

A conceptual framework for optimizing highway networks

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Abstract

Optimizing highway alignments between a pair of end points is a complex problem. The problem has been solved with genetic algorithms and geographic information systems in recent years by our research team. An extension to the single alignment optimization problem will be to obtain an optimal highway network between a set of points, i.e., optimizing several highway alignments that connect a given set of points (more than two points). The problem may be of particular interest in regions where one would like to develop a system of highways connecting several cities. In this paper we develop a conceptual framework for solving a highway network problem given a set of points. We develop a two-stage genetic algorithm for solving this problem. We also discuss future directions to the research.

Keywords: highway network optimization, highway alignment optimization, genetic algorithms, geographic information systems.

1 Introduction

Initial planning and design of a transportation facility, such as highway, rail line, or airport is quite complex since there are numerous alternatives that must be carefully analyzed. A set of competing optimized alternatives is typically desired before making a final decision through community and political participation. Current practices are manual and therefore, do not provide (1) an optimized solution while satisfying complex design, environmental, and geological constraints, or (2) a trade-off analysis allowing quick comparisons among competing alternatives. Worldwide, numerous road improvement projects, transit development projects, and airport and rail station projects are



underway, costing billions of dollars. A partial list of planned, ongoing, and recently completed transportation projects is shown in Table 1. It can be seen that the methods used for selecting routes and locations in those projects were based on engineering judgment, public/political input, and trial-error.

In the absence of automated methods for optimizing transportation facility locations or performing trade-off analyses there are often design and other failures costing additional time, resource, and money. Table 2 shows selected transportation project failures, primarily due to poor design, environmental and geological considerations, and cost estimates, costing billions of dollars in damages.

Table 1: Examples of major road improvement projects.

Project Description	Method used for selecting route	Source
Widening of 325 miles of Interstate 81 to separate car and truck lanes in Virginia, estimated cost: 6.3 billion	Engineering judgment, public/political input, and trial-error	Engineering News Record (ENR), March 1, 2004, p. 15.
The central artery/tunnel project along Interstate 93 in Boston costing \$14.6 billion	Engineering judgment, public/political input, and trial-error	ENR, Dec. 29, 2003, www.enr.com/news/transportation
Expansion of Interstate 99 in Pennsylvania costing \$700 million	Engineering judgment, public/political input, and trial-error	ENR, April 19, 2004, p. 25.
Construction of a 140,000 kilometer intercontinental highway system in Asia connecting 32 Asian nations, costing trillions of dollars	Engineering judgment, public/political input, and trial-error	ENR, May 3, 2004, p. 7.
Construction of a four-lane, 415 kilometer Brasov-Bors motorway in Romania costing \$2.7 billion	Engineering judgment, public/political input, and trial-error	ENR, March 8, 2004, p. 7.
Widening of a 100 km highway linking West Vancouver to Whistler in Canada costing \$451 million	Engineering judgment, public/political input, and trial-error	February 16, 2004, www.enr.com/news/transportation

The highway alignment optimization between a pair of points was extensively studied by our research team [1-15]. A GIS and Genetic Algorithms-based integrated model was developed to optimize 3-dimensional highway alignments. The objective of this research is to extend the methodology to optimize highway networks. Specifically, we wish to obtain optimal set of alignments connecting a given set of cities (more than two since connecting just two cities will reduce the

problem to a single highway alignment optimization that is already studied). This research is of particular significance to developing countries where large-scale road construction may be needed to connect several key destinations in an optimal manner.

Table 2: Examples of major transportation failures.

Project Description	Probable Cause	Source
Singapore Mass Transit Tunnel Collapse, April 20, 2004, estimated project cost: \$830 million	Poor cost estimation, design and location analysis	ENR, May 17, 2004, pp. 12-13.
Delay in Las Vegas Strip's high-speed monorail, \$650 million, 3.8 mile, January 2004	Poor cost estimation, design and location analysis	ENR, June 28, 2004, p. 14
Design and Scope changes with Boston's Center Artery/Tunnel Project along Interstate 93, total estimated cost \$14.6 billion	Poor cost estimation, design and location analysis	ENR, May 3, 2004, p. 12
I-95/395/495 interchange in northern Virginia, initial cost estimates inflated by \$435.5 million	Poor cost estimation, design and location analysis	ENR, www.enr.com/news/transportation
Problem with 12.9-kilometer-long Pinglin highway tunnel on the expressway between Taipei and Ilan in Taiwan	Poor design and location analysis	ENR, November 3, 2003, www.enr.com/news/transportation
Initial cost estimate of Arizona's \$1.3 billion 20 mile first light rail line increased by \$100 million	Poor cost estimation, design and location analysis	ENR, April 5, 2004, p. 19.
In Maryland 57 major construction projects experienced significant changes in project cost or scope in 1999, for a net increase of \$297.6 million.	Poor cost estimation, design and location analysis	Maryland Department of Transportation, Consolidated Transportation Program, 1999.

