ABSTRACT

Title of Document: GEOMETRIC AND ENVIRONMENTAL CONSIDERATIONS IN HIGHWAY ALIGNMENT OPTIMIZATION

Zun Wang, Master of Science, 2011

Directed By: Professor Paul Schonfeld
Department of Civil and Environmental Engineering

The highway alignment optimization problem is modeled to identify the preferred alignment alternatives which minimize total cost and satisfy the highway design standards. Several mathematical models have been developed during the past decades, among which the Highway Alignment Optimization (HAO) model has been used in several practical highway design projects with satisfactory results. However, several major cost components, such as vehicle operating cost and environmental cost are estimated roughly, and should be improved to yield more precise cost estimates and to allow optimization of lane widths. These are the HAO model features which this thesis seeks to improve.

Lane width is an important factor in highway design, which is related to the travel speed, safety, as well as earthwork cost. This thesis employs Newton's method and Finite Difference method to search for the appropriate lane width. The preferred

lane width found in the case study is 10.6 feet, for which the total cost is $233 million, and 12.5% less than the total cost at 12 feet lane width. In addition, this thesis improves the vehicle operating cost prediction by calculating the vehicle resistance force and horsepower, and estimating the fuel consumption based on the fuel consumption rate (g/hp-hr). Moreover, the environmental cost, particularly the vehicle emissions cost is incorporated in the newly improved HAO model. It is found that the vehicle emission cost decreases by 9% after including the environmental cost component in the model objective function.

The results of the case study and sensitivity analyses indicate that the improved HAO model can find good highway alignments efficiently in tough topographic environmental. Moreover, the model can jointly consider the social, economic and environmental consequences, and result in less fuel consumption and pollutant emissions.

Geometric and Environmental Considerations in Highway Alignment Optimization

By

ZUN WANG

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
[Master of Science]
[2011]

Advisory Committee:
Professor Paul Schonfeld, Chair/Advisor
Assistant Professor Cinzia Cirillo
Associate Professor Manoj Kumar Jha

DEDICATION

This work is dedicated to my parents.

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to my advisor, Professor Paul Schonfeld, for his instruction, encouragement and continuous support for this research. He spent his time to review and correct the draft of this thesis even on weekends and midnights. Without his valuable guidance and instruction, this work would not have been finished on time.

Besides my advisor, I am grateful to the members of my advisory committee, Professor Cinzia Cirillo and Professor Manoj Kumar Jha, for their suggestions and assistance on this research.

Finally, I would like to deeply acknowledge my entire family for providing a loving environment for me. I wish to thank my parents, Jinchao Wang and Shu Tian. They raise me, encourage me, love me and support me spiritually throughout my life. To them I dedicate this thesis.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1: Introduction

1.1 Background and Motivation

Highway alignment optimization has attracted intensive research over the past three decades due to the complexity of design procedures, and the potential economic benefits of improving alignments (Jong, 1998).

Highway design projects are usually started by clarifying the traffic problems and project scope. Conventionally, if right-of-way purchases were needed for a project, the CAD technician would generate a map showing property locations and construction limits. Based on this map and the project purposes, the potential alignment location was selected by the highway designers, followed by the preliminary highway alignment design including horizontal alignment, vertical alignment, typical cross sections, designed cross section and preliminary earthwork computations (FHWA, 1997). Though several popular computer-aided design software tools, e.g. Auto CAD and MicroStation have been applied to assist in the design procedure, the detailed geometric design still relied mainly on the professional experience of designers, rather than on automatic optimization by design software. However, it is difficult to generate the best design merely based on subjective adjustment of designers since there are many possible alignment alternatives, and the optimization procedure is too complex and repetitive to be solved manually. The challenges were overcome with the development of efficient mathematical models. Several elaborate and effective mathematical models were proposed to improve the highway design optimization (Parker, 1977; Jong, 1998; Chew 1998, Jha, 2000; Kim, 2001; Kang, 2008). GIS (Geographic Information Science) technology was also applied to provide a platform for visualized design and optimization (Lamm, 1994; Maidment, 1998; Jha, 2000a 2000b 2004).

The existing optimization models and applications speed up the highway design procedure, but they still need to be further improved. For instance, not all design factors are considered and optimized by the current design models and additional road features, such as lane width, should be examined and optimized. Moreover, given energy shortages and severe environmental problems, a well-designed highway should jointly consider the social, economic and environmental consequences, and result in less fuel consumption and pollutant emissions.

1.2 Problem Definition

Highway alignment optimization can be modeled as follows: given two points as start point and end points, find the optimal alternative connecting them which minimizes the total costs and also satisfies the design standards. There are many alternatives connecting those two points, as shown in Figure 2-1, and the optimization algorithms try to find the optimal one. The total cost considered in highway design consists of agency cost, user cost and other cost (Jong 1998). The agency cost include right-of-way cost, construction cost, pavement cost, and maintenance cost; the user cost are the travel time cost, vehicle operating (fuel consumption) cost and accident cost; and other cost here stands for the environmental cost, e.g. air pollution and noise, which is rarely comprehensively considered in previous models. Constraints on highway design may include the project budget, and design standards specified in the AASHTO Highway Design Manual (1997a, 1997b, 1997c) as well as different local standards. The highway alignment design is also affected by local terrain, soil type and land use. The comprehensive objective function and constrains indicate that the highway alignment problem is a typical optimization problem which is solvable by well-designed optimization algorithms. Figure 2-2 presents two highway alignment alternatives. Both of them are able to avoid the mountainous area and wetland protection area while minimizing cost and satisfying design rules.

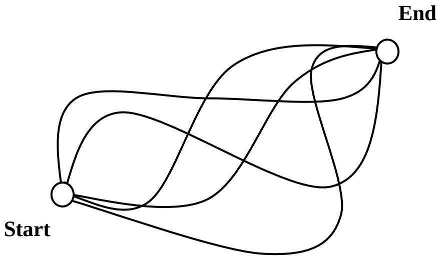


Figure 1-1 Multiple Alignment Alternatives Connecting the Endpoints

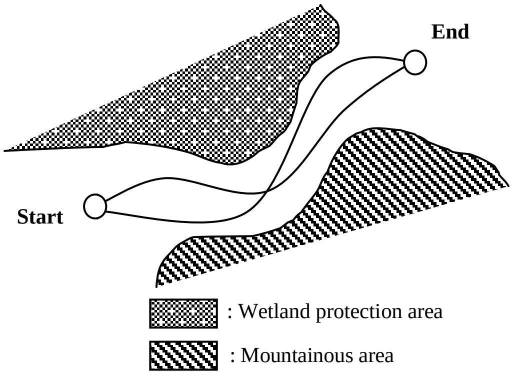


Figure 1-2 Effects of Terrain and Land Use on Highway Alignment Design

1.3 Research Objective and Scope

The review of current highway alignment methodologies indicates that the existing highway alignment models and applications speed up the design procedures. Among them, the Highway Alignment Optimization Model (HAO) developed at the University of Maryland can yield feasible and optimized highway alignment results and had been applied to several practical highway design projects in Maryland. However, there is still room to improve the HAO by incorporating more design features into the optimization procedure, and replacing the conventional models with the latest ones. Hence, this thesis seeks to improve the current Highway Alignment Optimization (HAO) model by (1) incorporating the lane width in the optimization procedure through the evaluation of lane width impacts on travel speed, safety and cost, (2) improving the vehicle operating cost prediction, (3) quantifying the effect of highway alignment on the environment in more details in terms of pollutant emissions.

1.4 Research Methodology

This research seeks to answer the following questions:

(1) What are the conventional and current methodologies for highway alignment optimization? What are the advantages and disadvantages of the existing HAO model?

(2) What are the cost components affecting highway alignment? How should the HAO model be improved to design highway with lower vehicle operating cost and environment cost, particularly the fuel consumption and pollutant emissions?

(3) How should the lane width factor be incorporated in the optimization procedure inside the HAO model?

(4) How does the newly improved HAO model perform in practical highway alignment projects with different design parameters?

The aforementioned questions set the outline of this thesis. Each question will be analyzed and answered in each chapter of the thesis. Emphasis will be placed on the improvement of the current HAO model and its application in a practical highway alignment project.

1.5 Thesis Organization

The thesis is organized as follows:

Chapter 1 outlines the research background and motivations, defines the research problem and scope, and states the questions to be addressed in this thesis. Chapter 2 reviews the current highway optimization modeling approaches, evaluates the major cost components which are associated with highway transportation, and examines the advantages and disadvantages of the existing HAO model. The various cost components constituting the objective function of the problem are formulated in Chapter 3, with emphasis on the user cost and environmental cost. Chapter 4 discusses the solution algorithm for optimizing non-backtracking 3-dimensional alignments, and the impacts of lane width on vehicle speed, accident rate and cost. Newton’s method and finite difference method are employed to solve the lane width optimization problem. In Chapter 5, a case study is presented to test the improved HAO model in a real world highway alignment project, followed by a discussion about the sensitivity analysis results. The thesis ends with a summary of the performance and outputs of the improved HAO model, the conclusions of the highway alignment study, and a discussion of possible future research.

Chapter 2: Literature Review

The literature review in Chapter 2 is divided into 6 sections. First, the existing alignment optimization models are reviewed, and their advantages and disadvantages are analyzed. Second, a chronological sequence of the HAO model's development is presented and the desired improvements are identified. The cost associated with highway alignment are discussed and classified in the Section 3. In Section 4, design constraints are presented. Section 5 analyzes the effects of lane width on travel speed and safety. Finally the summary of literature review is presented in Section 6.

2.1 Models for Optimizing Highway Alignments

A number of optimization methods (including dynamic programming, linear programming, and enumeration) have been found in the literature on highway alignment optimization. Most models are only able to optimize either the horizontal alignment (Lee and Cheng, 2009; Liatsis, 1999) or vertical alignment (Goh, 1988; Fwa, 1989; Lee, 2001). Models for simultaneously optimizing three dimensional alignments are rarely found. The earliest one found was developed by Parker (1979). It is a two-stage approach to select a route corridor. The major constraint for the alignment is the gradient constraint. In the first stage, a smooth cost surface is established according to the centroids' elevation of each cell in the region of interest. Meanwhile, the cost surface should ensure that the vertical profile of any horizontal alignment intersecting with the cost surface satisfies the gradient constraint. In the second stage, a shortest-path algorithm is used to find the optimal path. However, the alignment is not smooth, but consists of piecewise linear segments. Besides, the optimization method neglects the horizontal constraint, but only considers the gradient constraint. Moreover, only the earthwork cost is considered in Parker's model, and other cost components e.g. right-of-way cost, travel-time cost, and vehicle operating cost are excluded.

One of the most successful three-dimensional models is developed by Chew et al (1989). Instead of using a grid, the alignment is parameterized by a series of cubic spline polynomial function. The constraints are transformed into a one-dimensional constraint by using constraint transcription methods from optimal control theory. Then the model is formulated as a non-linear programming structure. The optimization problem is solved using a quasi-Newton descent algorithm. The advantages of Chew’s model are that it is able to optimize the horizontal alignment and vertical alignment simultaneously. It can also generate a smooth alignment compared with those found with the shortest path or dynamic programming methods. However, the choice of the initial variables affects the rate of convergence, but selecting a good initial solution is difficult. Moreover, the algorithm is only able to optimize non-backtracking alignments, and has no ability to optimize a backtracking alignment, which is frequently needed in mountainous areas.

Cheng and Lee (2006) employ the neighborhood search-heuristic approach to solve the complex 3-dimensional highway alignment problem. The number of intersection points (PIs) in the optimization procedure is not fixed. The IPs are added, deleted, or moved slightly randomly each iteration, in order to search for the preferred horizontal alignment alternatives. If an infeasible alignment is generated, it will be abandoned. Otherwise, the layout of the alignment is determined, and the goal is to generate a more accurate horizontal alignment by performing more iterations. The corresponding vertical alignment then will be generated according to the horizontal alignment layout.

None of the aforementioned algorithms are able to consider comprehensive design constraints and cost components. Therefore the HAO model uses a different approach for simultaneously optimizing 3 dimensional highway. Since the problem is complex and non-differentiable, it cannot be solved using traditional methodology such as Newton’s method. Jong (1998, 2003) develops an evolutionary algorithm which is modified from classic genetic algorithm to solve the optimization problem. Kim and Jha (2005) improve the computational efficiency by using a stepwise genetic algorithms approach. Kang (2007, 2008) further improves the computing efficiency and results quality by developing the feasible gate approach.

