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A simulated annealing approach to solve the network design of one-way streets: case of shiraz network

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Abstract

This study is devoted to the formulation of the network design problem of one-way streets and the application of simulated annealing (SA) algorithm to solve this problem for a large real network. It discusses some points of views on one-way street networks, the objective function used for design, the way in which design constraints may be considered, and the traffic problems concerning one-way streets. The results of applying the method to a real network are compared with the respective results of another heuristic approach of alternative one-way network generation, to test the goodness of SA algorithm. The SA solution to the problem became superior to any other solution at hand. Moreover, the question of the necessity of using the true values of the parameters of volume-delay functions, definition of "projects" (street segments), as well as the sufficiency of morning peak demand for design, are dealt with. Suggestions for further research end the discussion.

Keywords: Network design, one-way streets, meta-heuristics, Simulated Annealing.

1. Introduction

One-way operation of streets is a way of allocating the available resources (road space) to the traffic flows in a network. Normally, one allocates this resource equally between the two ways of movement in a street. However, unequal allocation of roadway width to each direction of movement in a street in the spectrum of 0-100 percent may sometimes become necessary. For example, a 6-lane street may operate in the form of 3-3, 2-4, 1-5, or 0-6 lanes in the two directions. In the latter case the street becomes a one-way street.

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There are several reasons for making a street to operate one-way, which include: insufficiency of the width of the street to operate in two ways, reduction of the delay at related intersections, increase in the safety of vehicles as well as pedestrians at these intersections, and reduction of congestion in the street. One-way operation may reduce congestion (e.g., vehicle–hours) in the direction of the movement; however it may reduce accessibility around the one-way street in the network, and hence may increase vehicle-kilometers. Thus, one may expect quantities such as fuel consumption and pollutants' emissions to rise as the percent of road length operating one-way in a network increases. Existence of such trade-offs between various aspects of network operational measures are some sources of complexity in the one-way street network design (OSND) problem.

The OSND problem is a difficult problem. In a simple version of this problem, where there are only 3 states for a candidate street (one-way in either direction, and two-way), one would have 3^n network configurations for an n-project (n candidate streets) case. This makes OSND more difficult than a conventional network design (ND) problem that in its simplest form has 2^n configurations for a build/no build decision for each project. Moreover, OSND is more difficult than the conventional ND in that it is harder to measure the outcomes of the decisions in OSND which are basically marginal, and multidimensional.

The literature on one-way street network design is quite limited, as described below, and the authors are not aware of any other work in this area, particularly in the application to real large scale cases. This has been the major motivation in undertaking this study: To define the peculiarities of one-way street network design problem, design a meta-heuristic algorithm to solve it, and to apply it to a real case to see the quality of the solution.

In what follows, first we review the limited available literature in the relevant area of network design, and then define the OSND problem and its characteristics in this paper. Next, we describe the SA algorithm which is designed to solve this problem. Then, the case under study is introduced. The results of the application of the algorithm on the case are presented next, which is followed by the discussion of a testing heuristic algorithm, whose results are compared with those of SA. The paper is then concluded and some points are mentioned regarding future research direction.

2. A literature survey

It is not the intention of this paper to cover the conventional ND problem. The interested readers may consult Steenbrink [1], and Wong [2] for the earlier algorithms and methods to solve ND problem, and Yang and Bell [3] and Farhani et al. [4] for a more recent endeavor in this respect. However, it is instructive to review such surveys. Soon after the formulation of the ND problem (see LeBlanc [5]); it was found that to solve this bi-level combinatorial optimization problem exactly is a prohibitive task. Thus, several avenues have been explored to trade off some accuracy for computational speed for real size problems. These avenues include: (a) replacing user equilibrium flow by system equilibrium flow (Dantzig et al. [6], and Chen and Sule Alfa [7]); (b) assuming constant link cost function instead of a nonlinear flow-dependant one (Boyce et al. [8], and Holmberg and Hellstrand [9]); (c) relaxing the integrality of project decision variables (Steenbrink [10], Abdulaal and LeBlanc [11], and Dantzig et al. [6]); (d) decomposition of the problem (Steenbrink [10], Dantzig et al.[6], and Solanki et al. [12]); (e) aggregation by link and node abstraction or extraction (Chan [13], and Haghani and Daskin [14]); (f) intrinsic approaches to by-pass the complexity of ND problem by defining a new problem to replace it (Yang and Bell [3]); and finally, (g) design and use of heuristic solution methods. The latter approaches, which basically retain the integrality of the projects, and adhere to the correct behavior of the users in path choice, have gained more momentum than others. There are several approaches in the latter category which include approximating the objective function with another function which simplifies the problem (Poorzahedy and Turnquist [15]), use of modern search techniques such as Genetic Algorithm (Yin [16]) Ant System (Poorzahedy and Abulghasemi [17]), Hybrid meta-heuristic algorithms (Poorzahedy and Rouhani [18], and others (see, e.g., Chen and Sule Alfa [7]). Most, if not all, approaches to solve the OSND problem may also be included in this category, as follow.

