Plan-Based Bus Bridging Strategy During Disruptions of Urban Rail Networks

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Introduction

In major metropolitan areas like Beijing and Shanghai, bus bridging strategies have been integrated into urban rail networks to mitigate congestion and prevent traffic gridlock situations.

However, the structuring of bus routes remains at a rudimentary level, relying on experience and intuition rather than effective theoretical frameworks and tools to aid decision-making.

This thesis addresses this issue by developing decision support models and algorithms, offering decision support solutions for public transport management and operations departments. These tools are designed to enhance emergency management in public transportation systems.

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Problem Description

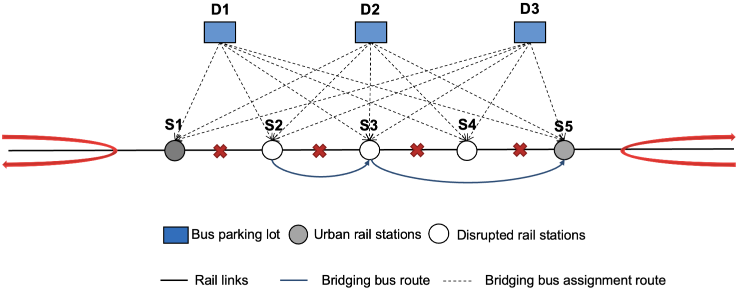

Figure: Illustrative Example of Transit Rail Network Disruption and Responsive Bus Bridging Routes

Assumptions

1. Interrupted stations do not include interchange stations
2. Passengers in the station only leave through emergency buses during the disruption
3. No passengers leave or enter the station during the interruption

Notations

Set and parameters

$\mathcal{B}$: Set of bus
$\mathcal{S}$: Set of disrupted urban railway station
$\mathcal{D}$: Set of bus parking lot
$\mathcal{K}$: Set of O-D pairs that require evacuation $k \in \mathcal{K}$
t_{ij}: Travel time between station i and station j
Q_{ij}: Demand between station i and station j
D_d: Number of bus at bus parking lot d
C: Maximal capacity of bus

Decision variables

x_{ij}^{br}: $\in \{0, 1\}$, 1 if the r_{th} transportation task of bus b is from station i to station j
y_{dj}^{b}: $\in \{0, 1\}$, 1 if bus b is initially assigned from parking lot d to station j
u_b: Number of tasks that bus b assigned to

Mathematical problem

Minimize $\quad Z$
subject to

$$Z >= T^{b} \quad \forall b \in \mathcal{B} \tag{1}$$

$$t^{b}_{assign} = \sum_{d \in D} \sum_{j \in \mathcal{S}} y^{b}_{dj} t_{dj} \quad \forall b \in \mathcal{B} \tag{2}$$

$$t^{br}_{bridge} = \sum_{(i,j) \in \mathcal{K}} t_{ij} x^{br}_{ij} \quad \forall b \in \mathcal{B} \tag{3}$$

$$T^{b} = t^{b}_{assign} + \sum_{n=1}^{u_b} t^{bn}_{bridge} \quad \forall b \in \mathcal{B} \tag{4}$$

$$\sum_{d \in \mathcal{S}} x^{br}_{dj} = \sum_{k \in \mathcal{S}} x^{b(r+1)}_{jk} \quad \forall b \in \mathcal{B}; r = 1, 2, ..., u_b - 1 \tag{5}$$

$$\sum_{(i,j)\in\mathcal{K}} x_{ij}^{br} = \sum_{(i,j)\in\mathcal{K}} x_{ij}^{b(r+1)} \quad \forall b \in \mathcal{B}; r = 1, 2, ..., u_b - 1 \tag{6}$$

$$\sum_{(i,j)\in\mathcal{K}} x_{ij}^{br} <= 1 \quad \forall b \in \mathcal{B}; r = 1, 2, ..., u_b \tag{7}$$

$$q_{ij}^{br} <= C x_{ij}^{br} \quad \forall (i,j) \in \mathcal{K}; \forall b \in \mathcal{B}; r = 1, 2, ..., u_b - 1 \tag{8}$$

$$\sum_{b\in\mathcal{B}} \sum_{r=1}^{u_b} q_{ij}^{br} >= q_{ij} \quad \forall (i,j) \in \mathcal{K} \tag{9}$$

$$\sum_{d\in\mathcal{D}} \sum_{j\in S} y_{dj}^{b} <= D_d \quad \forall d \in \mathcal{D} \tag{10}$$

$$u_b >= 0 \quad \forall b \in \mathcal{B} \tag{11}$$

$$u_b <= \alpha \quad \forall b \in \mathcal{B} \tag{12}$$

$$Q_{ij}^{s} >= 0 \quad \forall (i,j) \in \mathcal{K} \tag{13}$$

$$x_{ij}^{br} \in \{0,1\}, y_{dj}^{b} \in \{0,1\} \tag{14}$$

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Scenario[Small-scale]

