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Parallel implementation of the hyperpath based railway passenger assignment

Application to Tokyo's Metropolitan Rail Network

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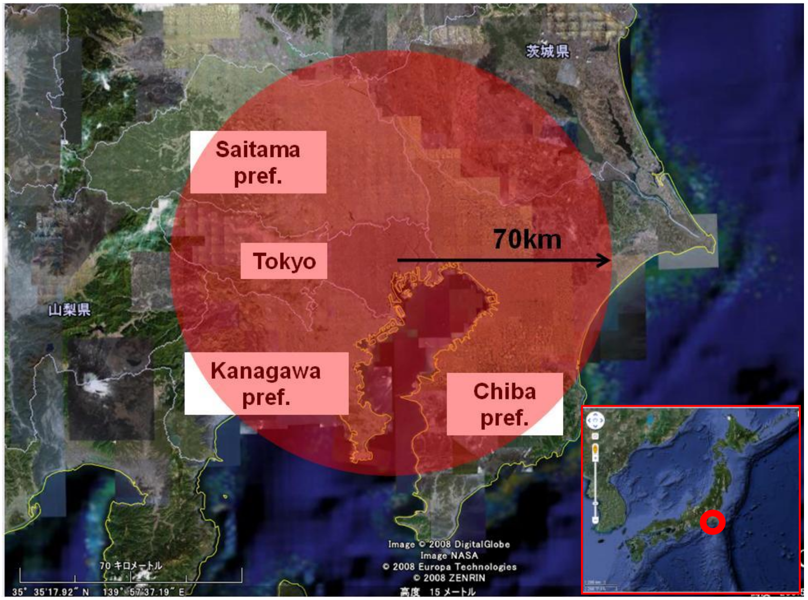
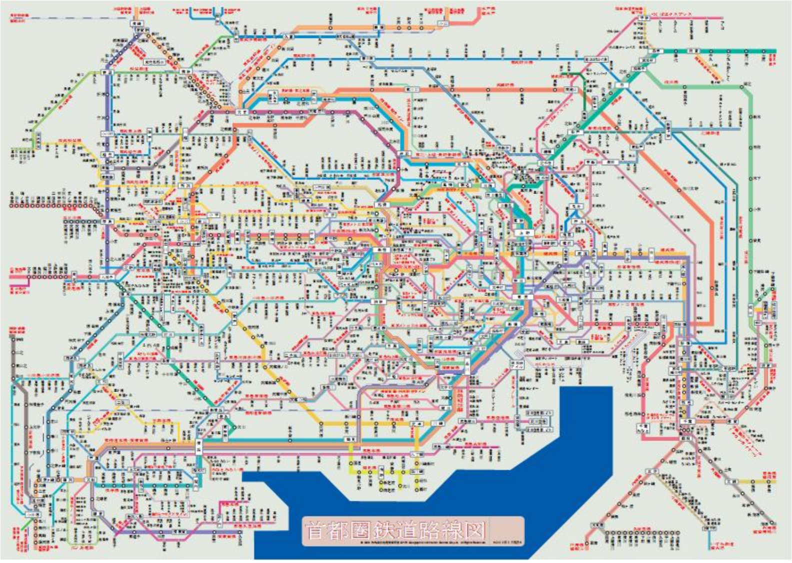
1. Urban railway network in TMA

Tokyo Metropolitan Area (TMA) is a huge capital area and has a highly dense railway network