Lee and Yang [19] use a meta-heuristic technique, namely Simulated Annealing, to solve the ND problem for the design of one-way streets. Their objective function is the total users' travel time, which is to be minimized. Each street is a link which can take 3 states (2 one-ways in either direction, and 1 two-way). Capacity of link a, Q_a, depends on the number of link lanes, which is increased by 12% for a one way operation of the link. Intersection delays are considered for right turn, thru and left turn traffic separately. All intersections are signalized with two phases, where delay of movement depends both on signal timing and the volumes of conflicting traffic. This latter dependency made Lee and Yang [19] to use Variational Inequality (VI) to solve the lower level equilibrium flow problem instead of the usual algorithm of Frank and Wolfe (Sheffi [20]). Then, they propose two heuristic algorithms to solve the network design problem of one-way streets, one of which was based on Simulated Annealing (SA) technique, and the other one basically serving as a base for comparison. They have tested the performance of the SA algorithm in a small test network under three demand levels. This test network is a 5x5 nodes square grid network, with randomly chosen link lengths, and randomly generated base O/D demand. There are 80 links, and all feasible movements are allowed at all intersections. The base O/D demand is multiplied by 0.5, 1.0, and 1.5 to represent low, medium, and high demand, respectively. They observe that *the size of the problem*, rather than *the extent of the constraints*, is the main complexity in its solution. The cpu time to solve the one-way network design for the medium and high demand cases of their small size test problem is *several days*. (The reader may guess a value for this time for a real size network of about 1000 nodes and several thousand links based on the assertion of these authors regarding the influence of the size of the problem on the complexity of its solution.) They report a *less than 1% reduction in their objective function*, the total travel time. The latter observation, in turn, reveals the importance of the measurement of the objective function, and raises question regarding the necessity of using a sophisticated lower level problem in a network design in which the whole improvement in the objective function of the optimal network is marginal, if not infinitesimal.

In a bi-level optimization problem, one has to note the compatibility of the speed of solving the lower level problem, the upper level objective function range of variation, and the solution technique employed. One difference between meta-heuristic and some exact solution techniques of solving optimization problems is that the exact techniques usually rely on a more computationally involved procedure in any iteration to improve the decision variable values and do less iteration, but the (meta-)heuristic ones rely upon an accelerated scanning procedure per iteration to cover a wide range of solutions in much higher number of iterations. This is particularly effective in non-convex optimization problems, where procedures of the exact type are unable to find a global optimum, but the meta-heuristic techniques present good solutions. Good solutions come from the observation that the reduction in the objective function is marginal, and that there are substantial number of solutions that are similar in the objective function values. Thus, it seems that increasing the inertia of meta-heuristic techniques by computationally demanding lower level problems (like solving a more general equilibrium flow problem instead of a simpler version of that) in cases where the range of variation of the upper level objective function is marginal, significantly increases the "weight-to-power" ratio of the search engines, and hinders the maneuverability of the search mechanism. This is one purpose of this research to build an algorithm with more balanced components.

Drezner and Wesolowsky [21] aim to minimize total user travel time in designing one-way street network. They have 3 choices for each link (2 one-ways and 1 two-way). Their model requires at least one path to exist between each O/D pair. They assume delay only in links, and neglect delay at nodes. Moreover, they assume constant travel time for each link, and that one-way operation of a two-way street would reduce its travel time to $\sim (\sim < 1)$ times the travel time in a two-way operation in same situations. These researchers present several algorithms to solve the problem, including a SA algorithm. For $\sim < 1$, they found that a combination of one-way/ two-way network performs better than a complete two- way network.

Drezner and Wesolowsky [22] present a network design problem in which a link is decided to be built or not, and if it is built it could be operated as one-way or two-way. The objective is to minimize total construction and transportation costs. Four problems have been defined based on two objective functions, and two cases of link operation (only two-way, or two-way and one-way mixed). A descent algorithm, Simulated Annealing, Tabu Search, and a genetic algorithm have been used to solve these problems, among which their genetic algorithm performed better.

Drezner and Wesolowsky [21, 22] test their algorithms on small problems having 40 nodes, but with 65, 99, and 164 links, to form sparse, medium, and dense networks respectively. They even consider smaller test network of 14 nodes and 20 links. Their assumption on the improvement of travel time by one-way operation, $\sim$, is rather hypothetical. The reductions in the objective function by the solutions found for these networks range 0.6 to a maximum of 3.5 percent.

In a recent attempt, Miandoabchi et al. [23] consider a more involved transportation decision problem, which includes lane allocations for two-way streets. Their problem includes decisions on lane addition to the existing links, new project construction, conversion of two-way links to one-way links, and allocating some street lanes exclusively for bus operations. They formulate the problem as a bi-objective bi-modal mathematical programming problem, which are tried to be solved by several proposed hybrid meta-heuristic algorithms made of Simulated Annealing and one of Genetic, Particle Swarm, and Harmony Search algorithm. They apply these algorithms on small test networks (less than 40 nodes, and less than 66 links).

The above overview of the existing literature shows that there is room for showing (a) the application of heuristic algorithms on the design of large and real networks, (b) how effective is solving local network operation problems by one way streets on the global network performance measures (vehicle-hours, vehicle-kilometers, etc.), and (c) how does technical OSND problem solution actually solve multi-criteria, and to some extent, non-technical problems (see Walker et al. [24] for this point), of one-way street network design problem. These are the motivations behind this research.

3. Problem definition

The street network design problem may be envisaged as a multi-objective problem. This will become clearer when the results of a case study are presented later in this paper. However, if one is to choose only one objective to design the network (for example, as in a lexicographic multi-attribute analysis of the problem), it seems that total user travel time would be a natural choice, as is in the well-known network design problem. This is for a multitude of reasons, among which are: (a) travel time is the most important objective in urban networks which is proportional to most other user costs; and (b) this choice would make the problem manageable.