2 Solution approach

The traditional highway network design problems [16-27] consider a subset of alignment-sensitive costs. In the proposed approach the highway alignments connecting the cities (see, Figure 1) are optimized based on minimization of a



comprehensive set of costs that are sensitive and significant to alignment selection.

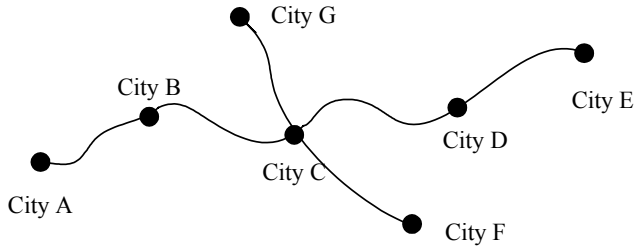


Figure 1: The highway network optimization problem.

Let $C = \{1, 2, \dots, n\}$ be the set of cities to be connected (see, an example of connecting cities $A, \dots, G$ in Figure 1). Then any two cities (i, j) can be randomly picked to be connected and an optimized highway alignment can be obtained between those cities using the GA-GIS model developed in our previous works [6, 8, 10, 15]. The optimized Objective Function thus obtained is the optimal cost C_{ij}^* of connecting cities (i, j) . The corresponding optimal alignment is L_{ij}^* . Next, another city k can be randomly chosen from set C to which city j can be connected and the corresponding optimal alignment and cost can be called L_{jk}^* and C_{jk}^* , respectively. Thus, the objective function for the network optimization problem can be expressed as:

$$\text{Min}_{1, 2, \dots, N} C_T = \sum_{i, j} C_{ij}^* \quad (1)$$

Please note that C_{ij}^* 's are obtained by applying our previously developed genetic algorithm-GIS optimization model [6, 8, 10, 15]. In that model the objective function C_{ij} is expressed as a sum of user, operator, and penalty costs (Eq. 2). User cost consists of accident cost, travel-time delay cost, and vehicle operating cost. Operator cost consists of pavement and construction cost, earthwork cost, and right-of-way costs. Penalties are imposed for violation of minimum length of vertical curves and maximum curvature constraint. Penalties are also imposed for the environmental damage (such as damage to floodplain and wetland) in the proportion of the damage.

$$\text{Min}_{x_L, y_L, z_L, \dots, x_U, y_U, z_U} C_{ij} = C_O + C_U + C_P \quad (2)$$

$$\text{subject to: } x_L \leq x_P \leq x_U, \quad \forall i = 1, \dots, n \quad (3)$$

$$y_L \leq y_P \leq y_U, \quad \forall i = 1, \dots, n \quad (4)$$

$$z_L \leq z_P \leq z_U, \quad \forall i = 1, \dots, n \quad (5)$$

C_o , C_U , and C_p are operator, user, and penalty costs, (x_L, y_L, z_L) and (x_U, y_U, z_U) are lower and upper limits on the decision variables (x_P, y_P, z_P) 's. Eqs. 3-5 impose upper and lower limits on the decision variables. The decision variables are the coordinates of points of intersections based on the concept of orthogonal cutting planes, which is extensively discussed in previously published works [8, 10, 15].

2.1 Two-stage genetic algorithm

In order to solve the network optimization problem we develop a two-stage genetic algorithm. Genetic algorithms are based on the survival of the fittest and their coverage can be found in standard textbooks and references [10, 15, 28]. In the first stage a random order of cities is selected to be connected to form the network. In the second stage previously developed genetic algorithm [8, 10, 15] is employed to optimize alignments between each selected city pairs obtained in the first stage. Please note that there are $(n-1)!$ possible ways to connect n cities. This problem somewhat resembles the Travelling Salesman Problem (TSP) with one exception: here it is possible to connect a city to multiple cities (Figure 2) whereas in TSP already visited cities are discarded from further consideration [29]. Since we don't know whether we need to establish all $(n-1)!$ alignments we call it the worst case solution.

Theorem: Let C_T^* be the optimal cost for establishing a n -city network. Then $C_T^* \leq C'_T(n-1)!$ where $C'_T(n-1)!$ is the cost of establishing all possible alignments among the n cities.

Genetic encoding: It is obvious from the above discussion that the network optimization problem reduces to finding the optimum number of city pairs between which highway alignments have to be constructed. The genetic algorithm (GA) starts with a set of possible solutions called initial population. Each individual in the population is encoded into a string representation called chromosome. At each generation, the individuals are selected to reproduce offspring based on their fitness (i.e., the objective function value) to the problem. After several generations, the most adapted individuals should survive whereas poor solutions are discarded. Thus, after searching through sufficient number of generations the solution generally converges to the optimal.

