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Optimal Design of Bike Lane Facilities in an Urban Network

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Abstract

Cycling can improve the health of riders, reduce carbon emissions from travelling, relieve congestion in the transport network, and save health and social care costs. According to the Australian National Cycling Strategy 2011-2016, the goal is to double the number of cyclists in the next 5 years. Bike lanes play an important role in promoting bike travel in a safe and protected environment. Currently there has been no methodology developed in the past to design an integrated bike lane system from the network point of view. This paper presents a Mixed Integer Programming (MIP) formulation to optimize the benefits associated with the development of a bike lane network in urban areas. The formulation balances the benefits to cyclists and potential dis-benefits to drivers. A route choice model is adapted for cyclists and a traffic assignment model is employed to model driver behaviour. The outcome is an optimal placement of bike lanes that can assist in designing bike lane networks. An application of the methodology is demonstrated using an example network.

1. Introduction

A lack of cycling facilities has been identified as a major barrier for persons riding (Bauman et al., 2008). Although off-street bike paths offer a safe and comfortable riding environment they are limited in urban areas due to the lack of suitable space and high costs of construction.

The recently released Victorian cycling strategy key strategic direction include, building networks to connect communities, reducing conflicts and risks for cyclists, integrating cycling with public transport and integrating the needs of cyclists with land use planning and built environment (Department of Transport, 2009). The strategy acknowledges the need for cycling networks to provide continuous quality connections to major destinations and public transport hubs. On-street bike-lanes can reduce conflicts between motor vehicles and bikes. However, principal bicycle networks (PBN) in many Australian cities are currently not well developed. The PBN only introduces candidates for a possible solution.

Although the reviewed studies have different focuses in terms of the spread of the proposed bike lanes, all researches evaluate a given Bike Lane Alternatives (BLA). Despite the level of details in some studies, the evaluation just reveals whether or not a BLA (i.e. a set of bike lanes) should be implemented. It does not mean that the given BLA is the best possible or optimum BLA for the network. Therefore, it is necessary to develop an optimization method to find the best set of links for having bike lanes installed.

This paper outlines a methodology to find the optimal BLA. The optimal BLA determines the links in the transport network on which a bike lane should be introduced. Furthermore it is aimed at presenting a methodology that can be applied to medium and large size networks. In the next section, the optimization method is formulated as a bi-level programming problem and each level is explained separately. Then, in section 3 a solution algorithms is presented based on Genetic Algorithm. In the last section the optimization problem is solved for a medium size network and the results are presented.

2. Bi-Level Optimization

There are two levels of stakeholders who determine the performance of a bike lane scheme. At the upper level, the Transport Authority would propose a Bike Lane Alternative (BLA) which is a set of links on which a type of bike lane is provided. Given this BLA, at the lower level, system users would choose a strategy to maximize their own benefit under the prevailing conditions. This problem can be modelled as a Stackelberg competition where the Transport Authority is the leader and system users are the followers (Yang and Bell, 1998). In equilibrium conditions, the optimal BLA is chosen. The Stackelberg model can be modelled as a bi-level optimization problem.

The Transport Authority's point of view is considered at the upper level. Therefore a system optimal is formulated in this paper for the upper level. The Transport Authority takes into account the total travel time of car as well as a bike system performance measure such as travel distance on bike lanes. There can also be a series of practical constraints for a priority scheme which is formulated in the constraints of the upper level. In the next subsection, an objective function and associated constraints are defined. The output of the upper level is the set of decision variables which define the location of the bike lanes.

User behaviour at the lower level is modelled by applying a traditional four step modelling approach. In this study, it is assumed that the travel demand in the network is not changed by introduction of a BLA. It is also assumed that two modes of private car and bikes use the network. Thus, the demand of each mode is known. In the last step of planning, car and bike demand should be assigned to the network links. At the lower level for private cars and bikes, a car demand assignment model and a bike demand assignment model are used, respectively. It is important to note that the BLA is determined at the upper level while it is in the lower level where the objective function can be calculated. The formulation of the lower level is discussed in the subsequent sections.