The decision variable is an integer variable, one for each street with the potential to operate one-way, which takes the value of 1 if it operates two-way and the value of 2 or 3 if it operates one-way in either direction.

3.1. Constraints on one-way operation of streets

There are several constraints on one-way operation of streets in a network. Some of these constraints are at street level, for example street width constraint which may restrict 2-way operation. Some other constraints on one-way operation of streets are at network level. The followings are examples of such constraints:

(a) *movement accordance*, which restricts two adjacent streets to operate in accordance with each other: (a1) both operate similarly, when they are in series; (a2) both operate one way in opposite directions, when they are parallel to each other.
(b) *feasibility*, which enforces the existence of at least one path between each O/D pair with positive demand.
(c) *reasonability*, which (for example) prohibits all links of a node from being directed into/out of that node.
(d) *special operation*, which (for example, for the case of countries driving on the right side of the roads) forces several one-way streets to form a cycle by right-turn movements only (left turn cycles have more conflicts).
(e) *security purposes*, which direct traffic into a special path away from certain places or buildings.
(f) *management of flow*, to relieve an arterial from congestion by directing all cross-streets outward.

3.2. A Formal Definition of One-way Street Network Design Problem

Let:

DS = the set of streets with the potential of one-way operation, $k = |DS|$;

d_i = the set of decisions for street i, which is either the set {1,2,3} or a 2-member subset of it;

Z_i = the movement direction of street i (chosen from the set d_i);

$Z = (z_1, z_2, \ldots, z_k)$ is a one-way network configuration;

$N(Z)$ = the network under consideration with one-way street configuration Z ;

FN = the set of permissible (feasible) networks;

A_Z = the set of links with configuration Z of one-way streets;

$x_a(z_a)$ = user equilibrium flow in link a with z_a as the respective decision;

$X(Z)$ = the vector of link flows when Z is the configuration of the one-way streets;

$t_a^{z_a}$ = volume-delay function of link a with configuration z_a ;

D = fixed Origin-Destination (O/D) demand; and

Assign(N,D) = a procedure which estimates the user equilibrium link volumes when demand D is assigned to the network N.

The authors defined the fixed demand OSND problem in 2002 as follows (Poorzahedy et al. [25] and Shirazi [26]):

$$\text{(P1)} \quad Min \sum_{a \in A_Z} x_a(z_a)\, t_a^{z_a}\,(x_a(z_a))$$

$$s.t.: Z = \{(z_1, z_2, ..., z_k) : z_i \in d_i, i = 1,2,...,k\} \tag{1}$$

$$N(Z) \in FN \tag{2}$$

$$X(Z) = Assign\,(N(Z), D) \tag{3}$$

Usually, the pattern of traffic in morning peak and evening peak are very different, and to some degrees opposite to each other, so that an appropriate one-way street configuration for the morning peak may not suit that of the evening. Reversing one way operation of a street may inflict upon safety. So, for a 2-period case, one may define the following problem to replace problem (P1):

$$\text{(P2)} \quad Min \sum_{i=1}^{2} \gamma_i \sum_{a \in A_Z} x_a^i(z_a)\, t_a^{z_a}\,(x_a^i(z_a))$$

$$s.t.: (1), (2), and$$

$$x^i(Z) = Assign(N(Z), D^i),\ i = 1,2 \tag{4}$$

where i = 1 and 2 represent, e.g., morning and evening peak periods, γ_i is the number of hours demand pattern similar to that of i prevails in the network. Other variables are as defined before but without superscript i.

4. The proposed solution algorithm

The approach of this study to solve the one-way street network design problem is that of SA. The algorithm will be presented below after a definition of its specifications.

4.1. The set of candidate links

Independent design (state choice) of candidate one-way streets from other candidate links is not a good practice. In other words, unlike the ND in which links are chosen according to the maximum efficiency/ minimum cost, in OSND the choices of links' directions are subject to additional grouping constraints. This point seems to have been lacking in practice in the previous hypothetical works reviewed in this paper. To observe this constraint, each street in the real network may be considered as a series of links or nodes. Then, decision of two-way operation $(d_i = 1)$, and one-way operation in either direction $(d_i = 2\, or\, 3)$, of these series of links should be made together.

4.2 Individual link constraints

If a two-way operation is not admissible by street width restriction, then the set of decisions for each link in the series would be {2, 3}. If movement of traffic in at least one direction is mandatory in a series of links (e.g., based on demand management policies), then either {1, 2} or {1, 3} is the set of decisions for these links.

4.3. Link Collection Constraints

To preserve access, a one-way link must be accompanied by a parallel link (not necessarily one-way) in the opposite direction. Therefore: (a) Two close parallel links must be either two-way, or one-way in the opposite directions, or one be one-way and the other two-way. Such two links will be called *partially opposing*. (b) To serve the directional peak flows in the morning and evening most, in this policy two nearly parallel similar width avenues would operate either two-way, or if one of them becomes one-way, the other would operate one-way in the opposite direction. Such two avenues will be called *completely opposing*. (c) Moreover, drivers expect a continuity of movement in their trips through a corridor in the network. This may require two avenues in series operate in accordance with each other: both be two-way, or one-way in the same direction. Such two avenues will be called *completely unidirectional*. However, it may be sometimes admissible that two such avenues do not operate in opposite directions. In this case, they will be called *partially unidirectional*.

