ABSTRACT

Title of Thesis: NETWORK DEVELOPMENT WITH BICYCLE LANES

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Bicycling as an active mode of transport can offer great individual and societal benefits. Allocating space for bicycle facilities is the key to promoting cycling as bicyclists perceive better safety and convenience in separate bikeways. In this thesis, a method is proposed for optimizing the selection and scheduling of capacity enhancements in road networks while also optimizing the allocation of road space to bicycle lanes. The goal is to determine what fraction of the available space should be allocated to bicycles, as the network evolves, in order to minimize the present value of the total cost of the system cost. The allocation method is combined with a genetic algorithm to select and schedule road expansion projects under certain budget constraints.

NETWORK DEVELOPMENT WITH BICYCLE LANES

by

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Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

Motivation

Bicycling as an alternative mode of transportation for commuting, shopping and other utilitarian trips can bring significant individual and societal benefits. Benefits for individuals include improved health and reduced travel cost (including fuel and parking cost). Choosing cycling over other modes of transportation also contributes to reduced congestion, improved air quality, reduced energy use (especially, reliance on petroleum-based products), and improved homeland security, enabled by increased options for quick evacuation. Moreover, cycling extends the catchment area of transit, which is often a greener alternative mode to personal vehicles.

The lack of a cycling infrastructure and other treatments to accommodate cycling puts cyclists at risk of accidents and reduces the convenience of cycling, thereby making this mode less attractive in terms of the numbers of cyclists and miles traveled by bicycle. In fact, Clarke, (2003) noted that fewer than 3% of all commuting trips, which constitute 20% of all trips, are made by bicycle in the U.S. Moreover, only 1% of all trips made in North America are completed on bicycle (Reynolds et al.,2009). This can be contrasted with a 10% cycling mode share in Switzerland, Germany and several other European countries and an even larger 20% share in Denmark and the Netherlands (Pucher & Buehler, 2008). Conversely, increasing bicycle lane mileage has been shown to increase bicycle ridership (Heinen, Wee, & Maat, 2010; Schweizer & Rupi, 2014). Several studies have found that improved cyclist safety can be accomplished by increasing bicycle usage (Jacobsen, 2003; Pucher & Buehler, 2008; Reynolds et al., 2009).

While the benefits to individuals and societies of improving bicycle infrastructure and related treatments are understood, the cost of such implementations can be exorbitant. Thus, given limited funds for design and implementation, careful bicycle infrastructure investment is crucial. To realize the intended benefits of such investment, the provision of bicycle facilities can ensure the cyclist's safety, provide connectivity between high demand origin-destination pairs and encourage more bicycle usage.

Problem Statement

Transportation agencies are facing the growing challenges of congestion and a limited ability to expand freeway or arterial capacity due to construction costs, right-of-way constraints, and environmental and societal impacts. As a result, agencies are looking for solutions to improve traffic conditions on existing facilities.

A new concept, namely managed lanes, has been considered for the problem mentioned above. This concept is a combination of limited capacity expansion together with operational strategies that seek to manage travel demand and improve transit and other form of ridesharing (Collier & Goodin, 2004).

Meanwhile, bicycling as an alternative mode of transportation for commuters, shoppers and others for whom traveling itself is not the goal, i.e. the so-called utilitarian trip, offers significant societal benefits. Benefits for individuals include improved health and reduced travel costs (including fuel and parking cost). Choosing cycling over other modes of transportation helps improve congestion, air quality and homeland security, the latter generated by increased options for quick evacuation in an emergency event and reduced reliance on petroleum-based products. Moreover, cycling extends the catchment area of transit, which is often a greener alternative mode to personal vehicles.

In spite of the benefits of bicycling mentioned above, the most recent data on bicycling mode share show that only 1.0% of all trips taken in the U.S. are by bicycle (NHTS 2009). Of commuters nationwide, 0.6% get to work by bicycle. The percentage is slightly higher in large cities, at 1.0% (Milne, Melin, & Alliance for Biking & Walking, 2014). These data suggest the desirability of providing more bicycle facilities to increase the mode share of cycling.

So far, there have been abundant studies on road space allocation problems. Most of those focus on studying the success of High-Occupancy Vehicle (HOV) and High-Occupancy Toll (HOT) lanes in cities such as San Diego, Houston, and New York. Many researchers (Collier & Goodin, 2004; Murray et al., 2000; Obenberger, 2004) are interested in introducing various pricing strategy to provide travel time savings and reliability on the managed lanes. These efforts can eventually help reduce the travel time for motorized vehicles on the managed lanes, while doing little to reduce the number of motorized vehicles, or the demand for road space.

The introduction of vehicle eligibility as a lane management strategy to improve travel conditions in special use lanes, such as bike lanes, can actually encourage people to drive less and thus relieve the growing congestion on roads.

Research Objectives and Contribution

This study aims to (1) optimize the allocation of road space between automobiles (or, more generally, motor vehicles) and bicycles, (2) select network improvement projects and (3) schedule the selected projects. The objective of this optimization problem is to minimize the present value of the total system cost. A traffic assignment model is used to determine the bicycle and automobile flows on various links at user equilibrium. The objective function values for various road space allocation solutions are compared and the best solution, which has the minimum present value of the total system cost, is chosen.

To solve the problem of selecting and scheduling interrelated projects. A Genetic Algorithm (GA) is used to determine which projects to select and the best schedule to implement those projects.

The work presented in this thesis contributes to the literature in several ways. First, this network development problem with bicycles is formulated and the optimization problem of road space allocation between two modes is solved based on the present value of total system cost. Second, it explores a method that considers bike lanes as one kind of managed lanes under the lane management condition (i.e. allocation of road spaces). Generally, the methodology presented in this work should also be applicable in allocating road space and scheduling network development for other kinds of managed lanes.

Thesis Organization

Chapter 2 of this thesis reviews the existing literature on managed lanes, including bicycle lanes, and on road space allocation with bicycle lanes. Chapter 3 presents the methodology used for road space allocation between bicycles and motorized traffic as well as important assumptions made in this research. Chapter 4 provides a detailed explanation of the Genetic Algorithm used. Chapter 5 presents the network configuration and characteristics of the case study. Chapter 6 discusses the results for the two problems. Chapter 7 summarizes the methodology and results of road space allocation between bicycles and motorized traffic and the selection and scheduling problem. Future studies are suggested and recommendations are provided.

Chapter 2: Literature Review

Bicycle facilities and bicycle usage

In Maryland (Md. Code Ann., Transp. §§11-176; 21-1202) and many other states, bicycles are recognized as vehicles and bicyclists have all the legal rights to use the road space as other road users. However, in situations with high travel speeds and high traffic volumes, it is both unsafe and challenging to require a cyclist to ride along with the traffic. It poses great danger to cyclists and reduces the automobile speed because of the necessary slow-down when drivers have to pass a bicycle at a distance of at least 3 feet or follow a bicycle if there is not sufficient space to overtake the bicycle. The provision of bike lanes or other similar bike facilities can increase not only the perceived and actual safety of cyclists but also help remain the normal operation of automobile travel as the separation between motor-vehicles and bicycles. The provision of bicycle facilities promotes bicycle sharing by encouraging more people to bike (J Dill & Carr, 2003; Nelson & Allen, 1997; Pucher & Buehler, 2008). It is not uncommon for city planners and bicycle advocates to think that if bicycle facilities are provided, people will use them. To confirm this conventional wisdom, Nelson & Allen (1997) conducted a cross-sectional analysis to the data from 18 U.S. cities. After considering factors such as weather, terrain, and number of college students, it is found that one additional mile of bikeway per 100,000 residents increases the number of bicycle commuters by 0.069%. The main limitation of this study is that the top four cities in terms of bicycle commuting are “college towns”: Boulder, CO, Eugene, OR, Gainesville, FL, and Madison, WI. Although the number of college students is controlled for, it could still affect the analysis results and the conclusion may not be convincing for large cities without so many college students. Building upon the work of Nelson & Allen (1997), Dill & Carr (2003) did the analysis with the new Census data, covering 35 cities, including Washington, DC, New York City, NY, Los Angeles, CA and other large U.S. cities. The study confirmed the results of Nelson & Allen (1997), indicating that higher levels of bicycle facilities have a significant and positive correlation to higher commuting rate by bicycles. More specifically, they found that for large U.S. cities with populations over 250,000, one additional mile of bike lane per square mile increases the share of bicycle commuters by 1%. All the authors above noted that the positive correlation does not indicate the existence or direction of a cause-effect relationship between bike facility and bike usage. However, as as Nelson and Allen stated, “This analysis confirms the hunches of public policymakers that at least some, but perhaps not an inconsequential number, of commuters will be responsive to the bicycling option if only it were made available”.

Krizek & Johnson (2004) estimated the effect of household proximity to a bicycle facility on the subjects’ bicycle usage. The results showed that people living less than 400 meters from an on-road bicycle facility had statistically significantly increased bicycle usage compared to people living more than 1600 meters from an on-road bicycle facility.

For a better understanding of cyclists’ preferences in using bicycle facilities, Tilahun, Levinson, & Krizek (2007) looked into cyclists’ preferences for using trails for commuting. In this study, it was found that cyclists were willing to switch from an unmarked on-road facility with on-street parking to an off-road trail, at the cost of up to 20 minutes more travel time. While the use of trails is out of the scope of this thesis, it is interesting to find that cyclists have a different perspective, compared to motorists, on the trade-off of travel time, comfort, and safety.

Stinson & Bhat (2003) estimated empirical models using data from an online SP survey and showed that travel time is the most important factor in route choice. Other factors such as the presence of a bicycle facility (especially a bike lane or separate bike path), the level of automobile traffic, and pavement or riding surface quality are also important. Hunt & Abraham (2006) concluded that the sensitivity to cycling trip time varies with bicycle facility type. It was found that 1 minute of cycling in mixed traffic is equivalent to 4.1 minutes on bike lanes or 2.8 minutes on bike paths in terms of comfort and stress. Dill & Voros (2007) found that positive perceptions of the availability of bike lanes are associated with more cycling and increased desire to cycle.

The methodologies and results from the above studies differ, but there are consistent conclusions. The key factors affecting cyclists' choice of route are travel time and the presence of on-road bike facility (especially bike lanes). All the studies mentioned in this section show that cyclists do value bicycle facilities and the provision of facilities (especially bike lanes) can lead to more bicycle usage.