Here we only describe the first stage GA development since the second stage GA is already covered in our previous works [8, 10, 15]. For developing a highway network for n cities let's define the chromosome, Λ as:

$$\Lambda = [\lambda_1, \lambda_2, \dots, \lambda_i, \dots, \lambda_{(n-1)!}] \quad (6)$$

where, λ_i 's take up the binary values of 0 or 1; $\lambda_i=1$ if a city pair is connected (i.e., an alignment is established between that city pair), 0 otherwise. The relationship between λ_i 's and city pairs are defined in Table 3 below (case of 4 cities).



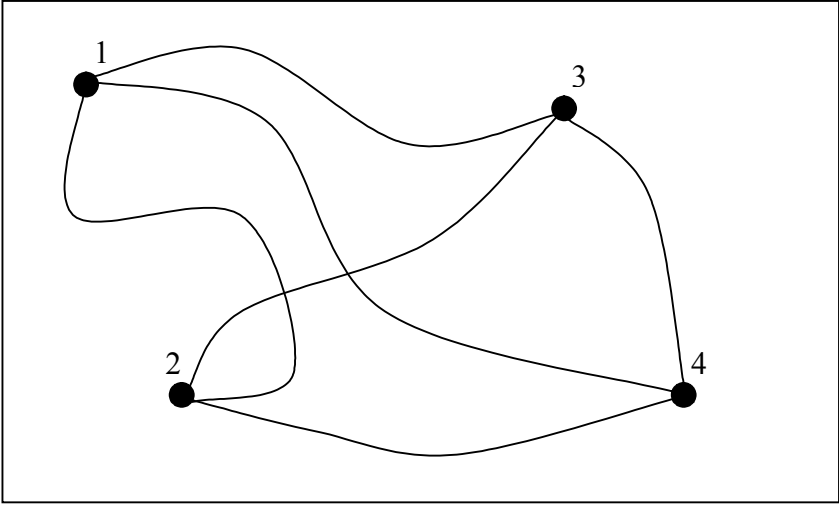


Figure 2: Number of possibilities to connect 4 cities

Table 3: Relationship between city-pairs and λ_i 's for a 4-city network.

City-Pair	λ_i
12	λ_1
13	λ_2
14	λ_3
23	λ_4
24	λ_5
34	λ_6

Thus, a chromosome for a 4-city network may take up the following value:

$$\Lambda_{4-city} = [1,0,1,0,0,1] \tag{7}$$

The resulting network is shown in Figure 3.

Constraints: (1) every city should be connected to at least one city. This can be satisfied by setting at least $(n-1)$ λ 's to be 1 for a n city network. (2) it is assumed that established highway alignments between city pairs will have adequate widths to accommodate required number of lanes for traffic to flow from either direction, with a provision of divided highways within specified corridor if desired.

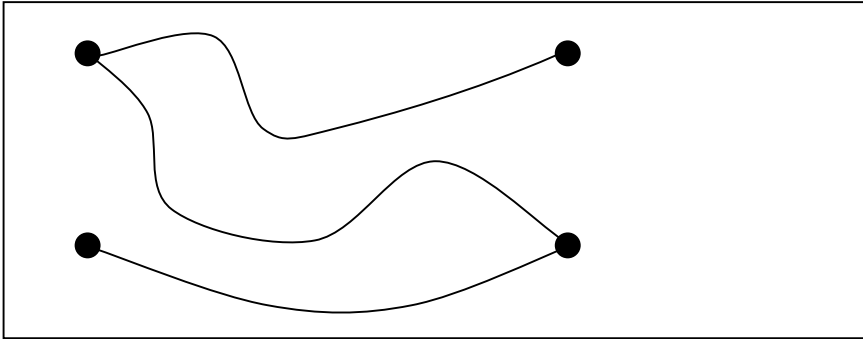


Figure 3: A 4-city network.

Assumptions: (1) A digital GIS map of sufficient accuracy is assumed to be available for the analysis region; (2) When alignments intersect (see, Fig. 2), at-grade intersections or interchanges can be constructed as desired [12-13]. These costs should be considered in the stage-2 genetic algorithm.

Initial population: The initial population for the stage-1 genetic algorithm is randomly generated by obtaining various combinations of λ 's in Eq. (6). The maximum number of candidate solutions in the initial population for a n -city network will be 2^n . The discussion of initial population for stage2 genetic algorithm is available in [10].

Genetic operators: We propose to use two operators for stage-1 genetic algorithm: mutation and crossover. Discussion of these operators is provided in standard references [10, 15, 28].

3 Conclusions and future research

In this paper a conceptual framework is developed for optimizing highway networks using a two-stage genetic algorithm. The developed framework certainly seems promising since it exploits the previously developed alignment optimization model for a single alignment optimization. The framework however, needs to be supported by testing it in some case studies, which is left for future work. The proposed work is a major improvement over what is reported in the highway network design literature since previous works neither considered all alignment significant and sensitive costs nor did they exploit a GIS for real-world applications.

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