Mathematically, one may express the admissible decisions for two streets i and j in the above cases as follows. Let d_i and d_j be the sets of decisions for streets i and j. The number of simultaneous decisions for these two streets would be $|d_i| \times |d_j|$, where $|d_i|$ is the cardinality of the set d_i (the number of d_i members). Let sd_{ij} denote the admissible simultaneous decisions of streets i and j. In general, $sd_{ij} \subseteq d_i \times d_j$, where $d_i \times d_j = \{(z_i, z_j) : \forall z_i \in d_i, \forall z_j \in d_j\}$, and one may write:

$sd_{ij} = d_i \times d_j - \{(2,2),(3,3)\},$ for partially opposing i and j;

$sd_{ij} = d_i \times d_j \cap \{(1,1),(2,3),(3,2)\},$ for completely opposing i and j;

$sd_{ij} = d_i \times d_j - \{(2,3),(3,2)\},$ for partially unidirectional i and j;

$sd_{ij} = d_i \times d_j \cap \{(1,1),(2,2),(3,3)\},$ for completely unidirectional i and j;

In the above statements, one-way operation of type 2/3, is defined as those directions of movement pointing to the two right/left quadrants of a plane, respectively.

Among the constraints that could possibly be imposed upon the design process, one could consider construction of one-way loops. Loops may operate two-way, or if one-way it will operate clockwise or counter clockwise. Clockwise operation seems to create fewer conflicts in traffic flow (for right-hand side driving countries). Such constraints may be imposed by sd_{ij}'s. However, there are constraints which may not be easily implemented by sd_{ij} sets. One important such constraint is the existence of a path between each O/D pair with positive demand for travel, which may be checked by shortest path algorithms.

4.4. Description of a SA algorithm for OSND problem

Consider a combinatorial optimization problem (R, C), where R is a finite, or otherwise infinite but countable, set of network configurations; and C a cost function, $C : R \to R$, which assigns a real number $C(i)$ to each network configuration $i, i \in \mathrm{R}$. (Recall that an infinite set is countable iff it is possible to list the elements of the set in a sequence, indexed by the positive integers. For example, the set of positive rational numbers is countable.) Without loss of generality, let us suppose that network configuration with a lower value of C is a better configuration. The problem is to find configuration i_o such that

$$C(i_o) = Min\{C(i) : i \in \mathrm{R}\}$$

Each network configuration is envisaged to correspond to a state of a solid in a simulated annealing process. The cost function C plays the role of the energy of the solid, and c the respective temperature (which is a control parameter). At first, c is taken high, and at each stage from a state i another state j in the neighborhood of i, R_i, could be reached. This will change the "energy" of the system by $\Delta C_{ij} = C(j) - C(i)$. If $\Delta C_{ij} \leq 0$ then the probability of moving from state i to state j would be 1.0, otherwise (when $\Delta C_{ij} > 0$) this probability will be governed by the Metropolis criterion $\exp(-\Delta C_{ij}/c)$. This process is continued for any given c until equilibrium is reached, at which point the Boultzman probability density function would govern the distribution of states:

$$q_i(c) = \Pr\{network configuration = i\} = \frac{1}{Q(c)} \exp[-C(i)/c] \tag{5}$$

where $Q(c)$ is a normalizing constant, which is dependent on the value of c. Then, c is reduced and the above process repeated, and another equilibrium point is reached. The process stops at a small value of c where no higher value of the objective function is practically accepted, at which point the current best solution would be (hopefully) a good solution to the problem.

The algorithm is as follows:

Step 0. (Initialization). Choose an initial value for c, and an initial networ configuration i.

Step 1. (Generation Process). Choose network configuration j from the neighborhood of network configuration i, R_i, and compute the difference between the respective objective functions $\Delta C_{ij} = C(j) - C(i)$.

Step 2. (Metropolis Acceptance Criterion). If $\Delta C_{ij} \leq 0,$ then $i \leftarrow j$, otherwise, if $\exp(-\Delta C_{ij}/c)$ is greater than a random number in [0,1), then $i \leftarrow j$.

Step 3. (Equilibrium Verification). If the network configuration process has become sufficiently close to an equilibrium state (or certain number of iterations have been completed), continue to the next step. Otherwise, go to step 1.

Step 4. (Temperature Reduction). $c \leftarrow w(c)$, where $w(c)$ is a temperature determination function.

Step 5. (Stopping Criteria). If stopping criteria are satisfied, stop. Otherwise, go to step 1.

A short description of the algorithm follows. The cost function C is the total user cost in the network. R , the allowable set of network configurations, is constructed by the vector *Z*. The generation process is a process which constructs a neighboring network configuration from a given network configuration. This is done by randomly changing the decisions for m (here, 2) streets simultaneously to some other allowable decisions. If there is an O/D pair with no path, this process is repeated, until no O/D pair exists that is not connected.

An initial configuration of the network may be constructed by randomly choosing from among each link's decision set (This is equivalent to increasing the temperature of a solid to a high degree, at which the molecular configuration becomes random). This configuration is then tested for constraint satisfaction as well as the existence of at least one path for each O/D pair. The process is repeated if the necessary conditions are not met.

The acceptance criterion of a new network configuration is that of Metropolis. The higher the temperature, the higher would be the acceptable portion of the produced network configurations. The initial temperature will be taken high enough to have the ratio of the accepted configurations over the total produced ones equal to at least 0.8. The temperature is reduced at a desirable rate, e.g. 5% (per unit of time), in order to converge to a desirable configuration. The stopping criteria will be chosen such that practically no better network configuration could be achieved, e.g. when none of the produced configurations in the last parts of the process are accepted.

