

Simple and Effective Solution Methodology for Transit Network Design Problem

Mahmoud Owais
Civil Engineering
Department, Assiut
University, Assiut, Egypt

Ghada Moussa
Civil Engineering
Department, Assiut
University, Assiut, Egypt

Yousef Abbas
Civil Engineering
Department, Assiut
University, Assiut, Egypt

Mohamed El-Shabrawy
Civil Engineering
Department, El- Mansura
University, El - Mansura,
Egypt

ABSTRACT

Transit Network Design Problem (TNDP) is the most important component in Transit planning and operation, in which the overall cost of the public transportation system highly depends on it. The main purpose of this study is to develop a simple and effective solution methodology for the TNDP, which goes beyond previous traditional sophisticated approaches. The solution methodology adopted in this research for the TNDP is based on partitioning the solution into two consecutive stages; Transit route Network Design Problem “TrNDP” stage and frequency setting stage. In the first stage; a deterministic solution for TrNDP is tackled to construct bus routes. The deterministic manner of the TrNDP solution relies on using linear and integer mathematical formulations that can be solved exactly with their standard solvers. In the second stage; bus frequencies are optimized among bus routes (obtained in stage 1) via Genetic Algorithm, for a total bus fleet size representing operator's main cost. The adopted solution methodology has been tested through Mandl's benchmark transit network problem. The test results showed that the methodology developed in this research is able to provide an effective solution in terms of the number of constructed routes, the direct demand coverage, and the total travel time.

General Terms

Transportation engineering, optimization, transit route design, frequency setting, integer programming, genetic algorithm.

Keywords

Transportation, transportation network design problem, transit route design, frequency setting, direct demand coverage, integer programming, genetic algorithm.

1. INTRODUCTION

With increasing traffic on roads, more mobility-related problems such as congestion, air pollution, noise pollution, and accidents are created. Public transportation is very important means to reduce traffic congestions, to improve urban environmental conditions and consequently affects people social lives. [1]. Planning, designing and management of public transportation are the key issues for offering a competitive mode that can compete with the private transportation [2]. These transportation planning, designing and management issues are addressed in the Transit Network Design Problem (TNDP) [3]. The TNDP aims to design a set of bus routes and manage their operation in an efficient manner for both users and operators [4].

TNDP is sorted as one of the most difficult problems to be solved in the field of transportation. This might be due to its

high degree of complexity. There are five main sources of complexity that often preclude finding a unique optimal solution for TNDP; Problem formulation, Non-linearity and non-convexity, Combinatorial complexity, NP-hard and Multi objective Nature of TNDP [4-7].

Over the last five decades, the TNDP has been under study for many researchers, most likely because the problem is practically important, theoretically interesting, highly complicated, and multi-disciplinary as well. Yu and Yang, used ant Colony Optimization to generate three types of bus routes to cover transit network demand, namely; skeleton, main and branch routes. Their objective function is to maximize demand coverage density. They tried to simulate ants' behaviour in searching for food to obtain best transit route network. Then, trips were assigned incrementally to transit network to reach an approximate equilibrium. Each portion was assigned to shortest path between origin and destination. After each assignment, the network travel time was updated by shortest hyper path algorithm calculating the expected waiting time and the change in the shortest hyper path [8].

Gao et al., proposed a bi – level programming model for TNDP which incorporated upper level objective function (Bus network design model) and lower objective function (transit equilibrium assignment model). Their solution approach focused on the interaction between supply side and demand side similar to continuous equilibrium network design problem. A solution algorithm based on sensitivity analysis was used for the proposed model [9].

Guan et al., developed a TNDP solution as an integer Mathematical Programming taking into account transit route configuration and transit passengers assignment simultaneously. Their model consisted of three weighted terms representing total route cost, total passenger in – vehicle time and total number of transfers. Their objective function balanced between transit route operator cost and passengers cost through the value of weighted factors. They indicated that the problem could be easily solved by standard branch and bound algorithm, since all model's variables were integer [10].

Pattnnik et al., implemented a two-phase procedure for TNDP. First phase, a set of feasible bus routes was generated through heuristic procedure and second phase Genetic Algorithm (GA) was applied to select optimal (or near – optimal) bus routes network. Their objective was to minimize the total system cost for users and operator [11].