2.1 Upper Level Formulation

A system optimal problem from the Transport Authority's perspective is formulated at the upper level. The goal of the objective function is to maximize the portion of bike travel on bike lanes; such a goal is best achieved by defining a bike lane where feasible. However, by introducing each bike lane, some road space would be taken from the cars and allocated to bikes. Therefore, the Transport Authority has take into account the performance of cars. The performance measure used for cars is the total travel time of car users.

The upper level can be proposed as follows.

$$MinZ = \alpha \sum_{a \in A_1} l_a x_a^b \Phi_a(x) - \beta \sum_{a \in A} x_a^c t_a^c(x) \tag{1}$$

Subject to :

$$\sum_{a \in A_1} l_a \left(\sum_m e_{am} \phi_{am}\right) \le Bdg \tag{2}$$

$$\Phi_a = \sum_m \phi_{am} \le 1 \qquad \forall a \in A_1 \tag{3}$$

$$\phi_{am} = 0 \text{ or } 1 \quad \forall a \in A_1 \tag{4}$$

Connected graph (5)

where:

A : Set of all links in the network, $A = A_1 \cup A_2$

A_1 : Set of links in the network where provision of priority is possible,

A_2 : Set of links the network where provision of priority is impossible,

l_a : Length of link (a),

$t_a^c(x)$: Travel time on link (a) by car (c) which is a function of flow,

φ_{am} : is 1 if bike lane type m bike lane is introduced on link (a) and 0 otherwise,

ϕ_a : is 1 if any type of bike lane is introduced on link (a) and 0 otherwise,

x_a^c : is the motor vehicle flow on link (a),

x_a^b : is the bike flow on link (a),

e_{am} : is the cost of bike lane type m for the length on link (a)

Bdg : Available budget,

α, β : weighting factors to convert the units and adjust the relative importance of each impact in the objective function, $\alpha, \beta \geq 0$,

The first term of the objective function is the total travel distance on bike lanes; while the second term represents the total travel time by car. The first term accounts for the length of the bike lanes in the transport network as well as the volume of riders on each bike lane. Coefficients α, β can reflect different policies in the relative importance of each term. They also convert the units. As Equation (1) shows, the objective function is formed from a Transport Authority's perspective. The budget constraint is accounted for in Equation (2).

There are two types of links in the network. The first type is the links that potentially can have a bike lane (set A_1). The second type is the links on which no lane can be dedicated to bikes (Set A_2). This classification could be the result of a road use hierarchy (e.g. Wall, 2008). Decision variables determine which type of bike lane would be introduced on potential links. Equation (3) ensures that only one type of bike lane to be chosen for a link. The binary decision variable is defined in Equation (4).

Constraint (5) demonstrates an important practical consideration of continuity. The proposed network of bike lanes in a BLA should be connected. Connectivity is defined if there is a path on bike lanes from the end point of any link with a bike lane to one of travel destinations. In graph theory terms, links with a bike lane should form a number of 'connected components' which have at least one destination node (vertex). This constraint can be verified using graph theory methods such as breadth-first search or depth-first search (Hopcroft and Tarjan, 1973) or more specifically, Dijkstra's shortest path algorithm (Dijkstra, 1959). Based on the set of decision variables in the upper level, flow and travel time are computed at the lower level.

2.2 Lower Level Formulation

When a BLA is determined, it is the users turn to decide on how they would utilize the provided facilities. In other words models at the lower level estimate users response to a given BLA. These models in the bi-level structure function as constraints to the optimization programming presented in the upper level. As a result of these models flow and travel time is obtained.

Assuming a constant travel demand, as discussed before, there are 2 models involved in the transport modelling:

(i) Car demand assignment, and

(ii) Bike demand assignment.

