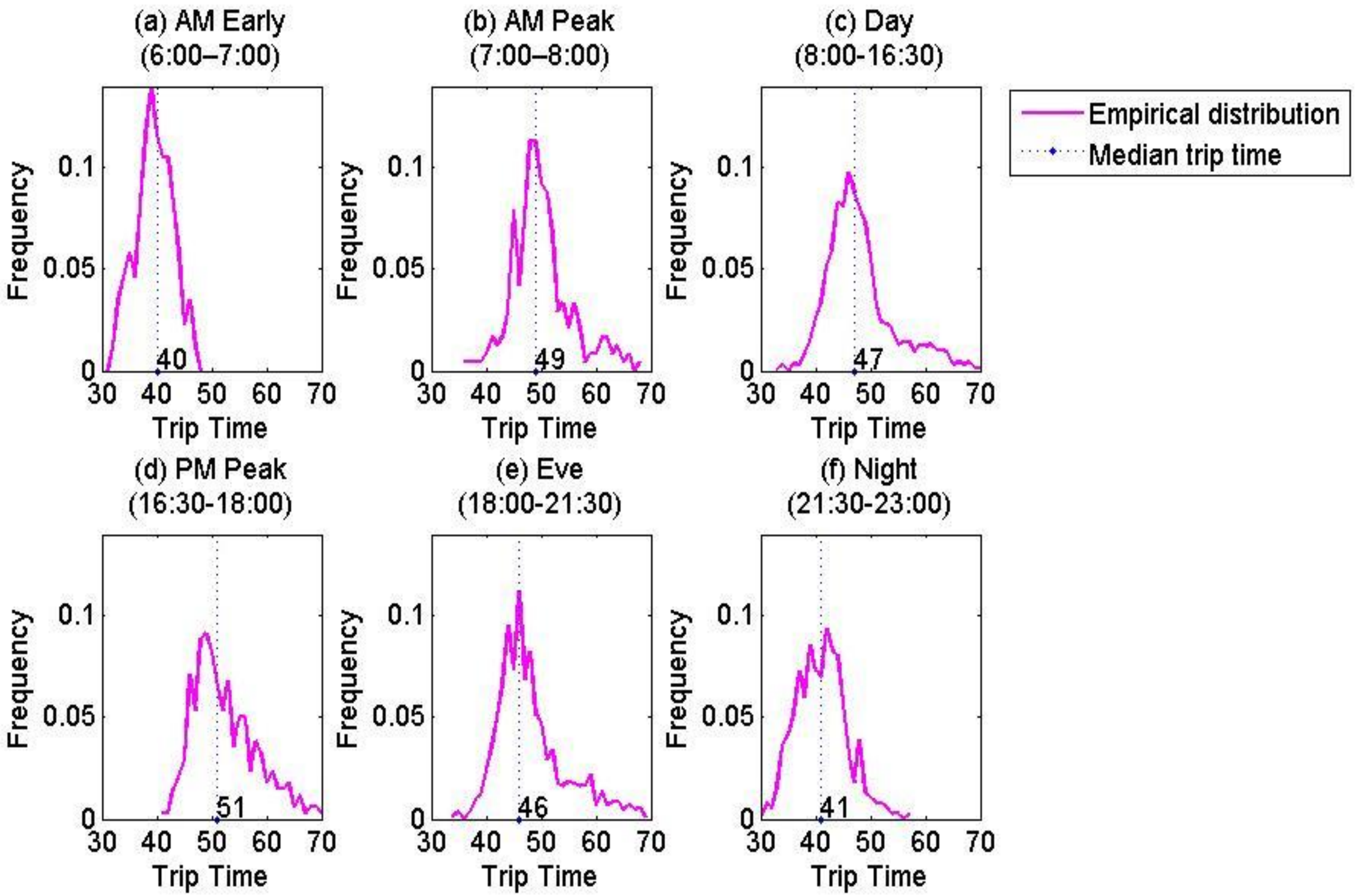
7 HRT bands/periods

Empirical distributions of HKB4 (outbound)

❖ The trip time distribution for each HRT period is abstracted based on the AVL data