2.2 Evolution of Highway Alignment Optimization (HAO) Model

The earliest version of HAO model is developed by Jong (1998, 2003). It is usually very difficult to describe the highway alignment problems due to its complex geometric features, and Jong proposes an efficient representation of highway alignment. (Details will be discussed in Section 3.1.) After defining the presentation of highway alignment, he identifies the design factors associated with highway cost. Then he formulates the optimization problem with objective function and design constraints, and solves it by designing genetic algorithms. Four models are proposed for optimizing non-backtracking horizontal alignment, non-backtracking 3-dimensional alignment, a backtracking horizontal alignment model and backtracking 3-dimensional alignment. Those two 3-dimensional alignment models are more suitable for hilly areas. Four evolutionary programs are proposed to solve these four models respectively, and eight genetic operators were applied. The case study indicates that Jong's model and algorithm can generate smooth highway alignments efficiently in different topographic environments. Also, the model can optimize the 3-dimensional alignment (both horizontal and vertical) simultaneously or separately, which is a great improvement since none of the previous models could do so.

Although Jong's model performs very well and yields satisfactory results, there is room for further improvement. First, the model is too abstract to be applied, and a combination with GIS should be considered in order to provide a user-friendly interface and useful spatial data management and analysis functions. Second, several cost functions should be improved to get better precision in estimating cost, e.g. the accident prediction model and bridge structure cost.

Jha (2000a) further improves the HAO model by introducing realistic GIS techniques into the HAO model and connecting the optimization algorithm with the GIS software ArcView 3. Four major components constitute his improved HAO model: the cost module, optimization module, GIS module, and communication module. The connection with GIS provides users with a graphic and user-friendly interface. Moreover, the GIS technology is good at managing and analyzing spatial data, which assists the optimization. For instance, Jha proposes the GIS-based algorithm to estimate the environmental cost using spatial relations. He overlays the wetland and floodplain layers with the property map, and calculates the fraction of each property taken by the alignment using GIS spatial analysis function. He also developes a method to enable more precise computation of right-of-way cost based on the spatial features of a GIS. With the integration of GIS, the model can be applied to real highway project directly. Moreover, Jha improves the genetic algorithm by introducing a bidirectional communication link between GIS and GA to enable continuous data exchange.

Both Jong, and Jha's research are applied to design new highways. However, most transportation improvement projects are based on existing network and aim to enhance the whole network performance by upgrading existing highways or building new segments connecting existing ones. Therefore, Kim (2001) further improves the model by incorporating bridge and intersection structure and maintenance cost in the objective function. Kang (2008) proposes alignment model to find a preferred highway which best improves the existing network at minimum cost. The model is capable of optimizing the highway alignment and junction points with existing roads. This model considers the impacts of new highways on traffic and other factors associated with construction during the optimization procedures. Moreover, Kang (2007; 2008) improves the optimization algorithm by developing the feasible gate optimization method, and by applying a prescreening and repairing method in the genetic algorithm. This method improves the computation efficiency and optimization solution quality.

The existing HAO model has been applied in several practical highway alignment projects. It was employed in designing the Brookeville Bypass in 2004 (Kang et al 2006), and the Maryland section of Route US 220 in 2010.

The review of the HAO model development indicates that the existing HAO model is well designed. It has also been applied into several practical highway alignment projects, and yields satisfactory results. However, there are several aspects which have not been addressed properly and should be further improved. First, the existing HAO model has no ability to optimize lane width. However, lane width is an important factor affecting the vehicle safety, travel speed and cost, and it should be optimized in highway alignment procedures. Second, the operating cost in the existing HAO model is estimated based on vehicle speed. However, for the highway alignment optimization problem, the most appropriate method for estimating the fuel consumption is to derive the function based on highway geometric features. Thus, a new fuel consumption prediction methodology with road geometric features consideration is needed. Moreover, the environmental cost in existing HAO model is considered as the penalty of crossing floodplains and wetlands. The cost resulting from vehicle emissions is expected to be addressed in the new HAO model.

2.3 Cost Associated with Highway Transportation and Its Classification

The objective of highway alignment optimization is usually to minimize the total cost of preferred alignment alternative. According to the Organization of Economic Co-operation and Development (OECD, 1973), the following cost components are significant in road link design:

1. Construction cost
2. Maintenance cost
3. Traffic cost
4. Social cost

5. Design and administrative cost

The HAO model developers Jong (1998), Jha (2000a) and Kang (2008) group cost into two basic categories from the perspective of supply-consumer, and name them as agency cost and user cost. The existing GIS-based HAO software provides users with two options to determine the objective function, either agency cost only or agency cost and consumer cost combined. In the existing HAO model, the agency cost is subdivided into different types according to their relationships with highway geometric, including length-dependent cost, location-dependent cost, area-dependent cost, volume dependent cost, and bridge and cross-section construction related cost. The user cost consists of travel time cost, vehicle operating cost and accident cost. Detailed classifications are listed in Table 2.1. As Table 2.1 indicates, the environmental cost is viewed as a location-dependent cost. Initially, the environmental cost is grouped into length-dependent cost by Jong (1998) since he employs an equation to estimate the net present value of the environmental cost per unit length, which is a function of average annual daily traffic (AADT) and vehicle miles traveled (VMT). The unit environmental cost per VMT is derived from summing up the unit costs of air pollution, water pollution, and noise pollution. Jha (2000a) re-examines the environmental cost estimation and divided them into two types 1) those requiring separate analysis, and 2) those obtainable from a GIS, which can be also incorporated into highway optimization models. He improves the HAO model by calculating the second type environmental cost using GIS. The environmental cost in Jha’s model is the penalty resulting from intersecting with the floodplain and wetland. It is associated with the fraction of protected land taken by the alignment. Therefore Jha groups the environmental cost into the location-dependent cost. However, he also comments that some environmental impacts, e.g. air pollution and noise, are difficult to quantify by GIS directly, and can be included in the extension of his research. Hence, one of objectives of this thesis is to improve the environmental cost estimation by considering the environmental impacts resulting from vehicle pollutants emissions.

Agency Cost
1. Length-Dependent • Construction Cost • Pavement Cost (lane width and depth are assumed fixed) 2. Location-Dependent • Right-of-way acquisition Cost • Environmental Cost 3.Volume-Dependent • Earthwork Cost 4. Bridge Construction Related • Structure Cost • Maintenance Cost
User Cost
1. Travel Time Cost 2. Vehicle Operating Cost 3. Accident Cost

Table 2-1 Cost Classifications of Existing HAO Model

2.4 Constraints and Operational Requirements in Highway Alignment

AASHTO publishes several books and reports addressing the design constraints and standards for highway alignment (1997a, 1997b, 1997c). Those design standards should be followed strictly, and can be formulated as constraints in the highway alignment optimization problem.

The design of a highway includes the horizontal alignment and the vertical alignment. A horizontal alignment consists of tangent section, transition curve and circular. Major constraints for horizontal alignment are minimum radius of curves and sight distance on curves. Vertical alignment consists of tangents connected with each other by parabolic curves. Important constraints on vertical alignment are maximum gradient, sight distance on crest and sag vertical curves, and headlight sight distance and motorist comfort on sag vertical curves.

2.5 Effects of Lane Width on Speed, Safety and Earthwork

Lane width is an important factor in highway design, which is related to the travel speed, safety, as well as earthwork cost. AASHTO provides flexibility of lane width in highway design procedures. For example, according to AASHTO (2004), lane width usually varies from 9ft to 12 ft, and lanes narrower than 9ft are still acceptable for rural roads and highways with lower speeds and volumes. Therefore, such variability of lane width requires assessment inside HAO model to find the optimal value, in order to generate the best fit alignment alternative.

Speed is one of the driver choices affected by lane width since narrower lanes lead to more influence from interactive traffic and obstacles along the side of the road, and result in slower speed (Martens, 1997; Parsons Transportation Group, 2003). There is no consensus on the relation between lane width and speed yet since there is wide variability among sites. However, most studies indicate that a wider lane can increase the travel speed. According to Ferreri’s (1968) research, a higher speed is observed for 3.4 m wide lanes than for 3.0 m lanes in Philadelphia. Yagar (1983) also finds that the speed decreases by 5.7 km/h for every meter of reduction in lane width. Therefore, wider lanes can decrease travel time cost.

In addition, wider lanes are associated with fewer accidents with lane with ranges from 9 feet to 12 feet (FHWA, 2000). Labi (2006) proposes the crash prediction models for rural major collectors, rural minor arterials and rural principal arterials in India. All models show that wider lanes are associated with crash reduction in both frequency and severity. He stated that the result is consistent with expectation since wider lanes serve more space and opportunities to avoid other vehicles and therefore reduce the risk of crash. . The Interactive Highway Safety Design Model (IHSDM) (1998), which is a suite of software analysis tools developed by FHWA for evaluating safety and operational effects of geometric design on highways, also indicates that wider lanes lead to fewer accidents. Thus wider lanes should reduce vehicle operating cost.

Lane width is also related to earthwork. According to the earthwork cost prediction model employed in existing HAO model (Jong, 1998; Jha, 2000a), the earthwork cost increases with wider lanes.

In conclusion, wider lanes can reduce both travel time cost and vehicle operating cost, but increase earthwork cost. Therefore, the optimization of lane width should be included inside HAO model.

2.6 Summary

The first section discusses the existing highway alignment optimization models. The four generations of HAO model are introduced in the second section. The existing HAO model is a useful software tool for highway alignment optimization with a graphic interface, a reliable cost function and an efficient optimizing algorithm. However, several aspects still need to be improved. The major components associated with highway alignment cost are discussed in Section 2.3. The Section 2.4 presents the design constraints for horizontal alignment and vertical alignment. Effects of lane width on speed safety and cost are discussed in Section 2.5.

Chapter 3: Model for Optimizing Three-Dimensional Non-Backtracking Highway Alignments

The existing HAO model can optimize both two-dimensional (horizontal) alignments and three-dimensional (both horizontal and vertical) alignments. The two-dimensional alignment only considers the horizontal alignment optimization, and it is applicable for relatively flat study areas, while the three dimensional one enables us to estimate more precise earthwork cost. Also, the user cost in the two-dimensional alignment only depends on the horizontal profile, and several variables have to be excluded. For example, the speed prediction model employed in HAO model is a function of road features. However, no information is provided about the vertical profile in two-dimensional alignment, and the vertical distance variable has to be omitted in the analysis. Hence the three-dimensional highway alignment can yield better alignment alternatives with better information, and this thesis employs the three-dimensional alignment model.

This chapter starts with basic idea and method for presenting and formulating the highway alignment optimization problem. An overview of cost function is given in Section 3.2. Detailed agency cost, user cost and environmental cost formulations are addressed separately in the following three sections. A completed optimization formulation is given in the last section. The agency cost is sufficiently well designed in the current HAO model, and emphasis in this chapter is placed on modeling user cost and environmental cost.

3.1 Data Format

The three-dimensional non-backtracking highway alignment model is subdivided into horizontal alignment and vertical alignment, which are discussed explicitly in Chapter 4 and Chapter 8 of Jong's dissertation (Jong, 1998). The basic concept of horizontal alignment design is to apply vertical cuts perpendicular with the line segment $\overline{SE}$, which connects the origination S and destination E, as shown is Figure 3-1. The cut line must intersect with the optimal alignment at exactly one point, denoted as P_i. (The proof can be found in Chapter 3 of Jong's dissertation.) Since we apply several vertical cuts, the intersecting points of these cuts along with S and E yield a candidate alignment. Therefore the highway alignment optimization problem is formulated to find the optimal P_i points. Let d_i to be the coordinate of the intersection point p_i on the i^{th} vertical cut. The upper and lower bounds of d_i are discussed in four cases separately in Jong's dissertation. Then, p_i can be obtained as

$$\begin{bmatrix} X_{pi} \\ Y_{pi} \end{bmatrix} = \begin{bmatrix} X_{oi} \\ Y_{oi} \end{bmatrix} + d_i \begin{bmatrix} cos\theta \\ sin\theta \end{bmatrix} \tag{3.1}$$

where: θ is the angle between the cutting line and the X axis

O_i is the intersection point of cutting line and segment $\overline{SE}$, and can be calculated based on the coordinates of original S. (Details can be found in Jong's dissertation.)