Managed lanes

The definition of "managed lanes" is ambiguous and can mean different things to different stakeholders. In some agencies, the term is commonly thought of as high-occupancy toll (HOT) lanes. In other agencies, a broader definition is adapted that includes high-occupancy vehicle (HOV) lanes, value-priced lanes (including HOT lanes), and special use lanes (such as express, bus-only, or truck-only lanes) (Collier & Goodin, 2004; Obenberger, 2004).

The above literature considers managed lanes on freeways, while the term can also apply to arterial streets. Some studies are found to consider bicyclists when analyzing arterial HOV lanes. Several cities such as London, Los Angeles, Paris, and Sydney, allow cyclists to travel on most bus lanes(Agrawal, Goldman, & Hannaford, 2012). Murray et al. (2000) pointed out that bicycles must be considered for the arterial HOV lanes. Bicycles may be allowed in the HOV lanes or may have a separate lane on the same roadway. Greater care must be given to pavement conditions if bicycles are permitted on the HOV lanes.

Currently, little research has been done to explore how bicyclists can take advantage of the arterial managed lanes. Bike lanes can be categorized into the group of special use lanes. Research is needed to decide what fraction of the available road space can be reserved for bicyclists to provide them reduced travel time and improved reliability in such managed lanes.

Road space allocation between automobiles and bicycles

If road space is fixed, bicycle lanes come at the expense of restricting the motorists to less space (Alliance for Biking & Walking, 2014), which reduces the roadway capacity and safety for motor vehicles (Petritsch, 2009). This concern has precluded the introduction of bike lane in many cities (S. Bagloee, Sarvi, & Wallace, 2016). However, as mentioned in the previous section, the provision of bicycle facilities, e.g. bicycle lanes, is vital to promote bicycling. Despite the abundant studies analyzing network design problems, mostly road space allocation problems with bus lanes and toll lanes (Bagloee & Ceder, 2011; Gan et al., 2003; Kim & Schonfeld, 2008; Mesbah, Sarvi, & Currie, 2008; Mesbah et al., 2011), there are only a few studies that address the network design problem with bike lanes.

In a search for the optimal road space allocation with bike lanes, Xu (1993) used the total system costs (user time costs, operating costs and other costs) as the objective function. A logit model was used for modal split and the software *MINUTP* (1991) was used for traffic assignment. Lane width was considered to be the only variable determining lane capacity. A unit environmental cost per vehicle mile was included in the total cost function. Accident impact was also considered in the form of accident rates multiplied by the total distance travelled.

In an effort to optimize the road space allocation problem among cars and bikes, Mesbah et al. (2012) proposed a bi-level optimization framework for the design of a network of bike lanes in an urban road network. The upper level objective function was formulated by a weighted sum of a measure for car users (total travel time) versus a measure for bicyclists (total travel distance on bike lanes). The lower level optimization model aims to assign car and bicycle demand in response to different network design alternatives. A genetic algorithm was suggested for solving this optimization problem. The limitation of the research is that the authors assumed all the road links were two-lane highways and the addition of a bike lane will reduce the roadway capacity by a fixed value no matter how the lane configuration was.

Elshafei (2006) proposed a multi-objective decision-making framework for roadway lane designation among different viable modes of transportation. The modes considered in Elshafei's study include automobiles, buses, and bicycles. The measures used to assess the efficiency of the lane designation scenario include not only traditional measures used by transportation agencies, such as delays, travel speeds, and travel times, but also the mobility, accessibility, and safety and environmental impacts.

Duthie & Unnikrishnan (2014) proposed a formulation for the network design problem with bicycles, aiming at connecting all origin-destination pairs where each roadway segment and intersection meets a low bound on its bicycle level of service. The formulation minimizes the total cost of construction and choses the optimal bicycle path based on the bicycle LOS instead of by distance (travel time), which represents bicycle route choice more realistically. A major limitation of this study is that it does not consider the bicycle demand when connecting the bicycle network. While a connected network may unleash the latent demand of bicycle travel, the cause-effect relationship between bicycle facility and bicycle usage is not confirmed (J Dill & Carr, 2003; Nelson & Allen, 1997). If the new bicycle facilities are not utilized by cyclists, it is then a waste of the road space and money. It is more cost-effective to improve bicycle facilities according to bicycle demand, especially when budget is limited.

Last but not least, it should be noted that there is a relation between roadway width and the roadway capacity. A method for estimating highway capacity, which was based on the adjusted saturation flow rate, was recommended in *Highway Capacity Manual (HCM 2000*):

$$s = s_o N f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$$

The lane width adjustment factor f_w is calculated as follows:

$$f_w = 1 + \frac{W - 3.6}{9}$$

W = lane width (m)

This formula suggests that each foot above or below the default 12-foot lane increases or decreases the capacity by 3.33% respectively. It should be considered when identifying different road space allocation plans as the addition of bike lanes in a network with fixed road space will decrease the width available for other traffic.

The effect of adding bike facilities on the reduction of crash rates varies from one location to another. Studies conducted in New York City (NYC DOT, 2012; Wolfson, 2011) compare the injury rates on protected bike lanes and streets without bike facilities. NYC DOT (2012) concludes that the provision of protected bike lanes reduce the injury rates of all users by 57% (56% for cyclists). The reduction rates range from 40% to 50% for all users in Wolfson's report. Lusk et al. (2011)'s study conducted in Montreal suggests 28% fewer injuries per mile for cyclists compared to reference streets with no bike facilities. Chen et al. (2012) concluded that the addition of many miles of new bike lanes in NYC does not increase bike crashes despite the increase in the number of cyclists. For testing purposes, the accident rates for the two modes are assumed to have a 30% decrease per mile, as suggested in (Lusk et al., 2011), after the addition of bike lanes on the link.

The present study solves the network design problem with bicycle lanes for a given budget. The study extends the current methodologies offered in the literature in the following aspects: First, it considers not only the locations for adding bike lanes but also the scheduling of these projects over a study period. Second, the effect of bike lane addition on the roadway capacity is calculated according to the lane width decrease instead of assuming a fixed capacity loss for all situations. It is fulfilled by calculating the lane width after adding the bike lane and adjusting the capacity according to the formula given in *Highway Capacity Manual* (HCM 2000). Last, a roadway network example is designed to test the performance of the proposed methodology.

Chapter 3: Research Methodology

The study develops a method for optimally selecting and scheduling bike lane addition projects to allocate the available road space between automobiles and bicycles. It is an effort to reallocate road space between the two modes and evaluate the resulting effect on different users. The objective function to minimize is the present value of the total system cost of these two modes, while satisfying the given demand and budget constraints throughout a study period. The total system cost consists of the travel time cost, operation cost, and accident cost of automobiles and bicycles. An optimization model using a genetic algorithm is developed to evaluate and schedule candidate projects. Traffic assignment models are incorporated in the optimization model to evaluate the effect of the projects on the two mode users. The optimized solution is calculated with the minimal present value of the total system cost in the study period.

Assumptions

The following important assumptions are made in this study:

(1) Trip demands of automobiles and bicycles are assumed to be known in the base year. The demands grow exponentially among all OD pairs over the planning period. The demand growth rates of the two modes may be different.

(2) Traffic assignment models are used to estimate traffic speed (travel time). Note that the travel times of two modes are assumed to stay constant within time periods (given that the demand remains the same) when the road space allocation is not changed.

(3) The addition of a bicycle lane is assumed to affect bicycle and motor vehicle speeds. The automobile travel lane widths are re-assigned and the lane capacities are adjusted according to the method proposed in HCM 2000 (*Highway Capacity Manual*, 2000).

(4) It is also assumed that the provision of bike lanes can reduce the interference between cars and bicycles, which is reflected in a decreased accident rate for both cars and bicycles. For testing purposes, the accident rates for the two modes are assumed to have a 30% decrease per mile, as suggested in (Lusk et al., 2011), after the addition of bike lanes on the link.

(5) Other interactions between these two modes are assumed to be negligible in this study.

(6) The bicycle flow characteristics are calculated based on a Greenshields model (Carter & Homburger, 1978).

<u>*Traffic assignment models*</u>

This research incorporates the *convex combination algorithm* (Frank & Wolfe, 1956) to assign motorized traffic in the network. Starting with an initial flow *x*, the search direction at each iteration is determined by solving a linear approximation of the objective function, determining the step size and moving in that direction. The algorithm eventually stops when the convergence criterion, which is based on the similarity of two successive solutions, is satisfied.

Given a current travel time for link *a*, t_a^{n-1} the *n*th iteration of the convex combination algorithm is summarized as follows:

1. *Initialization*: all or nothing assignment assuming t_a^{n-1} which yields x_a^n.

2. *Updating travel time*: using a BPR function $t_a^n = t_a(x_a^n) = t_0(1 + 0.15\ (\frac{v}{c})^4)$.
3. *Direction finding*: all or nothing assignment considering t_a^n which yields auxiliary flow y_a^n.
4. *Line search*: find α that solves $min \sum_a \int_0^{x_a^n + \alpha(y_a^n - x_a^n)} t_a(\omega) d\omega$.
5. *Move:* set $x_a^{n+1} = x_a^n + \alpha_n(y_a^n\text{-}\ x_a^n),\ \forall \alpha$.
6. *Convergence test*: If a convergence criterion met, stop. Otherwise set n=n+1 and go to step 1.

For assigning the bicycle traffic in the network, the congestion effect is not considered as the bicycle volume is very low. As a result, the all-or-nothing method is applied to assign all the bicycle demand to the network.