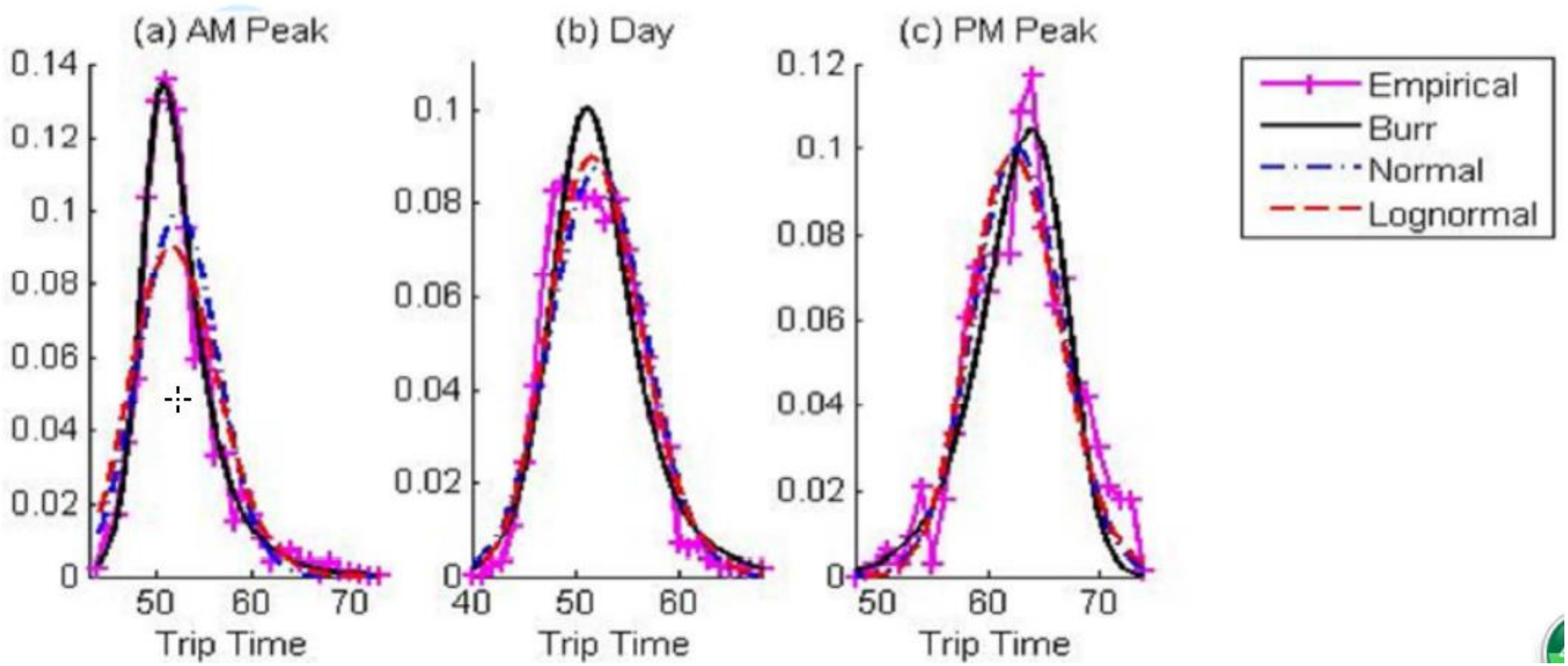


Empirical distributions of HKB4 (inbound)



Demonstrate the fitting of the distribution models to the empirical distributions