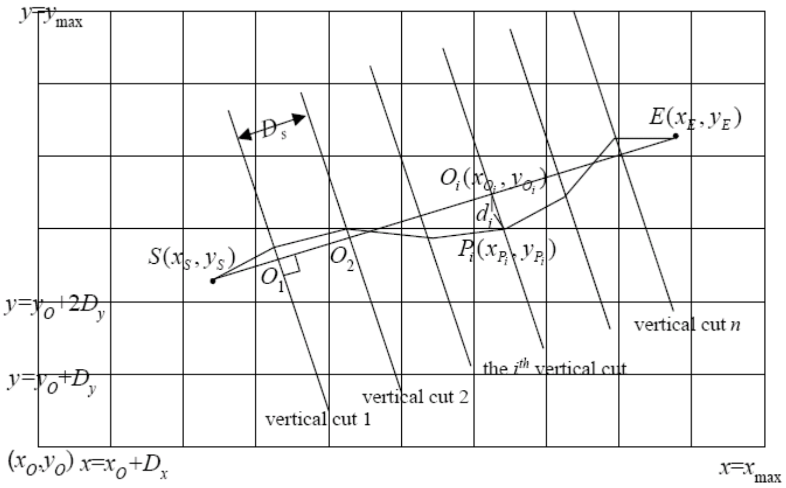


Figure 3-1 Decision Variables of Two-dimensional Highway Alignment (Jong 1998)

The path of the alignment is outlined by the set of p_i points. A piecewise linear trajectory is generated by connecting p_i points with straight-line (tangents), as shown in Figure 3-1. However, in order to yield a smooth road alignment, at these p_i points the tangents must be connected with horizontal curves, as shown in Figure 3-2. The calculations of curves and tangents are constrained by design standards, e.g. minimum radius and sight distance, and the detailed calculation is given in Algorithm 4.1 and 4.2 of Jong's dissertation.

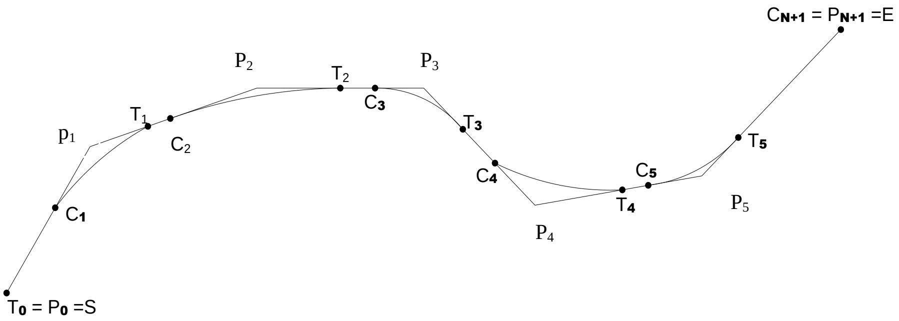


Figure 3-2 Smooth Road Alignment Connected by Curvatures and Tangents (Jong 1998)

Similarly to the horizontal alignment, the vertical alignment is determined by applying vertical cutting planes instead of cutting lines to the line segment SE, as shown in Figure 3-3. The potential optimal vertical control points must be located on each vertical cutting plane, denoted as P_i. The vertical alignment is formed by connecting all these P_i points, and the alignment algorithm is intended to find the optimal P_i points. The relation between Pi points and the horizontal alignment on XY plane is given in Figure 3-4.

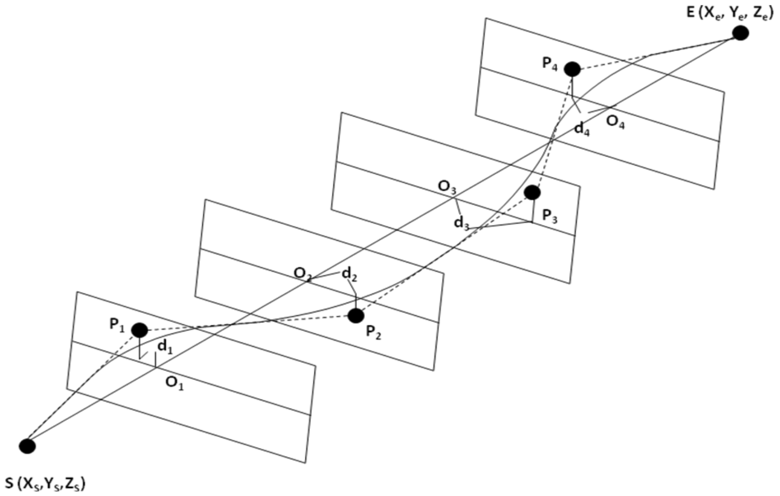


Figure 3-3 Decision Variables of Three-dimensional Highway Alignment (Jong 1998)

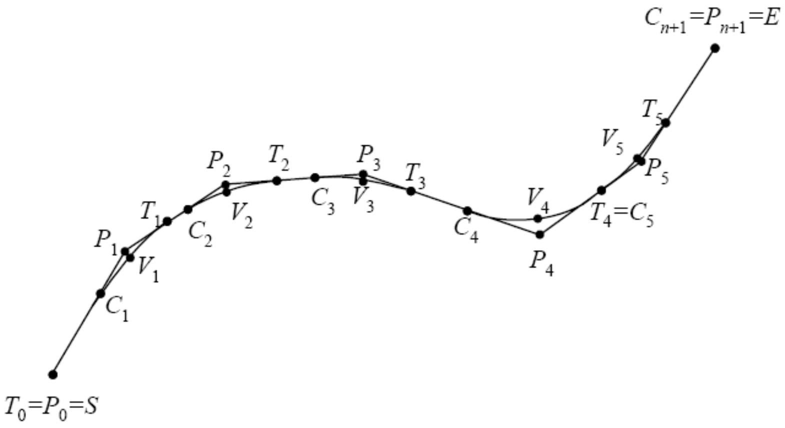


Figure 3-4 Geometric Relations of Reference Point for an Alignment on the XY Plane (Jong 1998)

3.2 An Overview of the Cost Function

As reviewed in Section 2.2, the cost associated with three-dimensional highway alignment is categorized into agency cost and user cost in the existing HAO model. The environmental cost is grouped into location-dependent agency cost and computed using GIS spatial functions. However, as Jha suggests (2000), some environmental impacts, e.g. air pollution and noise, are difficult to quantify by GIS directly, and can be included in the extension of his research. Therefore, the environmental cost in this research is studied as vehicle pollution emissions. It is then isolated from the location-based cost. The cost classification for the newly improved HAO model is presented in Table 3.1.

Agency Cost
1. Length-Dependent • Construction Cost • Pavement Cost (lane width is determined by the lane width optimization analysis result) 2. Location-Dependent • Right-of-way acquisition Cost 3.Volume-Dependent • Earthwork Cost 4. Bridge Construction Related • Structure Cost • Maintenance Cost

User Cost
1. Travel Time Cost 2. Vehicle Operating Cost 3. Accident Cost
Other Cost
Environmental Cost

Table 3-1 Cost Classifications of Newly Improved HAO Model

The objective function of highway alignment optimization is to minimize the total cost as presented in equation 3.2.

$$C = C_{agency} + C_{user} + C_{environment} \tag{3.2}$$

where: C = total highway alignment cost ($)

C_{agency} = agency cost ($)

C_{user} = user cost ($)

$C_{environment}$ = environmental cost ($)

Each type of cost consists of different components. Meanwhile, it is important that the design variables are related to the objective function. Detailed cost formulations are discussed in the following subsections.

3.3 Agency Cost

The agency cost of the existing HAO model is composed of right-of-way cost, earthwork cost, length-dependent cost, structure cost and maintenance cost. Table 3.2 shows the examples of each cost. The first three components are proposed by Jong(1998) and further improved by Jha(2000a), and the last two components are proposed by Kim (2001) and Kang (2008) for predicting the costs associated with bridges and intersections while optimizing the existing highway network.

	Type of Agency Cost	Examples
	Length-dependent cost	Pavement costs, median installation cost
	Right-of-way cost	Land acquisition and property damage cost

Agency costs	Earthwork cost	Cut and fill cost
	Structure cost	Bridge and interchange construction cost
	Maintenance cost	Maintenance cost for highway basic segments and bridges

Table 3-2 Agency Costs Associated with Highway Construction

The calculation of total agency cost is given in equation 3.3. Evaluation of each component of agency cost is discussed in Sections 3.3.1 to 3.3.5

$$C_{agency} = C_L + C_R + C_E + C_S + C_M \qquad (3.3)$$

where: C_{agency} is the total agency cost (\$/year)

C_L is the total length-dependent cost (\$/year)

C_R is the right of way cost (\$/year)

C_E is the earthwork cost (\$/year)

C_S is the structure cost (\$/year)

C_M is the maintenance cost (\$/year)

3.3.1 Length-dependent Cost

The Length-dependent cost (C_L) in HAO model is first proposed by Jong (1998). It is formulated by multiplying the highway length with the unit cost.

As mentioned in Section 3.2, the smooth alignment consists of successive circular curves and tangents. Hence, the total alignment length is calculated by summing up all curves with radius R, and straight-line. The length is denoted as L_n, and can be expressed as:

$$L_n = \sum_{i=0}^{n} \sqrt{(x_{T_i} - x_{C_{i+1}})^2 + (y_{T_i} - y_{C_{i+1}})^2} + \sum_{i=1}^{n} R_i \Delta_i \qquad (3.4)\ (\text{Jong, 1998})$$

where: L_n = total length of the alignment

(X_{Ci}, Y_{Ci}) = coordinates of C_i, which are shown in figure 3-2

(X_{Ti}, Y_{Ti}) = coordinates of T_i, which are shown in figure 3-2

R_i = the radius of the circular curve from C_i to T_i.

Δ_i = the intersection angle at intersection point P_i

Kang (2008) further improves the alignment length calculation by considering spiral transition curves between the horizontal circular curves and the tangents. His model is employed when the horizontal curve includes one circular and two spiral transition curves. Equation 3.4 is used when only a circular curve is used.

The unit cost of existing HAO model consists of unit construction cost, unit pavement cost and unit environmental cost. The unit construction cost includes miscellaneous items, such as fences and guardrails. The unit pavement cost is grouped into length-dependent cost since the lane width is a given fixed value. The optimization of lane width is discussed in Chapter 4. The environmental cost in Jong's model is estimated based on the unit cost per VMT and AADT data. Jha improves the environmental cost estimation by using GIS spatial analysis, and separates it from length-dependent cost. This thesis discusses more details about the environmental cost in terms of vehicle emissions in Section 3.5. Therefore, the length dependent cost here only includes the construction cost and pavement cost. The calculation is given in equation 3.5.

$$C_L = K_L \times L_n \tag{3.5}$$

where: K_L = unit length dependent cost (\$/ft)

L_n = total length of the alignment (ft), obtained with equation (3.4)

3.3.2 Earthwork Cost

Jong (1998) analyzes the earthwork cost explicitly and includes it in the HAO model. The earthwork cost refers to the cut and fill cost, and hauling cost. The cut and fill cost is associated with highway elevation and ground elevation, and it is sensitive to topography. The ground elevation in Jong's research is calculated on curves and tangents separately. Jha (2000) improves it by using GIS. The ground elevation is continuous and retrieved from

DEM data directly without any mathematical calculation. The vertical alignment is comprised of parabolic curves and tangents, and the highway elevation was analyzed on parabolic curves and tangents separately. Detailed analysis can be found in Chapter 8 of Jong's dissertation and Section 4.1.3 of Jha's dissertation. The methodology used for calculating cut and fill volume is "average-end-area" method. The calculation of earthwork volume, either excavation or embankment is determined by the differences between road elevation and ground elevation.

Besides considering the cut and fill cost, Jha also considers the hauling cost, which is calculated by multiplying the haul (cubic yard-feet) with the unit hauling cost ($ per cubic yard per mile). The haul, namely the volume of shrinkage and swell, is primarily determined by the soil type.

The calculation of earthwork cost is given in equation 3.6:

$$C_E = C_H + \sum_{i=1}^{n} K_{ci} E_{ci} + \sum_{j=1}^{m} K_{fj} E_{fj} \tag{3.6}$$

where: C_H = total hauling cost ($)

n = number of excavation sections

m = number of embankment sections

K_{ci} = unit cut cost for the ith excavation section ($ per cubic yard per mile)

K_{ci} = unit fill cost for the jth embankment section ($ per cubic yard per mile)

E_{ci} = cut volume in segment i (cubic yard)

E_{fj} = fill volume in segment j (cubic yard)

Detailed analysis of earthwork cost estimation can be found in Jong and Jha's dissertations and their early publications.

3.3.3 Right-of-way Cost

The right-of-way cost component is studied comprehensively by Jha (2000a, 2000b, 2004). The right-of-way cost prediction is quite complex, and requires more than summing up all the land property values intersected by a highway alignment. Jha formulates the right-of-way cost with 3 items, which are costs of the property take for temporary easement, just compensation paid for property, and appraisal fee associated with property. The fraction of property taken by highway construction is identified and measured by the GIS. The just compensation cost consists of damage to the value and structures on properties, cost of properties improving, and cost of the fraction of property taken for alignment. The right-of-way cost function applied in this thesis is:

$$C_R = \sum_{i=1}^{n_R} (C_{TEi} + C_{JCi} + C_{AFi}) \tag{3.7}$$

where: C_{TEi} = cost of the friction of property i taken for temporary easement ($)

C_{JCi} = just compensation paid for property i ($)

C_{AFi} = appraisal fees for property i ($)

n_R = total number of properties affected by the alignment

Detailed description and algorithm can be found in Jha's PhD dissertation and Jha and Schonfeld's early publications (2000a, 2000b, 2000c, 2004).