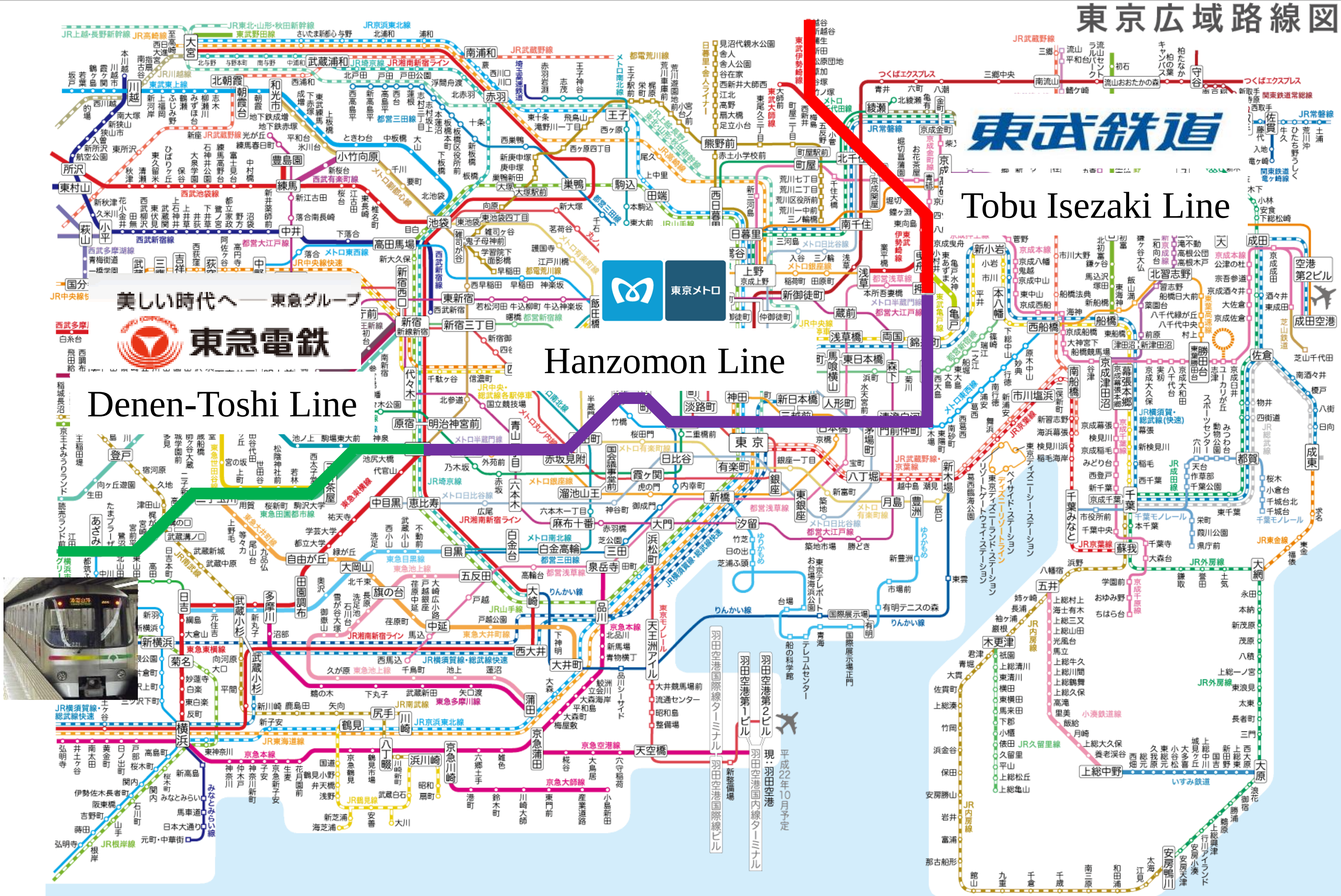


- **Area**
  - ✓ Size: Radius of 70km from the central (Tokyo station)
  - ✓ Population: About 35 million



- **Railway Network**
  - ✓ About 130 lines and 1800 stations
  - ✓ 40 million daily passengers
  - ✓ Various operating patterns (e.g. mutual direct operation)

1. Mutual direct operation in TMA



“Mutual direct operation” means direct operation across different lines operated by different railway companies.

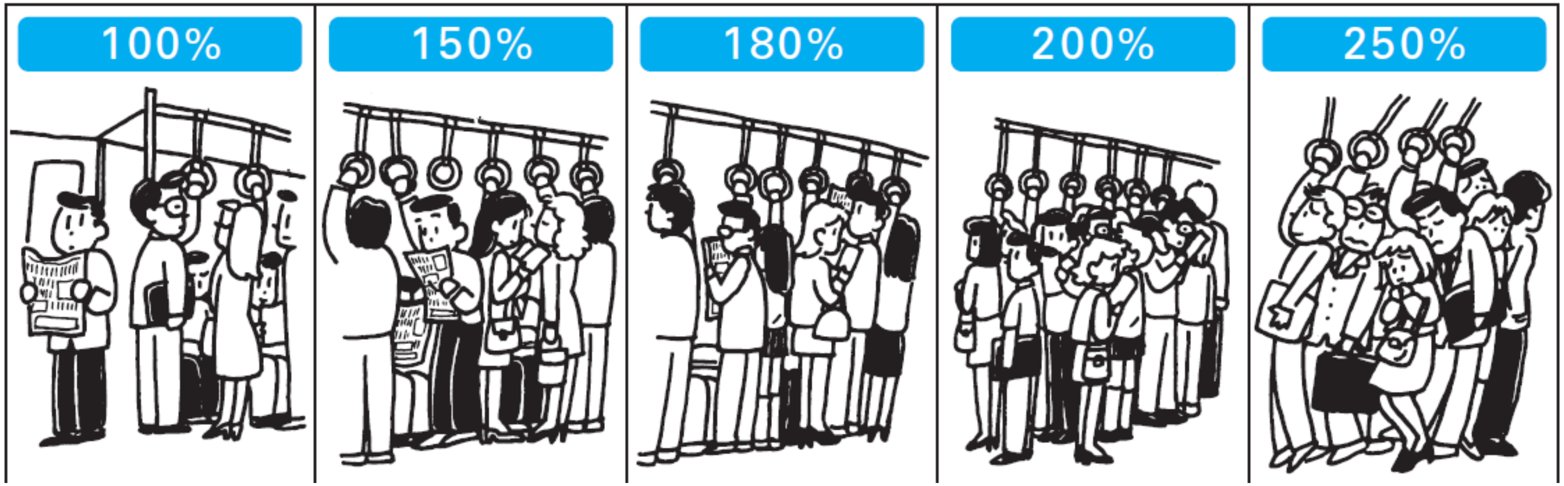
1. Railway congestion in TMA

Railway congestion has been a serious problem since 1960s.

Average congestion rate (CR) decreased to 170% in 2005 in comparison with 250% in 1960s.

<u>"Congestion Rate (CR)": index of congestion widely used in Japan.</u>

CR(%) := (passenger link volume) / (link capacity) * 100



Source: Ministry of Transport

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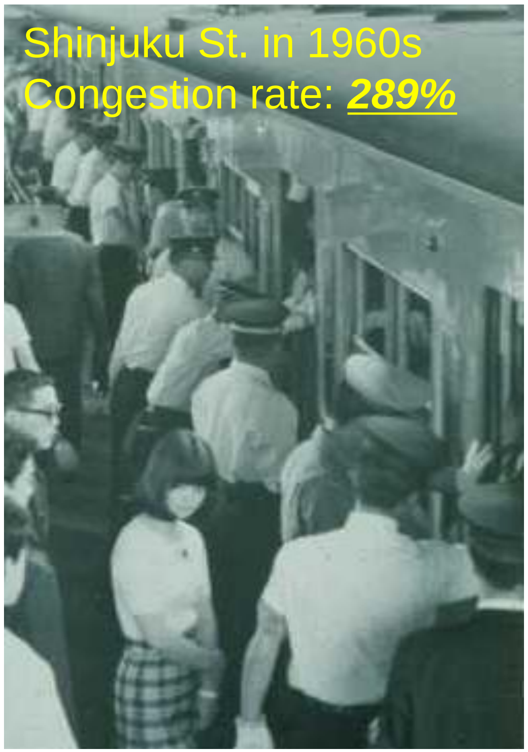

Commuters *still* suffer from physical and mental burdens caused by railway congestion during peak period.

1. Literature Review

- Railway network services have some specific characteristics:
  - Access/egress to stations
  - Service frequency (waiting time)
  - Line transfer
  - Fixed capacity of carriages and railroad

- Railway demand forecasting model in TMA:
  - Yai *et al.* (1997): Disaggregate multinomial probit model for route choice.
  - Ieda *et al.* (2002): Disaggregate route-departure time model.
  - Kato *et al.* (2010): Deterministic/stochastic user equilibrium model.