5. A case study

To test the applicability of the method in real cases, the network of the City of Shiraz, Iran, is chosen. This city had a population of about 1.3 million and an area of about 200 km^2 in 2002. The representative network of this city has 1077 nodes and 3487 (one-way) links, as shown in Figure1. So far as the authors know, no application of such algorithms to a real case of this size has been reported.

The need for one-way streets may be revealed most during the peak hours. To design a one-way street network suitable both for morning trips, and afternoon (or evening) return trips, both peak O/D (Origin/ Destination) demands may be required. In the study area, morning peak occurs during 7:00 to 9:00 (AM), and afternoon peak during 12:00 to 14:00 (PM). We have used an average hour demand for each of these two for design purposes. That is, two runs are made, one for each of these periods, and the weighted sum of the the objective functions of these two runs are taken as the design objective function, as given in Problem (4).

Demand for travel for the case under study may be predicted by a system of land-use, car ownership, trip production and attraction, trip distribution, mode choice, and traffic assignment models. Traffic on the network is obtained by optimal strategy (Spiess and Florian [27]) for transit passengers, and by user equilibrium (Sheffi [20]) for private vehicles. There are separate delay functions for links, un-signalized intersections, and signalized intersections. The model of network flow prediction has been prepared in EMME/2 (INRO [28]) environment. When the number of alternative networks is low (about 20), this detail model is used to estimate link flows and travel times, as well as many network performance measures. However, for rapid estimation of the same information, a shorter program has been

Figure 1. The size of the network of the City of Shiraz

written in Visual Basic environment which assigns the total O/D demand (in passenger car equivalent, pce), estimated by the original model, to the network in one run. This is in contrast with the original model which considers sufficient alternating runs between transit and auto assignments to reach equilibrium. The original model traffic assignment procedure takes about 8 minutes cpu time, once the detail O/D demands have been estimated by trip purpose, mode, time of day, etc., and prepared for assignment. On the other hand, the shorter version takes about 30 seconds, on 500 MHz Pentium III personal computer. Experiments show that the two models produce link volumes which are very much similar to each other for 3487 links, and hence similar measures of effectiveness for a given network of the case under study. The preparation of the shorter version of the program is in accordance with the spirit of the SA and many other modern heuristic algorithms which examine excessive number of solutions or alternatives during the course of their computations.

5.1. Choice of candidate projects

Choice of candidate project streets and the respective decision sets are very important elements of OSND problem in real cases. The authors have not found works elaborating on these issues, and other necessary details, in order to make the implementation of the final solution network possible. To identify the set of candidate streets, for one-way operation, a group of experts were asked to present their proposed one-way street networks. In another endeavor, all current one-way streets that could operate two-way have been changed to this state, to create a "base network." These networks presented the candidate streets for one-way operation, and their possible directions of movement. The candidate streets are defined so that to be minimum in number, and that all proposed networks could be created by combination of street-based decisions. A total of 67 candidate streets have been identified for the construction of the one-way street network for the case under study. Each street may contain a series of two-way links.

For each project street there is a set of decisions: (1) operating two-way, and (2) and (3) operating one-way in either direction. Two collections of such sets have been generated: In a rather free choice, there are 4 decision sets of the {2, 3} type and 63 sets of the {1, 2, 3} one, in our case. In a more restricted choice, based on the collective opinion of a group of experts, there are 23, 17, 23, and 4 streets with decision sets of the type {1,2}, {1,3}, {1,2,3}, and {2,3}, respectively. Of the various constraints discussed before, only the two partially opposing or partially unidirectional constraints are used in this case, which are defined based on the suggestions by the group of experts. In the case under study, there were 34 partially opposing and 18 partially unidirectional constraints.

5.2. Special considerations

There are some details in one-way network design which should not be overlooked. One such detail work relates to the management of parking on either side of a two-way street, when it is turned into a one-way street. This may be very important for the retail sales on that street, and should be dealt with before the one-way street network design. Otherwise, a safe decision is to preserve the parking spaces as before.

Some researchers believe that average vehicle speed and capacity of streets per unit width of one-way operation is higher than two-way operation. For example, Lee and Yang [19] have raised the capacity of one-way operation as compared to a two-way street of the same width by 12%. This efficiency (in capacity and speed) is believed to be accrued (basically) by smoother flow in one-way operation. Extensive data gathering for the construction of travel time functions for various types of links (e.g., arterial) within different environment (e.g., commercial with parking on one side), show that both free flow speed, and practical capacity, of a secondary arterial street in a commercial environment will be increased by one-way operation, as shown in Table 1 (Aashtiani et al. [29]). This observation shows about 8% decrease in free flow travel time (9% increase in free flow speed), and about 15% increase in practical capacity because of one-way operation. It is assumed that in moving from one network configuration to another, change of a two-way operation to one-way, or vice versa, does not change the *type* of street (i.e., an arterial remains an arterial). Moreover, design of the one-way street network is done both when improvement in the travel time function for one-way operation is/is not taken into account. When the improvement is taken into account, this improvement is considered as 5% decrease in travel time, and 15% increase in practical capacity, for changing a two-way operation into one-way.

Table 1. Improvements in free flow travel time and practical capacity in one-way operation of a two-way secondary arterial street*.

type of street operation	parking	free flow travel time (min/km)	practical capacity (pce/hr/m)
two-way	both sides	1.2	180
one-way	one side	1.1	210

*From Aashtiani et al [29].