Wu and Szeto, stated that there are two main approaches to handle TNDP; First approach is to solve the two sub-

problems simultaneously taking into account the interaction between them, second approach is to solve route design and frequency setting by separate procedures in a sequential manner [12].

Solving TNDP in one stage usually appears as bi-level problem. It stems from the trend to balance between operator's decision (upper level) and users reaction (lower level). Upper level would concern with route design problem and lower level would concern with frequency setting and passenger assignment problem. The model tries to take into account the interaction between supply side and demand side.

Chakroorty, 2003, suggested that it is an accepted approximation to take frequency setting phase after route design to alleviate the complexity of TNDP. This trend of solution was accepted by many researches [4, 11, 13-19].

The solution methodology adopted in this research for the TNDP is based on partitioning the solution into two consecutive stages; Transit route Network Design Problem "TrNDP" stage and frequency setting of bus service problem stage. In first stage; a deterministic solution for TrNDP is tackled to construct bus routes while achieving the maximum possible direct demand coverage. In Second stage; bus frequencies are optimized among bus routes (obtained in stage 1) via Genetic Algorithm for a total bus fleet representing operator's main cost. The main objective of the route design stage is to maximize direct demand coverage without violating other parameters of design, such as maximum route length and route network directness. The main objective of frequency setting stage is to minimize user's total travel time while taking into account users' reaction to the given transit network routes.

The structure of this paper is as follows. Section 2 provides the principal concepts of proposed methodology to design transit route network. Section 3 gives a simple procedure for bus frequency setting derived from optimal strategies concept. Section 4 Mandl benchmark transit problem is used to evaluate the proposed methodology. Section 5 is the conclusion.

The nominations used in the paper are presented in Table 1

Table 1. Nomenclature

d_{i-j}	the transit demand from (i) to (j) expressed as trips per unit time
t_{i-j}^r	minimum in vehicle travel time between (i) and (j) for passengers' demand ($d_{i,j}$) using route (r), $r \in R$
t_{i-j}^s	travel time between node (i) and node (j) through the shortest path
R	$R=(r_1, r_2, \dots, r_n)$ a set of bus routes
C_a	the fixed cost on link (a) (time or length)
X_a	flow on link (a) trips per unit time
q_{i-j}^k	flow on path k connecting node (i) and (j)
$\delta_{i-j}^{a,k}$	dummy variable, 1 if flow $q_{i,j}^k$ passes through link a, 0 otherwise
A	the set of network arcs (links)
θ_{i-j}	model decision variable equal to 1 if directed arc i-j is selected in bus route (r) under construction, 0 otherwise
f_r	frequency of route (r)

f_{min}	minimum allowable bus frequency
f_{max}	maximum allowable bus frequency
$L.F$	bus load factor
x_r	Dummy variable equals 1 if route (r) belongs to A_s , 0 otherwise
t_r	In-vehicle travel time according to route (r)
g_{i-j}^r	number of trips from (i) to (j) using (r), $r \in A_s$
A_s	is the set of attractive routes between (i) and (j)
b_{i-j}	flow value on link i-j obtained from assignment step
$d(R)$	Transit route network directness indicator
$d(R)_{max}$	maximum allowable directness value for bus routes
D_o	demand covered directly by the set of routes R
D_{o1}	Demand covered with one transfer by the set of routes R
D_{o1}^{max}	maximum passengers demand within service area to be covered indirectly (with one transfer)
D_o^{min}	minimum passengers demand within service area to be covered directly (without transfer)
D_{tot}	total passengers demand within service area to be covered by bus service
D_{tot}^{min}	minimum total passengers demand within service area to be covered by bus service
TD	network total demand
i, j, m	Origin, destination and transfer nodes $\in N$
K	set of available paths between (i) and (j) $k=1, 2, \dots, k_n$
S	of all network links combinations that include at least three nodes and perform closed circular route, $S = \{s_1, s_2, s_3, \dots, s_n\}$
LSI_{i-j}	Link Selectivity Indicator value on directed link i-j
N	network set of nodes
TBF	Total bus fleet size
t_{i-j}	arc travel time or length
T^r	bus route (r) time (or length)
T_{max}^r	maximum allowable bus route travel time (or length)
V_s	Vehicle seating capacity
X_{i-j}	decision variable represents flow on directed arc (i.e. flow from i to j)
α	is a parameter equal 1 for Poisson arrivals, or 0.5 for deterministic arrivals

2. TRANSIT ROUTE NETWORK DESIGN PROBLEM (TrNDP)

2.1 Problem Statement

TrNDP is considered the source of combinatorial intractability for TNDP. For any network there is a huge set of routes, that any subset of it is considered a solution. Main input data to the problem is the street network structure and the demand trips. Problem constraints refer usually to demand coverage and resources availability.