⇒ These models are analogous to car driver behavior in road networks, and do not consider some typical aspects of public transportation such as **the effects of common lines and passenger strategies.**

1. Literature Review

- <u>Transit assignment models:</u>
  - Spiess and Florian (1989), Nguyen and Pallotino (1988): frequency-based transit assignment model (FBTA) based on hyperpath concept.
  - De Cea and Fernandez (1993): consider congestion with effective frequency.
  - Kurauchi *et al.* (2003): capacity-constrained transit assignment model.
  - Cepeda *et al.* (2006): application to the real urban network (Stockholm in Sweden, Winnipeg in Canada).
  - Schmöcker *et al.* (2008): Dynamic FBTA in London Metro Network.
  - Yaginuma *et al.* (2010): Consider two congestion effects and application to the *small* subnetwork in TMA.

  - FBTA models explicitly consider waiting time uncertainty and passenger strategies. However, there **are no practical applications to as large-scale networks** as TMA.
  - Solution algorithms of FBTA models are **highly computationally** exhaustive compared to standard equilibrium assignment models.

1. Research purpose

1. Develop a hyperpath-based railway route assignment model considering in-vehicle and railroad congestions as well as station-to-station transfer behavior.
2. Accelerate hyperpath search by the parallelization for the practical use of the proposed system.
3. Apply the system to the whole Tokyo metropolitan area network and check the validity and the effectiveness of the model system.

2. Relevance of FBTA model in Tokyo, Japan

Railway lines are usually operated based on schedule in Japan.

✓ Highly frequent operations (e.g. 2 minutes headway during rush hours).

✓ Chronic train delay due to congestion.

⇒ Passenger might not understand timetable well but might recognize train frequency.

- During peak period, a FBTA model might not be an inappropriate assumption.
- For the analysis during peak-hour, a static frame-work might be sufficient and computationally cheaper.

2. Passenger's behavioral principle

- Passengers choose the hyperpath p that minimizes his/her expected generalized cost:

$$g_p = \phi \boxed{\sum_{a \in A_p} \alpha_{ap} t_a} + \varphi \boxed{\sum_{i \in I_p} \frac{\beta_{ip}}{F_{ip}}} + \xi \sum_{a \in A_p} \alpha_{ap} CDU_a + \omega \sum_{a \in A_p} tt_a,$$

※ϕ, φ, ξ, ω: Parameter, x: link volume
α, β: link choice / node traverse probabilities

Nominal frequency at node i :

$$F_{ip} = \sum_{a \in OUT_{p(i)}} f_{l(a)},$$

Effective frequency:

$$f'_{l(a)} = \frac{1}{w_{l(a)}} = \left[\frac{1}{F_{ip}} + \rho \left(\frac{x_a}{Cap_{l(a)}} \right)^{\kappa} \right]^{-1},$$

Congestion disutility:

$$CDU_a = t_a \left(\frac{x_a}{Cap_{l(a)}} \right)^{\psi}.$$

1. Expected in-vehicle time of link a

   - unchanged cost by congestion.

2. Expected Waiting time at node i

   - Effective frequency (EF) may change with the delay (railroad congestion) and is defined as the inverse of frequency.

   - EF describe the frequency change using "*congestion index*".
     if link flow increases: EF increase, or
     if capacity increase: EF decrease.

2. Passenger's behavioral principle

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Congestion disutility:

$$\boxed{CDU_a} = t_a \left(\frac{x_a}{Cap_{l(a)}} \right)^{\psi}.$$

→ Feedback loop exists if congestion is considered (Update link volume: x_a)

3. Congestion disutility at node i

- passengers perceived disutility changes with in-vehicle congestion, and is defined as the product of in-vehicle time and congestion index.

4. Station-to-station transfer time at link a

- unchanged cost by congestion.

3. Solution algorithm (MSA [Method of Successive Average] is applied)

STEP 0. Initialization
SET: Iteration n=0,
Link flow: x_a=0, CDU=0

STEP 1-1. Minimum cost hyperpath search
for a given destination.

STEP 1-2. Flow assignment
using service frequency for results of STEP 1-1.
And repeat flow assignment for all origin

Repeat for all destinations

MSA's iteration

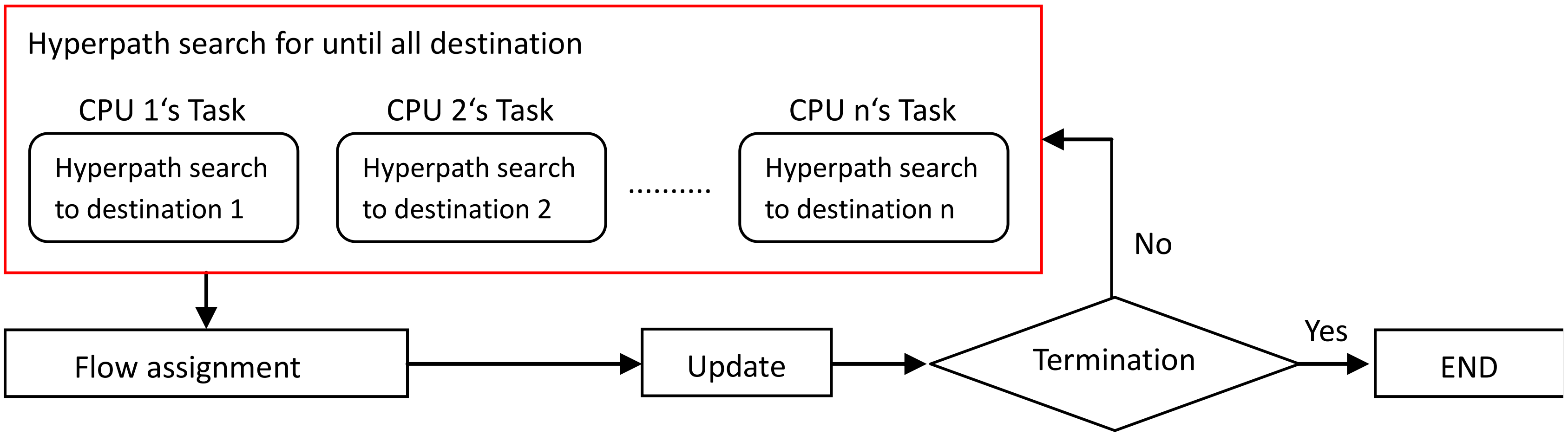
STEP 2. Update link flow and variables
Link flow=avarage x_{n+1} and x_n
Update: EF, CDU, and n=n+1.