3.3.4 Structures Cost

Besides the earthwork cost, structure cost is also one of the major components of construction cost. The structure cost in this thesis refers to the cost of bridge crossing the rivers and valleys, and cross-structures for intersecting existing highways. It is added to HAO model by Kim (2001) and the calculation is given in equation 3.8.

$$C_S = C_{BR} + C_{IC} + C_{IS} + C_{GS} \tag{3.8}$$

where: C_{BR} = Bridge construction cost

C_{IC} = Interchange construction cost

C_{IS} = Intersection construction cost

C_{GS} = Grade separation cost

The bridge construction cost depends on the bridge type. Kyte et al (2003) and Menn's (1990) model are employed to estimate the cost of small bridge used for grade separation of existing bridge, and O'Conner's (1971) model is used to access the cost of bridge designed for crossing rivers and valleys. Three types of cross-structures are considered, which are interchange, intersection and grade separation structures. Kim's model (2001, 2004 and 2007) is employed to evaluate the cost of 4-leg cross-structures. Kang (2008) also develops a model for estimating the cost of 3-leg cross-structures.

3.3.5 Maintenance Cost

The highway maintenance cost is also considered and incorporated in the HAO model. Jha (2003) studies the trade-offs between initial and maintenance cost of highway design. He formulates the maintenance cost as the function of sideslope width of highway cross section and AADT, so as to optimize highway alignment. The maintenance cost is further subdivided into two categories by Kim (2001, 2004): highway basic segments and highway bridges. The maintenance cost for road segment is associated with the length of segment. Therefore, the highway segment maintenance cost can be estimated if the segment length and unit maintenance cost (normally $ per unit distance per year) are given. The bridge maintenance cost is formulated by summing up all components, which include the annual inspection cost, annual maintenance cost and periodic rehabilitation cost. Kang (2008) employs the bridge operating cost calculation proposed by Menn (1990), in which the maintenance costs are estimated as percentages of bridge construction cost separately. Equation 3.9 presents the calculation of maintenance cost:

$$C_M = C_{HM} + C_{BO} \tag{3.9}$$

where: C_{HM} = present value of maintenance cost for highway basic segments

C_{BO} = present value of bridge operating cost

3.4 User Cost

User cost consists of travel time cost, vehicle operating cost and accident cost. All three components are associated with the road geometric features, and formulated with the alignment variables. It is expected that the user cost can be significantly reduced with a well-designed alignment. The user cost can be estimated with the following equation:

$$C_{user} = C_T + C_O + C_A \tag{3.10}$$

where: C_T = total travel time cost ($)

C_O = total operating cost ($)

C_A = total accident cost ($)

3.4.1 Travel Time Cost

The vehicle travel time cost is associated with time spent for traveling and users' perceived time value. There are many methods for estimating the vehicle travel time for given network and traffic conditions. Kang (2008) estimates the travel time based on the BPR function (Bureau of Public Roads, 1964). The traffic volume-capacity ratio can be calculated after assigning the traffic into the given network. Based on the assigned real traffic volume, Kang uses the BPR function to estimate the real travel time. Jong utilizes another travel time prediction method, which is straightforward: The travel time is calculated by using highway alignment length divided by vehicle travel speed. One of the advantages of Jong's method is that the vehicle running speed is related to road features, which is helpful for establishing relation between geometric feature and optimization problem. Therefore, this dissertation employs this method to predict travel time. It is also important to note that Kang's model is better for dealing with a network, while Jong's model is only applicable to a single road segment.

Two variables, which are alignment length and vehicle running speed, are required for estimating the travel time cost. The alignment length is discussed in Section 3.3.1 and the calculation is given in equation 3.3. Vehicle speed is influenced by many factors, e.g. vehicle characteristics, road geometry, traffic condition and drivers' behaviors. For the highway alignment optimization research, the vehicle speed is desired to be related to the highway geometric directly. Jong employs Polus' (1984) research of accessing the effect of traffic and geometric on highway average running speed in existing HAO model. The speed function is given in equation 3.11:

$$\begin{aligned} \overline{V} &= 55.124 - 0.0363\overline{C} - 0.0332\overline{H} - 0.0081G_N - 0.0137T \\ &\quad -2.4737D - 0.1678Q \end{aligned} \tag{3.11}$$

where: $\overline{V}$ = average running speed (miles/hr)

$\overline{C}$ = average curvature (degrees/mile)

$\overline{H}$ = average hilliness (ft/mile)

G_N = net gradient (ft/mile)

T = T factor, the percentage of heavy vehicles in the traffic stream

D = D factor, the directional distribution of traffic

Q = hourly one-way traffic volume (vehicle per hour)

Polus states that the lane width does not affect the average running speed since it is an insignificant variable in his speed prediction model. However, after reviewing the dataset used for his analysis, it is noted that the data was only collected from 16 sites, and the lane widths only ranged from 3.5 meters to 3.65 meters. It is not surprising that the lane width is insignificant when the observations are limited to such a narrow range. However, as discussed in Section 2.5, the effects of lane width on travel speed cannot be neglected.

Therefore, new speed prediction model with lane width consideration is desired. Yagar (1982) studies the geometric and environmental effects on speed of 2-lane highway. He finds that lane width has positive effects on vehicle travel speed, and the speed decreases by 1.1 mph for every foot of reduction in lane width below 13.12 feet. (Units are converted from metric.) Yagar's adjusted speed prediction model is given in equation 3.12

$$\overline{V} = 57.97 - 1.12G - 1.1L_W - 5.16LU - 4.97A - 0.43V_{sp} \tag{3.12}$$

where: $\overline{V}$ = average running speed (miles/hr)

G = grade factor (%)

L_W = difference between actual lane width and 13.12 feet (4 meter)

LU = land use

A = Access factor

V_{sp} = Speed limit lower than 55mph/hr (miles/hr)

Yagar's model is able to capture the impacts of lane width on travel speed, and the statistic test indicates that this model can yield reasonable results. However, it is difficult to replace the previous Polus' speed prediction model with this one since Yagar's model excludes the traffic condition variable, which is an important factor for determining vehicle speed as well. A better speed prediction model, which is able to consider both traffic and road geometry impacts, has not been found yet. Hence the combination of these two speed prediction models is used in this thesis. According to Yagar's model, the speed reduces by 1.1 mph for every foot of reduction. This thesis assumes that such effect of lane width on speed is still exist in Polus' model, and the lane width variable is incorporated in Polus' model with the same parameter as in Yagar's model. Polus' model is thus adjusted as

$$\begin{aligned}\overline{V} &= 55.124 - 0.0363\overline{C} - 0.0332\overline{H} - 0.0081G_N - 0.0137T \\ &\quad -2.4737D - 0.1678Q - 1.1L_W\end{aligned} \tag{3.13}$$

The traffic volume in the current HAO model is considered in three different cases, which are peak hour traffic in the prevalent direction, peak hour volume in the non-prevalent direction and off-peak volume. These three traffic volumes per hour are denoted as Q_{pp} Q_{pn} and Q_o separately. The calculation of traffic volumes in different cases are given in equation 3.14.

$$\begin{aligned} Q_{pp} &= AADT \times K \times D \\ Q_{pn} &= AADT \times K \times (1-D) \\ Q_o &= \frac{0.5 \times AADT \times (1-H_p K)}{18-H_p} \end{aligned} \tag{3.14}$$

where: AADT = annual average daily traffic (two-way) (vehicle/day)

K = the percentage of daily traffic occurring during the peak hour (%)

D =the directional distribution of traffic in peak hour (%)

H_p = number of peak hour per day

According to different traffic volumes, the vehicle speed can be expressed separately as follows:

$$\begin{aligned} \overline{V}_{pp} &= 55.124 - 0.0363\overline{C} - 0.0332\overline{H} - 0.0081G_N - 0.0137T \\ &\quad -2.4737D - 0.1678Q_{pp} - 1.1L_W \\ \overline{V}_{pn} &= 55.124 - 0.0363\overline{C} - 0.0332\overline{H} - 0.0081G_N - 0.0137T \\ &\quad -2.4737D - 0.1678Q_{pn} - 1.1L_W \\ \overline{V}_{o} &= 55.124 - 0.0363\overline{C} - 0.0332\overline{H} - 0.0081G_N - 0.0137T \\ &\quad -2.4737D - 0.1678Q_{o} - 1.1L_W \end{aligned} \tag{3.15}$$

As discussed at the beginning of this section, there are two factors determining the vehicle travel cost, which are travel time and unit travel time cost. The vehicle travel time can be calculated after estimating the travel speed, as shown in equation 3.16.

$$t = \begin{bmatrix} t_{pp} \\ t_{pn} \\ t_o \end{bmatrix} = \begin{bmatrix} \dfrac{L_n / 5280}{\overline{V}_{pp}} \\ \dfrac{L_n / 5280}{\overline{V}_{pn}} \\ \dfrac{L_n / 5280}{\overline{V}_{o}} \end{bmatrix} \tag{3.16}$$

The unit time value varies depending on the vehicle types. The classification of vehicle type in current HAO model employs the AASHTO's categorization of representative vehicle classes for economic analysis of highway projects, which are medium car (for passenger car), 2-Axle single-unit truck and 3-S2 truck. The first two types of vehicle consume gasoline, while the 3-S2 truck consume diesel. The T factor is usually used to present the percentage of heavy trucks. Therefore the composition of traffic can be denoted as follows:

$$T = \begin{bmatrix} (1-T) \\ P_{2A}T \\ P_{3s}T \end{bmatrix} \tag{3.17}$$

where: T is the vector of traffic composition

P_{2A} = percentage of 2A truck in total heavy trucks

P_{3s} = percentage of 3-S2 truck in total heavy trucks, and $P_{2A}+P_{3S}=1$

The value of one-hour of vehicle travel time depends on type of vehicle, vehicle occupancy, purpose of the trip. The travel time values of three different vehicle types are given in AASHTO, as shown in equation 3.18[*].

$$v = \begin{bmatrix} v_{MC} \\ v_{2A} \\ v_{3s} \end{bmatrix} = \begin{bmatrix} 12 \\ 28 \\ 34 \end{bmatrix} \tag{3.18}$$

---

[*] The value of travel time given in AASHTO is using 1975 dollars and is converted to 2010 dollars. Details are provided in appendix A

The final model for predicting the travel time cost in the base year is given in equation 3.19.

$$\begin{aligned} C_T^B &= Q_{PP} \times H_{TP} \times t_{pp} \times v \times T + Q_{pn} \times H_{TP} \times t_{pn} \times v \times T \\ &+ Q_o \times H_{TO} \times t_o \times v \times T \end{aligned} \tag{3.19}$$

where: C_T^B = total vehicle travel time cost in the base year ($/year)

Q_{pp} = traffic volume the prevalent direction per hour during peak hour

Q_{pn} = traffic volume the non-prevalent direction per hour during peak hour

Q_o = traffic volume both way during off-peak hour

t_{pp} = average travel time the prevalent direction per hour during peak hour

t_{pn} = average travel time the non-prevalent direction per hour during peak hour

t_o = average travel time both way during off-peak hour

T = vector of vehicle composition

v = vector of travel time value for three different types of vehicle

H_{TP} is the total peak hour per year[*]; $H_{TP} = 309H_p(hours)$

H_{TO} is the total off-peak hour per year; $H_{TO} = 6570 - 309H_P(hours)$

The net present value of total travel time cost for the entire analysis period n_y is:

$$C_T = C_T^B[\frac{e^{(r_t-\rho)n_y}-1}{r_t-\rho}] \tag{3.20}$$

where: C_T = net present value of total travel time cost ($)

r_t = the annual growth rate of AADT (%)

ρ = assumed interest rate (%)

---

[*] According to AASHTO's (1997) assumptions, there are 253 weekdays, 104 weekends, and 8 holidays per year.

3.4.2 Vehicle Operating Cost

AASHTO (1977) defined the vehicle operating cost as fuel and oil consumption, maintenance, tire wear, and vehicle depreciation. Fuel consumption is viewed as the most dominant and sensitive cost among all three components, and it is associated with road geometric design. Therefore, emphasis is placed here on fuel consumption estimation. The other three cost components are considered as unit costs per mile.