- It can be seen that the Burr distribution can match better the data



A compound travel time model

- Data from Bus Line 4 in Haikou

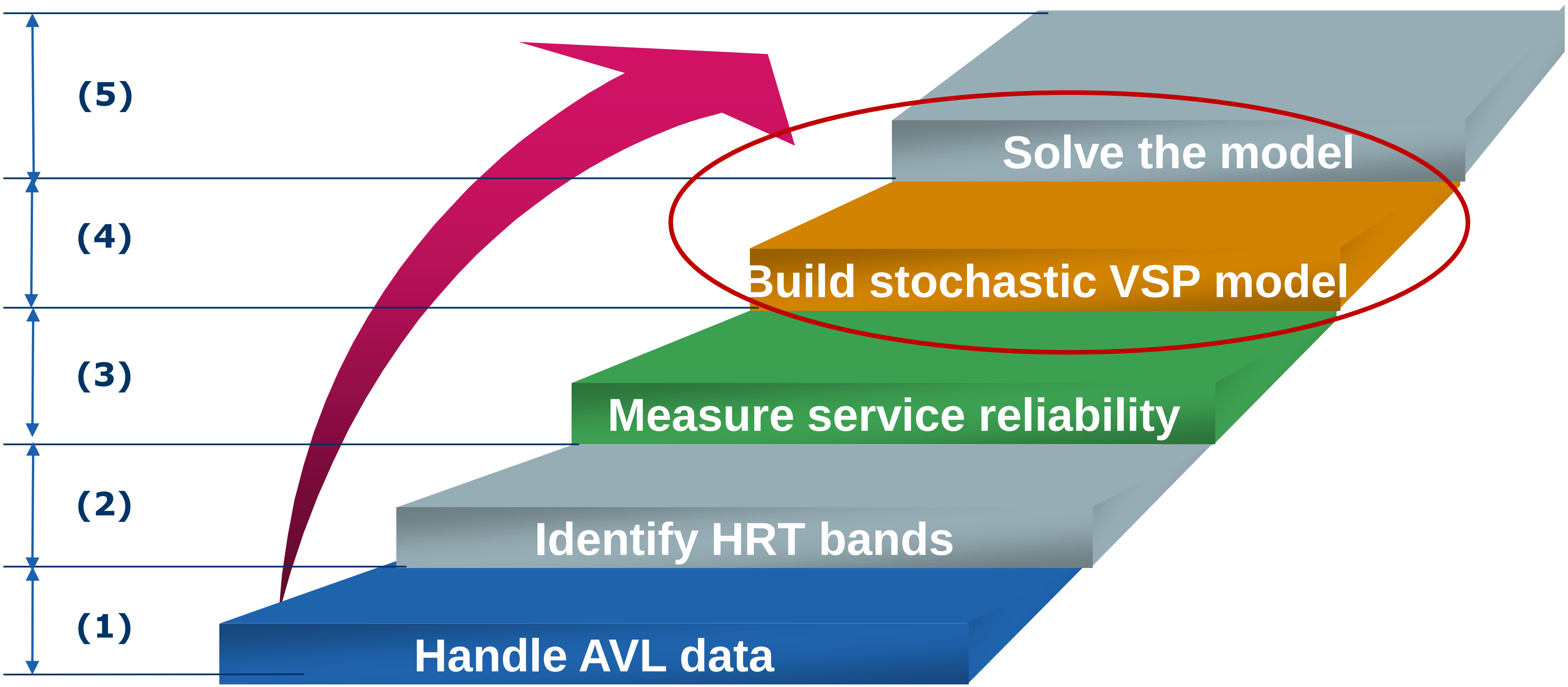
	HRT	样本数	AIC 指数				最优分布模型
			正态	Lognormal	Gamma	Burr	
上行	AM early	357	1922.3	1929.9	1926.5	1924.6	Normal
	AM peak	1019	5729.2	5652.7	5677.2	5523.4	Burr
	Day	1367	8020.1	7964.5	7980.4	7989.7	Lognormal
	PM peak	332	1864.5	1873.4	1870.1	1863.1	Burr
	Eve	620	3576.8	3554.9	3560.9	3556.0	Lognormal
	Eve peak	235	1337.6	1339.8	1338.7	1344.5	Normal
	Night	244	1538.0	1543.7	1541.1	1540.9	Normal
下行	AM early	86	495.7	479.9	492.1	474.7	Burr
	AM peak	239	1450.5	1440.6	1443.8	1430.6	Burr
	Day	2090	13485.5	13269.1	13335.8	13071.4	Burr
	PM peak	338	2162.6	2136.6	2144.6	2123.8	Burr
	Eve	857	5638.4	5536.4	8499.6	5431.6	Burr
	Night	385	2413.0	2368.7	2381.8	2350.3	Burr

Shen Yindong, Xu Jia, Wu Xianyi, Ni Yudong. Modelling travel time distributions using distribution fitting methods and its influence over stochastic vehicle scheduling. *Transport*, 2019, 34(2): 237-249.