Problem Formulation

The objective function for road space allocation is the total system cost, including total user time cost, total operating cost, and total accident costs for motorized vehicles and bicycles. The optimal space allocation solution will minimize the present value of the total system cost, subject to budget constraint in each given time period:

$$\mathrm{Z} = \sum_{j=1}^{T} \frac{1}{(1+r)^j} \sum_{i=1}^{n} L_i \times \left(C_{bi} \times Q_i^{bi} + C_{mv} \times Q_i^{mv}\right) + v \times \left(t_i^{bi} \times Q_i^{bi} + t_i^{mv} \times Q_i^{mv}\right)$$

$$+ L_i \times \left(x_i(t) + \mu \times \left(1 - x_i(t)\right)\right) \times \left(Acc_{bi} \times Q_i^{bi} + Acc_{mv} \times Q_i^{mv}\right)$$

where

$\mathrm{Z} = present\ value\ of total\ cost\ (dollars)$

$n = number\ of\ links\ in\ the\ network$

$x_i(t) = dummy\ variable\ indicating\ if\ bike\ lane\ is\ added\ on\ link\ i\ at\ time\ t$

$L_i = length\ of\ link\ i\ (miles)$

$C_{BI} = bicycle\ operating\ cost\ (dollars/mile)$

$C_{MV} = motor\ vehicle\ operating\ cost\ (dollars/mile)$

$t_i^{bi} = bicycle\ travel\ time\ on\ link\ i\ (hours)$

$t_i^{mv} = motor\ vehicle\ travel\ time\ on\ link\ i\ (hours)$

$Q_i^{bi} = bicycle\ volume\ on\ link\ i\ (bicycles/hour)$

$Q_i^{mv} = motor\ vehicle\ volume\ on\ link\ i\ (pcu/hour)$

$v = value\ of\ time\ (dollar/hour)$

$Acc_{bi} = bicycle\ accident\ cost\ (dollars/million\ bicyle\ miles)$

$Acc_{mv} = motor\ vehicle\ accident\ cost\ (dollars/million\ vehicle\ miles)$

$\mu = adjustment\ facotr\ of\ accident\ costs$

$r = interest\ rate$

The demand of both modes increases exponentially as a function of time over the planning horizon as follows:

$$d_{ij}^t = d_{ij}^0 \times (1 + r_{bike})^t$$

$$d_{ij}^t = d_{ij}^0 \times (1 + r_{car})^t$$

where

$d_{ij}^t = demand\ at\ time\ t;$

$d_{ij}^0 = demand\ in\ the\ base\ year;$

$r_{bike} = growth\ rate\ for\ bicycles;$

$r_{car} = \ growth\ rate\ for\ cars.$

The provision of a bike lane will reduce the width of motor vehicle lanes and, consequently, decrease the lane capacity. According to the BPR volume-delay function (United States Bureau of Public Roads, 1964):

$$TT = FTT \times (1 + \alpha \times (\frac{v}{c})^{\beta})$$

where

TT = predicted travel time;

FTT = free-flow travel time;

v = volume;

c = roadway capacity;

α = coefficient ($\alpha = 0.15$);

β = coefficient ($\beta = 4$).

As capacity decreases, even if the volume on the link remains the same, the adjusted travel time will increase. As a result, the assignment of motor vehicle traffic flow will be affected (i.e. some drivers will change their chosen route). That is the main effect on motor vehicles of bike lane additions.

The proposed optimization method will minimize the travel cost, including operating costs, user time costs, and accident costs, of both bicyclists and motorists under the given budget.

Jong & Schonfeld (2001) formulated this problem by defining the decision variables as the completion time of projects. In this formulation the budget constraint is defined as follows:

$$\sum_{i=1}^{n_p} c_i x_i(t) \le \int_0^t b(t)dt, \quad 0 \le t \le T$$

$$\begin{cases} x_i(t) = 0 \quad if\ t < t_i \\ x_i(t) = 1 \quad if\ \ t > t_i \end{cases}$$

where

t_i = the time when project *i* (construction of bike lane on link *i*) is finished;

$x_i(t)$ = binary variable indicating whether project i is finished by time t;

c_i = capital cost of project *i*;

$b(t)$ = budget function at time t.

Note that the set of all $t_i's$ eventually determines the schedule of all selected projects. This occurs because under the given budget, which is continuously distributed over time, it is assumed that there will always be a set of justified projects waiting for funding. It is reasonable to fund one project as long as there is sufficient budget since the system will gain benefits once the project is finished. In other words, funding multiple projects at the same time increases the completion time which means the time savings of bike lane additions are delayed. Thus, under certain budget flow, it is desirable to fund and complete one project at a time and avoid funding overlaps. As a result, the schedule of the projects is automatically determined considering the budget flow over the time period.

Optimization models

For a large-scale problem, evaluating all possible solutions is undesirable because the scope of the problem grows very fast with the number of candidate projects n_p. The solution space for all possible sequences of the projects is (Jong & Schonfeld, 2001):

$$\sum_{i=0}^{n_p} \frac{n_p!}{(n_p - i)!\, i!} = \sum_{i=0}^{n_p} \frac{n_p!}{(n_p - i)!}$$

For this kind of problem, a heuristic method is preferred. In the past studies, many researchers recommended the use of genetic algorithms for solving the project selection and scheduling problem (Jong & Schonfeld, 2001; Shayanfar et al., 2016). Moreover, Shayanfar et al. (2016) compared three metaheuristic algorithms and found that a genetic algorithm yields the most consistent solution with lower total cost than the other two. Thus, a genetic algorithm is used here to find optimal solution(s) of the project selection and scheduling. Each time a new bike lane is added to the network, all traffic is re-assigned to reflect the new travel times of each link. The framework of the whole model is shown in Figure 2-1 while the details of the genetic algorithm used are discussed in the next chapter.

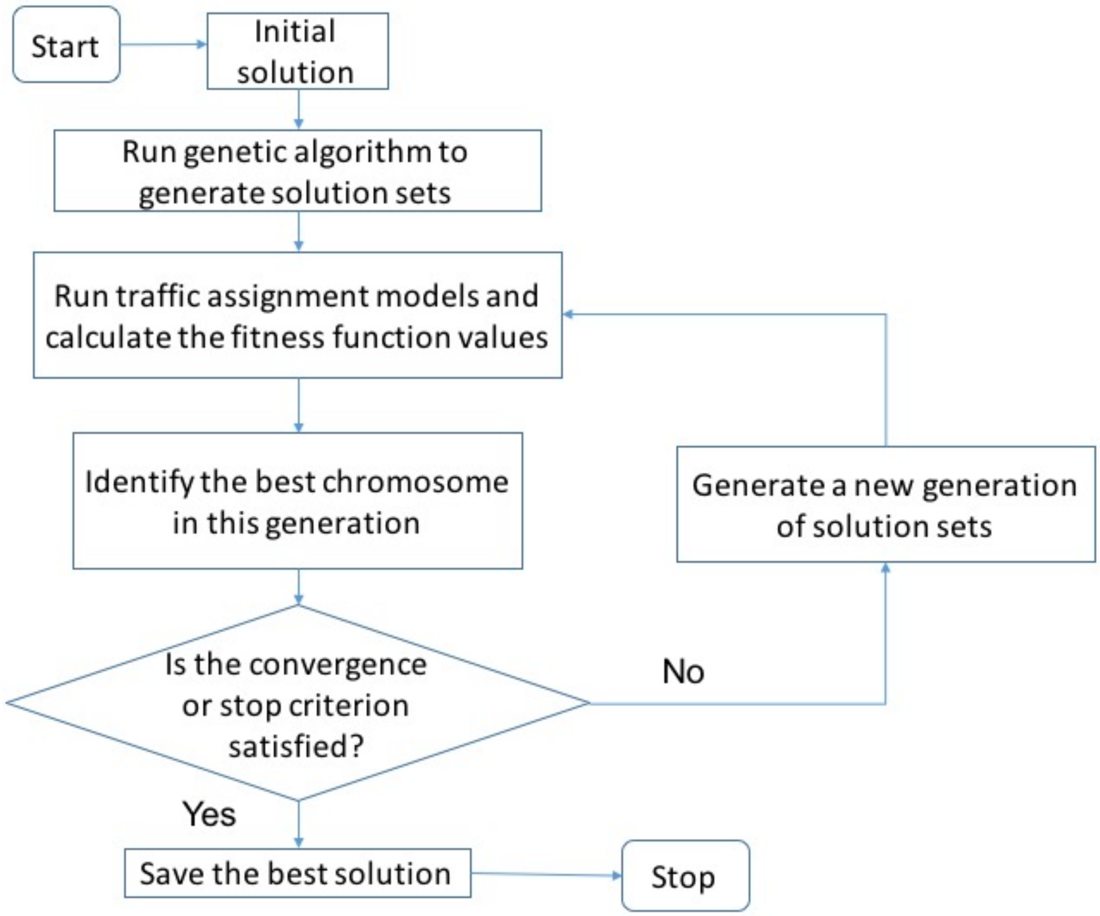

Figure 3-1 The framework of the optimization model

Chapter 4: Genetic Algorithm

Introduction

A genetic algorithm (GA) is a meta-heuristic method inspired by the basic principles of biological evolution and natural selection. It has been widely used as the solving algorithms in a wide range of optimization problems. GAs simulate the survival of the fittest among individuals over consecutive generation to solve a problem. At each generation, there are a set of potential solutions called the population. Each solution is represented by a string of encoded genes that we call a chromosome. Solutions from the population are selected to form off springs according to their fitness value, the fitter they are the more changes they have to reproduce. The selected solutions are then processed through GA operators, namely crossover and mutation, which create offspring and randomly change the new offspring. The two operators significantly influence the performance of the algorithm.

Solution representation

The solutions are presented by the sequence of the projects selected. In this thesis, it is assumed that each project has to start after its predecessor has finished and before its successor starts. Figure 4-1 shows an example of a solution.

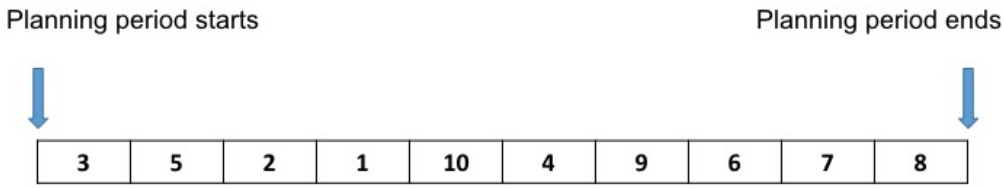

Figure 4-1 Example of a feasible solution

<u>*Fitness function*</u>

The fitness function minimizes the total system cost subject to the budget constraint which are formulated in the second chapter. To account for the budget constraint, the fitness function consists of two terms: the total system cost (TC) and a penalty function. The penalty function should be minimized when the budget constraint is binding while discouraging the total construction costs from exceeding the available budget. The penalty function is formulated as:

$$penalty = \sum_{a \epsilon A_1} c_a \times \left| \sum_{a \epsilon A_1} c_a \times x_a - bdg \right|$$

where

$A_1 = the\ set\ of\ links\ that\ are\ candidate\ links\ for\ bike\ lane\ addition$

$c_a = the\ cost\ to\ add\ a\ bike\ lane\ on\ link\ a$

$x_a =$

$dummy\ variable\ specifying\ if\ bike\ lane\ added\ on\ link\ a. (1\ if\ bike\ lane\ added; 0\ otherwise)$

$bdg = the\ budget\ constraint$

Thus, the fitness function is

$$\min Z = TC + penalty$$

Parameters of GA (Ecker & Kupferschmid, 1988)

(1) Population size

Population size specifies how many chromosomes there are in each generation. On one hand, too small a population size will lead to a small possibility for GA to perform crossover and thus a small part of search space is explored. On the other hand, GA slows down if the population size is too big. An appropriate population size must be chosen so that sufficient search space is explored while the computation time of GA remains acceptable.