Different methods are employed to estimate the fuel consumption. Chesher (1987) estimates the fuel consumption per unit distance based on the vehicle speed. Jong (1998) employs Chesher's model to compute the fuel consumption in the current version of HAO model. Kang (2008) groups vehicles into two categories (automobiles and trucks) to study the operating cost and estimates the vehicle fuel consumption based on the "speed-fuel consumption" rate table accessed from reliable reference. Those two methodologies are quite similar since both of them estimate the fuel consumption based on the vehicle speed. However, speed is not the only factor affecting fuel consumption. Other factors that should be considered include vehicle characteristics and road conditions. Moreover, for the highway alignment optimization problem, the best method for estimating the fuel consumption is to derive the function from highway geometric features. Deriving such equation is not easy. Therefore the thesis starts by calculating the resistance force for running vehicles, which is affected by vehicle types and road geometric features, then estimating the required horsepower, and combining fuel consumption rate to obtain fuel cost.

As mentioned in Section 3.4.1, vehicles are grouped into three classes according to AASHTO (1997): medium car, 2-Axle single-unit truck and 3-S2 truck. The vehicle resistance consists of three major sources: (1) aerodynamic resistance, (2) rolling resistance and (3) grade or gravitational resistance. Detailed analysis of each component is addressed in Mannering (2004)'s book, and the final vehicle resistance model is given in equation 3.21.

$$R = \frac{\rho}{2} C_D A_f \overline{V}^2 + 0.01(1 + \frac{\overline{V}}{147}) \times W + WG \tag{3.21}$$

where: R = vehicle resistance (lb)

ρ = air density (slugs/ft^3), the value of ρ is in table 3.3

C_D = coefficient of drag (unit less), the value of C_D is in table 3.4

A_f = frontal area of the vehicle (projected area of the vehicle in the direction of travel) (ft^2), the value of A_f is in table 3.5

$\overline{V}$ = speed of the vehicle (ft/s)

W = total vehicle weight (lb), the value of W is in table 3.6

G = percent grade (%)

Altitude (feet)	Temperature (℉)	Pressure (lb/in^2)	Air Density (slugs/ft)
0	59.0	14.7	0.002378
5,000	41.2	12.2	0.002045

Table 3-3 Value of Air Density ρ

Vehicle Type	Drag Coefficient (C_D)
Medium Car	0.25-0.55
Bus	0.5-0.7
Tractor-trailer	0.6-1.3

Table 3-4 Value of Drag Coefficient (C_D)

Vehicle Type	Frontal Area (ft^2)
Medium Car	22
2 Axle Single-unit Truck	35
3-S2 Truck	56

Table 3-5 Vehicle Frontal Area (ft^2)

Vehicle Type	Vehicle Weight (lb)
Medium Car	3,000
2 Axle Single-unit Truck	12,200
3-S2 Truck	33,600

Table 3-6 Vehicle Weight (W)

Horsepower is determined by the resistance force and vehicle running speed, and can be calculated as shown in equation 3.22:

$$P = \frac{R \times \overline{V}}{375 \times \eta} = \frac{R \times \overline{V}}{308}[1] \tag{3.22}$$

where: P = horsepower (hp)

R = vehicle resistance (lb)

$\overline{V}$ = running speed (ft/s)

η = transmission efficiency $\approx$ 0.83

The horsepower is a function of vehicle running speed, and the speed is considered in three conditions as discussed in the last section. Thus the horsepower can be denoted as follows:

$$P = \begin{bmatrix} P_{pp} \\ P_{pn} \\ P_{o} \end{bmatrix} = \begin{bmatrix} f(V_{pp}) \\ f(V_{pn}) \\ f(V_{po}) \end{bmatrix} \tag{3.23}$$

Fuel consumptions vary among different vehicle types due to the variation of required horsepower and fuel consumption rates, as expressed in equation 3.24.

$$F(P, sfc) = \begin{bmatrix} F_{MC} \\ F_{2A} \\ F_{3s} \end{bmatrix} = \begin{bmatrix} P_{MC} \times sfc_{MC} \\ P_{2A} \times sfc_{2A} \\ P_{3s} \times sfc_{3s} \end{bmatrix} = \begin{bmatrix} F(R_{MC}, \overline{V}, sfc_{MC}) \\ F(R_{2A}, \overline{V}, sfc_{2A}) \\ F(R_{3s}, \overline{V}, sfc_{3s}) \end{bmatrix} \tag{3.24}$$

---

[1] The value 308 in Equation 3.22 is an approximate one, which is calculated by using the approximate transmission efficiency 0.83.

where: F_{MC} = Fuel consumption per hour of motorcar (lb/hr)

F_{2A} = Fuel consumption per hour of 2A-truck (lb/hr)

F_{3S} = Fuel consumption per hour of 3-S2-truck (lb/hr)

P_{MC} = horsepower of motorcars (hp)

P_{AC} = actual horsepower of 2A-trucks (hp)

P_{3S} = actual horsepower of 3-S2trucks (hp)

sfc_{MC} = fuel consumption rate of motorcars (lb/hp-hr)

sfc_{2A}= fuel consumption rate of 2A-trucks (lb/hp-hr)

sfc_{3S}= fuel consumption rate of 3-S2 trucks (lb/hp-hr)

The fuel consumption rate for cars consuming gasoline is 0.45 lb/hp-hr, and trucks consuming diesel is 0.35 lb/hp-hr.

t = vehicle travel time, given in equation 3.16

The fuel consumption cost per vehicle per hour is equal to the amount of fuel consumption multiplied by the fuel prices, as expressed in equation 3.25.

$$F_c\,(R,\overline{V},sfc)=\begin{bmatrix} U_g\times\dfrac{F_{MC}}{\rho_g} \\ U_g\times\dfrac{F_{2A}}{\rho_g} \\ U_d\times\dfrac{F_{3s}}{\rho_d} \end{bmatrix} \tag{3.25}$$

where: F_C = fuel consumption cost per vehicle per hour ($/hr)

U_g = gasoline price ($/gallon)

U_d = diesel price ($/gallon)

ρ_g = density of gasoline = 6.073 (lb/gallon)

ρ_d = density of diesel = 6.943 (lb/gallon)

Other operation costs, including maintenance, tire wear, and vehicle depreciation are calculated as equation 3.26:

$$F_{o-o} = \begin{bmatrix} U_{MC} \times L_n \\ U_{2A} \times L_n \\ U_{3S} \times L_n \end{bmatrix} \tag{3.26}$$

where: F_{o-o} = maintenance cost, tire cost and vehicle depreciation cost ($/mile)

U_{MC} = maintenance and tires cost of motorcar ($/mile)

U_{2A} = maintenance and tires cost of 2A truck ($/mile)

U_{3S} = maintenance and tires cost of 3-S2 truck ($/mile)

L_n = length of alignment (miles)

U_g , U_d , U_{MC} , U_{2A} , and U_{3S} are given in table 3.7

Cost	Motorcar	2A Truck	3-S2 Truck
Fuel* (2010 dollars/gallon)	2.993	2.993	3.243
Maintenance* (2010 cents/mile)	4.06	4.69	13.31
Tires (2010 cents/mile)	1.09	1.21	4.25
Depreciation (2010 cents/mile)	6.24	7.05	8.05
Total operating cost (except fuel consumption) (2010 cents/mile)	11.39	12.95	25.61

Table 3-7 Maintenance and Tires Costs of Motorcar, 2A Truck and 3-S2 Truck

The vehicle operating cost is calculated as:

$$\begin{aligned} C_o^B &= Q_{pp} \times (309H_p) \times [(t \times T \times F_C) + F_{o-o}] \\ &\quad + Q_{pn} \times (309H_p) \times [(t \times T \times F_C) + F_{o-o}] \\ &\quad + Q_o \times 2(6570 - 309H_p) \times [(t \times T \times F_C) + F_{o-o}] \end{aligned} \tag{3.27}$$

where: C_o^B = total fuel consumption cost in the base year ($/yr)

Q_{pp} = traffic volume the prevalent direction per hour during peak hour

---

[*] Maintenance, tires and depreciation cost per mile data is accessed from the research report "The Per-mile Costs of Operating Automobiles and Trucks", data are converted to 2010 dollars from 2003 dollar. Details are provided in appendix A

Q_{pn} = traffic volume the non-prevalent direction per hour during peak hour

Q_o = traffic volume both way during off-peak hour

t = average travel time per vehicle (hr), given in equation 3.16

T = traffic composition, given in equation 3.17

F_C= fuel consumption per vehicle per hour, given in equation 3.26 ($/hr)

$F_{O\text{-}O}$ = maintenance cost, tire cost and vehicle depreciation cost, given in equation 3.27 ($)

The net present value of total travel time costs for the entire analysis period n_y is:

$$C_O = C_O^B[\frac{e^{(r_t-\rho)n_y}-1}{r_t-\rho}] \tag{3.28}$$

where: C_O = net present value of total vehicle operating cost ($)

r_t = the annual growth rate of AADT (%)

P = assumed interest rate (%)

Highway geometric features affect the vehicle travel speed, resistance, horsepower, and further influence the fuel consumption. Therefore, a well-designed highway may decrease the vehicle operating cost.

3.4.3 Accident Cost

Many factors contribute to the accident rate, and the highway geometric feature is recognized as one of the major sources. Generally, sharper curves, narrower lanes and inadequate sight distance may all lead to higher accident rates. Jong (1998) employs the model developed by Zegeer (1992) to estimate the number of accidents on curves of a two-lane highway in each 5-year period. The drawback of this model is that it is not able to predict the accidents occurring on tangents.

Jha (2000) replaces the accident prediction model by using the accident analysis module of the Interactive Highway Safety Design Model (IHSDM) developed by Vogt and

Bared (1998). This model is developed with negative binomial regression analysis for rural road traffic data collected in the states of Minnesota and Washington. It is able to estimate the impacts of two-lane highway characteristics on accident rate of current and future highway projects. This model is evaluated by different studies, and the results indicate it is a reliable model. Vogt's model is given in equation 3.29:

$$\begin{aligned}\hat{y} &= 1.92\times A\times exp(F)\times\sum_j B_j\times exp(0.045D_{cj})\times\sum_i C_i\times exp(0.465V_i)\\ &\times\sum_i D_i\times exp(0.105g_i)\end{aligned} \tag{3.29}$$

where: $\hat{y}$ = predicted mean number of accidents on the segment

A = traffic exposure (million vehicle miles)

F = 0.0084D +0.668H -0.0591S-0.0846W

W = lane width (feet)

S = average of left and right shoulder width (feet)

H = average roadside hazard rating along the alignment

D = driveway density (driveway per mile)

B_j = fraction of the total alignment length occupied by the jth horizontal curve

D_{cj} = degree of curvature of the jth curve

C_j = fraction of the total alignment length occupied by the ith vertical crest curve

V_i = absolute change in grade

D_i = fraction of the total alignment length occupied by the ith uniform grade section

G_i = absolute value of the ith grade

Therefore, the base accident cost per year is:

$$C_A^B = U_a\times\hat{y} \tag{3.30}$$

where: C_A = total accident cost per year ($/year)

U_a = average accident cost ($)

According to AASHTO, the average accident cost is $53,000 in 2003 dollars, which is equal to $63,900 in 2010 dollars.[2]

The net present value of total accident costs for the entire analysis period n_y is:

$$C_A = C_A^B\left[\frac{e^{(r_t-\rho)n_y}-1}{r_t-\rho}\right] \tag{3.31}$$

where: C_A = net present value of total accident cost ($)

r_t = the annual growth rate of AADT (%)

P = assumed interest rate (%)

3.5 Environmental Costs

The impacts of a new highway on the environment should not be neglected. Jha incorporates environmental cost considerations into HAO model by identifying and avoiding floodplains, wetlands and other environmentally sensitive areas in GIS while designing new a highway, as discussed in Chapter 2. Other major environmental impacts such as emissions and noise are excluded in current HAO model. However, vehicle emissions are recognized as one of the major sources of air pollution. For instance, passenger cars contribute 60% of total carbon monoxide (CO) emissions, 60% of hydrocarbon (HC) emissions, and more than one third of oxides of nitrogen (NO_X) emissions (Tsunokawa and Hoban, 1997). Freight transportation is responsible for 27% of total NO_x emissions in the U.S. The emissions adversely affect public health and the environment. Therefore, the air pollution resulting from transportation should be considered for all projects in which a new road or an improvement in road capacity of existing road is proposed.[35] The prediction of vehicle emissions cost should be incorporated into HAO model. Extensive research has been conducted on modeling and mitigating the vehicle emissions. The emissions are found to be associated with many factors, which include vehicle characteristics, driver behavior, environmental conditions, and

---

[2] The adjustment is listed in Appendix A

roadway classification (CA DOT, 1999). Basically, there are three methodologies to compute pollutants. One type of model uses lookup tables of emission rate at various speeds for different vehicle types. One example is the software StartBENCOST (CA DOT, 1982). StartBENCOST calculates the vehicle emission based on the emission rate table for each pollutant for each vehicle type (three types: small vehicle, trucks and buses, and for both peak and off-peak time periods. The unit of emission rate is in grams per mile, and the pollutant emitted is calculated by manipulating vehicle miles traveled with emission rates. The second type of the emission prediction model operates with aggregate traffic statistics and considers the dispersion of pollutant. The software MOVES developed by U.S. Environmental Protection Agency (EPA, 2009) is a typical example. The third kind of model predicts vehicle emission based on detailed vehicle parameters, and second-by-second acceleration and deceleration data. Neither of the above three methodologies are associated with road geometric characterizes directly. It is noted that the vehicle emissions are also closely related to road design since the emissions are associated with vehicle horsepower, which is affected by road features, as shown in equations 3.21 and 3.22. It is also expected that the emissions could also be reduced by well-designed highway. Therefore this thesis incorporates the emissions cost in the HAO model. The emissions analysis starts by calculating the required horsepower for running vehicles with given roadway geometric features, and then estimates the vehicle emissions based on the emission rate per horsepower-hour.