Traffic assignment is the first model at the lower level. By the introduction of a bike lane, the lane width of the general traffic lanes and therefore, their capacity may reduce. The capacity reduction depends on whether the bike lane is introduced by allocating a part of the existing pavement or by using the width of nature strip or median. If the road capacity is reduced, drivers may decide to choose alternative routes in the network. Traffic assignment is carried out to consider route choice behaviour of car users. A static User Equilibrium (UE) model is used for car demand assignment which is a conventional model for strategic planning (Sheffi, 1984). This model determines car flow and travel times in the network using an optimization approach. The effect of the decision variables on the flow and travel time cannot explicitly be expressed; this is one of the reasons that a bi-level approach is proposed. The UE formulation is as follows:

$$MinY = \sum_{a \in A} \int_0^{x_a^c} t_a^c(x)dx \tag{6}$$

Subject to :

$$\sum_k f_k^{c,rs} = q_{rs}^c \qquad \forall r,s \tag{7}$$

$$f_k^{c,rs} \geq 0 \qquad \forall k,r,s \tag{8}$$

$$x_a^c = \sum_{rs} \sum_k f_k^{c,rs} \delta_{k,a}^{rs} \qquad \forall (i,j) \in A \tag{9}$$

where $f_k^{c,rs}$ is the car flow on path k connecting origin node r to destination node s, q_{rs} is the trip rate between r and s, and x_a^c is related to f_k^{rs} by the incident matrix $\delta_{k,a}^{rs}$ where δ is 1 if link (a) is on path k for any OD pair rs and zero otherwise.

In the above constraints, the first two (Equations (7) and (8)) are conservation of flow and non negativity constraints. The third constraint defines the relationship between paths and links.

Bike demand assignment is the second model to be used which assigns the bike demand to the transport network. Bike assignment is the second reason for which a bi-level approach is proposed. Many of the models proposed in the literature for traffic assignment can be applied in this framework. In this paper, a model based on User Equilibrium is adapted.

$$MinW = \sum_{a \in A} \int_0^{x_a^b} t_a^b(x)dx \tag{10}$$

Subject to :

$$\sum_k f_k^{b,rs} = q_{rs}^b \qquad \forall r,s \tag{11}$$

$$f_k^{b,rs} \geq 0 \qquad \forall k,r,s \tag{12}$$

$$x_a^b = \sum_{rs}\sum_k f_k^{b,rs}\delta_{k,a}^{rs} \qquad \forall (i,j) \in A \tag{13}$$

Similar to the car assignment model, $f_k^{b,rs}$ is the bike flow on path k connecting origin node r to destination node s, q_{rs} is the trip rate between r and s, and x_a^b is related to $f_k^{b,rs}$ by the incident matrix $\delta_{k,a}^{rs}$ where δ is 1 if link (a) is on path k for any OD pair rs and zero otherwise.

In the above constraints, the first two (Equations (11) and (12)) are conservation of flow and non-negativity constraints. The third constraint defines the relationship of paths with links.

3. Solution Algorithm

A bi-level structure even with linear objective function and constrains at both levels is a NP-hard problem and difficult to solve. In this study a heuristic approach based on a Genetic Algorithm (GA) proposed in which new solutions are produced by combining two predecessor solutions (Russell and Norvig, 2003). Inspired from evolutionary theory in the nature, a GA starts with a feasible set of solutions called a population (see **Figure 1**). Each individual answer in the population (called a chromosome) is assigned a survival probability based on the value of the objective function. Then, the algorithm *selects* individual chromosomes based on this probability to breed the next generation of the population. GA uses *cross over* and *mutation* operators to breed the next generation which replaces the predecessor generation. The algorithm is repeated with the new generation until a convergence criterion is satisfied. A number of studies applied GA to bi-level formulation. Two recent examples are a transit network design problem considering variable demand (Fan and Machemehl, 2006) and optimization of a bus lane network (Mesbah et al., 2011).

In this study, a GA is applied to optimize a bike lane network. To adapt a GA to this study, a genome is defined as the binary variable φ_{am} and a gene is defined to represent the binary variable Φ and a chromosome is the vector of genes (**Φ**). In this GA, a chromosome represents a BLA. A chromosome (or BLA) contains a feasible combination of links on which an exclusive lane may be introduced (set A_1). Therefore, the length of the chromosome is equal to the size of A_2. The algorithm starts with a feasible initial population. The chromosomes of the initial population are produced randomly.