(2) Crossover probability

Crossover probability decides how often crossover is performed. It is made in hope that new chromosomes will keep good parts of parents, or even better in terms of the fitness function.

(3) Mutation probability

Mutation probability decides how often parts of the chromosome will be mutated. If no mutation, offspring is the exact result of crossover between parents. Mutation is the procedure to prevent GA from converging to local optimum.

More details of how changes in these parameters can affect the output in the optimization model are discussed in Chapter 6.

Selecting default values for genetic parameters

Factors such as population size, mutation and crossover probability influence the performance of genetic algorithms. Analysis is conducted on these factors to select the default values for the genetic parameters in the algorithm.

(1) Population size

Population size is an important parameter of genetic algorithms. If the population size is too small, genetic algorithms have few possibilities to crossover and only a small part of search place is explored. On the other hand, too large a population size increases optimization reliability while reduces the optimization speed. Therefore, a good selection of population size could increase the optimization speed. This analysis examines four different population sizes, namely 10, 20,30, and 40.

Table 4-1 presents the outcomes including computation time, present value of the total cost, and the optimal sequence for different population sizes. Figure 4-1 shows that when the population size increases the computation time grows dramatically. However, as shown in Table 4-1, the larger population size achieves a lower (i.e., better) objective function value when the number of generations is held constant. Therefore, it is important to set the population size so that useful balances can be achieved between computation time and solution quality.

Table 4-1 Algorithm training (Population size)

Population size	Computation time (min)	Total cost ($)	Optimal sequence
10	120.69	4983013.28	9,53,76,50,23,25,58
20	220.22	4839470.95	76,53,23,11,9,56,6

30	239.60	4782168.19	11,9,73,58,76,50,53
40	338.19	4777188.66	11,58,73,53,9,25,50

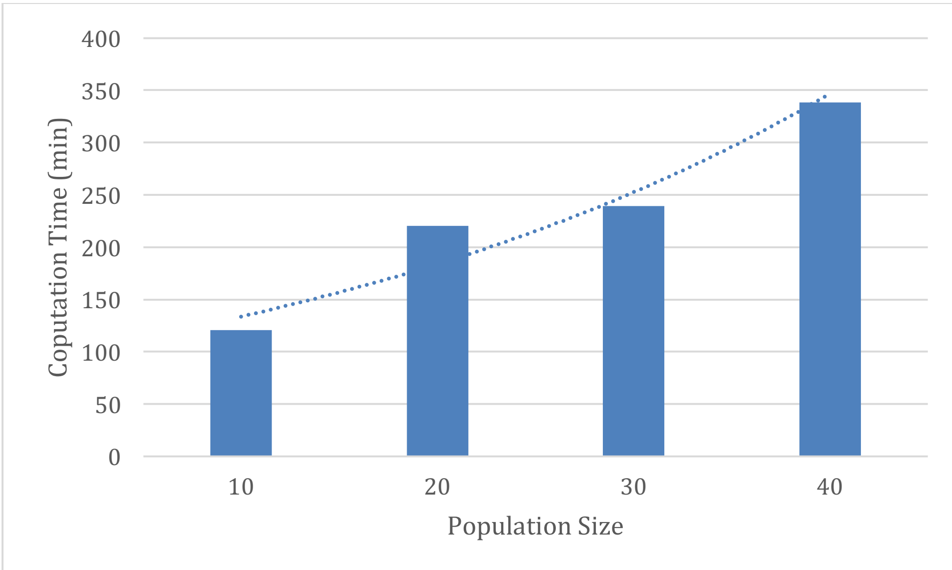

Figure 4-2 GA performance with different population sizes

We can see that choosing a population of 20 instead of 10 significantly increases the solution quality. Selecting the population size of 40 does not yield much significant improvement in terms of solution quality, but requires much more computation time. The population size of 30 slightly increases the computation time over that of 20 but yields a better solution. Thus, the population of 30 seems to be the most reasonable choice.

(2) Crossover and mutation probabilities

Crossover probability and mutation probability are two key parameters of GA, which significantly affects the computation time and solution quality. In genetic algorithms, mutation operators are used to provide exploration and crossover operators are used to lead population to converge to a sub-optimal, if not optimal, solution (exploitation). While crossover tires to converge to a specific point, mutation tries to explore more search areas. More specifically, crossover probability indicates the ratio of how many parents will be selected for mating. Usually, a higher probability is used with the expectation that converge will come faster using the already explored regions. Higher mutation probabilities increase the chance of searching more areas in the search space, while presents the population to converge to any optimal solution. On the other hand, overly small mutation probabilities may result in premature convergence to local optimum instead of global optimum. Thus, one should carefully select an appropriate balance between exploration and exploitation of the algorithm.

For this study, crossover probabilities ranging from 0.5 to 0.8 and mutation probabilities ranging from 0.1 to 0.3 are examined. The crossover probability is set to 0.8 while testing the mutation probabilities. The mutation probability is set to 0.2 while testing the crossover probabilities.

Table 4-2 Algorithm training (Crossover probabilities)

Crossover probabilities	**Number of generations**	**Total cost ($)**	**Optimal sequence**
0.5	30	4937233.57	9,23,50,53,76,25,58
0.6	30	4821864.23	9,23,53,11,9,76,50
0.7	30	4821783.38	11,9,73,58,76,50,53
0.8	30	4777188.66	11,58,73,53,9,25,50

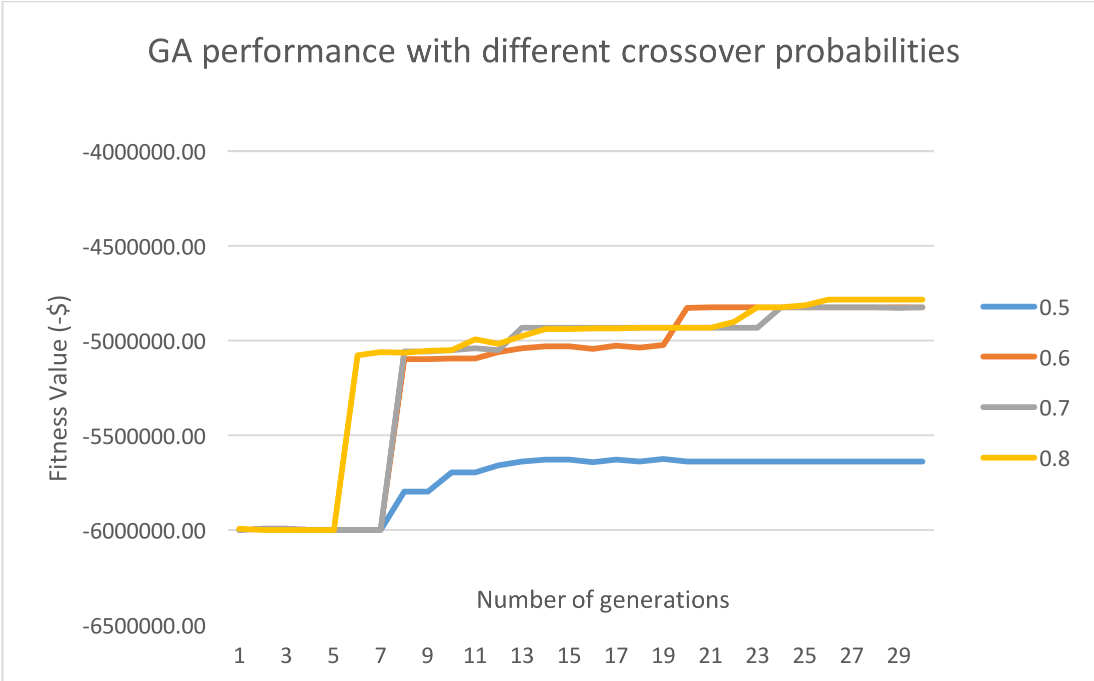

Figure 4-3 GA performance with different crossover probabilities

As shown in Figure 4-3, the crossover probability of 0.8 yields a better solution than other values. It converges a little faster and yields a better solution than the probability of 0.7. The corresponding present worth of total cost is $4777188.66.