The major pollutants of significance to air quality in vehicle emission are nitrogen oxides (NO_X), carbon monoxide (CO), sulfur oxides (SO_X) and particulate matter (PM_{10}). Vehicle emissions are determined by the horsepower of running the car and the emission rate of certain pollutants. The calculation of horsepower is addressed in equation 3. 22. To estimate the amount of different pollutants, the emission rate per horsepower-hour is desired. EPA published several documents addressing the emission rate and emission rate standards of passenger cars, light trucks and heavy trucks. The vector of emission rate is expressed as equation 3.32.

$$E_r = \begin{bmatrix} E_{r-MC} \\ E_{r-2A} \\ E_{r=3S} \end{bmatrix} \tag{3.32}$$

where: E_r = vector of emission rate of three types of vehicles

$E_{r\text{-}MC}$ = the emission rate of motorcar (lb/hp-hr)

$E_{r\text{-}2A}$ = the emission rate of 2A truck (lb/hp-hr)

$E_{r\text{-}3S}$ = the emission rate of 3-S2 truck (lb/hp-hr)

The accuracy of emission rates of different pollutants and vehicle types is critical in predicting the highway emission. The unit of emission rate is desired to be “weight (e.g. lb) per horsepower hour” since the computation is based on the horsepower required for running the vehicle. EPA (1997) and U.S. Department of Transportation (2011) released the heavy truck emission rate standards for different heavy truck engines with the unit “g/brake horsepower-hour” as shown in Table 3.8.

Year	CO (g/bhp-hr)	HC (g/bhp-hr)	NO_X (g/bhp-hr)	PM_{10}(g/bhp-hr)
1990	15.5	1.3	6.0	0.6
1991-93	15.5	1.3	5.0	0.25
1994-97	15.5	1.3	5.0	0.1
1998+	15.5	1.3	4.0	0.1

Table 3-8 Emission Rate for Heavy-Duty Highway Engines (EPA, 1997; U.S. DOT, 2011)

The estimated average emission rates of motorcar and light-duty truck are usually given in units of “g/mile”, rather than “g/bhp-hr” (EPA, 2010). The emission rates with unit “g/bhp-hr” for non-road industry engines are presented in Table 3.9 (EPA,1995). The emission rates of industrial engines are higher than for vehicles. Before finding a more reliable reference, we calculate the gasoline fuel emission based on the emission rates in Table 3.9, and the diesel fuel emission rate based on the emission rate in Table 3.8. Model users can also input the emission rate themselves if a more reliable reference is found.

Pollutant	Gasoline Fuel Emission Rate (lb/hp-hr)	Diesel Fuel Emission Rate (lb/hp-hr)
NO_X	0.011	0.031
CO	6.96 E-03	6.68 E-03
SO_X	5.91 E-04	2.05 E-03
PM_{10}	7.21 E-04	2.20 E-03

Table 3-9 Emission Rate for Gasoline and Diesel Industrial Engines (EPA, 1995)

The emissions per vehicle per hour then can be calculated with equation 3.34:

$$E = \begin{bmatrix} E_{pp} \\ E_{pn} \\ E_o \end{bmatrix} = E_r \times \begin{bmatrix} P_{pp} \\ P_{pn} \\ P_o \end{bmatrix} \tag{3.33}$$

where: E = vector of emissions per vehicle per hour (lb/hr)

E_{pp} = peak hour emissions per vehicle per hour in the prevalent direction (lb/hr)

E_{pn} = peak hour emissions per vehicle per hour in the non-prevalent direction (lb/hr)

E_o = off-peak emissions per vehicle per hour (lb/hr)

The total emissions of three pollutants are:

$$\begin{aligned} E_{Ti} &= (Q_{pp} \times (309H_p) \times t \times T \times P \times E_{ppi} + Q_{pn} \times (309H_p) \times t \times T \times P \times E_{pni} \\ &\quad + Q_o \times 2(6570 - 309H_p) \times t \times T \times P \times E_{oi}) \\ i &= 0,1,2 \end{aligned} \tag{3.34}$$

where: i =0 to 3, stands for pollutants NO_x, CO, SO_x, and PM_{10}

E_T = emission of each pollutant (lb)

The economic cost of each pollutant per unit is denoted as U_i, and the value is given in Table 3.10 (CA DOT, 1999).

Pollutant	Rural Area	Urban Area
Dollar Value of Motor Vehicle Emissions (year 2010$/ton)		
Carbon monoxide (CO)	68	75
Nitrogen oxides (NO_x)	12,847	16,016
Sulfur oxides (SO_x)	50,321	69,745
Particulate matter (PM_{10})	78,618	110,258

Table 3-10 Pollutants Cost per Ton in 2010 dollars *

---

* Data were given in 2000 dollars, and had been converted to 2010 dollars. Refer to Appendix A

Total base emission cost per year can be expressed as:

$$C^{B}_{environment} = \sum_{i=0}^{3} E_i \times U_i \tag{3.35}$$

The net present value of total accident costs for the entire analysis period n_y is:

$$C_{environment} = C^{B}_{environment}[\frac{e^{(r_t-\rho)n_y}-1}{r_t-\rho}] \tag{3.36}$$

where: $C_{environment}$ = net present value of total environmental cost ($)

r_t = the annual growth rate of AADT (%)

P = assumed interest rate (%)

3.6 Final Model

The objective function minimizes the sum of all components of total cost. Therefore the final model can be formulated as:

$$\underset{d_1,d_2,\ldots d_n}{\text{Minimize}} \; C_T = C_{agency} + C_{user} + C_{environment} \tag{3.37}$$

$$\text{subject to } d_{iL} < d_i < d_{iU}, \text{ for all } i = 1,\ldots..n$$

where: C_T = total cost per year ($)

C_{agency} = total agency cost per year ($), given in equation 3.3

C_{user} = total user cost per year ($), given in equation 3.10

$C_{environment}$ = total environmental cost per year ($), given in equation 3.27

d_{iL} and d_{iU} are lower and upper bound of the i^{th} decision variable as discussed in Section 3.1.

The objective function and constraints are all associated with alignment variables. The solution and results are discussed in the following two chapters.

Chapter 4: Solution Algorithm for Optimizing Non-backtracking 3-Dimensional Alignments

4.1 Genetic Algorithm for Solving Non-backtracking 3-dimensional Alignments

Many search methods are available for solving optimization problems. Jong (1998) develops a special genetic algorithm to solve the non-backtracking 3-dimensional alignment optimization problem. Jha uses the same method in his research and he also improves the HAO model as a combined genetic algorithm and GIS highway alignment optimization model. Kang utilizes the same genetic algorithm as the base search-method in his research, and he also improves the computing efficiency by developing his feasible gate approach and by employing a prescreening and repairing method.

The basic principle of a genetic algorithm is "survival of fittest". It starts with an initial set of solutions called the "population". Individual solutions are selected through the fitness-based process, and solutions with better fit of fitness function are more likely to be selected. The fitness function is also called the objective function of the optimization problem. In this research, the total cost of a highway alignment is the objective function to be minimized, as shown in equation 3.37. Surviving solutions are used to generate new solutions based on genetic operators. Newly generated solutions then go through the fitness-based selection process again until after many generations, further improvements are considered too small or unlikely. The genetic operators can defined differently according to the inherent differences of the optimization problems. Jong (1998) develops eight different types of genetic operators which are customized to solve the highway alignment optimization problem. The first four genetic operators are mutation-based, while the last four are crossover-based. Detailed descriptions can be found in Chapter 8 of Jong's PhD dissertation (1998).

Kang (2007, 2008) improves the computing efficiency of HAO model by developing the feasible gate search method, which is used in the current version of the HAO model. Initially, the HAO model utilized the penalty approach to satisfy constraints. However, such a method is computationally expensive. Therefore Kang defines the representation of feasible area to handle the geographic constraints and to avoid generating infeasible solution outside the boundary. The feasible gates were designed for horizontal and vertical alignment separately. An input data preparation module (IDPM) was developed to assistant users to define the feasible study area. The feasible area is defined as the area inside the study area, as well as outside the environmentally sensitive area. Considering the user preferences, e.g. political issues, the IDPM also enables users to define the feasible area themselves. As discussed in Section 3.1, Jong formulated the problem by treating the intersection points (PIs) for a candidate alignment as design variables whose locations on cutting planes must be optimized. Thus the search range for intersection points is the entire area of cutting planes. Fortunately, the feasible gate method enables us to reduce the search ranges to only the feasible areas. The cutting lines are divided into several sub-segments based on their feasibility, and the searching is only conducted on those feasible sub-segments. Compared with the feasible range for horizontal alignment, the range for vertical alignment is relatively easy, which is usually constrained by the maximum allowed gradient. The key contribution with the feasible gates search is that it improves the search efficiency and quality. According to some test results, the model with feasible gates saves about 28% in computation time.

4.2 Lane Width Optimization

As discussed in Section 2.5, the lane width is interrelated with several cost components in alignment optimization problem. The costs associated with lane width include accident cost, travel time cost, vehicle operating cost, environmental cost, and earthwork cost. According to the IHSDM model (equation 3.29) employed in the current HAO model to predict the accident rate, wider lanes contribute to lower accident rates and improve speed. According to Yagar’s research (equation 3.12), travel speed increases by 1.1 mph for every foot of increase in lane width. The increased speed decreases the travel time cost (equation 3.19). However, it increases the required horsepower for a vehicle, which increases vehicle operating cost (equation 3.27) and environmental cost (equation 3.34). Moreover, wider lanes increase earthwork cost. Overall, wider lanes decrease accident cost and travel time cost, but also increase vehicle operating cost, environmental cost and earthwork cost. Thus it is important to optimize lane width in order to minimize the total cost of an alignment.

The detailed computation of accident cost, travel time cost, vehicle operating cost, environmental cost and earthwork cost are addressed in Chapter 3. The objective function to the highway alignment optimization problem is presented in equation 3.37, which is also denoted as $C = f(W_L)$ in the lane width optimization procedure, where W_L is lane width, and ranges from 9 feet to 12 feet.

The total cost is higher with narrower lanes because the accident cost is high and dominates other costs. With wider lanes, the accident cost decreases while other costs, especially earthwork cost, increase. The total cost is minimized with a reasonable lane width. Wider lanes increase other costs rapidly while no significant accident cost decrease can be observed, and thus increases the total cost.

Newton’s method is used to find the lane width that minimizes the total cost. The iterative relation is:

$$W_{L\ n+1} = W_{L\ n} - \frac{f'(W_{L\ n})}{f''(W_{L\ n})} \tag{4.1}$$

It is quite hard, if not impossible, to calculate derivatives of $f(W_L)$ analytically. Hence, the finite difference is used to approximate them, as shown in equations 4.2 and 4.3.

$$f'(W_L) \approx \frac{f(W_L + h) - f(W_L)}{h} \tag{4.2}$$

$$f''(W_L) \approx \frac{f(W_L + h) - 2f(W_L) + f(W_L - h)}{h^2} \tag{4.3}$$

The approximation is calculated with decreasing h until the result is close enough to the actual derivative.

In summary, the optimal lane width determination procedure is as follows:

Step 1: Specify the objective function.

Step2: Determine the lane width that minimizes the total cost using Newton's method.

Step 2.1: Begin with an initial lane width value based on experience or observation, and calculate the total cost with this lane width.