- $\mathcal{D} = \{D_1, D_2, D_3\}$
- $\mathcal{S} = \{S_1, S_2, S_3\}$
- 10 buses: 3 in D_1, 4 in D_2, 3 in D_3

Results:

- Excavation time: 65 minutes
- Program running time: 42.72s

表 3-7 应急公交的疏运计划

驻车点	应急公交序号	疏运计划
	B1	D1-S3-S1-S3
D1	B2	D1-S3-S1-S3
	B3	D1-S2-S3-S2-S3
D2	B4	D2-S3-S1-S3

续表 3-7

	B5	D2-S3-S2-S1-S2-S3
	B6	D2-S1-S2-S1-S2-S3
	B7	D3-S1-S3-S1
D4	B8	D3-S1-S3-S1
	B9	D3-S1-S3-S1
	B10	D3-S3-S2-S1-S2-S1

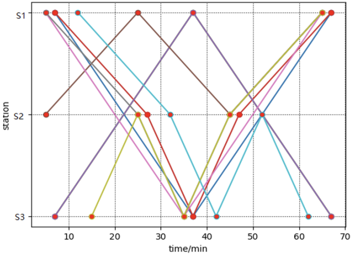

Figure: Bus scheduling plan

Scenario[Large-scale]

- $\mathcal{D} = \{D_1, D_2, D_3, D_4\}$
- $\mathcal{S} = \{S_1, S_2, S_3, S_4\}$
- 30 buses

Results:

- Excavation time: -
- Program running time: More than 24 hour
- *Need algorithms that converge quickly to high quality solutions*

```
Elapsed time = 78255.17 sec. (8342646.40 ticks, tree = 230.52 MB, solutions = 13)
 704294 81952        75.0000   153        85.0000        75.0000 2.54e+08   11.76%
 705466 82097     infeasible              85.0000        75.0000 2.55e+08   11.76%
 706939 82345        75.0000   178        85.0000        75.0000 2.55e+08   11.76%
 708305 82452        75.0000   175        85.0000        75.0000 2.56e+08   11.76%
 709895 82840        75.0000   201        85.0000        75.0000 2.56e+08   11.76%
 711132 83185        75.0000   159        85.0000        75.0000 2.57e+08   11.76%
 712451 83651     infeasible              85.0000        75.0000 2.58e+08   11.76%
 714129 84250        77.0000   127        85.0000        75.0000 2.58e+08   11.76%
 715457 84738        75.0000   202        85.0000        75.0000 2.59e+08   11.76%
 717045 84906     infeasible              85.0000        75.0000 2.60e+08   11.76%
Elapsed time = 78753.94 sec. (8495320.90 ticks, tree = 293.19 MB, solutions = 13)
```

Figure: CPLEX console

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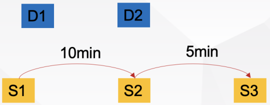
Average Algorithm

From the point of view of maximising the use of resources, the time each bus spent should be as equal as possible.

After the random initial assignment, in each round:

1. identify the bus with the longest operating time
2. allocate one task to other buses

until all tasks have been assigned.



T(min)	S1	S2	S3
D1(1)	5	10	15
D2(2)	10	5	15

	Initial assignment	1st task	2nd task	3nd task
B1	D1——S1 5min	S1——S2 **15min**	15min	S2——S1 25min
B2	D2——S2 5min	S2——S3 10min	S3——S2 15min	(no task left) 15min
B3	D2——S1 **10min**	10 min	S1——S3 **25min**	S3——S1 30min

Figure: Illustration of Average Algorithm

Improvement to Average Algorithm

After generating the initial solution using the average algorithm, continuously decrease the operating time of the longest-running bus through neighborhood actions.

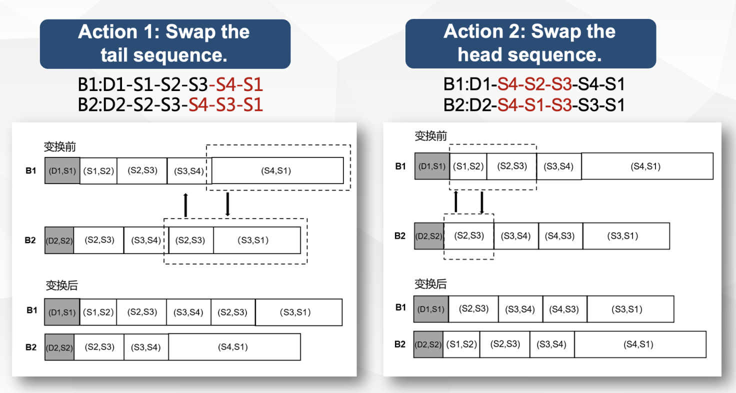


Figure: Illustration of neighborhood actions

Comparisons

Note.
AA represents Average Algorithm and IAA represents Improved Average Algorithm.

	Optimal Time (min)	**Running Time (s)**	**Optimality Gap**
CPLEX	87	3600	0
AA	108	33	24.1%
IAA	85	34	2.2%