yindong@hust.edu.cn

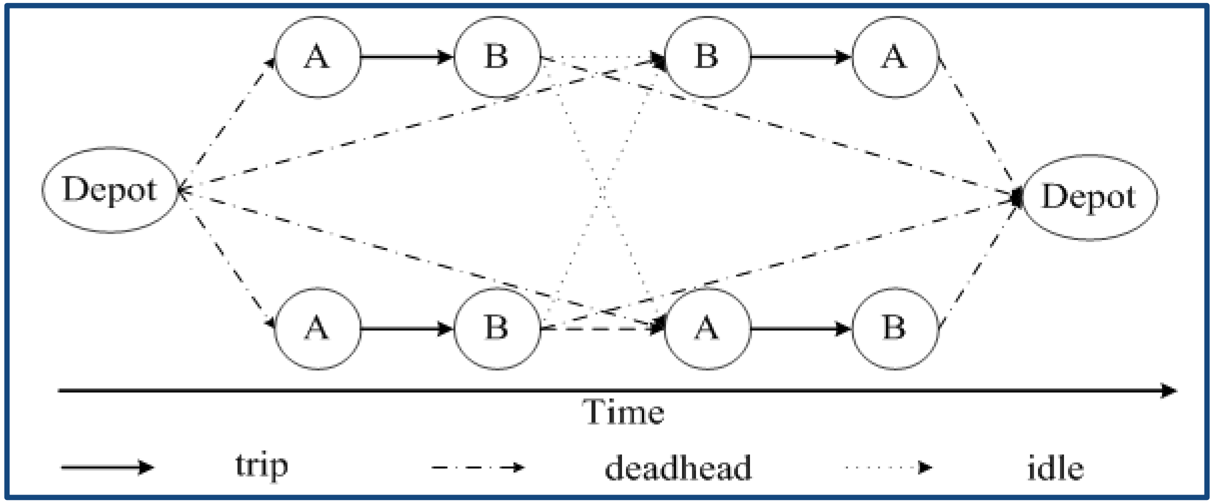
Stochastic Vehicle scheduling

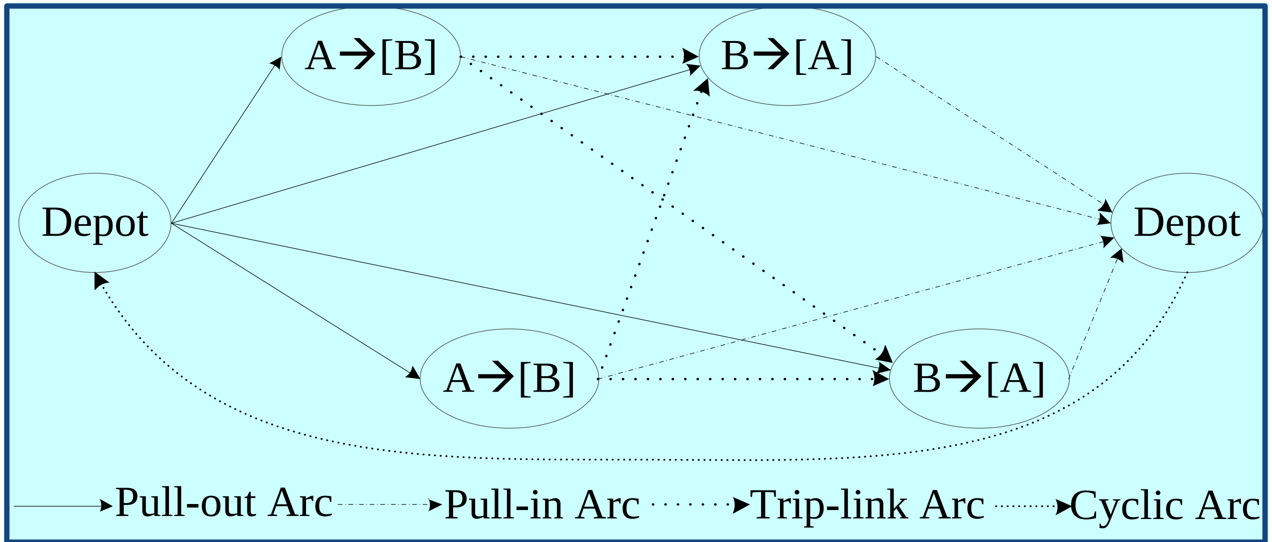
- **To incorporate the stochastic trip times in the VSP model (in the light of AVL data)**



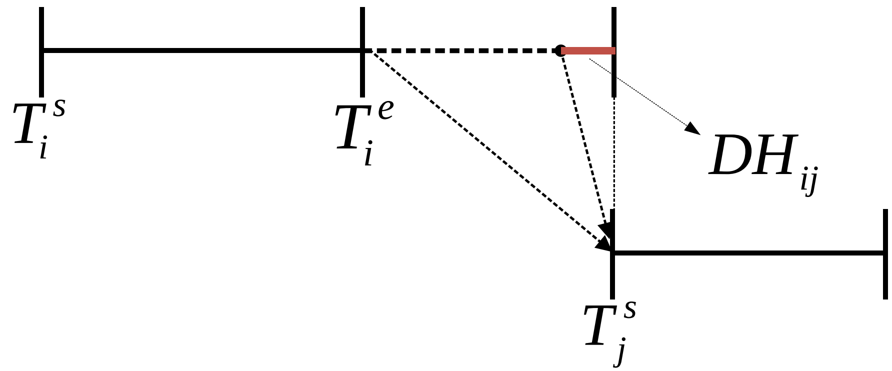
Compile a schedule based on stochastic trip times