2.2 TrNDP objectives

TrNDP objectives would be stated in this simple minimization problem;

$$\text{minimize } \sum_{i \in N} \sum_{j \in N} d_{i-j} \times t_{i-j}^r \quad (1)$$

s.t.

$$D_{o}(R) \geq D_o^{\min} \quad (2)$$

$$D_{oI}(R) \leq D_{oI}^{\max} \quad (3)$$

$$D_{tot}(R) = D_o + D_{oI} \geq D_{tot}^{\min} \quad (4)$$

$$d(R) = \frac{\sum_{i \in N} \sum_{j \in N} d_{i-j} \times \frac{t_{i-j}^r}{t_{i-j}^s}}{TD} \leq d(R)_{\max} \quad (5)$$

$$T^r \leq T^{\max} \quad \forall r \in R \quad (6)$$

(1) represents the general objective of TrNDP of minimizing total routes costs (times) for covered demand. (2-4) represent demand coverage constraints. (5) represents route directness. Route network directness (d(R)) is an indicator to measure bus routes deviation from the shortest path among main transit nodes pairs since; d(R) = 1 indicates that all bus users would take the shortest path along their travel between origin and destination. Value of d(R) which exceeds one, it would indicate the delay caused by the set of bus routes to all users. (6) represents maximum allowable bus route length.

2.3 TrNDP Solution methodology

Approach

Our primary concern in route design phase (route planning side) is to meet both operator and user common point of view (trips should be laid on the shortest path as possible). We would assign transit demand with linear model to get an approximate transit network. This assumption would be valid in case of high frequency service, in which shortest transit line is the attractive one. We wouldn't take into account users' reaction towards bus service (choice) over network routes, because user's reaction would be taken in second stage (frequency setting) after defining bus routes. Then, another linear model is developed to generate a selection criterion on links from approximate assigned transit network. Finally, integer route construction model is adopted to define transit routes to obtain final transit network.

Assignment model would be easily written as follows to get approximate transit network with passenger's loads on links:

$$\text{minimize } \sum_{a \in A} C_a \times X_a \quad (7)$$

s.t.

$$\sum_{k \in K} q_{i-j}^k = d_{i-j} \quad \forall i, j \in N \quad (8)$$

$$X_a = \sum_{k \in K} \sum_{i \in N} \sum_{j \in N} \delta_{i-j}^{a,k} \times q_{i-j}^k \quad \forall a \in A \quad (9)$$

$$X_a \leq L.F \times f_{\max} \times V_s \quad (10)$$

$$q_{i-j}^k \geq 0 \quad \forall i, j, k \quad (11)$$

$$X_a \geq 0 \quad \forall a \quad (12)$$

K represents the set of shortest paths between node pair (i) and (j), it could be obtained by using Dijkstra's Algorithm and Yen's K-shortest Path [20, 21]. Assignment model would be considered an effective solution for TrNDP, while all trips are being assigned to the shortest path or kth shortest path. Each link is associated with certain flow (X_a). If a directed graph is considered, links would be divided into two reversed directions. Each direction is associated with half flow value (b_{i-j}).

In real world, bus begins from its start terminal traversing other nodes in its route (path) till it reaches its end terminal. Buses are routed in an environment to pick – up and deliver passengers demand among – what is called – Transit (O/D) locations. There are some facts; first buses go in a directed path, second the bus paths should meet high demand nodes at first, third bus passenger capacity entering any node is equal to bus passenger capacity out (whatever number of passengers are in or out).

