Competition Effects and Transfers in Rail Rapid Transit Network Design

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Contents

Introduction

- The problem of increasing traffic congestion has raised the concerns about energy constraints and greenhouse emissions.

- Increasing mobility and longer journeys caused by the growth of cities have stimulated the construction and expansion of rail transit systems (metro, urban rail, light rail).

- The strategic and tactical railway planning problems may be summarized by the two following steps:
  - the railway network design problem;
  - and the line planning problem.

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Rail rapid transit network design

- Designing a Rapid Transit Network: strategic.

  It may reduce traffic congestion, passenger travel, time and pollution.

- Main goals:
  - location decisions;
  - and the maximum coverage of the demand for the new public network.

- List of potential rapid transit corridors and stations,
- Topology design
- and budget availability.

Line planning

- The following step: planning lines (tactical planning level).

- It consists of designing a line system such that all travel demands are satisfied and certain objectives are met:
  - maximizing the service towards the passengers;
  - and minimizing the operating costs of the railway system.

- In this phase the system capacity is considered.

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Contributions

We present a mixed integer non-linear programming model for the rail rapid transit network design problem. Our major contributions include:

1. introduction of competition effects through a logit model;
2. introduction of transfers in the modeling approach; a decisive attribute for attracting passengers;
3. computational experiments in real networks.

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Infrastructure

- The rapid transit network consists of arcs and nodes.
- We assume that the location of the potential stations are given.
- Each node has an associated construction cost and each arc a construction cost and a distance.
- Lines support the design: but neither frequencies nor capacity.
- The new infrastructure: not isolated from the current network.
- We consider the existence of a current transport network formed by different modes of transport.

Passenger demand I

- Passenger groups: origin centroid, destination centroid, and passenger group size.
- The number of potential passengers from each origin to each destination is in average given.
- Passengers choose a path (new or current network).

Passenger demand II

- Demand will choose its path based on the generalized travel cost (distance).

$$P_{new}^{w} = \frac{e^{-(v^{new}+\beta u_w^{new})}}{e^{-(v^{new}+\beta u_w^{new})} + e^{-(v^{cur}+\beta u_w^{cur})}}$$

- Generalized costs for the current network are not well known.
- Congestion: different scenarios in the current network.

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Input Notation

- Parameters:

d_{ij} length of arc (ij).

c_{ij} cost of constructing an arc (ij).

$c_{\max}$ upper budget bound.

g_w number of passengers in passenger group w = (o(w); d(w)).

u^w_{cur} generalized cost for passenger group w through the current network.

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Output Notations

x_{ij}^{l} binary variable: = 1 if line l is located using the arc (ij); = 0, otherwise.

y_i^l binary variable: = 1 if station i is located; = 0, otherwise.

f_{ij}^{w} binary variable: = 1 if demand w uses arc (ij) in the new network; = 0, otherwise.

P_{new}^{w} probability for a passenger in demand w of selecting the new network.

u_w^{new} the generalized cost in the new network for passenger group w.

ϑ_w binary variable: = 1 if a path within the new network exists for demand w; 0, otherwise.

τ_w^l binary variable: =1 if demand w uses line l, and 0 otherwise.

Model formulation

$$\min z = \alpha z_{cur} + \beta z_{loc} + \gamma z_{route}$$

Objective function

$$z_{cur} = \sum_{w \in W} g_w (1 - P^w_{new}),$$

Demand coverage

$$z_{loc} = \sum_{l \in L} \sum_{(ij) \in A_r, i<j} c_{ij} x^l_{ij} + \sum_{i \in N_r} c_i \psi_i,$$

Location costs

$$z_{route} = \sum_{w \in W} u^{new}_w.$$

Routing costs

Model formulation

$$z_{loc} \leq c_{\max}$$

Budget

$$x^l_{ij} \leq y^l_i \qquad \forall (ij) \in A_r : i < j, \forall l \in L$$
$$x^l_{ij} \leq y^l_j \qquad \forall (ij) \in A_r : i < j, \ \forall l \in L$$
$$x^l_{ij} = x^l_{ji} \qquad \forall (ij) \in A_r : i < j, \ \forall l \in L$$
$$y^l_i \leq \psi_i \qquad \forall i \in N_r, \ \forall l \in L$$

Line location

$$\sum_{j \in N_r(i): i<j} x^l_{ij} + \sum_{j \in N_r(i): i<j} x^l_{ji} \leq 2 \qquad \forall i \in N_r, \forall l \in L$$
$$\sum_{(ij) \in B: i<j} x^l_{ij} \leq |B| - 1 \qquad \forall l \in L, \forall B \subset N_r, |B| \geq 2$$

Line paths

+ other: location constraints, line constraints, etc.