Step 2.2: Calculate the approximation of the first and second order derivatives with equations 4.2 and 4.3 and calculate the next lane width with equation 4.2. Calculate the total cost with this lane width.

Step 2.3: If the two total costs are close enough, stop. Use the lane width with the smaller objective function value (i.e. total cost) as the optimal lane width.

Step 2.4: If not, return to 2.2 and recalculate the next lane width, which is $W_L + h$.

Example study:

One scenario is tested for the McCooler case. (Detailed information regarding the topography and land use information of the region of interest is introduced in Chapter 5.) The design parameters used in this case study are a two-lane road, 65mph as design speed, 8% superelevation, and 5% maximum allowable gradient. In order to find an appropriate initial value which is close to the optimal one, four lane width values (9, 10, 11, 12 feet) are tested to obtain the corresponding total cost. The total costs with different lane widths are listed in Table 4.1 and are plotted in Figure 4-1.

Lane width (feet)	Total cost (million dollars)
9	260.42
10	243.77
11	246.16
12	267.20

Table 4-1 Total Cost with Different Lane Widths

Based on the curve shown in Figure 4-1, the minimum cost is achieved when lane width is equal to 10 feet. Therefore, the initial value of lane width is set at 10 feet, and h is set at 0.1.

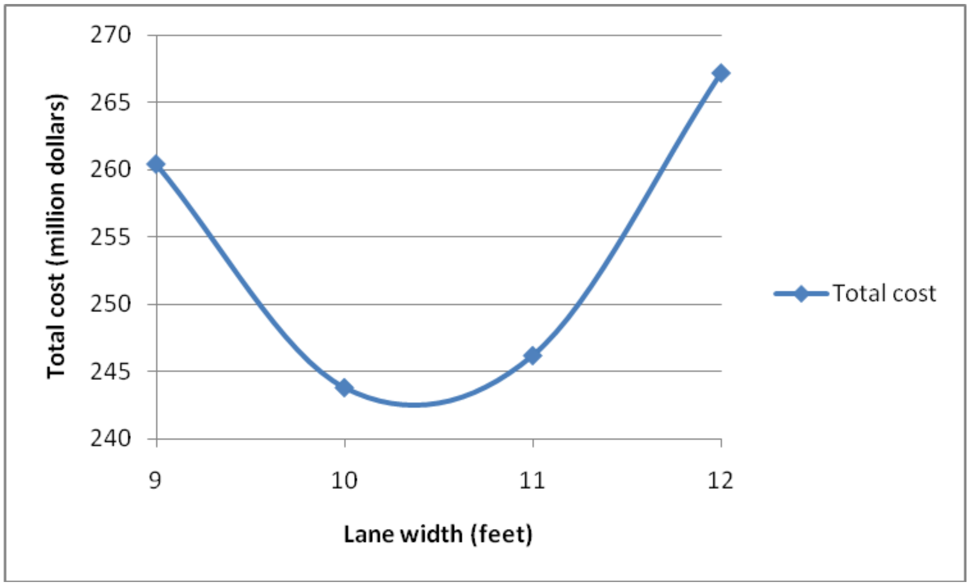


Figure 4-1 Total Costs with Different Lane Widths

The total cost of $f(W_{L5})$ is very close to $f(W_{L4})$ after searching for five iterations. The optimized lane width for the region of interest with given design parameters is 10.6 feet, for which the total cost is $233.91million.

To verify if 10.6 is the optimal lane width, the total cost with 10.8 and 10.5 feet, and 9.5, 10.5 and 11.5 feet are also calculated, and plotted in Figure 4-2. This shows that the total costs are higher at all lane widths other than 10.6 feet.

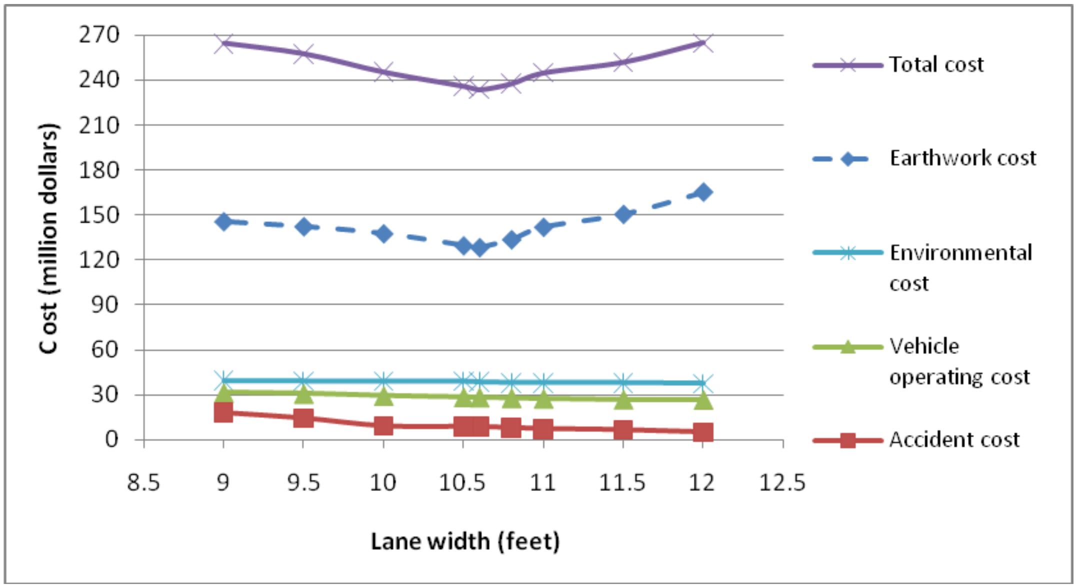


Figure 4-2 Costs with Different Lane Widths

The breakdown of detailed objective values in Figure 4-2 shows that the lane width effects accident cost and earthwork cost significantly. It is expected that the earthwork cost decreases with narrower lane. The HAO model outputs do show that the earthwork cost decreases while the lane width reducing from 12 feet to 10 feet. However, it also finds that the earthwork cost increases with narrower lanes when the lane width is narrower than 10 feet. It can be explained that the accident cost increases while the lane width is narrower than 10 feet, and the HAO model seeks to design longer and smoother curves to minimize the impacts, which consequently leads to the increase in earthwork cost. Figure 4-2 also indicates that the environmental cost and vehicle operating cost are not affect by the lane width considerably in the case study.

The above analysis indicates that this proposed method can find the optimized lane width, for which the total cost is minimum. However, one must also be aware that this method cannot guarantee finding the global optimal value, and the choice of initial value affects the convergence rate. It is difficult to identify the appropriate initial lane width value merely based on experience. In the given case study, the lane width is selected based on the observations of total costs using seven different lane widths from 9 to 12 feet. The minimum total cost is found with 10 feet lane. Therefore 10 feet is set as the initial value. However, it cannot be guaranteed that 10 feet is a good initial value which leads to quick convergence. More observations is required to identify the appropriate initial value which leads to quick convergence, but the calculating is time consuming.

Chapter 5: Case Study and Sensitivity Analysis

This chapter provides a case study to demonstrate the new HAO model for non-backtracking 3-dimensional alignment optimization. First, the study area is described, with a summary of the input geographic data, design criteria and parameters. Second, the solutions generated by the new HAO model are presented and analyzed. A goodness test of the optimized solution found by the proposed HAO model is performed in Section 5.3. The outputs include the cost of each component, horizontal alignment, vertical alignment, and fractions of each land use type taken by the alignment. In order to assess the model's capability of finding the best fit alignment with various critical inputs and constraints, sensitivity analyses with different optimization objective functions, fuel prices, and maximum allowable grades are comprehensively investigated in Section 5.4.

5.1 Problem Description

The objective of this case study is to test the performance of the new HAO model in finding the best fit alignment with the given study area and design parameters, especially in a hilly area. The optimized alignment should be the one that minimizes total costs while satisfying the design standards and other constraints. The major improvements in the new HAO model are vehicle operating cost estimation, environmental impacts assessment, and lane width optimization. The methodology developed for lane width optimization and its results are addressed in Chapter 4. Emphasis in this chapter is on analyzing the alignment results and the model's sensitivity. The vehicle operating cost in the new HAO model refers to the fuel consumption, maintenance, tier wear, and depreciation cost. Environmental cost is defined here as the vehicle emission cost. Both of the two costs are determined by the vehicle characteristics and road geometric characteristics (particularly the alignment length, curvatures and gradients). Therefore, an area with complex topography (hilly area), diverse landforms and lane use patterns would be the ideal area of interest for testing the new HAO model's performance and for assessing the impacts of those two new cost components on the optimized alignments.

5.1.1 Study Area

The region of interest for optimizing 3-dimensional non-backtracking alignment is selected as 4 miles north-east from the town of McCoole, Maryland. A new highway segment which is approximately 4 miles long is designed as one of the segments of the highway connecting McCoole and Cumberland. Figure 5-1 shows the location of the study area.

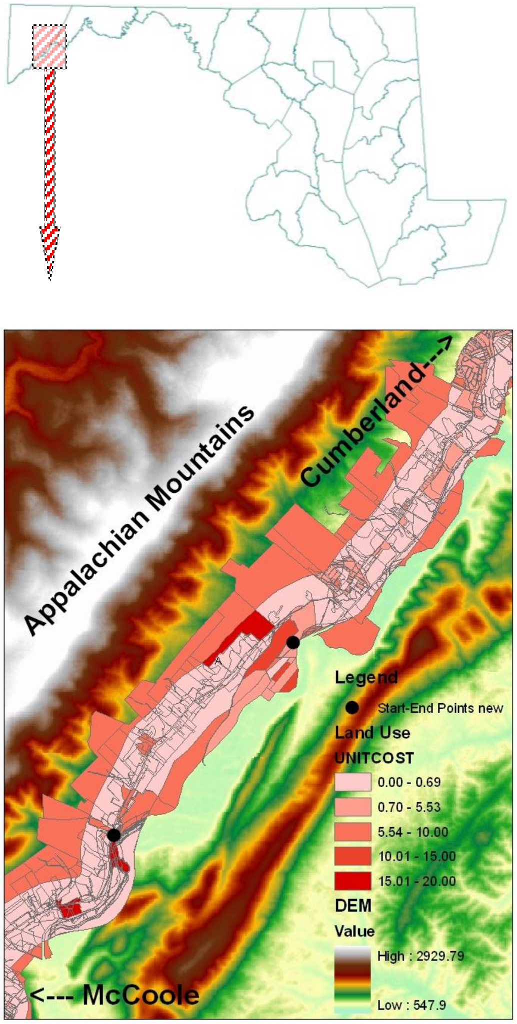


Figure 5-1 Map of Study Area

As mentioned previously, the study area is hilly with diverse land use patterns. The area of interest selected for the case study is located in the Appalachian Mountains area, and the ground elevation varies greatly from 548 feet to 2930 feet. According to the legend, the darker area in left graph of Figure 5-2 represents higher elevation. The slopes range from 0 to 61 degrees. Digital Elevation Model (DEM) data is used for conveying the terrain data of the study area. DEM data is a digital presentation of the ground surface. It divides the area into rectangular cells and stores the elevation of each pixel.

The location of the start and end points are shown separately on two sides of the mountain in Figure 5-2. Since the algorithm is non-backtracking optimization algorithms, the alignment has to cross the mountain. How and where to cross the mountain is critical in minimizing total cost. Therefore, this case study is well suited for verifying the capability and effectiveness of the new HAO model in optimizing alignments in tough topography. Figure 5-2 shows the elevation and slope map of the study area.

