# Urban Transit Network Design with Distinct Passenger Groups: Model and Application


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## Background


The design of public transportation networks usually focuses on maximizing total welfare, under resource and operation constraints and the assumption on average trip characteristics for a typical user. Nevertheless, there exist different passenger groups (such as captive and choice travelers), whose needs may vary and should be prioritized in the planning stage. This paper proposes a model for designing a public transportation network, which considers the needs of different passenger groups. A mathematical programming model is formulated for that purpose and solved using a hybridized Genetic Algorithm based procedure. An application of the model for Mandl's benchmark network is presented and results show that prioritizing captive users may be achieved with minimum impact to the service quality of the public transportation network.


## Background

- The design of a transit network is a complex compromise of two contradicting objectives:
  - Riders seeking to optimize their generalized (user) travel cost
  - Transit agencies seeking to minimize their operating cost
- Characteristics of an efficient transit network (Kepaptsoglou, 2009):
  - Maximized performance so that:
    - Traveler requirements are met
    - Current ridership is retained
    - New riders are attracted to the system
  - Financial viability ensured
- The TRNDP problem (Chakroborty 2003, Kepaptsoglou 2009, Farahani 2013):
  - Complex optimization problem, aiming at maximizing efficiency for given criteria
  - Objectives:
    - Design an efficient transit network structure
    - Define operational characteristics (frequencies, fleet size, etc)
  - Constraints:
    - Demand
    - Resources
    - Topology
- Current methods of addressing TRNDP
  - Genetic Algorithms
  - Simulated Annealing
  - Tabu Search
  - Ant Colony Optimization, Bee Colony Optimization, Particle Swarm Optimization
  - Hybrid models

## Objectives

- Existing standard TRNDP models fail to represent current network and ridership conditions by:
  - Redesigning the whole network from the ground up
  - Not considering current ridership and non-users
- Proposed model objectives:
  - Split demand into two groups, current riders and non-riders
  - Design an efficient public transit network structure that satisfies at least current ridership
  - Optimize the network structure to satisfy current riders and non-riders
  - Define route frequencies and selected vehicle types
  - Minimize user cost


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## Methodology

### Travel Time Minimization

$$\min Z = w_1 \cdot Z_1 + w_2 \cdot Z_2 = w_1 \cdot TTT + w_2(a \cdot d_1 + b \cdot d_2 + c \cdot d_{un})$$

$N$ : Network Node
$E_{i,j}$ : Network Edge ($i,j \in N$)
$G(N,E)$ : Network Graph
$LS$ : Set of lines $\{L\}$
$L$ : Line $\in LS$ – Set of nodes $\{n \in N\}$
$LN$ : Number of lines $L$ in $LS$
$CD$ : Current Users' Transit Demand Matrix (N x N)
$TD$ : Total Transit Demand Matrix (N x N)
$d_{i,j}$ : Demand for transit from node $i$ to node $j$ ($i, j \in N$) ($CD/TD$)
$s_L$ : Number of stops per line $L$
$s_{min,L}$ : Minimum number of stops per line $L$
$s_{max,L}$ : Maximum number of stops per line $L$
$Z_c$ : Objective Function component $c$
$TTT$ : Total Travel Time
$ATT$ : Average Travel Time
$d_0$ : Percentage of passenger demand satisfied without transfers
$d_1$ : Percentage of passenger demand satisfied with one transfer
$d_2$ : Percentage of passenger demand satisfied with two transfers
$d_{un}$ : Percentage of unsatisfied demand
$w_c$ : Weight factor for component $c$
$a,b,c$ : Penalties associated with transfers and unsatisfied demand
$f_L$ : Frequency for line $L$
$f_{min,L}$ : Minimum frequency for line $L$
$f_{max,L}$ : Maximum frequency for line L

subject to:

$$s_{min,L} \le s_L \le s_{max,L} \ \forall \ L \in LS$$

$$L \neq K \ \forall \ L, K \in LS$$

$$d_0 + d_1 + d_2 + d_{un} = 100$$

### Frequency Calculation

$$f_L = \frac{\max d_{ij}}{vc}, i, j \in N$$

$$f_{\min L \le} f_L \le f_{\max L}$$

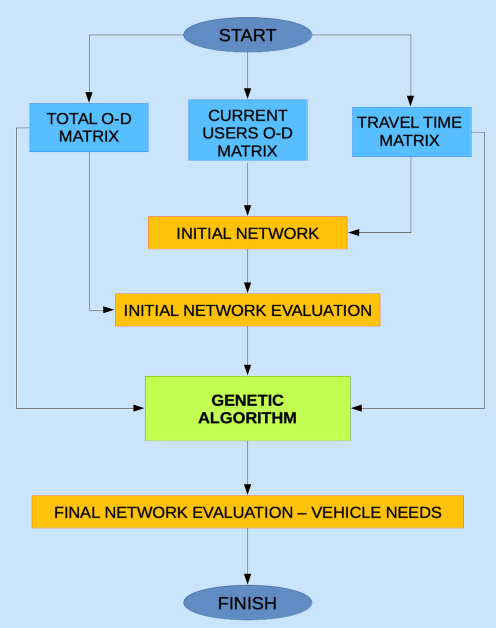
### Fleet Size Calculation

$$vc = \begin{cases} 80\dfrac{veh}{h}, \text{if } f_L \le 30 \\ 150\dfrac{veh}{h}, otherwise \end{cases}$$

$$ct_L = 2.2 * \sum_{i=1}^{S_L-1} \sum_{j=i+1}^{S_L} t_{ij} \qquad L \in LS, i, j \in N$$

$$V_L = \text{int}\left[ f_L * \left(\frac{ct_L}{60}\right) + 0.5 \right] \qquad L \in LS$$