Repeat this until n reaches a predefined maximum or until the convergence criteria are satisfied.

3. Parallelization of hyperpath search

- In the algorithm, the hyperpath search accounts for 91% of the total computation time.
- It is possible to conduct hyperpath search for each destination node separately.

➡ Parallelization of hyperpath search for each destination node is implemented with multi-thread computing.



4. Application to Tokyo Railway Network

- Network data

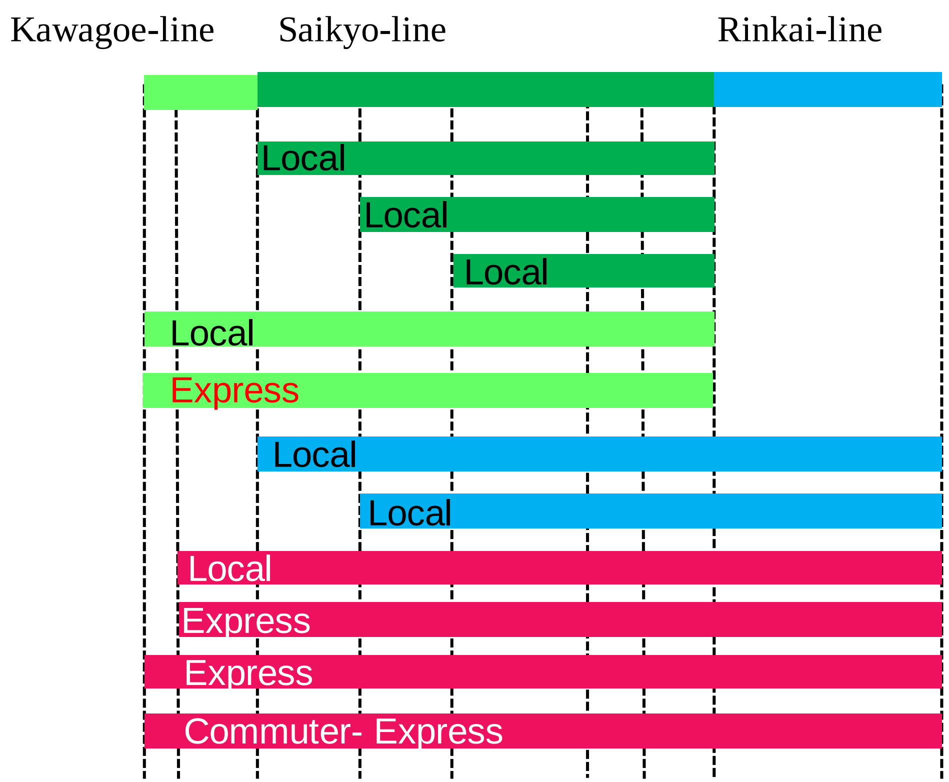
1. Network (nodes, links): 2005 Tokyo metropolitan census
2. OD table, link flow: 2005 Tokyo metropolitan census

   Tokyo metropolitan census is an authorized survey conducted every 5 years. It collects railway users' daily travel behavior (e g. departure time, origin-destination & route).
3. Link travel time: Railway timetable in TMA
4. Frequency (each line segment): Railway timetable in TMA
5. Train vehicle capacity: (120 persons/veh.) * (# of veh.)

4. Line segmentation

Many "sublines" are called as the *same line* but actually have different origin and destination stations and have several types of operations (e.g. Local, Semi-Express, Express train; Mutual direct...)

Ex.) Saikyo line



"Saikyo line
has 3 types segment

Sailkyo-Kawagoe line
has 2 segment

Saikyo-Rinkai line
has 2 segment

Among mutual direct line
has 4 segment

4. Application to the Tokyo network

- Specification:

<u>Physical Network</u>:

Lines : 124

Line Segments: 837

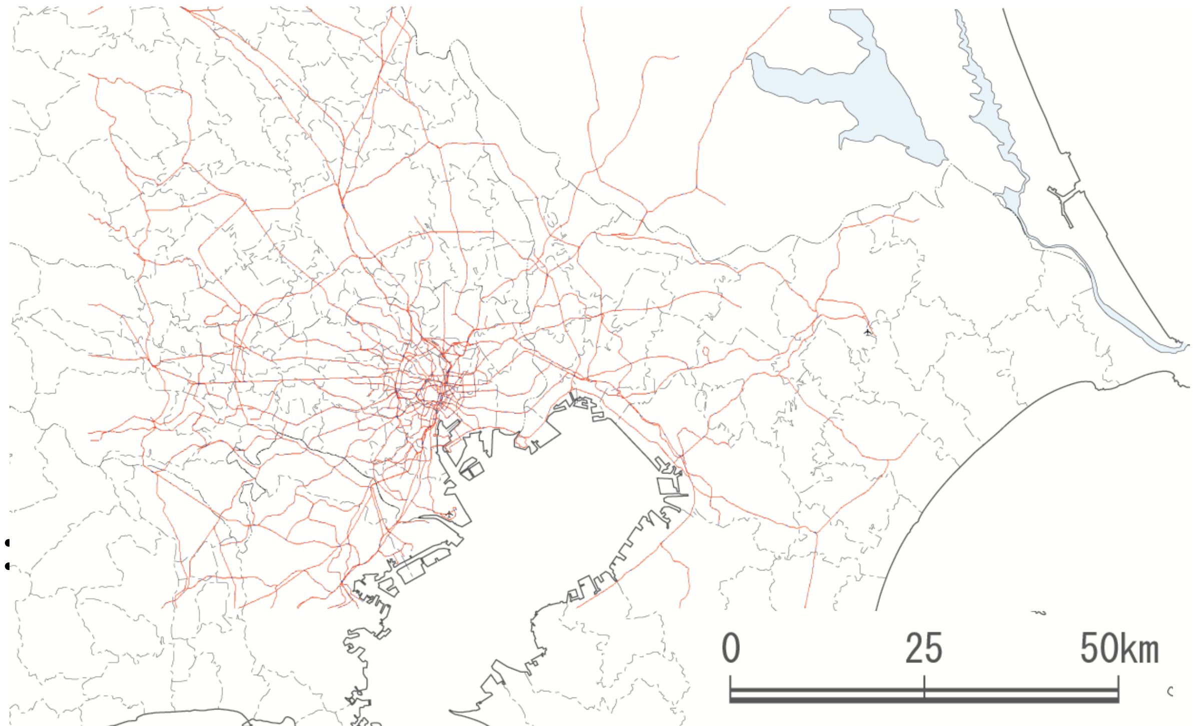
Stations : 1416

Links : 40,701

<u>Graph Representation</u>:

Nodes : 29,902

Links: 55,972



- Calculation environment:

✓ C++ with OpenMP
✓ "TSUBAME2.0" (64 CPUs available)

http://tsubame.gsic.titech.ac.jp/

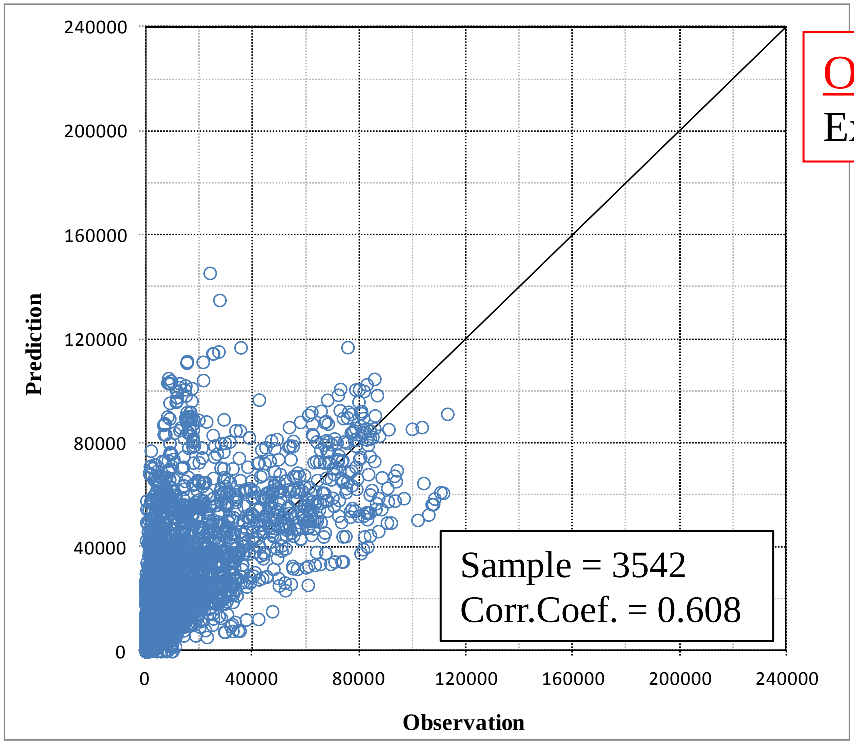
4. Goodness-of-fit of the Models (Link Volumes)

- Parameter values used in the analysis:

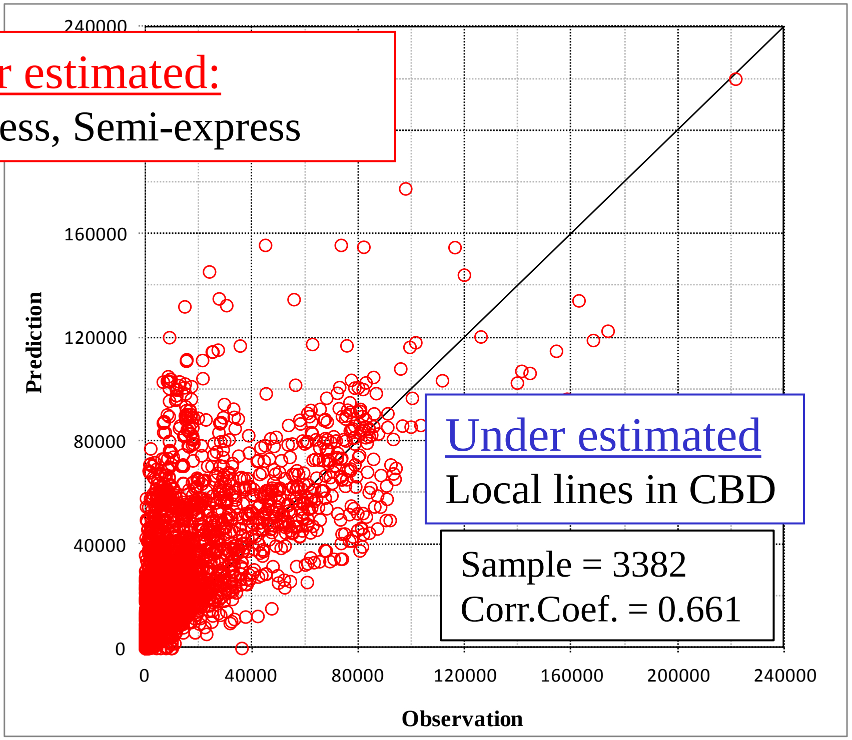
ϕ	φ	ξ	ω	ρ	κ	ψ
1.00 (Normalised)	1.45*	2.07*	1.20	1.06*	2.21*	2.50

* indicates parameters taken from Kato *et al*. (2007) and Iwakura *et al*. (2000)

Different "sublines" distinguished:

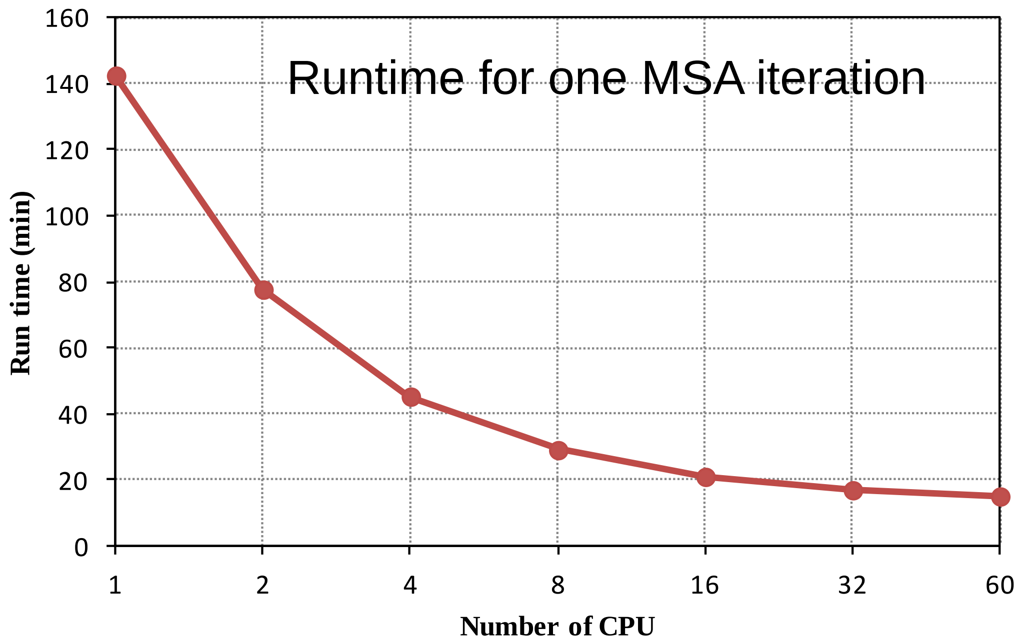


Railtrack level (only lines distinguished):



4. Effects of Parallelization

- The parallelization decreased runtime significantly.



However, "Depletion effect" becomes distinct with the increase in the number of CPUs.

⇒ Need to consider the optimization of programming code and to check the property of CPUs.

5. Conclusions & Future Works

Conclusions:

- We proposed a frequency-based railway route assignment model with two different congestion effects (in-vehicle and on-railroad) and applied this to the TMA rail network.
- Parallelization of hyperpath search enabled to reduce the run time significantly for large-scale applications.

Future works:

- Consider explicitly the transfer behavior between platforms.
- Check convergence property and solution uniqueness of the model.
- Incorporate the railway fare into the generalized cost function.
- Further speed-up with the improvement of parallelization code.

Thank you for your kind attention.

4. Test application to the partial network in TMA

Test network:

O : South Saitama

D : Inner Yamanote

Line segment : 22

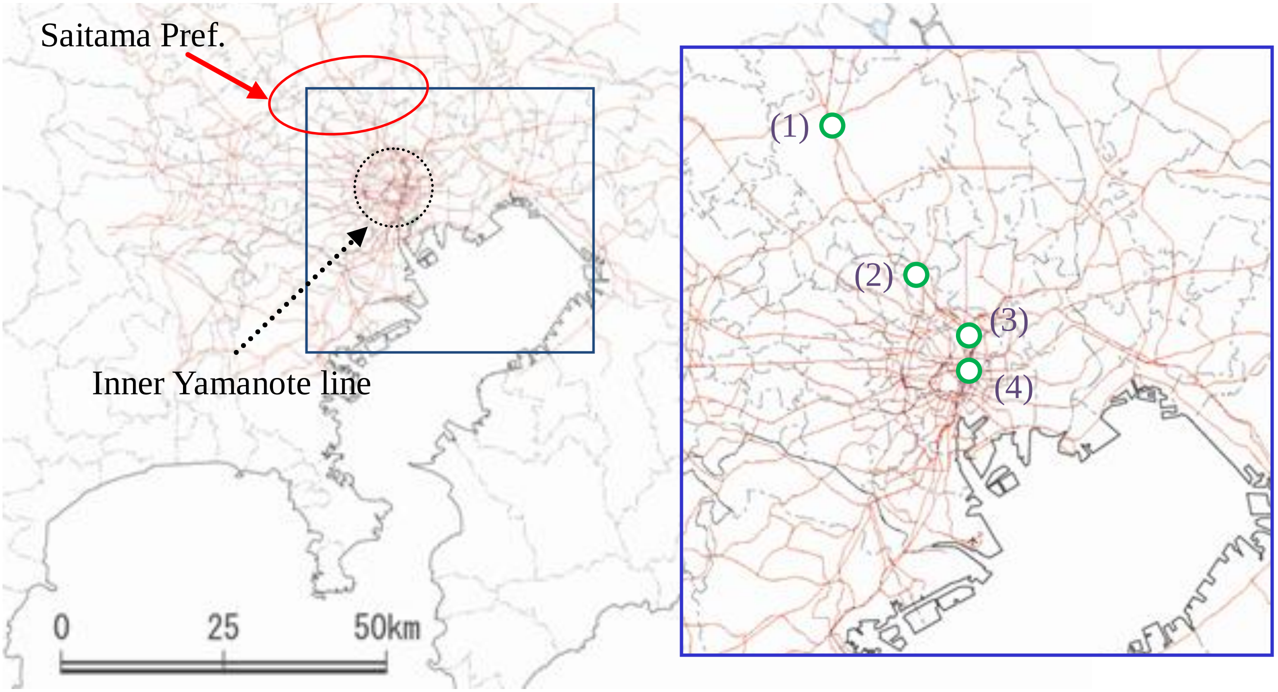
Stations : 70

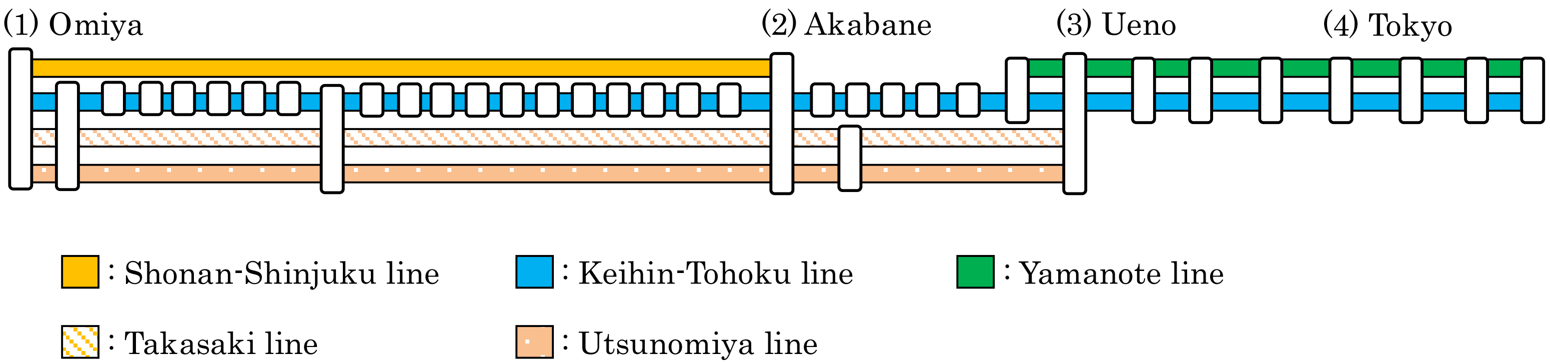
Nodes : 919

Links : 1611

OD-pairs : 1064

(in peak 7AM-8AM)





Passenger flow data is taken from Tokyo metropolitan railway census (2005).

4. Purpose in this chapter

- Develop the parallelized algorithm for solving the proposed model to reduce computation time.
  - ➢ Hyperpath-based model has complex computational process compared with the standard shortest path algorithm.
  - ➢ The speed up of computation time is very important in applying to large scale railway networks line in TMA.
- Apply to the Tokyo Metropolitan Railway network.
  - ➢ Test the standard model without congestion effects.
  - ➢ Test the proposed model with congestion effects.

2. Definition of hyperpath

- Behavioral assumptions:
  - Transit: operated based on **frequency** (not on schedule)
  - Passenger: can only observe the next line to be served

  ⇒Passengers make en-route choice with **common lines problems**

Common lines problems (Chiriqui & Ronolland 1975)

*Passenger who takes the first vehicle to come within his/her "**attractive set**" lines can get to his/her destination earliest.*

Attractive set (choice set) = "Hyperpath"

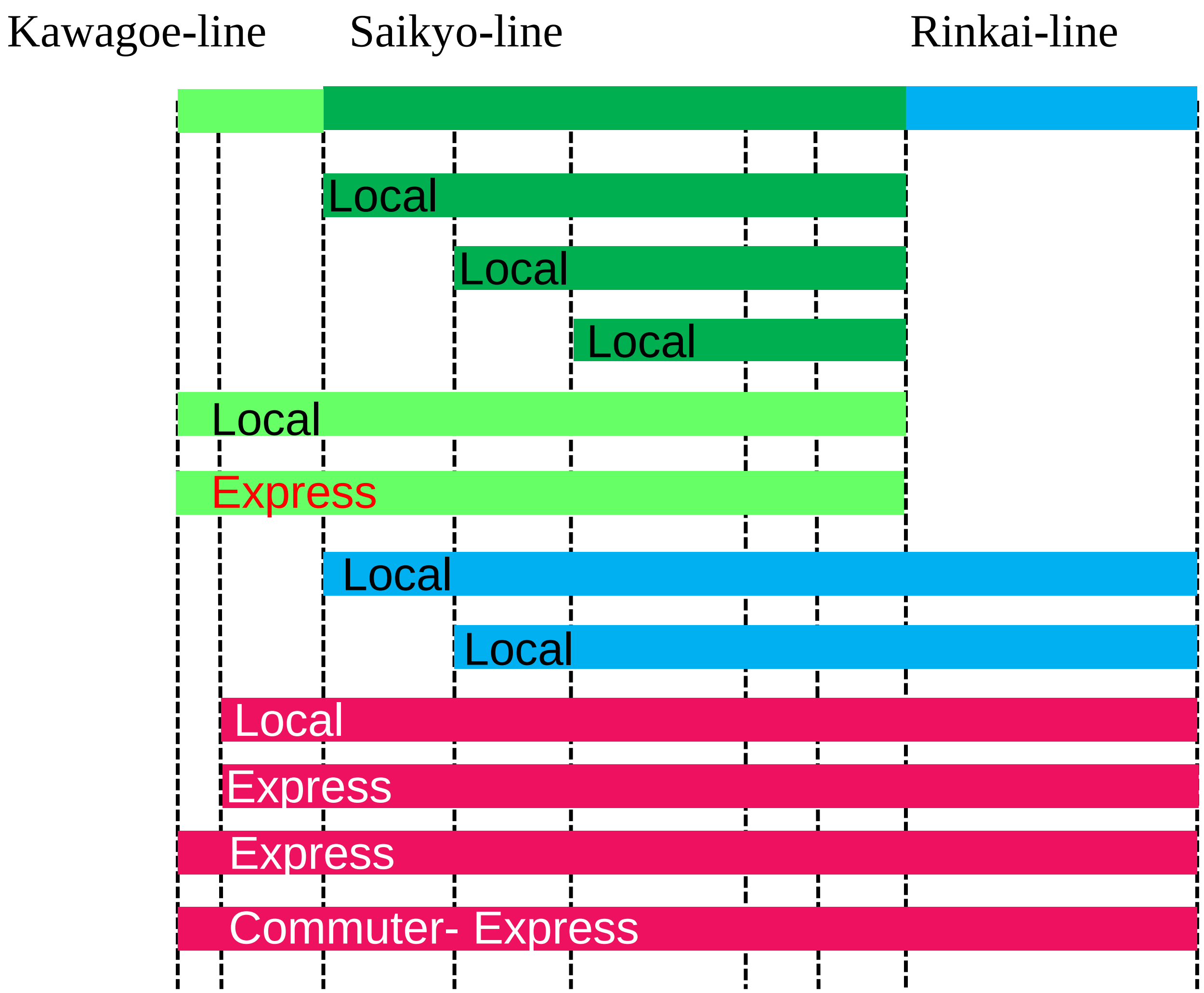
Strategy of riding trains to destination (choice set of links)

Passenger's hyperpath

= An Attractive Set with *minimum* expected cost.