Table 4-3 Algorithm training (Mutation probability)

Mutation probabilities	**Number of generations**	**Total cost ($)**	**Optimal sequence**
0.1	30	4807343.23	9,11,23,50,,76,25,58
0.2	30	4782168.19	11,9,76,58,73,50,53
0.3	30	4781172.81	11,58,73,76,9,53,50

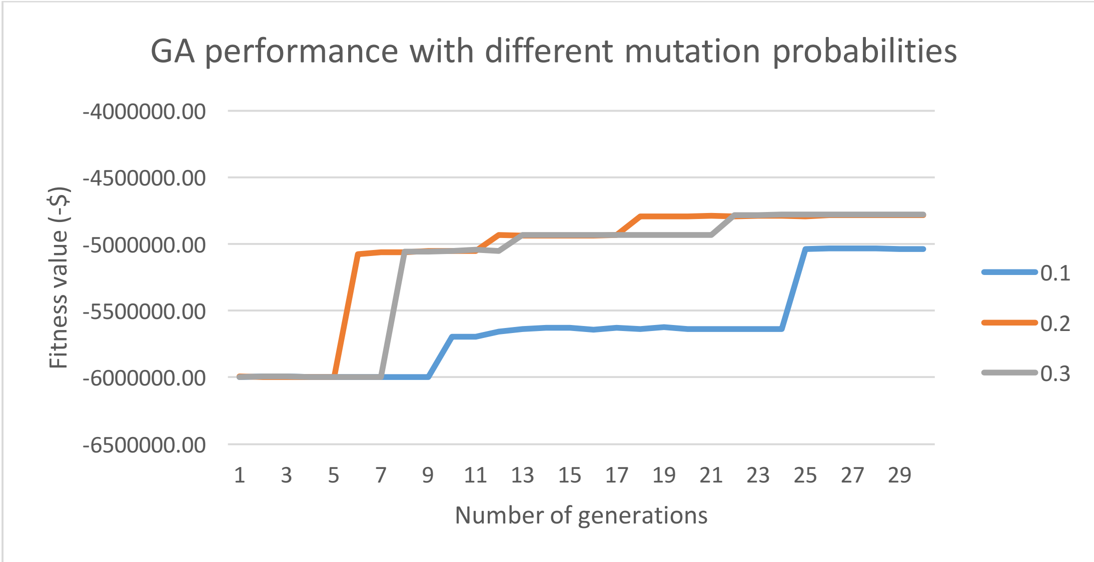

Figure 4-4 GA performance with different mutation probabilities

Figure 4-4 shows that the mutation probability of 0.2 yields a better solution than other values. Table shows the optimal sequence and the present value of the total system cost for different mutation probabilities. The probability of 0.2 gives a better solution with the present value of the total cost of $4782168.19 over the study period. Note that in this case, the mutation probability of 0.3 yields a slightly better solution with less cost ($4781172.81) but requires more time to reach to optimal solution. Thus, the mutation probability of 0.2 is most proper for this study.

Stopping criterion

Two stopping criteria, namely the number of iterations and the running time, are set for the algorithm. The algorithm will be terminated either after a certain number of iterations or after a certain amount of computation time.

Validation test

To check if the optimization algorithm is working well and the result it produces is reasonably reliable, a validation test is conducted. Assuming the budget flow is continuously and evenly distributed over the study period (10 years) at the rate of $195,000/year. The cost for adding a bike lane to the existing road network is $130,000/mile. The optimal selection of promising links to add bike lanes is link 4-5, 5-4, 16-18, 17-19, 19-17, 23-24, and 24-23. The optimized schedule given by the optimization algorithm is listed in Table 4-4. The present value of the total cost is $4,782,168.19.

Table 4-4 Optimized schedule of projects given by optimization algorithm

LINK	COMPLETION TIME (YEAR)
5-4	1.33
4-5	2.67
23-24	4.00
19-17	5.33
24-23	6.67
16-18	8.67
17-19	10.00

The number of all possible schedules to implement the seven selected projects is

$$P(7,6) = \frac{7!}{(7-6)!} = 5040.$$

The present values of total cost for all the schedules range from $4,750,460.48 to $5,210,158.78. The smallest present value is given by the schedule of projects: 5-4, 4-

5, 23-24, 24-23, 16-18, 19-17, and 17-19. Comparing the result given by the optimization algorithm with the actual optimal value, the optimized result is only 0.67% larger than the actual globally optimal one. An error of this magnitude seems fairly insignificant compared to errors due to other factors that are difficult to estimate such as future demand, project costs and budgets. In other words, the optimization algorithm can be reliably produce a good solution for selecting and scheduling bike lane addition projects.

Chapter 5: Case Study

Network configuration

The Sioux Falls network is used as a case study for this problem. Sioux Falls is the largest city in South Dakota. Figure 5-1 shows the map of this city. However, the network used in this research is partially different from the network that has been used for Sioux Falls in many publications. This network is good for testing algorithms and software and also provides an opportunity to examine the data format.

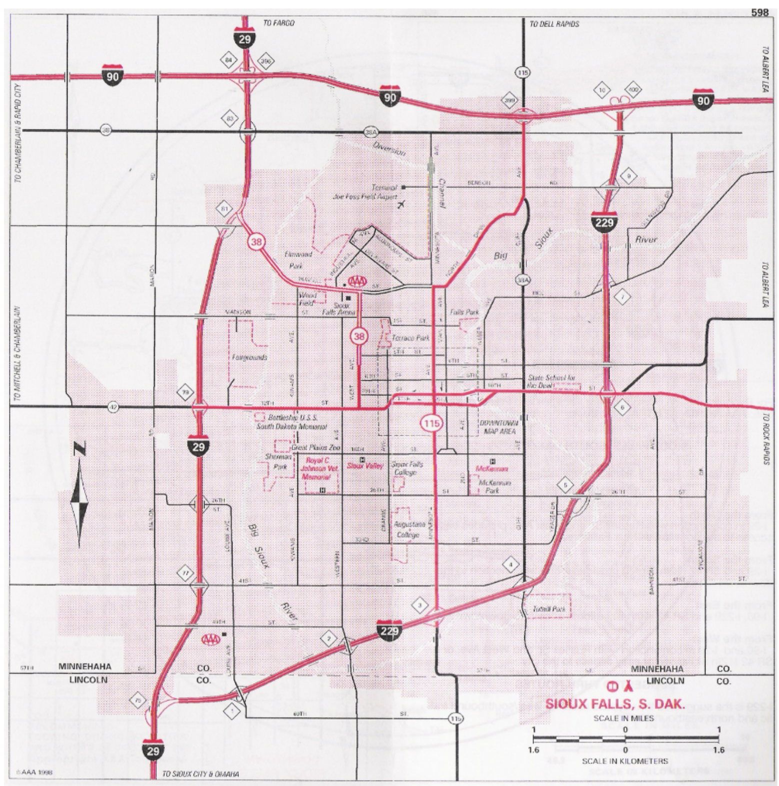

Figure 5-1 Sioux Falls Network Map

The network used to test the optimization model, which based on that in Sioux Falls City in South Dakota, is shown in Figure 5-2. This network consists of 24 nodes and 76 links. The motor vehicle and bicycle OD matrix are listed in Table 5-1 and Table 5-2, respectively.

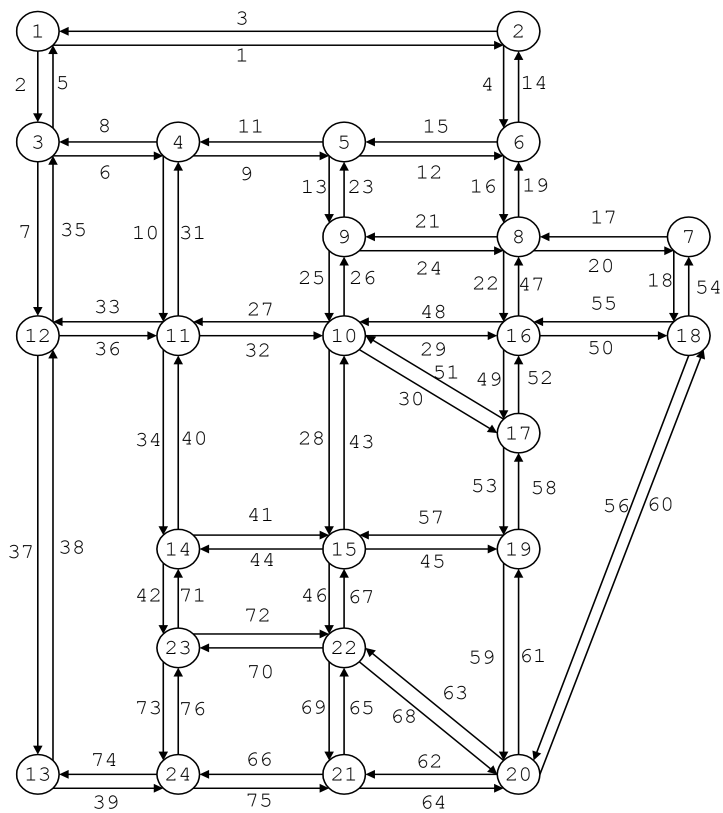

Figure 5-2 Sioux Falls Network

Table 5-1 Motor vehicle OD matrix

	1	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***
1	0	40	24	72	36	48	60	96	72	168	72	36	72	36	60	72	60	24	36	36	12	48	36	24
2	40	0	12	36	12	60	24	60	36	72	24	24	36	12	24	48	36	12	12	24	12	24	12	12
3	24	12	0	36	12	36	12	24	24	36	36	36	24	12	12	24	12	0	12	12	12	12	12	12
4	72	36	36	0	60	60	60	84	96	144	180	84	72	60	60	96	60	12	36	48	24	48	60	36

5	36	12	12	60	0	36	24	72	96	120	72	24	24	24	36	72	36	12	24	24	12	24	24	12
6	48	60	36	60	36	0	48	96	48	96	48	36	36	24	36	120	72	12	36	48	12	36	24	12
7	60	24	12	60	24	48	0	132	72	228	60	96	60	36	60	168	120	120	60	72	36	72	24	12
8	96	60	24	84	72	96	132	0	0	192	108	72	72	48	84	264	168	36	84	108	48	72	48	24
9	72	36	24	96	96	48	72	0	0	336	180	84	72	72	120	180	120	24	60	84	48	84	72	24
10	168	72	36	144	120	96	228	192	336	0	480	252	228	264	480	528	0	84	216	312	156	324	216	108
11	72	24	36	180	72	48	60	108	180	480	0	180	120	192	180	168	120	24	60	84	60	132	168	72
12	36	24	36	84	24	36	96	72	84	252	180	0	168	84	96	84	84	24	36	60	48	96	84	60
13	72	36	24	72	24	36	60	72	72	228	120	168	0	72	84	84	72	12	48	84	72	156	96	96
14	36	12	12	60	24	24	36	48	72	264	192	84	72	0	90	84	84	12	48	60	48	144	132	48
15	60	24	12	60	36	36	60	84	120	480	180	96	84	90	0	156	180	36	96	132	96	312	120	60
16	72	48	24	96	72	120	168	264	180	528	168	84	84	84	156	0	336	200	168	204	72	144	72	36
17	60	36	12	60	36	72	120	168	120	0	120	84	72	84	180	336	0	84	204	204	84	204	72	36
18	24	12	0	12	12	12	120	36	24	84	24	24	12	12	36	200	84	0	48	200	12	48	12	12
19	36	12	12	36	24	36	60	84	60	216	60	36	48	48	96	168	204	48	0	156	60	156	48	24
20	36	24	12	48	24	48	72	108	84	312	84	60	84	60	132	204	204	200	156	0	156	0	84	60
21	12	12	12	24	12	12	36	48	48	156	60	48	72	48	96	72	84	12	60	156	0	228	84	72
22	48	24	12	48	24	36	72	72	84	324	132	96	156	144	312	144	204	48	156	0	228	0	0	144
23	36	12	12	60	24	24	24	48	72	216	168	84	96	132	120	72	72	12	48	84	84	0	0	96
24	24	12	12	36	12	12	12	24	24	108	72	60	96	48	60	36	36	12	24	60	72	144	96	0