Model formulation

$$u_w^{new} = \sum_{(ij)\in A_r\cup A_d\cup A_o} d_{ij} f_{ij}^w + \nu_w \left(\sum_{l\in L} \tau_w^l - \vartheta_w\right) + \varphi_w(1-\vartheta_w) \qquad \forall w \in W$$

$$\vartheta_w \leq \sum_{(ij)\in A_r\cup A_d\cup A_o} d_{ij} f_{ij}^w \qquad \forall w \in W$$

Generalized cost

$$P_{new}^w = \frac{e^{-(\upsilon^{new}+\beta u_w^{new})}}{e^{-(\upsilon^{new}+\beta u_w^{new})} + e^{-(\upsilon^{cur}+\beta u_w^{cur})}} \qquad \forall w \in W$$

$$o_{o(w)}^w \geq P_{new}^w \qquad \forall w \in W$$

$$d_{d(w)}^w \geq P_{new}^w \qquad \forall w \in W$$

Mode choice

$$\sum_{k\in N(i)} f_{ki}^w - \sum_{j\in N(i)} f_{ij}^w = -o_{o(w)}^w + d_{d(w)}^w \qquad \forall i \in N, w \in W$$

Flow conservation

$$M_\tau \tau_w^l \geq \sum_{(i,j)\in A_r} f_{ij}^w x_{ij}^l \qquad \forall w \in W, l \in L$$

Transfers

+ other: location-allocation constraints, etc.

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Lagrangian relaxation

- The objective function in the Lagrangian relaxation approach is as follows:

$$\min \quad \alpha z_{cur} + \beta z_{loc} + \gamma z_{route} + \sum_{ijw} (f_{ij}^{w} + f_{ji}^{w} - \chi_{ij}) \mu_{ij}^{w}$$

- The dual function is the function defined by:

$$\mathcal{R}^{+} \ni \mu \to \theta(\mu) := \min_{\chi \in \chi} \mathcal{L}(\chi, \mu).$$

- The dual problem is then:

$$\max \theta(\mu), \mu \in \mathcal{R}^{+}.$$

Lagrangian relaxation

- Two submodels:

$$\min \quad \beta z_{loc} - \sum_{ijw} \chi_{ij} \, \mu_{ij}^{w}$$

Location submodel

$$\min \quad \alpha z_{cur} + \gamma z_{route} + \sum_{ijw} (f_{ij}^{w} + f_{ji}^{w}) \mu_{ij}^{w}$$

Passenger submodel

Lagrangian relaxation

- For given values of the duals we are able to solve problem easily.

- We use a cutting plane method to estimate the value of the duals at each iteration.

$$\max r$$

$$r \leq \theta(\mu_{it}) + g^{it,T}(\mu - \mu_{it}) \qquad \forall it \in IT$$

$$r \in \mathcal{R}$$

$$\mu \in \mathcal{R}^{+}.$$

- We subtract the following stabilization term to the objective function:

$$\frac{1}{2t} \left\| \mu - \hat{\mu} \right\|^2$$

Recovering the solution

- Store the location variables for each iteration in: χ_{ij}^{it}.
- Construct a linear combination of the solutions at each iteration: $\chi_{ij} = \sum \lambda_{it}\chi_{ij}^{it}$.
- Solve the original model using λ_{it} as decision variables, imposing $\sum_{it} \lambda_{it} = 1$.