To avoid additional complexity, the signal timings are set fixed for all intersections in this study, and hence it is assumed that changes in green times of various approaches do not change the total network travel time appreciably. This has been experimentally verified. (Of course, one may redesign the signal timings appropriately for each network configuration by some extra work in this dimension.)

5.3. Calibration of parameters of the SA algorithm

To determine a proper initial temperature, several initial temperatures have been used. An initial network has been constructed for each initial temperature by randomly changing the decisions for two streets in the current network. For each initial temperature, 100 such initial random networks have been produced, and accepted based on Boultzman distribution and Metropolis criterion. For the temperatures 100 and 50, for example, percent accepted networks became 90 and 70 for the morning peak only objective function (total travel time, in vehicle-hours), and 84 and 67 for the sum of morning and afternoon peak total travel times. The initial temperature of 100 degrees has been used in this study to conform to the generally accepted figure of 80% acceptance level for the initial temperature.

No final temperature is set in this study. The algorithm is terminated when the probability of accepting a new network configuration becomes negligible. For example, when in several consecutive temperature levels (4, in this study) no new configuration is accepted, the process will be stopped.

Let, t_i and t_f be the initial and final temperatures of the "solid" of concern, respectively, and the coefficient of temperature reduction: $t^{m+1} = .t^m$, where t^m is the temperature level m, m = 0, 1, 2, …, n, and $0 < \; < 1$. Let, also, r be the number of iterations (for making new network configurations) at each temperature level. Then, the total number of network configurations, and the final temperature, will be $(n+1)r$, and $^n t_i$, respectively, when the algorithm stops. Thus, to have the final temperature of the "solid" less than certain level, t_f, the initial temperature should be reduced by $n^+ = <(\ln t_f - \ln t_i)/\ln \; >$, where $<x>$ represents the smallest integer greater than x. This makes the total number of network configurations equal to $(n^+ + 1)r$.

Given t_i and t_f, one may change and r such that to have the number of constructed network configurations constant. This number is taken to be so for any temperature in this study. The closer to 1.0, the better would be the "quality" of the final product. The highest value of for which the problem of one-way street network design could be solved within a reasonable time frame was found to be about 0.95 in this study.

To find the value of the objective function (total travel time) for each network configuration one needs to solve a user equilibrium flow problem (for each peak hour in the morning and in the afternoon). This is done by the shorter traffic assignment procedure.

6. Computational results

The operational characteristics of the base network, with minimum (possible) one-way streets (in number or length); and those of the current one-way street network, are shown in Table 2. Using morning peak only, the algorithm of SA has been run under the parametric condition discussed before. The result is shown in Table 2, under "SA, run 1." This network is better than both the base network and the current one-way street network of the city, as may be seen from the values of the objective function of these three networks. A second run produced the solution named "SA, run 2" in Table 2, leaving SA, run 1, still a better network.

A third run with the same specifications as the first two, but with the difference of changing the operational condition of only one street randomly, instead of 2 streets as in the first 2 runs of SA algorithm, created the results shown in Table 2 as run 3. The resulting network happens to be better than the first two networks of SA algorithm, possibly because of less abrupt changes in the current network to produce the next one. Higher, rather drastic, changes in the current network lend themselves to more random networks, and deviate more from a smooth cool down of the procedure of SA.

To find a better network than the configuration in run 3 of SA algorithm, by escaping this possibly local optimum, 4000 networks have been generated by changing the decisions for 2 streets in the current network, and another 4000 other networks by following the same procedure and changing the decisions of 5 streets at the same time. However, none produced a better network configuration; increasing the probability that run 3 network configuration is a global optimum.

Table 2. Some configurational and operational characteristics of the reference networks and solution networks in peak hours.*

Network		Current one-way street network	Base network	SA, run 1	SA, run 2	SA, run 3	SA, run 4
No. of one-way streets		67					
Length of one-way streets (km)		36.1	32.7	43.6	44.9	43.5	32.9
No. of links in operation decision:	1	33		27	28	27	35
	2	22		17	15	15	14
	3	12		23	24	25	18
Total number of produced networks				6757	4958		
Vehicle-hours	MP	24250	24030	23744	23760	23726	23796
	AP	22028	21903				
Vehicle-kilometers	MP	1059012	1053208	1054319	1054832	1054147	1053725
	AP	980204	975432				
Gasoline consumption (liters)	MP	120735	119962	119570	119624	119522	119619
	AP	111043	110493				

* (MP=Morning Peak hour, AP=Afternoon Peak hour).

6.1. Effect of link decision sets

Run 4 of SA algorithm has been performed by expanding the decision set for each street, to safeguard against possible expert biases in seeing a particular street in a special condition. The result is presented in Table 2 with no better performance, but with lower number of one-way streets.

6.2. Effect of the parameters of volume-delay functions

To investigate the changes in the link operation decisions because of the changes in the parameters of the respective volume-delay functions resulting from one-way operation as discussed before, the following tests have been undertaken. First, using the new improved parameter values of the volume delay functions (5% improvement in free flow travel time, and 15% improvement in practical capacity of one-way operation) the total user travel times (vehicle-hours) are recalculated for the solutions of SA runs 1 to 3 in Table 2, yielding the values 23719, 23740, and 23706 instead of the original values of 23744, 23760, and 23726, respectively. It may be seen that appreciable changes in the parameter values did not produce much changes in the objective function of these 3 solutions. Moreover, this change in parameter values not only did not change the preference order of these 3 solutions, but also did not change appreciably the difference between them.