- Diverting from the traditional vehicle scheduling,



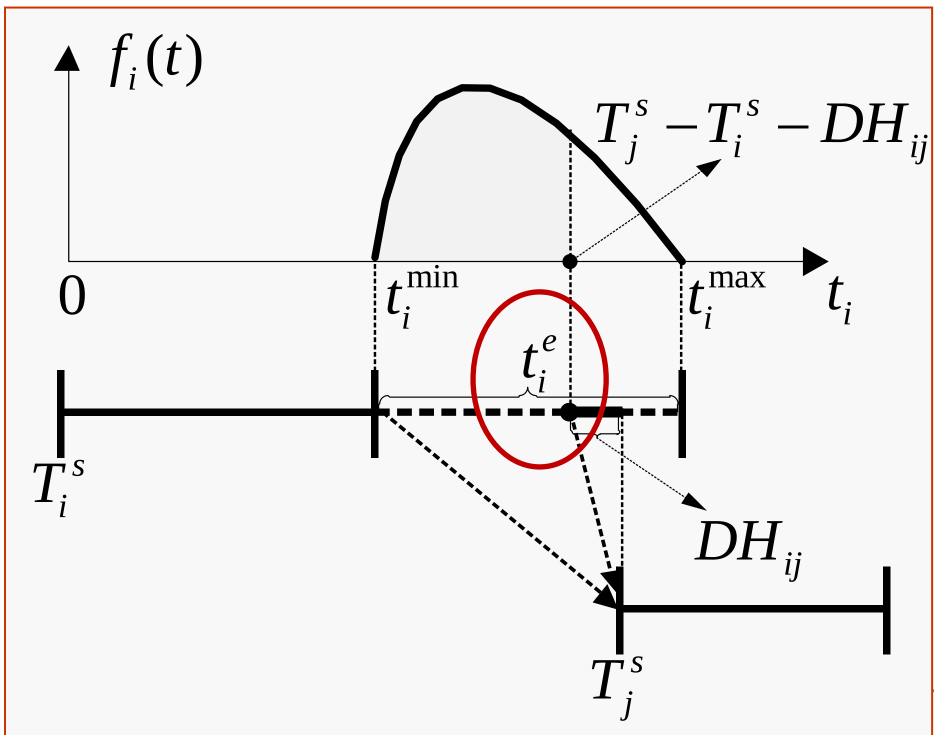


Compatibility of a pair of trips



- Bertossi et al.(1987) defined the **compatibility** of any two trips *i* and *j* as

$$T_j^s - T_i^e \geq DH_{ij}$$



- The **compatibility probability** can be expressed as

$$P\{i \ \Theta \ j\} = \int_0^{T_j^s - T_i^s - DH_{ij}} f_i(t)dt$$

Compatibility and incompatibility probability

- Between the trips *i* and *j*, an arc (*i*, *j*) is defined if $P\{i \ \Theta \ j\} > 0$; otherwise, no arc exists.

- Each arc (*i*, *j*) is also associated with an incompatibility probability

$$\mathrm{P}\{i \ \overline{\Theta} \ j\} = 1 - P\{i \ \Theta \ j\}$$

where, $i \ \overline{\Theta} \ j$ denotes the incompatibility of trips *i* and *j*.

A probabilistic model for VSP (PVSP)

$$\min \sum_{(d,j)\in P} C_{veh} x_{dj} + \sum_{(i,j)\in A} C_{ij} x_{ij} + \alpha \cdot \sum_{(i,j)\in R} P_{ij} x_{ij} \quad (1)$$

$$\text{s.t.} \sum_{i:(i,j)\in A} x_{ij} - \sum_{i:(j,i)\in A} x_{ji} = 0, \quad \forall j \in T \quad (2)$$

$$\sum_{j:(d,j)\in P} x_{dj} - \sum_{i:(i,d)\in Q} x_{id} = 0, \quad \forall d \in D \quad (3)$$

$$\sum_{i:(i,j)\in A} x_{ij} = 1, \quad \forall j \in T \quad (4)$$

$$x_{ij} \in \{0,1\}, \quad \forall (i,j) \in A \quad (5)$$

- The cost and penalty for the trip-link arcs:
  - Cost (deadhead & idle time)

$$C_{ij} = DH_{ij} + E(ID_{ij}) = DH_{ij} + \int_0^{T_j^s - T_i^s - DH_{ij}} (T_j^s - T_i^s - t - DH_{ij}) f_i(t)\, dt$$

  - Penalty (infeasible time --- When the trips i and j are incompatible, $IF_{ij} \geq 0$; otherwise, let $IF_{ij} = 0$.)

$$P_{ij} = E(IF_{ij}^2) = \int_{T_j^s - T_i^s - DH_{ij}}^{+\infty} \left(T_i^s + t - T_j^s + DH_{ij}\right)^2 f_i(t) dt$$

Enhancement of PVSP considering delay propagation

- In practice, the delay can propagate between the consecutive trips operated by the same vehicle.
- Such delay propagation can cause more delays to the pre-compiled schedule.