Any produced chromosome could be feasible or infeasible according to constraint represented in equations (2) to (5). In this study, a penalty function is used to ensure that the feasible answers would be given a higher chance in the reproduction process. The penalty is proportional to the amount that a constraint has been violated.

Once a chromosome population is produced, the upper level objective function for all chromosomes should be determined. Each chromosome identifies the leader's decision vector for the network. It is users' turn at the lower level to choose their route. Thus, for each chromosome, the lower level models are carried out as depicted in **Figure 1**. Using the flow and travel time at the lower level, the objective function for the chromosome is determined. The lower level calculations are repeated for all chromosomes in the population (**Figure 1**).

The chromosomes with higher value of the objective function are assigned a higher survival probability. Then, the GA operators of selection, cross over, and mutation are employed to produce the next generation (set of BLAs). Similar to the process in the initial population, the process ensures the feasibility of the new generation. The new generation is replaced the previous one and the calculations are repeated. It should be noted that to increase the convergence rate of the algorithm (it is recommended that) the best chromosome of the previous population is kept. The algorithm stops when either the number of iterations reaches the maximum number of iterations or the best answer does not improve in a certain number of iterations. This cycle is also demonstrated in **Figure 1**.

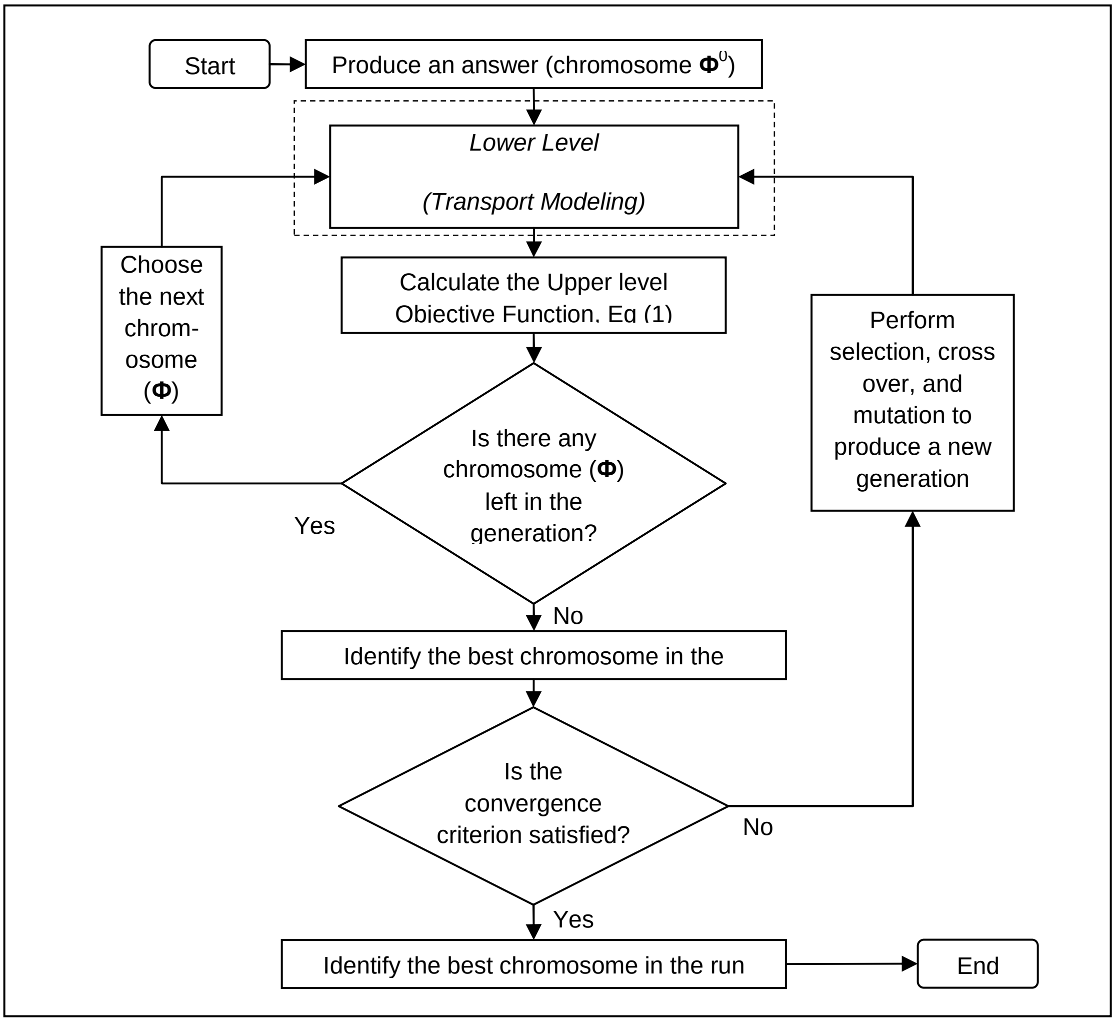

Figure 1 GA Solution Flowchart

4. Numerical Example

In this section, the proposed method is applied to an example network. Figure 2 shows the layout of the network. This grid network consists of 42 nodes, 142 links, 15 origins, and 2 destinations. All the 15 interior centroids are origins and the 2 exterior centroids are destinations. A flat demand of 150 cars/hr and 15 bikes/hr travel from all origins to all destinations. The total demand for all the 30 origin-destination pairs is 4950 trips/hr.