Based on these simple facts, we would try to find one way directed system from bi-directional network, which would work together to give best possible bus routes (paths). So, in the beginning, we would take an arbitrary system of directions. Then, we would consider the flow from assigned step as flow capacity (maximum required bus passenger capacity), which shouldn't be exceeded. We would search for flow directions on network links, which maximize the overall flow of network by the following linear model;

$$\text{maximize } \sum_i \sum_j X_{i-j} \quad (13)$$

s.t.

$$\sum_i X_{i-j}(in) - \sum_m X_{j-m}(out) = 0 \quad \forall j \in N \quad (14)$$

$$-b_{i-j} \leq X_{i-j} \leq b_{i-j} \quad \forall i, j \in N \quad (15)$$

(13) is linear programming model aims to maximize the overall flow on the network. (14) considers conservation at each network node (flow in = flow out). It should be noted that directed graph is presented at (15), that there are upper and lower bounds of the flows on the links. A negative lower bound on the links flow is permitted during optimization process. This means; if X_{i-j} takes a negative value, it is an opposite flow direction on that link (i.e. the direction of flow is from (j) to (i)). The resulted network is an optimized directional system with new adjusted flows on links. These flows would be named Link Selectivity Indicator (LSI) i.e. X_{i-j} = LSI_{i-j} for each link. For a certain link, higher value of LSI denotes either this link is common in many OD shortest paths (assigning model depends on shortest path enumeration), or is a member of a path of high demand node pair(s) or both of them. This criterion reflects high demand coverage possibility along with route directness. Therefore, it would be considered as criterion for selecting these links on required bus routes

In routes construction process, we would measure the effectiveness of bus route in terms of highest loaded links of LSI (LSI summation over bus route). It would be useful to

relax the problem into the following integer programming (IP) optimization process;

$$\text{maximize } \sum_{i \in N} \sum_{j \in N} \theta_{i-j} \times LSI_{i-j} \quad (16)$$

s.t.

$$\sum_i \sum_j \theta_{i-j} \times t_{i-j} \leq T_{\max}^r \quad (17)$$

$$\sum_i \theta_{i-j} = \sum_m \theta_{j-m} \quad \forall j \in N \quad (18)$$

$$\sum_i \theta_{i-j} + \sum_m \theta_{j-m} \leq 2 \quad \forall j \in N \quad (19)$$

$$\sum_i \theta_{i-f} + \sum_m \theta_{f-m} = 2 \quad (20)$$

$$S = \{s_1, s_2, s_3, \dots, s_n\} \quad s_n \subset N, |s_n| \geq 3 \quad (21)$$

$$\sum_{i \in s_n, j \in s_n} \theta_{i-j} \leq |s_n| - 1 \quad \forall s_n \in S \quad (22)$$

Integer programming algorithm presented in (16) is a search tool for constructing a circular closed bus route from directed graph. (17) asserts that bus round trip travel time won't exceed its maximum allowable time or length, (18) provides a connected bus route [22]. (19) assures that every node will be visited once at most. (20) asserts that bus route under-construction must visit node (f). Node (f) is a fictitious node connected to all network nodes with imaginary links, as depicted in Fig. 1. *LSI* values on these imaginary links are equal to zero. The only role for this fictitious node f is to create open bus routes.

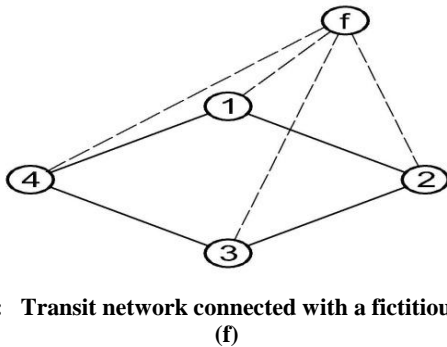


Fig. 1: Transit network connected with a fictitious node (f)

Equation (21) defines S as the set of all network links combinations that include at least three nodes and perform closed circular route [23]. (22) prevents the possible existence of any group of circular bus routes except the one passing the fictitious node (f).

The set S may be defined as follows; 1- Apply (16-19) before adding the fictitious node to the network. 2- This would result in circular or combination of detached circular routes. 3- The resultant circular (or circulars) will be defined to the set S and be prevented by applying (22). 4- Apply again (16-19), this may result in another circular routes subset of S. 5-This process would be repeated till all S set are defined and there isn't any internal closed circular route can be formed.

(16-22) are used to construct bus routes iteratively and this gives the operator flexibility to discard any unprofitable route from the solution of TrNDP.