- Considering delay propagation between two trips *i* and *j*:
  - The departure time of trip *j* is no-longer deterministic and depends on the compatible probability of trips *i* and *j*.
  - When the trips *i* and *j* are compatible, trip *j* can either depart on-time, or, experience a departure delay.
  - The arrival time of trip *j* is affected by both its departure time and its trip time.

An enhanced probabilistic model for VSP (PVSP-DP)

- Formulate the probabilistic model of VSP with delay propagation (PVSP-DP)

1. The expected idle time E(ID_{ij}) in the cost of a trip-link arc, is expressed as:

$$E(ID_{ij}) = \int_{0}^{T_j^s - DH_{ij}} (T_j^s - t_i^e - DH_{ij}) f_i^e(t)\, dt \qquad (1)$$

2. The penalty of trip-link arc, is expressed as:

$$E(DD_{ij}^2) = \int_{T_j^s - DH_{ij}}^{+\infty} \left(t_i^e - T_j^s + DH_{ij}\right)^2 f_i^e(t)\, dt \qquad (2)$$

3. The other parts of the model remains unchanged.

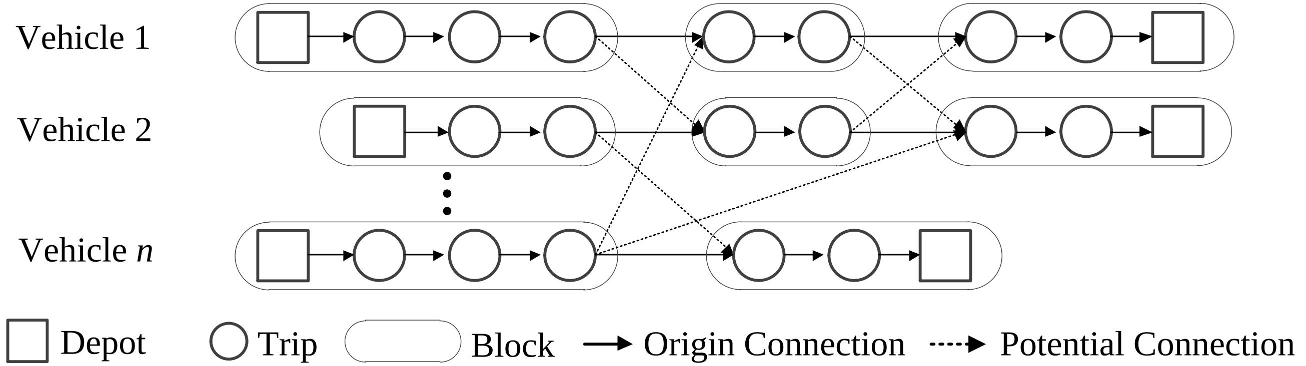
A heuristic approach for the PVSP-DP model

- **Stage 1: Matching based heuristic to form an initial schedule:**

(1) The tier partitioning is to partition all the trips into different tiers;

(2) Link all the tiers into a initial schedule by solving a sequence of matching problem.

- **Stage 2: Refinement.** The iterative greedy local search method is to firstly break part of the arcs in the current schedule, and then to re-link the nodes by solving the sub-problem containing a small subset of nodes.