To ponder further on the matter, the algorithm has been run by the improvements included in the procedure, using the best solution found of SA run 3 as the initial configuration. New configurations have been found by randomly changing the decisions of 5 streets simultaneously, to increase the possibility of escaping local optima. After much iteration, a solution has been found which only differed from the initial solution in changing the decision of one street from 1 to 3. This changed the travel time of network from 23726 to 23704 vehicle-hours. Then, 4000 new configurations have been generated, none of which had a better objective function than the new solution found. This strengthens the belief that the solution with the improved parametric values is not very much different from that for the original parameters. If this happens to be true, then the investment for finding more precise values of the one-way operation of links may not be justified.

6.3. Comparison with other heuristic solutions

Similar to Lee and Yang [19], to show the superiority of the SA solution as compared to expert solutions and locally optimized sub-networks, another experiment has been undertaken, as follows. The one-way street study of the network of the City of Shiraz has been divided into 10 zones (see Figure 2). These zones are identified by the sub-networks of arterials. It is hypothesized that arterials are hardly suitable for one-way operation, as they form the skeleton of the city network. Moreover, it is assumed that the rather more local parts of the network surrounded by the arterials are basically independent from each other, with the arterials acting as their interfacing media. This assumption decomposes the OSND problem into some (here 10) small OSND problems. Each of the small OSND problems may be solved by enumerating the reasonable combinations of one-way links in the respective zone including the base network of do nothing alternative, with the remaining links held as in their base network states. The better network (of the zone of concern) may be found by applying the assignment model to the so generated alternative networks, and comparing them based on a measure of effectiveness. One solution of the original OSND problem is obtained by combining the combination of the better network configurations for all zones. In doing this, one should make sure that the zonal solutions are conformable at the boundaries, and in cases of topological infeasibility the next best solutions may be selected.

In this study, several alternative networks have been generated for each of the 10 zones based on the possible decisions of the corresponding one-way operation candidate links suggested by the experts, as mentioned before. The original assignment model in EMME/2 environment has been run on the resulting 55 networks for the 10 zones, and 9 measures of effectiveness have been evaluated for them for the morning and the afternoon peak hours. These measures are shown in the bottom line of Table 3 under the heading "…zone-based decomposition procedure." The better zonal one-way network has been identified based on the average morning and afternoon peak values for each of the above-mentioned measures of effectiveness. The corresponding zonal solutions are, then, combined to form a solution to the respective original problem of one-way street network, for each of the above measures of effectiveness, safeguarding network conformity mentioned above.

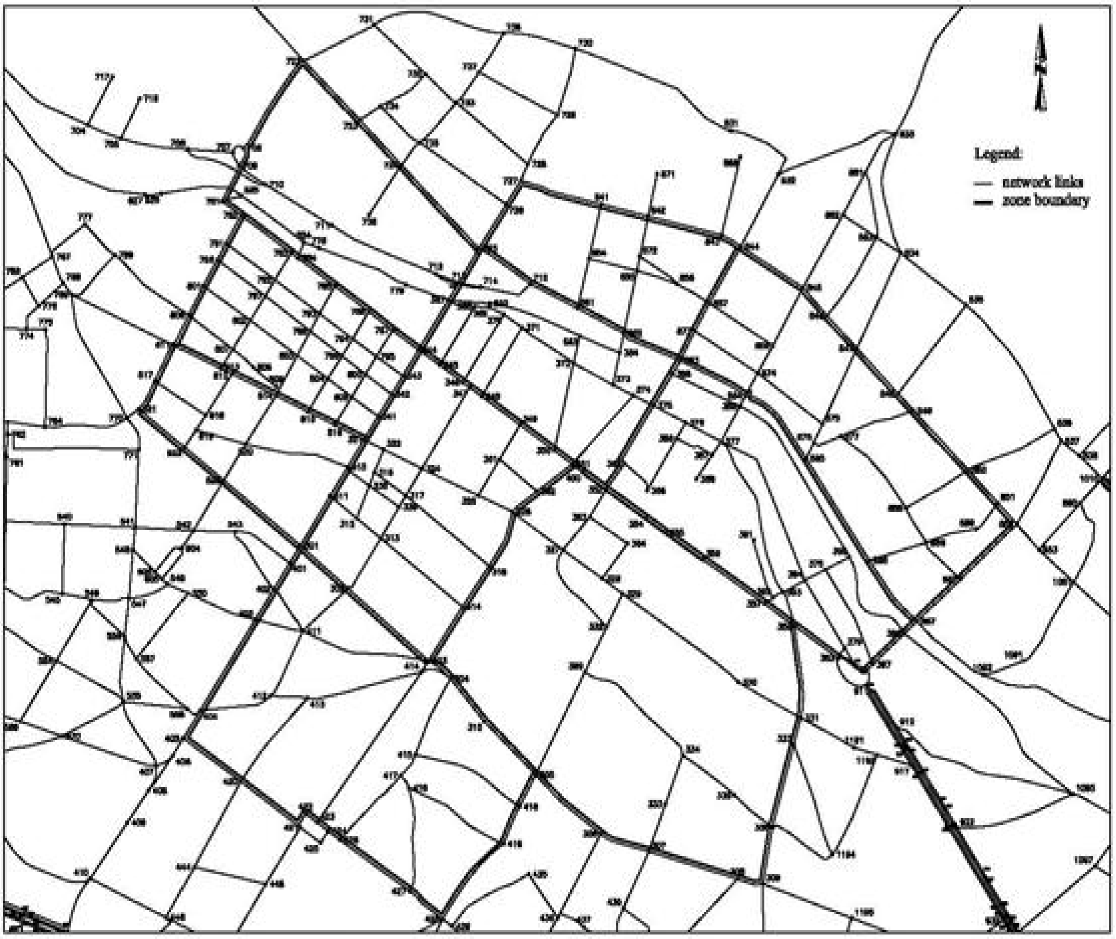

Figure 2. One-way street network study area and its 10 zones.