2.4 TrNDP solution methodology structure

The structure of the proposed solution methodology for TrNDP can be concluded in the following steps:

- Step1. Construct coded route network.
- Step2. Identify travel time (or length) on links.
- Step3. Assign nodes transit trips using assignment model (7-12), reaching loaded base – network.
- Step4. Assign half loaded links values and assume arbitrary directed graph arrows (N.B the algorithm adjusts the direction later in the process of reaching optimized network directions).
- Step5. Optimize the loaded base – network (13-15), reaching optimized directed loaded base – network with LSI values on links.
- Step6. Construct the first bus route (16-22), covering the highest LSI summation, set $r = 1$.
- Step7. Subtract the least value of LSI on the constructed route from the route links along its path to get updated network with new LSI values.
- Step8. Compute the total demand satisfied by the set of R th routes (using -0- and -1- transfer), if that demand $\geq D_{tot}^{min}$ (the minimum total demand needed to be satisfied) terminate route construction process and output the set R routes; otherwise, go step 6.

3. FREQUENCY SETTING

3.1 Problem definition

In planning side (stage one), we proposed a deterministic solution methodology for TrNDP. It would result in a number of bus routes which satisfy some of TrNDP objectives. These routes main objective is to achieve maximum direct demand coverage for the transit network with a reasonable value of route network directness. The output routes of this stage are considered as the input for the second stage (frequency setting problem).

In the operational side (stage two), two approaches for frequency setting are found in literature namely, capacity free and capacity restraint frequency setting [24]. In this paper, we considered capacity free type (i.e. congestion wasn't taken into consideration).

The planner is interested in setting bus frequency on the network in the most precise way regarding which routes to be used and loaded, according to passengers' interest. The problem arisen here is transit passenger assignment. It can be considered the major component in transit route frequency setting. It could be defined as the query of passenger flows on transit networks segments. Passenger assignment is a process of predicting passengers' behavior in selecting bus routes according to route time length and bus frequency for each bus route [25].

Transit passengers in many cases have to deal with overlapping bus routes with some routes sharing sections and common stops. This problem is sub-problem of transit passenger assignment, called common-lines problem. Various assumptions and studies are made in order to track

passengers' behavior towards a given supply of transit service [26-28].

In passenger assigning, it is necessary to identify the set of attractive routes for transit passenger for each Origin-Destination node pair, the solution of the following optimization problem will define the set of attractive routes A_s [9, 29].

$$\text{minimize } \frac{\alpha + \sum_1^n t_r f_r x_r}{\sum_1^n t_r f_r} \quad (23)$$

s.t. $x_r = 0$ or $1 \quad \forall r \in A_s$

α is a parameter equal 1 for Poisson arrivals, or 0.5 for deterministic arrivals

Where the objective function of (23) denotes the total expected travel time between (i) and (j). A route (r) would be considered a part of attractive routes if $x_r=1$. The fraction of passengers (P_r) served by each route (r), considering A_s is the set of attractive routes between (i) and (j), would be estimated by using frequency sharing rule [30];

$$P_r = \frac{f_r}{\sum_{r \in A_s} f_r} \quad (24)$$

To alleviate the complexity of determining optimal strategies for transit users, these assumption were made;

1. Passenger would select bus route, among subset of bus routes (attractive routes), boarding the first incoming bus from this subset.
2. Attractive bus routes set, between any node pair, would be considered bus routes within 1.10 long of the least travel time bus route.
3. Passengers arrival is deterministic (the expected waiting time equals to half headways).
4. Passenger wouldn't transfer, if there is a direct route to his/her destination.
5. Passenger, who would transfer, predetermines a certain transfer node which is the closet possible transfer node to his/her destination node.
6. Arriving bus capacity is enough for waiting passengers.

We could relax the model of frequency setting into this optimization problem

$$\text{minimize } \sum_{i \in N} \sum_{j \in N} \sum_{r \in A_s} g_{i-j}^r \frac{0.5 + \sum_{r \in A_s} f_r t_{i-j}^r}{\sum_{r \in A_s} f_r} \quad (25)$$

s.t.

$$g_{i-j}^r = d_{i-j} \frac{f_r}{\sum_{r \in A_s} f_r} \quad \forall r \in A_s, i, j \in N \quad (26)$$

$$f_{\min} \leq f_r \leq f_{\max} \quad (27)$$

$$\sum_{r \in R} f_r \times 2T^r \leq \text{TBF} \quad (28)$$

$$L.F \times f_r V_s \leq \sum_j g_{i-j}^r \quad \forall r \in R, i \in N \quad (29)$$

(25)'s binary variables are removed due to the assumption No.2 (i.e. the attractive routes are determined before the step of frequency setting). The only decision variable in this model becomes each bus route frequency (it is assumed to be continuous using nearest integer rule). (26) splits d_{i-j} flow among attractive routes according to each route frequency. (27) presents minimum and maximum allowable routes frequency. (28) denotes available Total Bus Fleet. (29) asserts that there is enough bus seating capacity at each origin node (i). For one transfer trips (25) would be applied twice, firstly at origin node (i) and secondly at the predetermined transfer node.