Huazhong University Of Science & Technology

Benchmark schedules with DVSP model

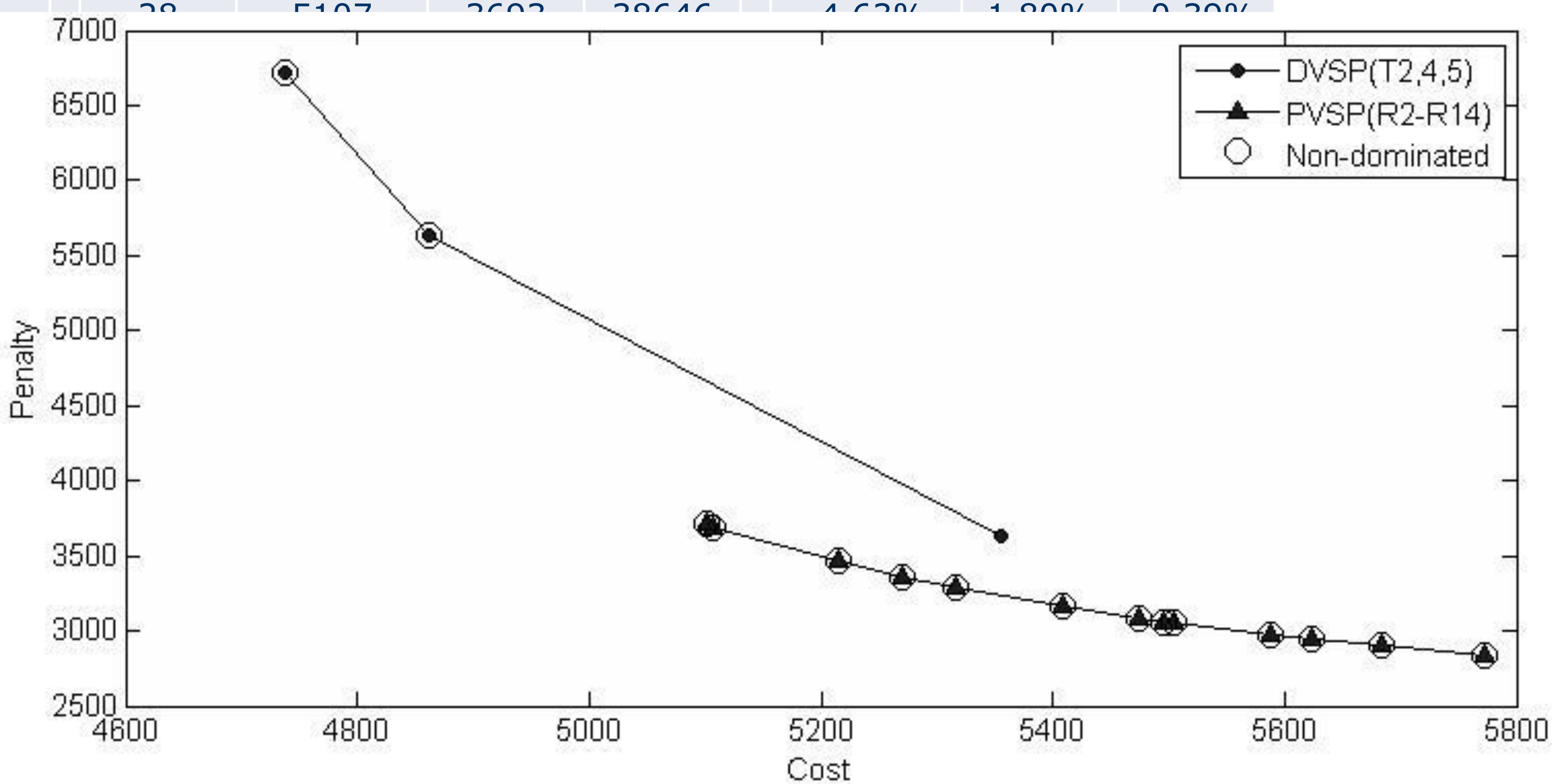
- Compile benchmark schedules with DVSP model:
  - To rules-of-thumb for setting the scheduled trip times are adopted: the 85th percentile of trip time; the sum of mean and standard deviation of trip time.
  - Adjust by +/- 1 minute based on the two rules-of-thumb, 6 groups of scheduled trip times forms 6 problems of vehicle scheduling. Solved by CPLEX, 6 vehicle schedules are produced.
  - From the results, along the increment of ST, the operating cost of schedule is increased, while the penalty is decreased(better on-time performance), however, the fleet size is greatly influenced by the ST.
  - The best benchmark schedule is selected with respect to the best on-time performance of 28 vehicles

Problem	ST setting method	ST adjustment	Fleet size	Trip time	E(ID)	Deadhead	Operating cost	Penalty	Objective value
T1	Rule-of-thumb 1	-1	27	22816	2313	1980	4293	9577	45659
T2		0	**28**	23270	2698	2040	4738	6713	42807
T3		1	29	23724	3372	2100	5472	3497	39718
T4	Rule-of-thumb 2	-1	**28**	23290	2762	2100	4862	5637	41317
T5#		0	**28**	23744	3315	2040	5355	3627	38796
T6		1	29	24198	3611	2250	5861	2769	39015

Schedules compiled with PVSP model

❖ Schedules produced by PVSP model:

Problem	α	Results produced by PSVP model				RPD over the benchmark		
		Fleet size	Operating cost	Penalty	Objective value	Operating cost	Penalty	Objective value
R1	0.2	27	5394	6098	41541	0.73%	68.11%	7.08%
R2	0.3	28	5102	3708	38664	-4.72%	2.22%	-0.34%
R3	0.4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
R4	0.5							
R5	0.6							
R6	0.7							
R7	0.8							
R8	0.9							
R9	1							
R10	1.1							
R11	1.2							
R12	1.3							
R13	1.4							
R14	1.5							
R15	1.6							
AVG								