Table 5-2 Bicycle OD matrix

	1	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***
1	0	14	13	0	1	16	8	11	10	6	8	17	20	12	18	15	20	10	12	18	19	15	2	5
2	14	0	11	11	7	5	18	2	1	13	3	13	3	18	16	11	8	10	19	1	5	20	10	4
3	13	11	0	7	19	15	15	11	8	20	13	10	2	6	1	0	18	9	19	20	5	16	14	3
4	0	11	7	0	2	18	8	7	18	3	20	10	15	13	11	4	7	18	4	16	7	20	10	11
5	1	7	19	2	0	13	10	6	15	6	12	16	10	4	7	18	10	13	9	3	12	15	20	6
6	16	5	15	18	13	0	17	4	4	19	10	16	16	3	13	8	10	18	11	17	13	7	19	12
7	8	18	15	8	10	17	0	7	1	19	1	19	6	18	4	10	1	9	16	3	1	4	16	7
8	11	2	11	7	6	4	7	0	10	1	14	16	6	13	18	8	19	9	7	18	5	19	18	16

9	10	1	8	18	15	4	1	10	0	14	3	16	17	11	4	19	19	6	20	0	3	17	2	5
10	6	13	20	3	6	19	19	1	14	0	8	17	6	14	2	9	20	2	17	11	18	4	6	7
11	8	3	13	20	12	10	1	14	3	8	0	8	15	18	12	0	12	5	14	2	5	14	16	14
12	17	13	10	10	16	16	19	16	16	17	8	0	3	12	20	9	16	20	17	16	10	5	19	0
13	20	3	2	15	10	16	6	6	17	6	15	3	0	12	12	3	7	14	7	6	8	5	18	18
14	12	18	6	13	4	3	18	13	11	14	18	12	12	0	11	0	20	2	5	1	16	4	6	8
15	18	16	1	11	7	13	4	18	4	2	12	20	12	11	0	0	1	18	14	6	11	9	9	9
16	15	11	0	4	18	8	10	8	19	9	0	9	3	0	0	0	15	5	9	20	11	9	12	3
17	20	8	18	7	10	10	1	19	19	20	12	16	7	20	1	15	0	9	0	2	6	4	10	14
18	10	10	9	18	13	18	9	9	6	2	5	20	14	2	18	5	9	0	4	13	4	20	8	17
19	12	19	19	4	9	11	16	7	20	17	14	17	7	5	14	9	0	4	0	7	3	7	0	19
20	18	1	20	16	3	17	3	18	0	11	2	16	6	1	6	20	2	13	7	0	15	8	15	18
21	19	5	5	7	12	13	1	5	3	18	5	10	8	16	11	11	6	4	3	15	0	12	19	16
22	15	20	16	20	15	7	4	19	17	4	14	5	5	4	9	9	4	20	7	8	12	0	8	7
23	2	10	14	10	20	19	16	18	2	6	16	19	18	6	9	12	10	8	0	15	19	8	0	13
24	5	4	3	11	6	12	7	16	5	7	14	0	18	8	9	3	14	17	19	18	16	7	13	0

In general, 12-foot lanes are considered ideal and used where practical on higher speed principal arterials. Thus, the initial road space allocation case used here assumes the motor-vehicle travel lane to be 12-foot wide, while the rest of the available road space is left for shoulders (greater than 6 feet wide or less than 4 feet wide) or bike lanes (if the space is within the range of 4 to 6 feet). The initial road space allocation result is shown in the following table. The present worth of the total system cost is $4,801,051.39.

Table 5-3 Initial distribution of the road spaces

Link Number	Travel lane width	Number of Lanes	Total Capacity	Space left
1	12	2	3200	11
2	12	3	4800	10
3	12	2	3200	11
4	12	4	6400	0

5	12	3	4800	10
6	12	3	4800	0
7	12	3	4800	7
8	12	3	4800	0
9	12	3	4800	0
10	12	3	4800	2
11	12	3	4800	0
12	12	2	3200	11
13	12	3	4800	0
14	12	4	6400	0
15	12	2	3200	11
16	12	3	4800	7
17	12	3	4800	11
18	12	3	4800	4
19	12	3	4800	7
20	12	3	4800	11
21	12	2	3200	11
22	12	4	6400	2
23	12	3	4800	0
24	12	2	3200	11
25	12	4	6400	0
26	12	4	6400	0
27	12	4	6400	0
28	12	4	6400	2
29	12	3	4800	1
30	12	2	3200	6
31	12	3	4800	2
32	12	4	6400	0
33	12	2	3200	9
34	12	4	6400	1
35	12	3	4800	7
36	12	2	3200	9
37	12	3	4800	6
38	12	3	4800	6

39	12	2	3200	9
40	12	4	6400	1
41	12	3	4800	8
42	12	2	3200	7
43	12	4	6400	2
44	12	3	4800	8
45	12	2	3200	10
46	12	2	3200	9
47	12	4	6400	2
48	12	3	4800	1
49	12	3	4800	5
50	12	4	6400	2
51	12	2	3200	6
52	12	3	4800	5
53	12	3	4800	1
54	12	3	4800	5
55	12	4	6400	2
56	12	3	4800	1
57	12	2	3200	10
58	12	3	4800	1
59	12	3	4800	6
60	12	3	4800	1
61	12	3	4800	6
62	12	3	4800	2
63	12	3	4800	5
64	12	3	4800	2
65	12	2	3200	10
66	12	2	3200	10
67	12	2	3200	9
68	12	3	4800	5
69	12	2	3200	10
70	12	2	3200	7
71	12	2	3200	6
72	12	2	3200	7

73	12	3	4800	0
74	12	2	3200	9
75	12	2	3200	10
76	12	3	4800	0

If the space left is wider than 6 feet, cyclists can travel on that while placing themselves sufficiently far away from the moving vehicles. These links are excluded from the candidate set for improvement. There are 32 links with the left space ranging from 0 to 3 feet and they are considered candidates for improvement (adding a 4-foot bike lane on the link). Note that it is not guaranteed that the addition of bike lanes is symmetric, which means the addition of a bike lane at one direction does not automatically add a bike lane at the opposite direction.

The costs of bike lanes can vary greatly from city to city and state to state due to differences in project specifications and the scale and length of the treatment. For test purposes, the average value of $130,000/ mile (Bushell, Poole, Zegeer, & Rodriguez, 2013) is used in this thesis.

For the first scenario, the available funding is assumed to be fixed. The problem is to find the optimal solution with feasible bike lane adding projects, which minimizes the objective function.

For the second scenario, a stable source of budget is assumed for funding the road expansion project, which distribute evenly over the study time. The proposed solution method aims at finding the optimal solution for selecting and scheduling projects.

Scenario 1：Project selection under fixed budget

In this scenario, the budget is assumed to be fixed as $1,950,000 and the priority is to add bike lanes to the candidate links as long as there is still funding available. The meta-heuristic method described in the previous section is applied to find the optimal solution for the selection of roadway links to add bike lanes. The solution set of links to be improved are 4-3, 4-5, 5-4, 6-2, and 19-17. The after-improvement total system cost is $458,593.30, which decreases by 4.7% compared to the original total system cost of $481,218.80. It is worth to note that the improvements to bike lanes help decreases the total bike user cost, including operating cost, travel cost, and accident cost, by 13.6%.

The parameters of the genetic algorithm are listed below:

Table 5-4 Parameters of genetic algorithm

Parameter	Value
Population size	30
Mutation probability	0.1
Crossover probability	0.8
Elitism	2

The algorithm was tested with 50 replications, with each replication consisting of 150 iterations. In each replication, the algorithm converges within 150 iterations. The best solution with the minimal objective function value out of the 50 replications was then selected and plotted as in Figure 5-2 to present the performance of the genetic algorithm.

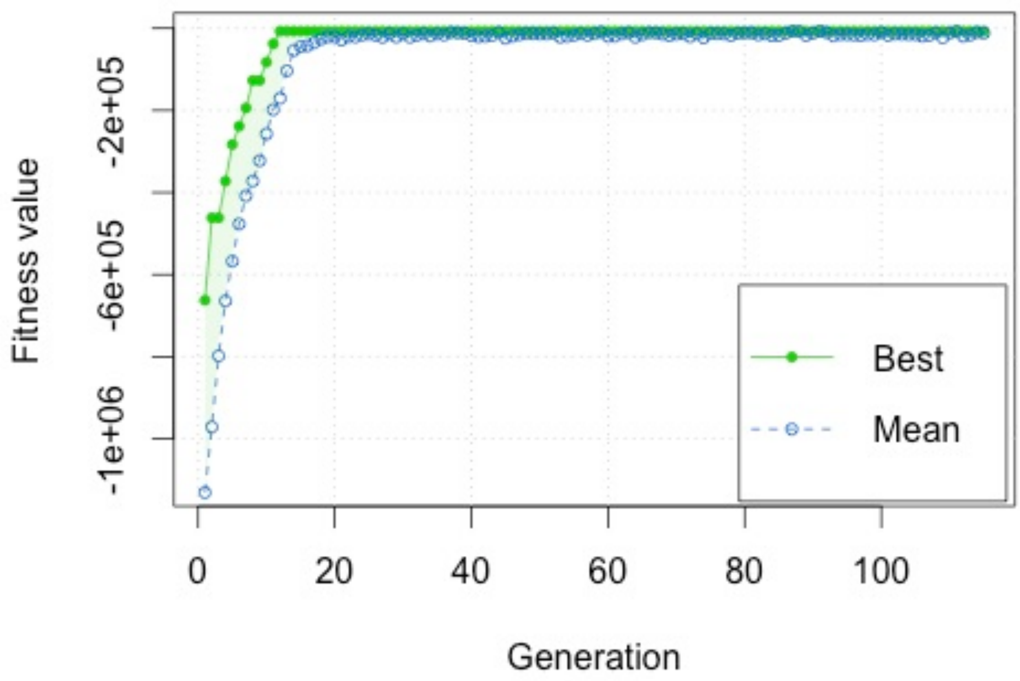

Figure 5-3 Performance of the genetic algorithm

Scenario 2: Project selection and scheduling under stable budget flow

The budget in this scenario is assumed to be continuously and evenly distributed over the study period (10 years) at the rate of $150,000/year. The optimization algorithm aims at finding a near optimal solution set of project selecting and scheduling of bike lane addition. The best solution set of the sequence and the completion times of the projects that add bike lanes are listed in Table 5-5.