3.2 Solution Search Tool

The proposed model at (25) is a nonlinear model, which is difficult to be solved by exact methods, so we would propose Genetic Algorithm (GA) as a stochastic search tool for solving the proposed model. GA is one of the most preferable tools used in solving many transportation engineering applications due to its simple adaptation to the problem. It is used in solving many mathematical programming problems by examining a large part of search space aiming to find optimal or near optimal solution. It depends on the evolutionary theory of genetics, i.e. the next generation would be better than parents. Representing random population of individuals (feasible solution) as binary code (chromosomes) is considered the first generation for GA. Three sequential operators deal with this Generation to produce the next one, these operators namely, Selection, Reproduction and Mutation. The reproduced generation is considered an initial solution for the next generation. The process continues until defined criteria of convergence are met, GA procedure is illustrated in next Pseudo-code [31, 32].

GA Procedure Pseudo-code

Create Initial Population

Calculate Fitness value (model 25) for each chromosome

Rank the population;

For k= 1 to Number_of_GA_ iterations do

For j= 1 to population_size/2 do

Select two parents p1, p2 using roulette wheel selection method

Generate a random number r

If r < crossover_probability then

Apply crossover method over p1, p2 to generate two offsprings s1, s2

Else

Let s1 = p1 and s2 = p2

Endif

Generate a random number r2

If r2 < mutation_probability the

Apply mutation method on s1

Apply mutation method on s2

Endif

Insert s1 and s2 into the new_generation_list;

Rank the new_generation_list;

Set population_i = new_generation_list;

Endfor

Endfor

Return the best chromosome in the population_i

End of GA

4. COMPUTATIONAL CASE STUDY

4.1 Mandl's Benchmark transit Network

In order to demonstrate the effectiveness of the solution methodology proposed in this paper, a popular benchmark network is solved (Mandl's Swiss transit network). Mandl's Swiss transit network is the most popular transit network that has been utilized by many researchers as a benchmark network to compare their results with Mandl's solution results. Mandl's transit network consists of 15 nodes connected by 21 links with a total demand of 15570 trips [4, 7, 13-15, 17-19, 24, 33-35].

4.2 Solution procedure for Mandl's transit network

As indicated early, the solution methodology proposed in this research for the TNDP is based on partitioning the solution into two consecutive stages: 1) Transit route Network Design Problem "TrNDP" stage and 2) Frequency setting of bus service problem.

In the first stage, TrNDP solution methodology described in section (2.4) is implemented. Equations (7-22) are mainly linear and integer programming models. Therefore, they can be solved with their standard solvers. Bus routes constructions are continued until no improvement happened in the network direct demand coverage. The output from the first stage is used as an input for the second stage. The proposed solution assumes that maximum allowable route time length is 40 min.

In the second stage, the proposed frequency setting optimization problem represented in Equations (25-29) is solved via GA, the minimum and the maximum bus frequency on each bus route are 6 and 30 bus/hr, respectively. Bus vehicle capacity is fixed at 40 seats per bus and bus load factor (L.F) 0.8 ~ 1.25. Transfer penalty is calculated by assuming five minutes as penalty for each trip hasn't a direct route to its destination. For GA; Number of GA iterations = 200, Population size = 400, crossover probability = 0.75 and mutation probability = 0.15. Solution methodology was run on a PC with Intel(R), Core (TC) I7, 2.8 GHz processor and 6 gig of RAM which take about ten minutes for one run execution. Four executions were made using total fleet sizes; 99, 87, 84 and 82.

4.3 Results and Discussions

The first stage (Transit route design) resulted in six bus routes. A summary of constructed routes is presented in Table 2. For total fleet size equals to 99 buses (Mandel's fleet size), the convergence process of GA is shown in Fig. 2.