Vertical and horizontal links are 800m long with two lanes in each direction and a speed limit of 50 km/hr. It is assumed that if a bike lane is introduced on a link, the opposite direction may or may not get an exclusive lane. There are a total number of 90 candidate links (one directional) in the network of Figure 2 on which a bike lane can be introduced. These links are highlighted in Figure 2 by a thick dotted line. The following cost functions are assumed for links with a bike lane (Equation (14)) and without a bike lane (Equation (15)):

$$t_{1,a}^{c} = t_{0,a}(1 + m(\frac{x_a^c}{Cap_{1,a}^c})^n), t_{1,a}^{b} = t_{0,a} \tag{14}$$

$$t_{0,a}^{c} == t_{0,a}(1 + m(\frac{x_a^c}{Cap_{0,a}^c})^n), t_{0,b}^{b} = t_{0,a} \tag{15}$$

where t_0 determines travel time with free flow speed, m and n are model parameters and Cap is the link capacity. It is assumed that one type of on-road bike lane will be introduced in the network which reduces the car capacity from 1800 veh/hr to 1500 veh/hr. There could be different types of bike lanes introduced where the capacity of a link remains the same or increases. The capacity may remain the same if the width of nature strip of median is used to introduce a bike lane. The capacity may even increase if a parking lane turns to a bike lane in which the bike lane creates a ‘clear way’ condition for the road. In this example however, the bike lane reduces the capacity since it takes some of the road space. It is assumed that each link has 2 car lanes and:

$$m = 1, n = 2$$

$$Cap_{0,a}^c = 1800 veh / hr$$

$$Cap_{1,a}^c = 1500 veh / hr$$

Once the demand matrices are determined, car demand and bike demand are assigned using two UE models. It is assumed that the number of bikes on a link does not affect the travel time. The lower level transport model is implemented using Visum modeling package (PTV AG, 2009).

In this example, weighting factors of the upper level objective function are assumed to be 0.001 and 0.01 for α and β, respectively. These factors may vary depending on the relative importance of the factors from the viewpoint of Transport Authorities. The upper level objective function includes total travel distance on bike lanes (veh.km) and total travel time by cars (veh.sec). The absolute value of the objective function therefore can be very large. In order to avoid numerical problems, the improvement of each term compared to a base case is considered instead of the absolute value of the term in the objective function. The base case is assumed to be the case where no link is provided with an exclusive lane ($\mathbf{\Phi}=\mathbf{0}$). Regarding the constraints, it is assumed that budget allows for 10 bikes lanes out of a total of 90 candidate links to be constructed.