## Solution Process




**Genetic Algorithm**

**Representation Scheme:** Array of routes, each route is a sequence of stops

**Initial Population (based on current demand):**

- Current user demand in descending order
- Shortest paths are added to the population one-by-one until all population is served.
- Each group of routes is considered one population member

**Evaluation:** Average Travel Time (including transfers)

**Simple Deterministic Assignment:**

- Total demand assigned to shortest route
- Minimum amount of transfers is considered in case of a tie

**Genetic Operators**

**Crossover:** Two routes split in half at a random iterator and their parts are swaped

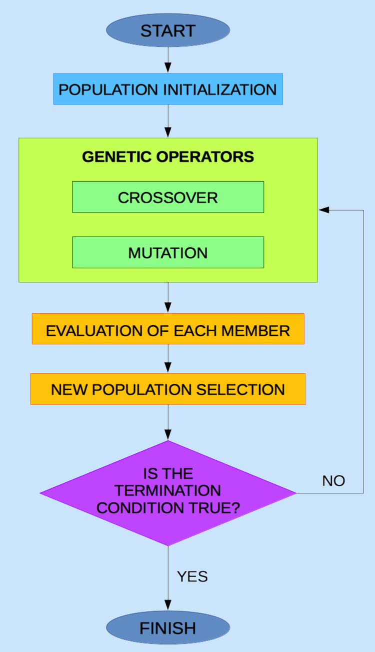
**Mutation:** A node is added/deleted from route (small mod), or a new shortest path is chosen from the starting/ending stop of the route (big mod)

**Elitism (Nayeem, 2014)**

A predefined number of members are copied to the next population, based on their fitness.

**Termination**

Fixed number of iterations.




## Application

**Application for Mandl's Swiss benchmark network:** (Mandl, 1979)

- 6, 7, 8 route alternatives
- Stops per route: 4-8
- Transfer burden: 5 minutes
- Vehicle size: 80, 150 passengers

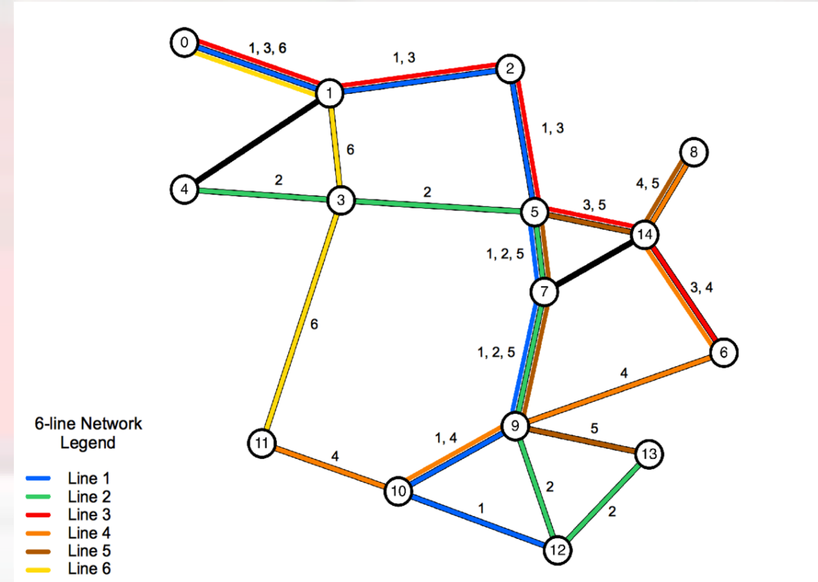
- GA Population size: 20
- Elite members: 8
- GA iterations: 150
- Crossover Probability: *1/LN*
- Mutation Probability: 0.8 (small), 0.3 (big)

**Two alternative scenarios:**

- Initialization for current riders and improvement for all passenger groups (Scenario C – Proposed)
- Initialization and improvement for all passenger groups (Scenario U – Usual Practice)