The above procedure yielded a set of 8 distinct alternative networks, which was augmented by the following 4 networks: (a) the current one-way street network of the city, (b) the base (minimum) one-way street network, (c) an independent expert-opinion network of one-way streets based on zonal analysis, and (d) the SA solution network. Application of the original traffic assignment model on these 12 networks for the morning and afternoon peaks gave the average values of the measures of effectiveness for these two demands as given in Table 3.

As may be seen in Table 3, the network created by SA algorithm has the better values of all measures of effectiveness and appreciably overcomes the other alternatives, except for vehicle-kilometer traveled in the network, under which the base network (with minimum length or number of one-way links) is better. This is of-course expected, as one-way operation of the links decreases physical accessibility in the network.

A final sensitivity analysis using expert opinion showed that the resulting SA solution is really an acceptable one. This analysis was done by asking the experts to raise any doubt regarding the decisions made by SA for each project streets. Thus, for each such doubtful decision the results of the traffic assignment model for the expert suggested decision were compared with the respective SA figures. The results were unanimously in favor of SA solution.

Table 3. The results of detailed traffic assignment model for 12 alternative one-way street networks. (Ave.values for morning and afternoon peak hours.)

* Base of network choice	NO_x emission	HC emission	CO emission	Gasoline consumption	% veh-km in congested links	Vehicle -hour	Ave. speed in collectors and secondary arterials	Ave. network speed	Total travel time	Measures of effectiveness
	kg	kg	kg	liter	%	veh-hr	km/hr	km/hr	veh-hr	Unit
current network	821	3865	32762	85188	10.7	684138	25.3	33.0	20735	Current network
do nothing alternative	818	3850	32612	84574	10.3	679421	25.0	33.0	20582	Base network
expert opinion	820	3859	32688	84925	10.5	682677	25.2	33.1	20644	Expert network
total vehicle hour	818	3836	32500	84367	10.0	679828	25.3	33.2	20477	1
network average speed	819	3849	32641	84703	10.2	681843	25.3	33.1	20581	2
collector-secondary arterial ave. speed	820	3851	32652	84735	10.2	681889	25.4	33.2	20552	3
vehicle –km traveled	818	3845	32574	84550	10.3	679465	25.1	33.1	20560	4 Alternative better networks of zone-based decomposition procedure*
%veh-km in congested links in network	819	3852	32617	84785	10.1	680568	25.0	33.0	20624	5
%veh-km in congested links in CBD	821	3857	32709	84965	10.1	681635	25.4	33.1	20622	6
consumption or total pollutant	818	3842	32556	84487	10.1	679721	25.1	33.1	20545	7,8
CO emission (only)	819	3843	32548	84506	10.1	679826	25.2	33.1	20536	9
Simulated Annealing	819	3828	32455	84291	9.6	680826	25.7	33.4	20414	SA

7. Summary and conclusions

This paper presents an application of a simulated annealing (SA) algorithm to the design of one-way street networks. It briefly discusses the literature of the network design problem and the rather limited literature on one-way street network design (OSND).

The OSND problem is defined formally, and several important points are discussed regarding problem constraints, decision variables, and several subtle points associated with the problem and its algorithmic, as well as practical, implementation.

The algorithm of SA is presented and discussed in detail in some aspects of the problem for real case analysis, such as traffic assignment models, choice of candidate projects, street parking, and intersection traffic signal manipulations, as well as link improvements due to one-way operation. The model has been calibrated for a real case network. An initial temperature of 100 degrees, with a reduction rate of 5% were found suitable.

Experiments with the calibrated SA design procedure showed that changing two candidate link decisions at a time to move from one network configuration to an adjacent one is an effective strategy, but reducing it to one candidate link decision change at a time produced a better solution, as expected. Moreover, limited experiments showed that link improvement due to one-way operation had no appreciable effect on the solution.

The SA solution to the problem was found impeccable as several attempts to find better solutions failed. These attempts included simultaneous 5-street-decision change to produce thousands of random solutions to try to come out of possible local optima, and extensive alternative heuristic searches to find better solutions. Thus, it seems that SA is a suitable solution procedure to solve one-way street network design problem.

The authors believe that the overall benefit of the optimal design of one-way street network is marginal, as may be seen in Table 3. The one-way street network design is not a local transportation network problem alone. However, global network measures, such as vehicle-hours, or vehicle-kilometers, may come short of reflecting these local problems properly. This is why we suggest designing the one-way street network based on a multi-criteria formulation of the decision problem. Never the less, this study shows the existence of a lexicographic type of decision with vehicle-hour at forefront, may suffice for attaining a good solution.

Furthermore, our analysis of the extended vs. the shorter version of the traffic assignment problem show that there is a high correlation between the corresponding flows in the network under the original and the approximate versions of the assignment problem. It is suggested to test the existence of such co-linearity between the simpler and more complicated versions of the assignment problems, and its effects on the final design decisions.

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