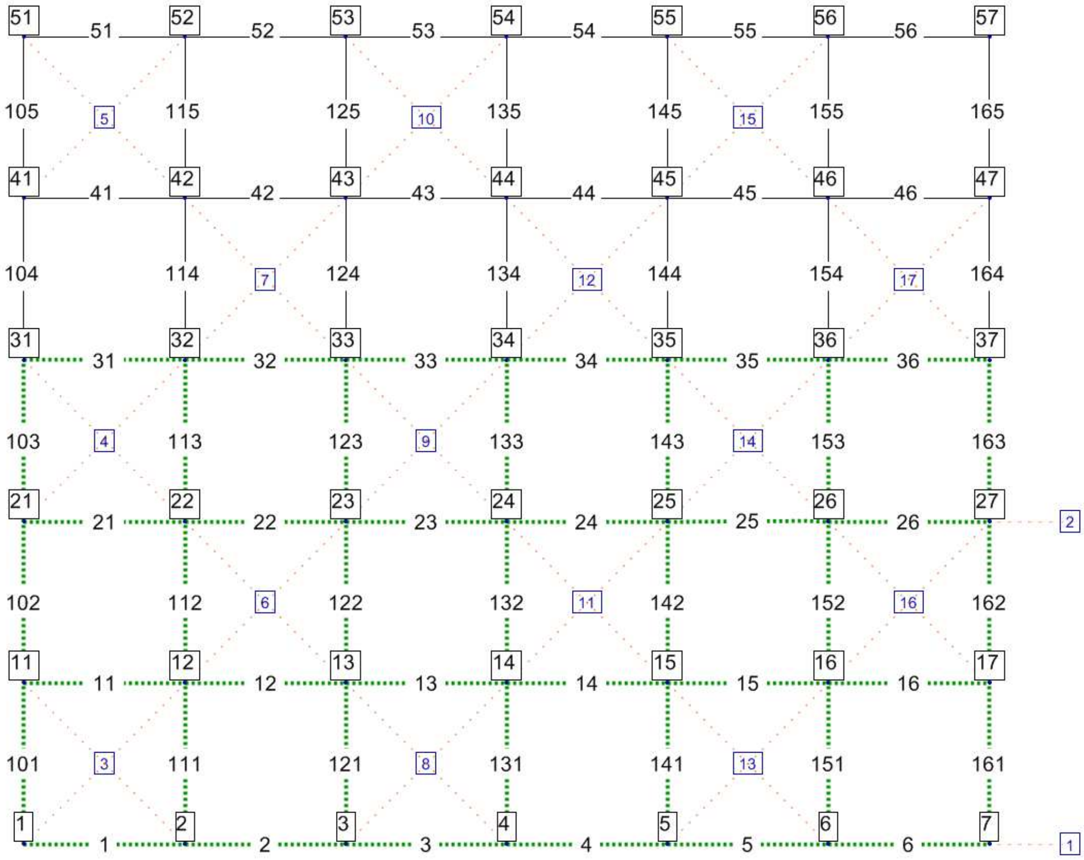

Figure 2 Example network with candidate links in thick dotted lines and normal links in solid lines

In this example, weighting factors of the upper level objective function are assumed to be 0.001 and 0.01 for α and β, respectively. These factors may vary depending on the relative importance of the factors from the viewpoint of Transport Authorities. The upper level objective function includes total travel distance on bike lanes (veh.km) and total travel time by cars (veh.sec). The absolute value of the objective function therefore can be very large. In order to avoid numerical problems, the improvement of each term compared to a base case is considered instead of the absolute value of the term in the objective function. The base case is assumed to be the case where no link is provided with an exclusive lane ($\mathbf{\Phi}=\mathbf{0}$). Regarding the constraints, it is assumed that budget allows for 10 bikes lanes out of a total of 90 candidate links to be constructed.