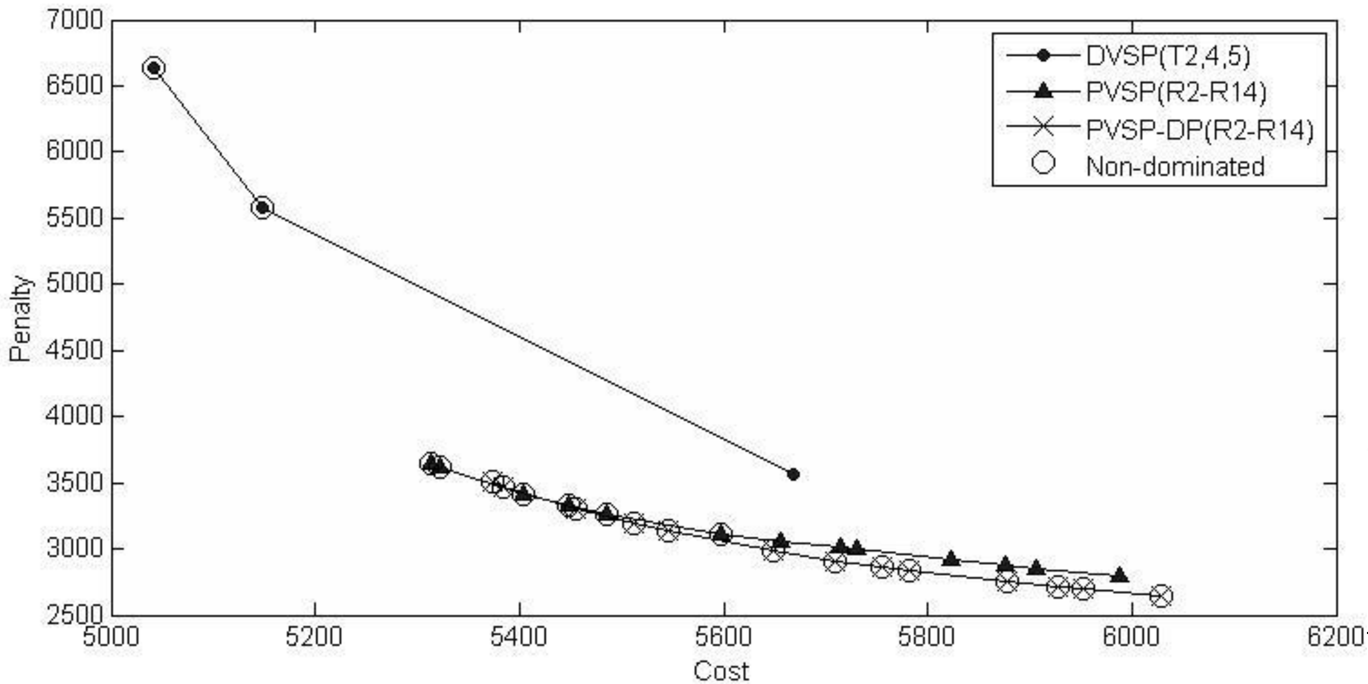
華中科技 Huazhong University Of Scie

α

Schedules produced by the PVSP-DP model

- Solution with PVSP-DP model:

Index	α	Fleet size		Cost				Penalty				Objective value			
		PVSP	PVSP -DP	PVSP	RPD	PVSP -DP	RPD	PVSP	RPD	PVSP -DP	RPD	PVSP	RPD	PVSP -DP	RPD
R1	0.2	27	27	5618	4.91%	5670	5.88%	5997	65.34%	5857	61.48%	41614	7.26%	41456	6.86%
R2	0.3	28	28	5314	-0.77%	5373	0.34%	3641	0.37%	3507	-3.31%	38775	-0.05%	38634	-0.42%
R3	0.4	28	28	5323	-0.60%	5385	0.56%	3614	-0.37%	3474	-4.23%	38744	-0.13%	38596	-0.52%
R4	0.5														%
R5	0.6														%
R6	0.7														%
R7	0.8														%
R8	0.9														%
R9	1														%
R10	1.1														%
R11	1.2														%
R12	1.3														%
R13	1.4														%
R14	1.5														%
R15	1.6														%
Avg.															%



Conclusions

(1) Experimental results show that both of the probabilistic models can produce the schedules with the same fleet size but considerably higher on-time performance than the best known schedule generated under DVSP model.

(2) Comparing the two probabilistic models, the PVSP-DP model may further increase the on-time performance, while the fleet size remains the same but with a little compromise in the operating cost.

(3) Moreover, with the aid of the probabilistic models, human schedulers can be saved from the work of determining scheduled trip times, which is non-trivial and often frustrates schedulers.

Shen Y, Xu J, Li J. A probabilistic model for vehicle scheduling based on stochastic trip times. *Transportation Research Part B*, 2016, 85(1): 19-31.

華中科技大學
Huazhong University Of Science & Technology

我喜欢公交！

Thank You!

Questions?