Table 5-5 Completion year of projects in scenario 2

LINK	COMPLETION TIME (YEAR)
5-4	1.33
4-5	2.67
23-24	4.00
19-17	5.33
24-23	6.67
16-18	8.67
17-19	10.00

The present worth of the total system cost is $4,782,168.19 with the total construction cost of $1,950,000. It still presents a good performance as it decreases the present worth of the total system cost by 0.39%. The percent increases in bicycle usage on those improved links are as shown in Table 5-6. The effect of increase of bike demand over years has been accounted for.

Table 5-6 Increase of bicycle usage in the final year in scenario 2

LINK	INCREASE OF BIKE USAGE IN THE FINAL YEAR(%)
5-4	0.13%
4-5	0.15%
23-24	19.50%
19-17	28.21%
24-23	32.96%

16-18	0.06%
17-19	40.38%

The parameters of the genetic algorithm remain the same as in scenario 1, while it takes more iterations (over 300 iterations) to converge because it has to consider the sequence of the selected projects. The performance is shown in Figure 5-4.

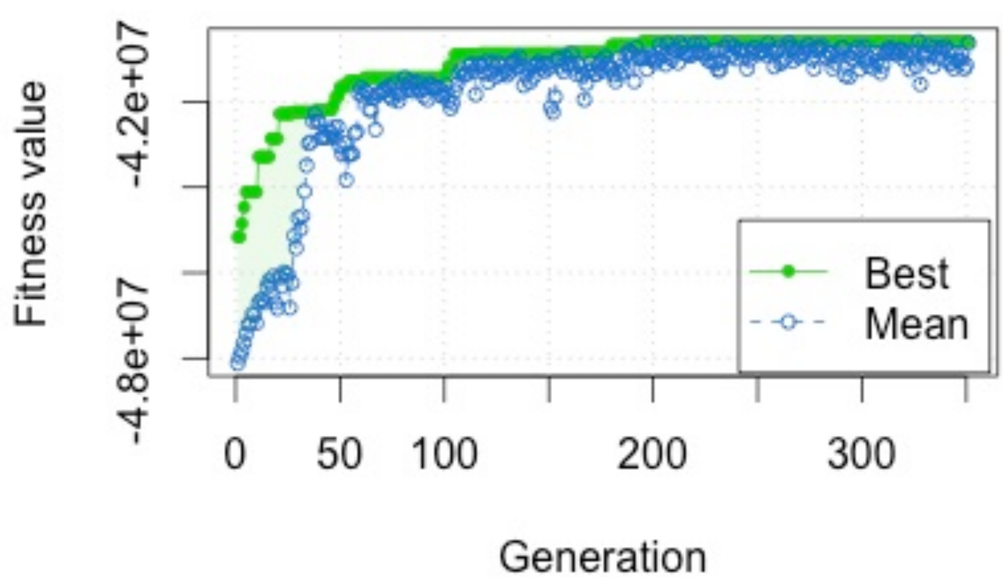

Figure 5-4 Performance of the genetic algorithm

The computation time increases to 93.43 minutes and the total cost is higher than in scenario 1, which only tries to select the best solution set. This occurs because besides selecting the optimal projects, the optimization algorithm tries to fund a project as soon as there is sufficient funding available, so that the system can benefit from the project.

Scenario 3: Project selection and scheduling under unevenly distributed budget flow

In this scenario, the budget is assumed to be $800,000 in the starting year and the other sources of budget come in at a rate of $300,000/year within the study period (10 years). The optimization algorithm aims at finding a near optimal solution set of project selecting and scheduling of bike lane addition. The best solution set of the sequence and the completion times of the projects that add bike lanes are listed in Table 5-7.

Table 5-7 Completion year of projects in scenario 3

LINK	COMPLETION TIME (YEAR)
5-4	1.00
4-5	1.00
17-19	1.00
19-17	1.80
10-9	3.10
23-24	3.83
24-23	4.83
18-16	6.13
9-10	8.43
16-10	9.17

The present value of the total system cost is $4,729861.23 while the total construction cost is $3,250,000. The computation time is 100.27 minutes. Table 5-8 shows the increase of bicycle usage in the final year in this scenario.

Table 5-8 Increase of bicycle usage in scenario 3

Link	Increase of bicycle usage in the final year (%)
5-4	2.21
4-5	3.16
17-19	1.66
19-17	1.85
10-9	0.96
23-24	0.72
24-23	0.19
18-16	0.27
9-10	0.7
16-10	2.21

Chapter 6: Sensitivity Analysis

This section studies the relationships between input and output variables in the model. For this purpose, sensitivity analysis is conducted to investigate the effects based on network specifications. Factors such as the problem size significantly determine the computation time and thus the efficiency and feasibility of the algorithm.

In this section, analysis is also done on network parameters such as demand growth rate and cost of the bike lane addition projects. The aim of the sensitivity analysis is to examine how the uncertainty about such parameters affects the outputs of the model.

Problem size

Computation time grows more than linearly as the problem size increases. Thus, it is of great importance to investigate how the increase of problem size affects the computation time and reliability of the algorithm. In this study, problem size is defined as the number of candidate projects for implementation. While increasing the problem size, the population size should also increase to guarantee sufficient search space. The network characteristics remain the same for test reasons. The only variable changes in this subsection is the problem size.

This section explores 4 different alternatives with different problem sizes, 3, 5, 7, and 7 candidate projects respectively. The planning period is adjusted accordingly. The following table and figure show the results and the computation time for different problem sizes.

Table 6-1 Sensitivity analysis (Problem size)

Problem size	Population size	Computation time	Total cost	Optimal sequence	Planning Horizon (years)
3	10	36.27	4193821.23	58,53,9	5
5	13	48.15	4574217.65	58,53,9,11,32	7
7	15	73.56	4782168.19	11,9,73,58,76,50,53	10
10	18	95.32	5132498.92	11,9,73,58,76,50,53,55,45,57	15

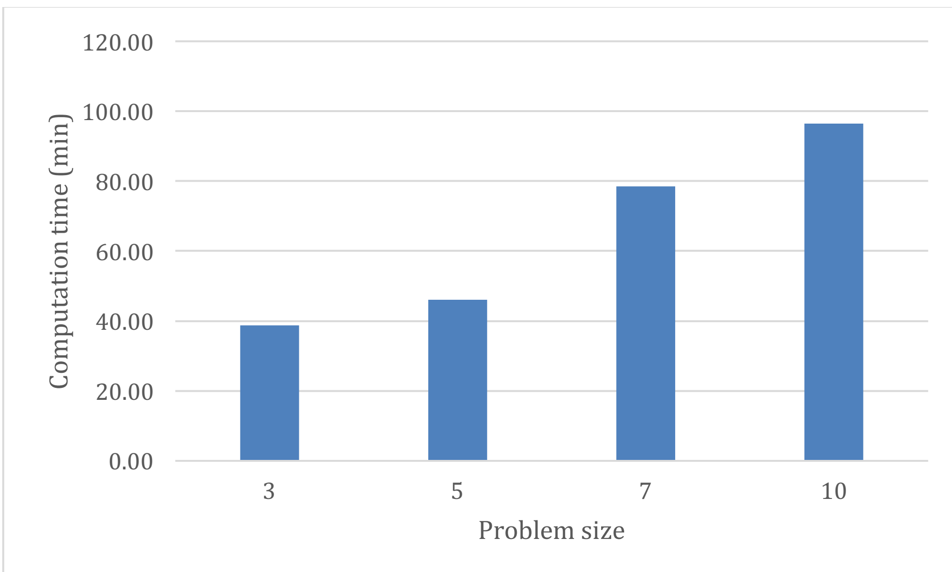

Figure 6-1 Computation time (Problem size)

Demand growth rate

As described in the previous section, the demand is assumed to increase exponentially as a function of time over the study period:

$$d_{ij}^{t} = d_{ij}^{0} \times (1 + r_{car})^{t}$$

This section explores how different growth rates for car demand can affect the optimization procedure and the optimized solution. For this purpose, demand growth rates of 0, 0.01, 0.02, 0.03, and 0.04 are tested.

Table 6-2 Sensitivity Analysis (Demand Increase Rate)

Demand growth rate	Computation time	Total cost	Optimal sequence
0	60.53	4457733.28	9,11,58,53,73,55,76
0.01	90.49	4782168.19	11,9,73,58,76,50,53
0.02	120.48	4782168.19	11,9,73,58,76,50,53
0.03	308.02	5132498.92	58,11,9,73,53,26,55
0.04	485.43	5423928.38	73,11,58,9,53,25,76

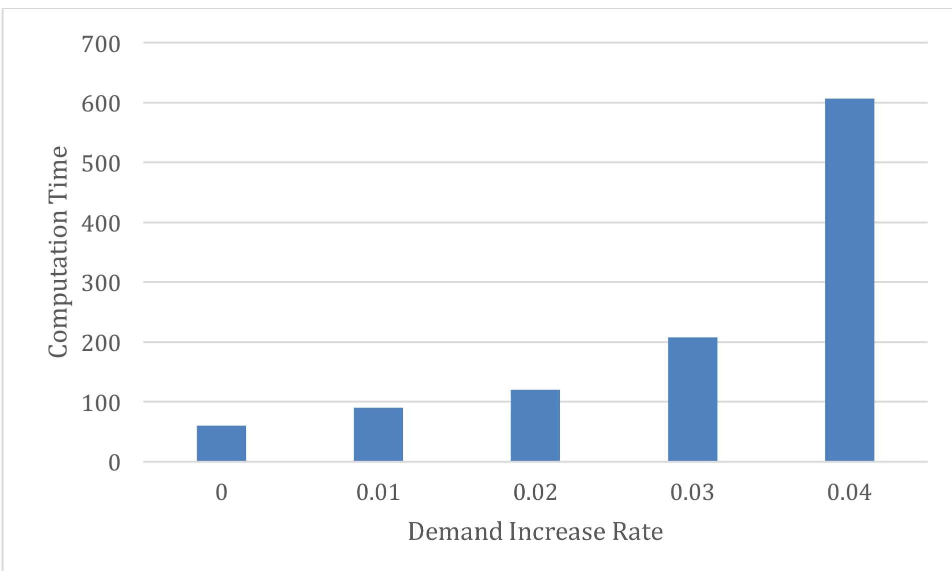

Figure 6-2 Computation time with different demand growth rates

As we can see in Table 6-5, the optimal sequence changes as the growth rate increases from zero, remains constant for values between 0.01 and 0.02, and changes again when the growth rate increases to 0.03 and 0.04. This indicates that the optimal sequence somewhat depends on the assumed growth rate. Thus, the accuracy of demand forecasting is significant in determining the project sequence. Figure 6-2 presents the computation times for different growth rates. It can be seen that the computation time increases as the demand growth rate increases and it increases drastically as the growth rate reaches 0.04. The oversaturation in some links as the demand grows causes disproportionate convergence time in the traffic assignment model.