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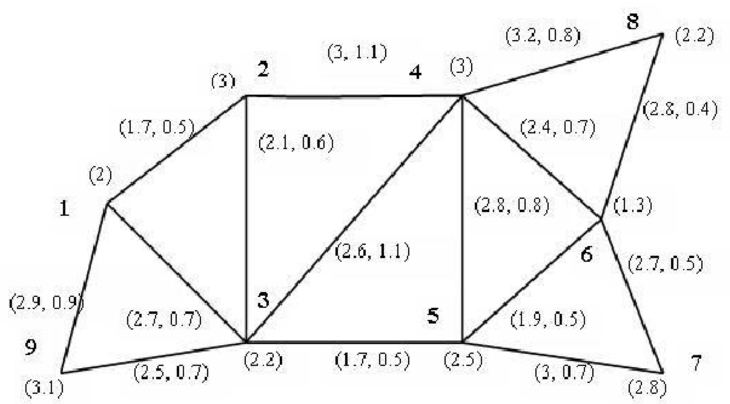
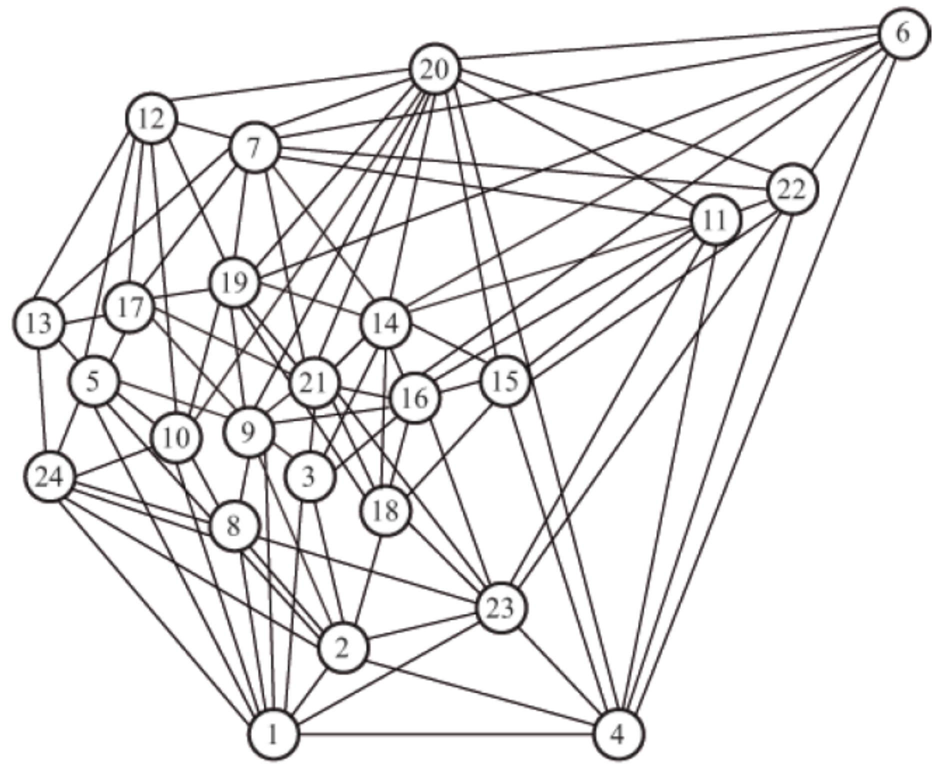
Case study



Network R1



Seville network

Case study

101 iterations

Network R1

2 minutes

Case study

<u>Competition effects & Transfers</u>

Total demand: 1044
Captured demand: 646.56
Transfers: 199.14

<u>Competition effects & No Transfers</u>

Total demand: 1044
Captured demand: 654,47
Transfers: 457.71

<u>No Competition effects & No Transfers</u>

Total demand: 1044
Captured demand: 980
Transfers: 648

Conclusions

- We have propose a new formulation for the rapid transit network design problem:
  - We have integrated the network design and the line planning.
  - We have modeled the transfers of passengers and minimized them;
  - And we have introduced competition effects in order to better estimate demand coverage.

- Future research: robust solutions. Further research needs to redefine the concept of robustness: recoverable robustness.

THANK YOU FOR YOUR ATTENTION

Any question, comment?

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