Table 3 presents a comparison between this study analysis results and highlighted previous work that tackled Mandl's transit network in their solution as a benchmark problem. In Table 3, both planning and operational parameters, for the benchmark transit network, using the proposed solution methodology and previous work are presented. Planning parameters include: number of generated routes, percentage of transfer trips (zero-, one-, and two-transfer), percentage of total satisfied demand, network directness, transfer directness, total route length in min., and direct trips over route length in pass/min. Operational parameters consider: total in vehicle travel time in min, total waiting time in min, total transfer penalty in min, and the total travel time in min which is the summation of all of them. For the sake of fair comparisons,

operational parameters are considered at previous work fleet sizes (operator costs), as shown in Table 3.

The key indicators of good transit planning and operation are to achieve maximum direct demand coverage and a minimum total travel time while keeping good value of other network parameters. These would encourage more people to select public transport and consequently achieving one of the most important goals of transit planning and operation. For the same benchmark transit network, the proposed solution methodology provides a significantly better solution than others in terms of both planning and operational parameters, particularly in percentage of direct demand coverage and the total travel time, which make the transit network more attractive to the users, as shown in Table 2.

Moreover, the number of routes can be consider the most precise criteria -in regard with other parameters of comparison- for judging the efficiency of any search method, in the process of seeking more direct routes. Where, less number of routes reveals the methodology strength in assembling candidate links in one continuous bus route and entails – accordingly – fewer amounts of computational effort of the bus and the driver scheduling part. As shown in Table 2, the proposed solution methodology provides less number of routes than other solutions (except Mandl's).

Furthermore, at the same fleet size (the same operator cost), the proposed solution methodology achieves the lowest total travel time in almost all cases (fleet sizes). The total travel time is a combination of in-vehicle travel time, waiting time, and transfer penalty. The proposed solution methodology reaches a reasonable in vehicle travel time, due to the good value of route network directness. Moreover, the proposed solution methodology gains the smallest transfer penalties while attained the highest waiting time for all cases (fleet sizes). This is due to the trade-off between waiting time and transfer (passengers are not willing to make transfer, if there is a direct route serving their origin destination).

The results of proposed methodology present an efficient solution for TNDP which is attained by simple while efficient procedure. The presented solution methodology can be used as an initial solution for other meta-heuristic ones to improve the results in attempt of reaching global optima. The quality of any meta-heuristics technique depends mainly on the quality of initial solution, besides it acquires for the number of desired routes as input (which isn't known in advance).

Table 2: Constructed routes summary

Route No.	Route node sequence	Time length	$\sum LSI$	$\% \sum D_o$	%Total demand satisfied
1	3-4-1-2-5-14-6-9-7	35 min	2955.36	50.16	50.16
2	6-14-5-7-9-12-10-11	40 min	2132.04	73.15	87.63
3	2-1-4-3-5-7-9-6-14	35 min	1501.72	73.15	87.63
4	8-14-5-7-9-12-13	33 min	982.36	78.87	91.52
5	0-1-2-5-14-6-9-10-12	35 min	790.00	93.12	100
6	0-1-2-5-3-11	27 min	399.16	96.01	100