Project cost

As described in previous sections, the budget constraint is defined as follows:

$$\sum_{i=1}^{n_p} c_i x_i(t) \leq \int_0^t b(t)dt, \quad 0 \leq t \leq T$$

$$\begin{cases} x_i(t) = 0 \ \ if \ t < t_i \\ x_i(t) = 1 \ \ if \ \ t > t_i \end{cases}$$

where

t_i = the time when project *i* (construction of bike lane on link *i*) is finished;

$x_i(t)$ = binary variable indicating whether project i is finished by time t;

c_i = capital cost of project *i*;

$b(t)$ = budget function at time t.

In this study, the cost of each improvement project is a function of the length of the road link. For testing purpose, the cost of adding one bike lane is $130,000 per mile. This section explores how variations of project costs may affect the optimization results by increasing the cost per mile up to 5%, 10%, and 20%. Table 6-3 shows the optimized results for different project costs. It is obvious that the present worth of the total system cost increases as project costs increase. The optimal sequence of project implementation changes and fewer projects are selected as the cost of projects increases while the budget remains unchanged.

Table 6-3 Sensitivity analysis (Project cost)

Cost per mile ($)	Total cost ($)	Optimal Sequence
130,000	4,782,168.19	11,9,73,58,76,50,53
136,500	4,845,245.29	11,9,73,50,76,53
143,000	4,923,723.17	11,9,73,50,76,53
156,000	4,973,829.38	11,9,73,25,76

Ratio of initial bicycle demand to car demand

Currently in most cities of the U.S., a very small amount of trips is done by bicycling. As the mode share of bicycling increases, the need to add bike lanes to the existing road is urgent. However, the trade-off between the comfort of cyclists and the travel time of motorists should be made with great caution. In order to see how the mode share of bicycling can affect the optimization results, different ratios of initial bicycle demand to motor vehicle demand are used. In this section, ratios of 5%, 10%, and 20% are tested, with the initial car demand holds unchanged.

Table 6-4 Sensitivity analysis (Ratio of bike demand to car demand)

Ratio of bike demand to car demand	Total cost	Optimal sequence
5%	4783483.6	58,11,9,53,73,76,26
10%	4680425.8	11,53,58,25,76,9,73
20%	4693295.2	11,9,58,73,53,55,73

As we can see in Table 6-4, as the ratio increases from 5% to 10%, the present value of total cost drops significantly while it increases a little as the ratio increases from 10% to 20%. It indicates that when the bicycle demand is of a large amount of the total demand (10% in this case), adding bicycle lanes can significantly bring down the present value of the total system cost. The optimal selection and sequence of projects alters as the ratio changes. It shows that the optimal sequence selection and sequence somewhat depends on the ratio of initial bicycle demands to car demands. Figure 6-3 shows the change of present values of the total cost along time with different ratios.

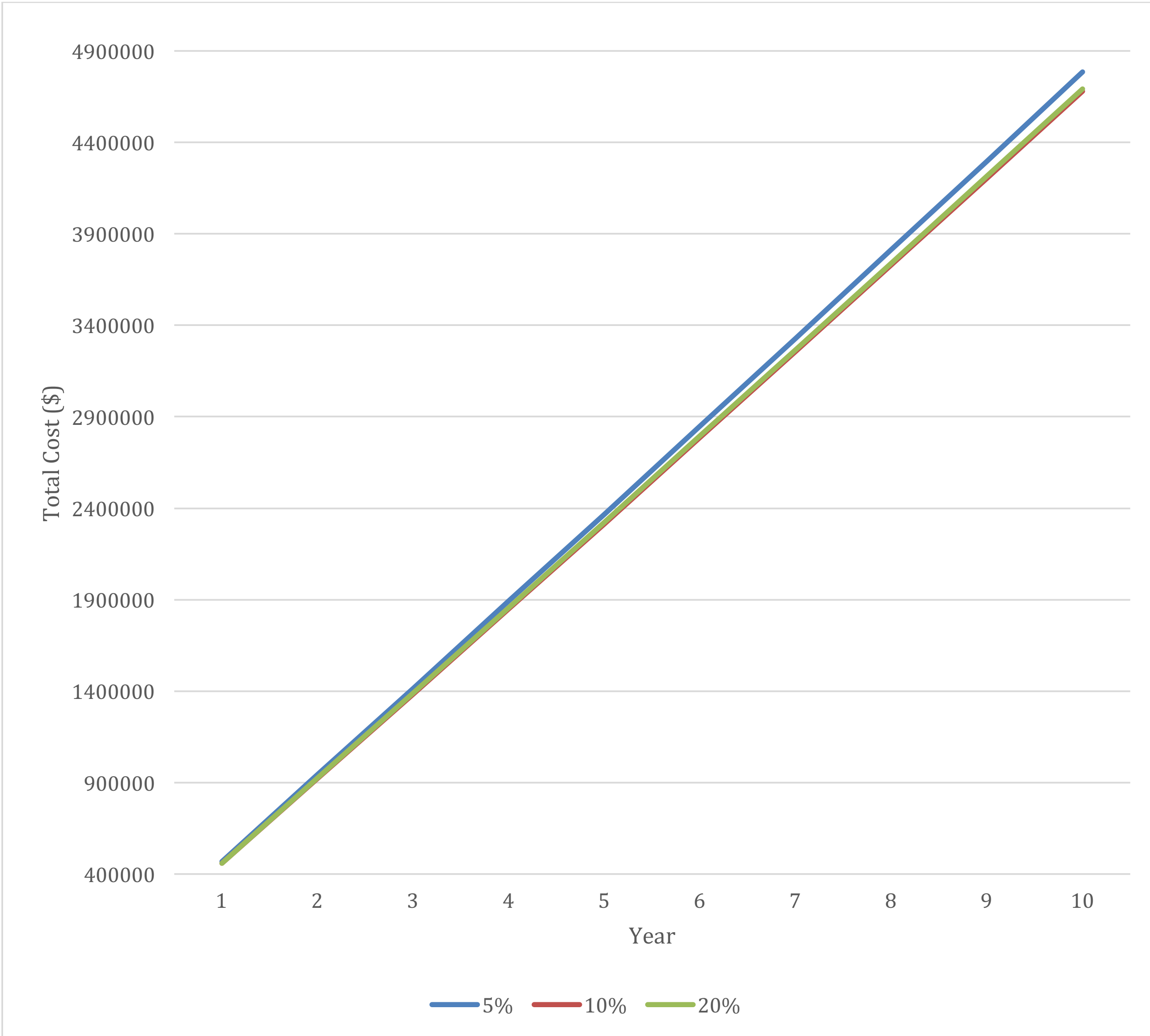

Figure 6-3 Present value of total costs with different ratios of bike demand to car demand

Chapter 7: Conclusions and summary

The road space allocation problem (RSAP) is of great significance in congested urban networks. The RSAP considering bike lanes should be given enough attention as the bike usage in the U.S. (1%) is very low compared to countries like Denmark, the Netherlands, and Germany (10%). The provision of bike facilities is a key factor in promoting the use of bicycles.

This thesis combines the traffic assignment model for evaluating the objective function with genetic algorithm for optimally selecting and scheduling the bike lane addition project. It is worth noting that under certain budget, it is reasonable to fund and finish the justified projects on at a time to gain benefits from the project as soon as its completion. Thus, the sequence of the project will automatically determine the optimal schedule of the selected projects.

The main contribution of this thesis is to develop an optimization model that reallocates road space between general travel lanes and bike lanes under given budget flows. The second contribution is to optimally schedule the projects subject to the given budget flows. The methodology presented in this work should also be applicable in allocating road space and scheduling network development for other kinds of managed lanes.

Some limitations of this research, which might be overcome in future studies are listed below:

(1) In this thesis, any bike facility added to the network is assumed to be a 4-foot bike lane. Many other types of bicycle facilities might be considered, such buffered bike lanes and separated bike lanes. Incorporating bicycle performance measures,

such as BLOS (*Highway Capacity Manual*, 2000) (a function of motor vehicle volume, speed limit, percentage of heavy vehicles, etc.), in the objective function could be one future research focus so that the benefits of adding different bike facilities can be analyzed.

(2) The connectivity of a bicycle network is crucial for bicycle travel. A well-connected bicycle network can encourage more people to use their bikes. The future research could focus more on the effect of bike lane additions on bicycle network connectivity and usage rather than only on total system cost.

(3) The current study assumes that the demand increases exponentially over time. It is a reasonable assumption for motor vehicles, while remaining questionable for bicycles. The bike demand depends heavily on the amount and quality of the bicycle facilities provided. The provision of good bicycle facilities can greatly promote bicycle usage. The future research should try to capture the effect of bike facility addition on the bicycle demand increase.

(4) The current study does not consider the effect of bicycle facility improvement on the mode share change among bicycles and motor vehicles. A mode choice model could be incorporated into the exiting model to capture this effect.

(5) The optimization algorithm developed in this studies might be further refined and tested on larger problems.

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