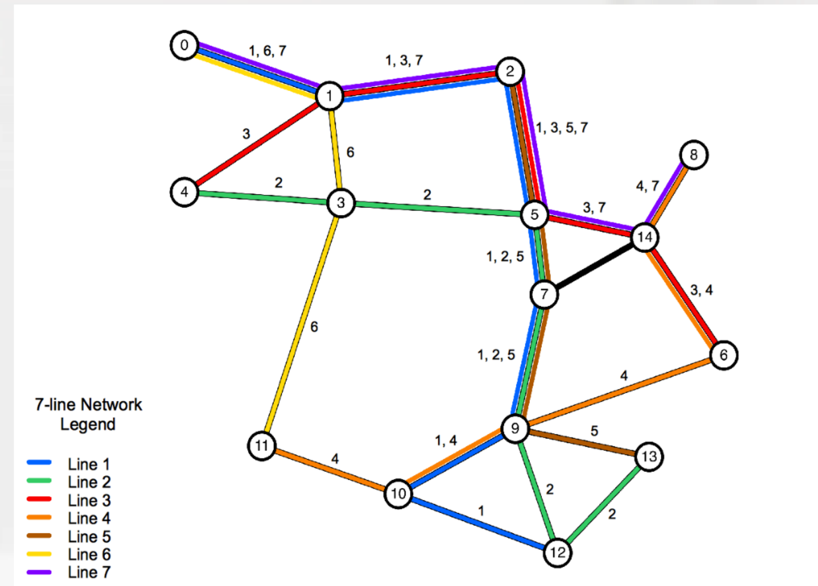
### 6-route Alternative

| | Scenario U- Usual Practice | | | Scenario C – Passenger groups | | |
|---|---|---|---|---|---|---|
| | Current | Non-Users | Total | Current | Non-Users | Total |
| ATT (min) | 10.55 | 10.40 | 10.44 | 10.58 | 10.45 | 10.48 |
| $d_0$ (%) | 93.43 | 92.13 | 92.49 | 93.00 | 91.49 | 91.91 |
| $d_1$ (%) | 6.20 | 7.30 | 7.00 | 7.00 | 8.51 | 8.09 |
| $d_2$ (%) | 0.38 | 0.57 | 0.51 | 0.00 | 0.00 | 0.00 |
| $d_{un}$ (%) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |



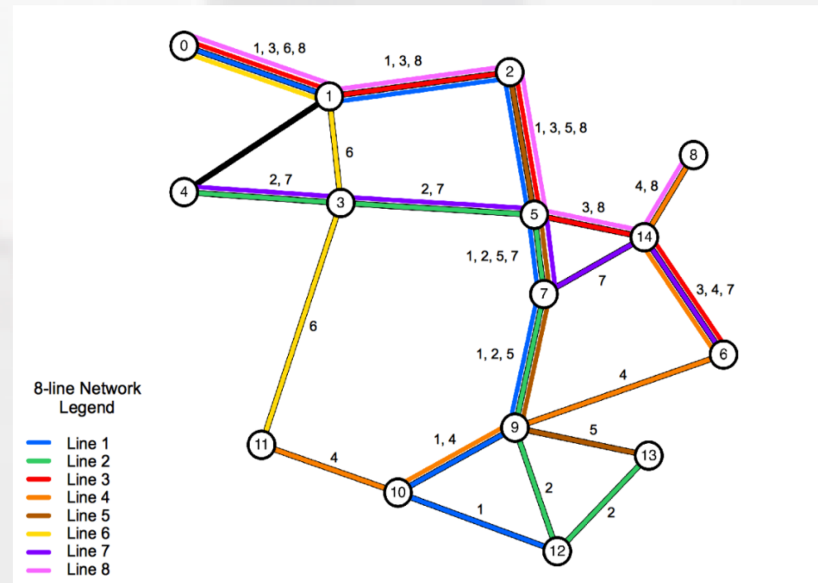

### 7-route Alternative

| | Scenario U – Usual Practice | | | Scenario C – Passenger groups | | |
|---|---|---|---|---|---|---|
| | Current | Non-Users | Total | Current | Non-Users | Total |
| ATT (min) | 11.33 | 11.16 | 11.21 | 10.52 | 10.36 | 10.40 |
| $d_0$ (%) | 95.68 | 93.23 | 93.90 | 93.80 | 92.61 | 92.94 |
| $d_1$ (%) | 4.32 | 6.77 | 6.10 | 6.20 | 7.39 | 7.06 |
| $d_2$ (%) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $d_{un}$ (%) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |




### 8-route Alternative

| | Scenario U- Usual Practice | | | Scenario C – Passenger groups | | |
|---|---|---|---|---|---|---|
| | Current | Non-Users | Total | Current | Non-Users | Total |
| ATT (min) | 10.61 | 10.51 | 10.54 | 10.44 | 10.32 | 10.35 |
| $d_0$ (%) | 95.40 | 94.92 | 95.05 | 95.54 | 93.63 | 94.16 |
| $d_1$ (%) | 4.60 | 5.08 | 4.95 | 4.46 | 6.37 | 5.84 |
| $d_2$ (%) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $d_{un}$ (%) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |




## Conclusions

- The proposed method creates a network that is based on current ridership, but also optimized and more attractive to non-riders
- Genetic algorithms are very flexible and can be customized to fit specific performance needs
- The distinct passenger groups can be customized to fit specific policies
- The proposed method produced satisfactory results compared to the literature
- The proposed model can be further improved, based on future network design methods, while still being applied to distinct passenger groups
- The consideration of each group can be further customized for each step within the model