4. Line segmentation

<u>Ex.) Saikyo line (one of the longest north-south corridor line with mutual operation)</u>



"Saikyo line
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Among mutual direct line
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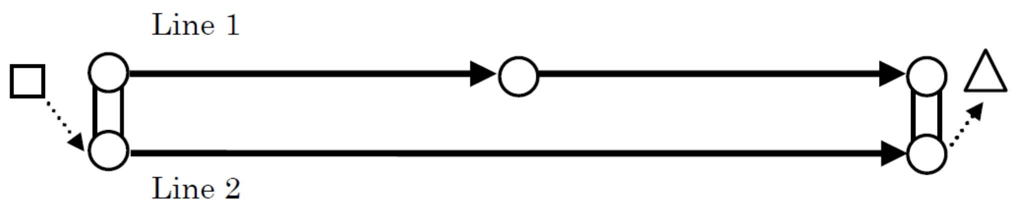
Input network data is increase by mutual direct and different O/D station

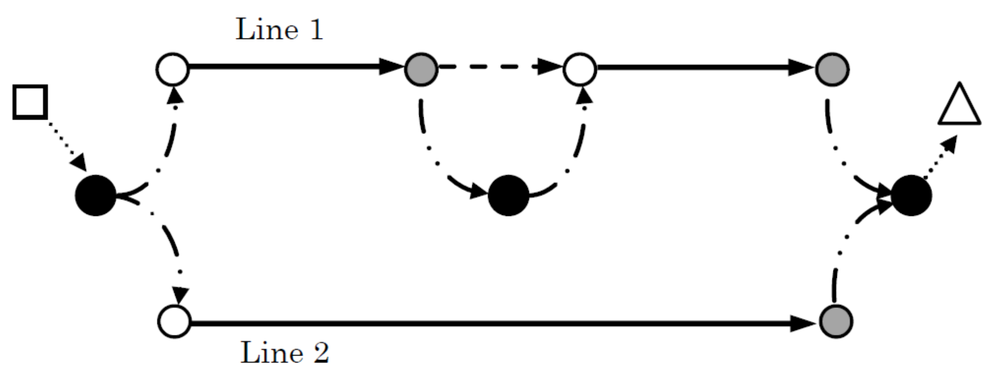
Hypergraph Representation:

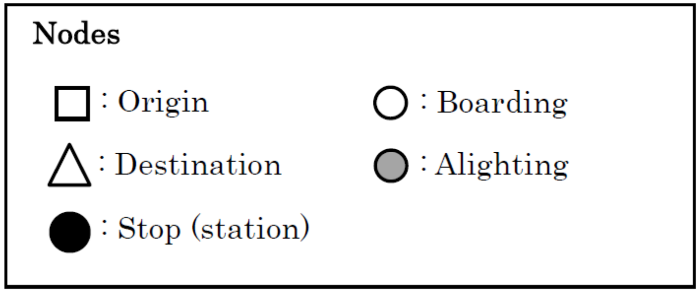
Describe passenger behavior in detail between OD pairs:
(Origin-Destination)

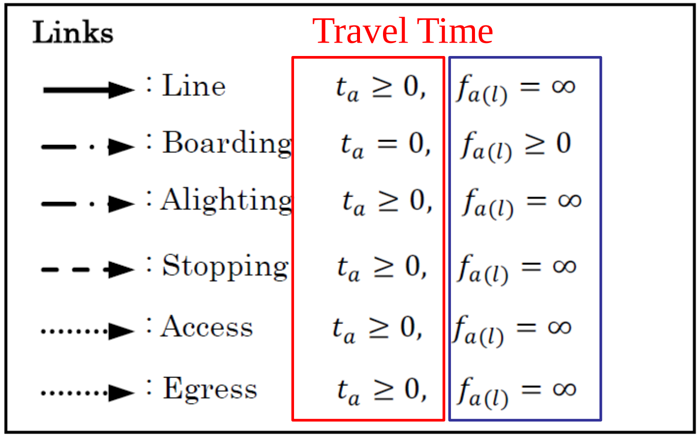
Example Transit Network



Hyper-graph Network







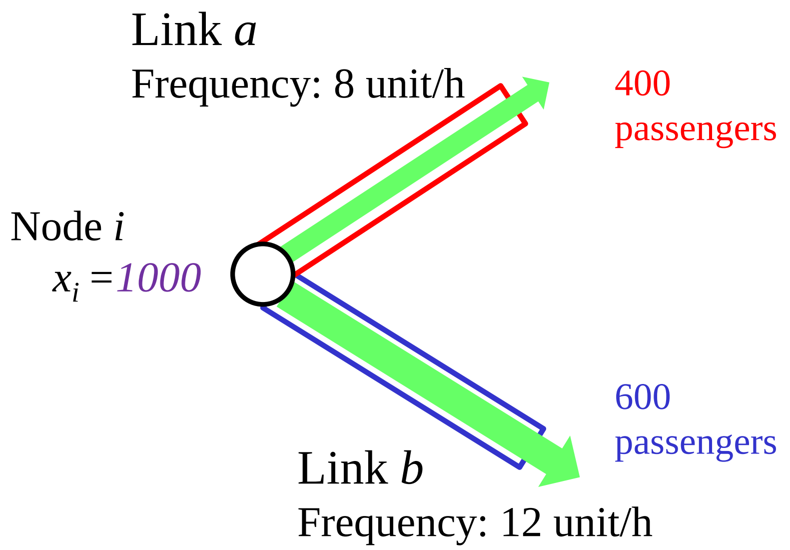
Service Freq.

2. Loading passenger demand to the network

Loading OD demand on the minimum hyperpath :

- Passengers are loaded to each link proportionally to the service frequency of the link.

Example: two separate links



When *1000* passengers come to node *i*, they are loaded to links *a* and *b* by

links a = *400* $\left(=1000\times\frac{8}{8+12}\right)$
and
links b = *600* $\left(=1000\times\frac{12}{8+12}\right)$
respectively.