A common stopping criterion for GA is the number of generations. If the objective function does not improve for a considerable number of generations, calculations are terminated. In this example, the number of generations is increased to 600 to investigate a proper stopping criterion. Figure 3 demonstrates the value of the objective function for two independent runs of the GA. As this figure shows the objective function did not improve after 200 generations which can be introduced as the stopping criterion for this example.

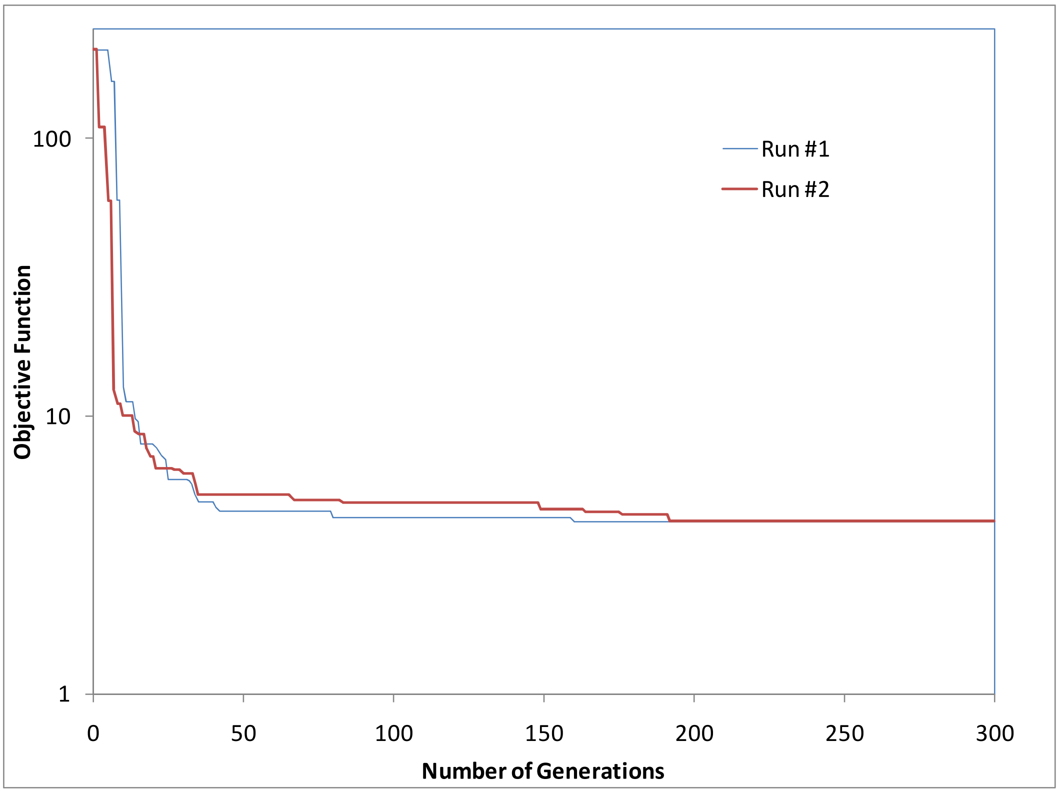

Figure 3 Effect of Number of Generations on the Value of the Objective Function

Application of the proposed method to the network of Figure 2 resulted in introduction of a bike lane on the following 10 links.

4, 5, 6, 22, 23, 24, 25, 26, 61, and 62

This answer is anticipated since it includes all links close to the destinations. These links are the ones that carry relatively more bikes than those far away from the destination centroids.

5. Conclusions

A heuristic approach to optimise bike lane facilities is presented in this paper. It was stated that all the previous approaches consider only a limited number of alternatives for a bike lane project while all the feasible combinations are taken into account in the approach presented. The problem is elaborated in a framework of bi-level programming formulation where the upper level is system optimal from the Transport Authority's perspective and the lower level is adapted using four-step modelling to predict user's behaviour. An efficient solution algorithm based on Genetic Algorithm is suggested to solve the bi-level optimization problem. The method is applied to a medium size example network and the results are presented. The proposed method should also be tested on a real scale network with additional of practical constraints at the upper level.

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