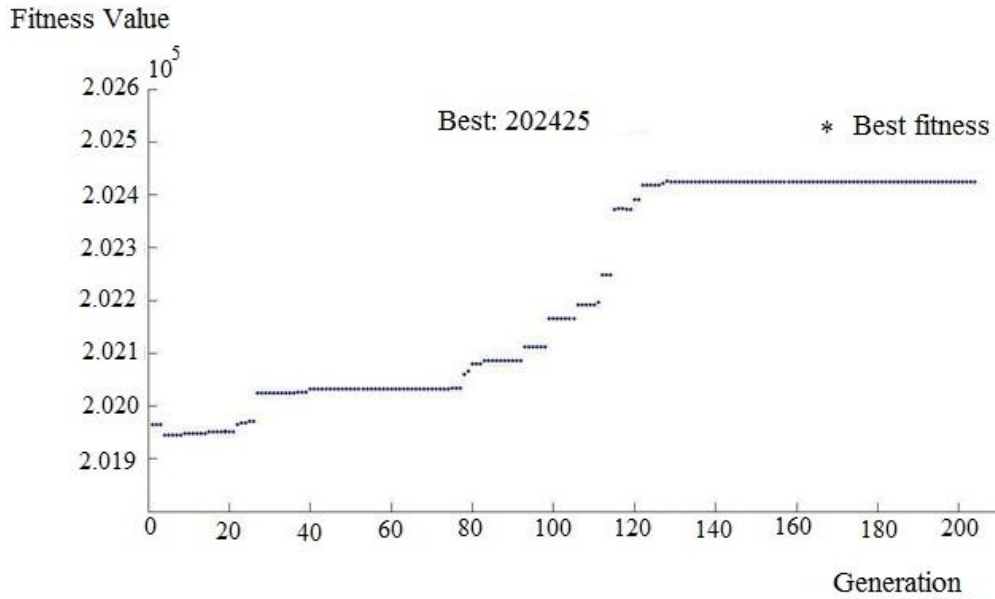


Fig. 2: Convergence process of GA

Table 3: Comparison of Approaches for Mandl's Benchmark Network problem

Problem source		Mandl		Baaj and Mahmassani		Shih and Mahmassani		Bagloee & Ceder		
Year		1980		1991		1994		2011		
Search method		Mandl ¹	This study	B&M ²	This study	S&M ³	This study	GI&AS ⁴	This study	
Parameters	Planning	Number of routes	4	6	7	6	8	6	12	6
		-0- transfer trips % (D_o)	69.94	96.01	80.99	96.01	87.73	96.01	83.66	96.01
		One transfer trips% (D_{o1})	29.93	3.99	19.01	3.99	12.27	3.99	15.21	3.99
		Two transfer trips% (D_{o2})	0.13	0	0	0	0	0	0.95	0
		Total Demand satisfied % (D_{tot})	100	100	100	100	100	100	99.82	100
		Network directness $d(R)$	1.05	1.15	1.16	1.15	1.03	1.15	RNR ⁵	1.15
		Transfer directness ⁶	1.3	1.05	1.19	1.05	1.12	1.05	RNR	1.05
		Total route time length (min)	82	205	106	205	151	205	261	205
	Direct trips / route length (pass./min)	132.8	74.35	118.96	74.35	90	74.35	49.9	74.35	
	Operational	Total bus fleet	99	99	82	82	84	84	87	87
		Total in-vehicle time (min)	177,400	178,270	180,356	178,270	191,826	178,270	167,198	178,270
		Total waiting time (min)	18,194	23,673	22,804	32,366	19,726	29,724	24,591	28,563
		Total transfer penalty (min)	23,500	3,106	14,800	3,106	13,550	3,106	10,465	3,106
		Total travel time (min)	219,094	205,049	217,954	213,742	225,102	211,100	202,255	209,939

1Mandl's method 2 Baaj and Mahmassani's method 3 Shih and Mahmassani's method 4 Gravity Index and Ant – System
 5Results not Reported 6Calculated as d(R) but for transfer trips only

5. CONCLUSION

Transit Network Design Problem (TNDP) differs from the ordinary network design problem. Network design problem is concerned with network improvements by adding new links or increasing capacity of existing ones. TNDP concerns with finding bus routes and frequencies over the studied network, so it consists of two sub-problems, namely; route network design and frequency setting. In this paper, the adopted approach is to solve these two problems in sequential manner. Providing transport community with simple and effective transit route design technique is the main purpose of this paper. Solution methodology depending only on linear and integer operators was presented to solve Transit route Network design problem. The proposed solution methodology goes beyond previous traditional heuristics and Meta – heuristics (approximate) approaches. It is highly depended on demand matrix. It is generic method since it confirms to several network routes configurations. It doesn't bias towards any existing transit network. It is flexible; since planner can classify generated bus routes according to demand coverage, which enables operator to execute selected routes according to available existing resources. Frequency setting phase was conducted to evaluate the transit route network configuration in terms of operational parameters. The key indicators of good transit planning and operation are to achieve a maximum direct demand coverage and a minimum total travel time while keeping good value of other network parameters. These would encourage more people to select public transport and consequently achieving one of the most important goals of transit planning and operation.

In future work, elastic demand would be considered, in order to model the changes in the origin-destination matrix according to the supply of public transport. Further, more studies of TNDP with environmental impact would be considered in the future, since the impact of emissions on health and global warming is one of today's hot topics.

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