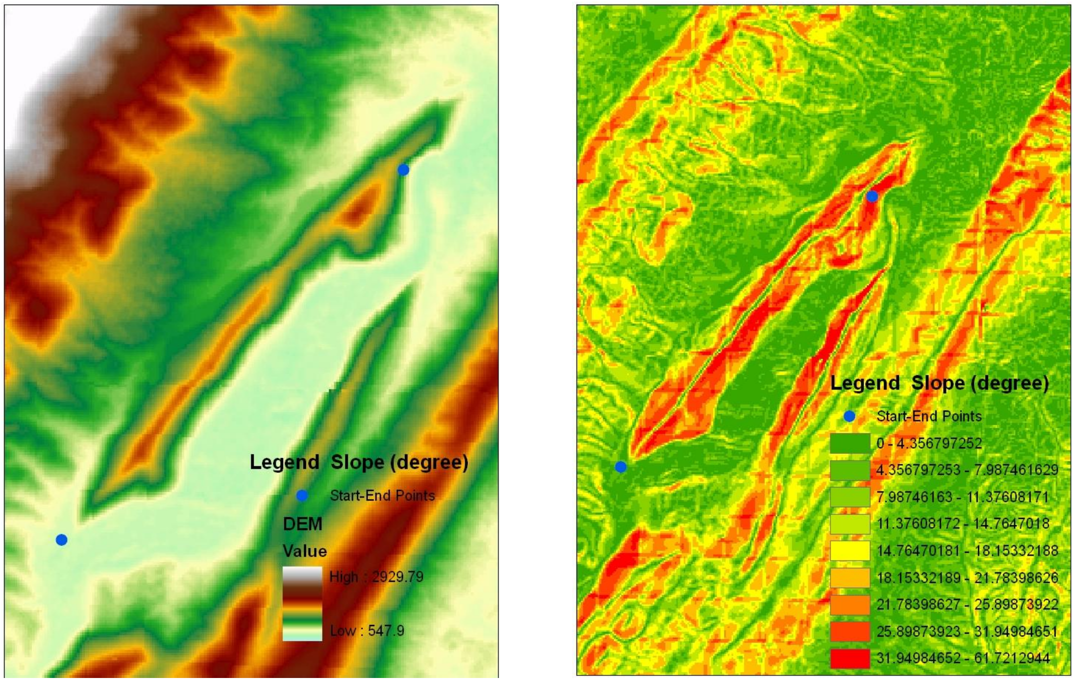


Figure 5-2 DEM Map and Slope Map of Study Area

The original horizontal map is the property map which is provided by the Maryland State Highway Administration (MSHA). In order to present the existing sensitive area and land use types, the data have been digitalized in ArcMap 9.3. As shown in Figure 5-3, the land use patterns in the given region are quite diverse, which are good for testing whether the new HAO model can design alignments with minimized right-of-way cost. The study area is composed of 920 geographic entities. There are eight different types of land use characteristics: floodplains, protected forests, deciduous forest, residential area (high, medium and low density), commercial area, cropland, and other properties, as shown in the left graph of Figure 5-3. The unit cost of each property is assigned for calculating the right-of-way cost. The cost of crossing floodplains, protected land and other geographically sensitive area are extremely high, and the interaction with such area should be avoided. The land use information is conveyed by GIS data. The information assigned to the GIS layer includes parcel ID, land use type, area and unit cost. The land use layer will be overlaid with the alignment results in GIS module, in order to identify the areas taken by each alignment segment, and to calculate the right-of-way cost. The land use type is shown in the left graph of Figure 5-3, and the unit cost is rendered with different colors in right graph of Figure 5-3.

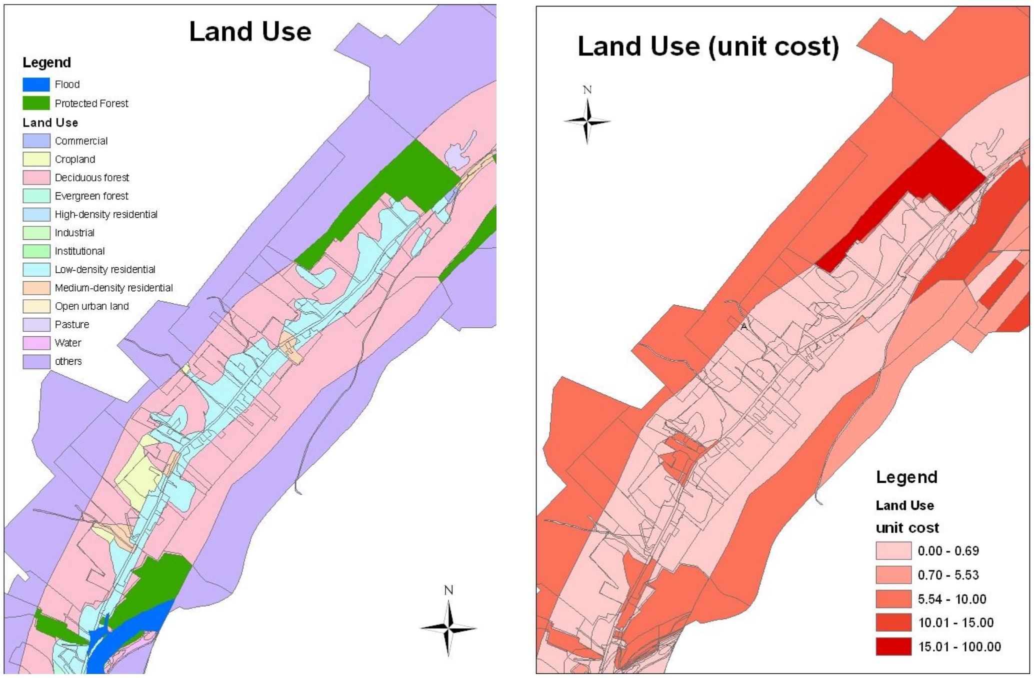


Figure 5-3 Land Use Map and Unit Cost Map of Study Area

5.1.2 Input Spatial Data and Design Parameters

The objective function for the optimization problem includes the agency cost, user cost and environmental cost. Many design features and parameters must be pre-specified, for instance, number of lanes, lane width, design speed, maximum allowable superelevation, and maximum allowable grade. The two endpoints in this case study are (764008, 667496, 754) and (777516, 68198, 1000). The road is designed as a two-lane highway, with 37.2 feet width (10.6 feet for lanes, and 8 feet for shoulder). The design speed limit is 65 mph. The maximum allowable superelevation is 8%. Unit cost of cutting and filling, fuel price and length-dependent cost are user-defined. The input parameters used in the case study are summarized in Table 5-1. It is noted that the optimization results vary depending on the input parameters. Therefore users need to determine the parameters carefully. Different input variables are also used for sensitivity analyses in Section 5.4.

Inputs variables		Assumed Value	
Number of points of intersection (PI's)		12	
Number of generation		300	
Lane width		10.6 feet	
Shoulder width		8 feet	
Number of lane		2	
Design speed		65 mph	
Maximum superelevation		8%	
Maximum allowable grade		5%	
Fill slope		0.4	
Cut slope		0.5	
Earth shrinkage factor		0.9	
Unit cut cost		$35\ \$/\text{yard}^3$	
Unit fill cost		$20\ \$/\text{yard}^3$	
Cost of moving earth from borrow pit		$2\ \$/\text{yard}^3$	
Cost of moving earth to fill		$3\ \$/\text{yard}^3$	
Unit length-dependent cost		$600\ \$/\text{yard}^3$	
Terrain height range		548 – 2929.79 feet	
Unit land use cost range		$0 - 100\ \$/\text{ft}^2$	
AADT		8000 vehicles per day	
D factor		0.5	
K factor		0.15	
T factor		0.05	
Number of peak hour per day		3	
Percentage of 2A-SU trucks in heavy vehicles		0.5	
Percentage of 3-S2 trucks in heavy vehicles		0.5	
Traffic growth rate		5%	
Interest rate		3%	
Analysis period		5 years	
Value of travel time ($/hr)	Motor car	12 $/hr	(See equation 3.19)
	2A truck	28 $/hr	
	3S truck	34 $/hr	
Vehicle weight (lb)	Motor car	3,000	(See Table 3-6)
	2A truck	12,200	
	3S truck	33,600	
Fuel consumption rate (lb/hp-hr)	Motor car	0.45	
	2A truck	0.45	
	3S truck	0.35	
Fuel price ($)	Gasoline	2.993	
	Diesel	3.243	

Table 5-1 Design Parameters for Case Study

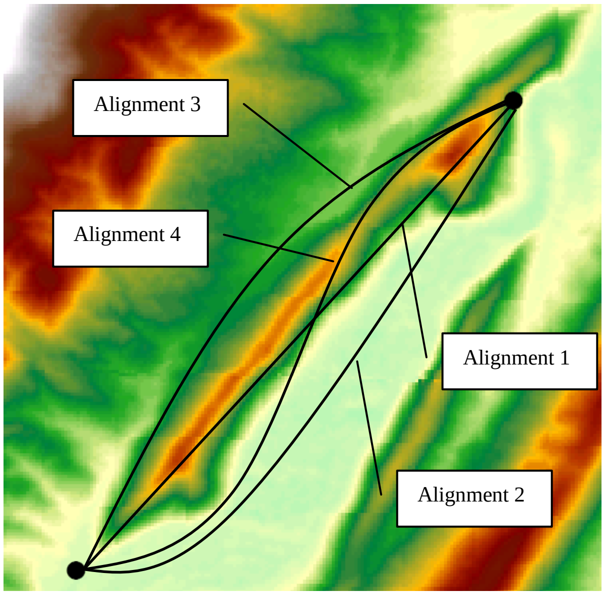


Figure 5-4 Possible Alignment Alternatives

After the geographic data and input parameters are prepared, the HAO model is ready to optimize the road alignment. There are countless possible alignments connecting two endpoints. Figure 5-4 shows some of the possible alignments. According to the map, Alignment 1 is the shortest one. However, the alignment crosses through the high elevation area and protected land, which results in higher earthwork cost and right-of-way cost. As for Alignments 2 and 3, both avoid the hilly area, and Alignment 3 is shorter. It is noted, however, that Alignment 3 passes through a dense residential area, which increases right-of-way cost. Alignment 4 avoids the high land cost area successfully. However, it is difficult to tell if the total cost is smaller than for the other 3 options. Therefore, it is hard to optimize alignment in areas with complex topography and land use patters based on experience merely. Fortunately, the HAO model was designed to assist the optimization procedures. It is expected that areas with high unit cost and high elevation are avoided by HAO model. The model outputs are shown and discussed in the following section.

5.2 Optimization Results

The number of PI's (points of intersection) used in this case study is 12. The more PI's, the better alignment results are expected to get, especially in areas with complex topography and land use patterns. However, the computation time will then increase.

The model outputs include the optimized horizontal alignment and vertical alignment, and the objective function value. Cost breakdown by categories are obtained as well.

The optimal horizontal alignment is generated with the new HAO model after searching for over 300 generations. Figure 5-5 plots the objective function values over the successive generations. At the initial stage, the objective function value is extremely high. The reason is that the genetic algorithm is designed to generate alignments randomly, and those alignments will very probably pass through the high cost areas. The values drop dramatically during first 90 generations. The improvement in the objective function value becomes slower after 100 generations, and reaches $233 million as the final total cost. This indicates that the HAO model works efficiently and has the potential to find a near-globally optimal solution quickly.

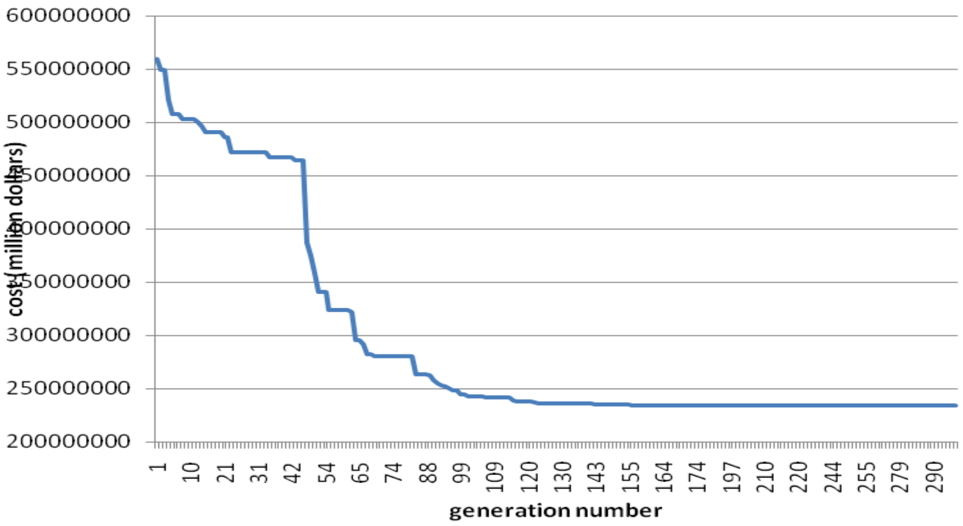


Figure 5-5 Changes in Objective Function over Successive Generations

Figure 5-6 presents the optimized horizontal alignment. The total alignment length is 21267.6 feet (4.03 miles). As shown in the left graph of Figure 5-6, the alignment skirts most high elevation areas to minimize the earthwork cost, and it crosses part of the mountain area as highlighted in Figure 5-6 since only non-backtracking highway alignment are considered. Thus it unavoidably connects the end points by crossing the mountain. However, the alignment crosses the hill at a relatively flat area, which demonstrates that the model is capable to guide the optimization search towards the alignment with minimum earthwork cost in a hilly area. As shown in the right graph, the alignment is able to avoid most high unit cost areas (darker red areas), which indicates that the HAO model succeeds in reducing the right-of-way cost.

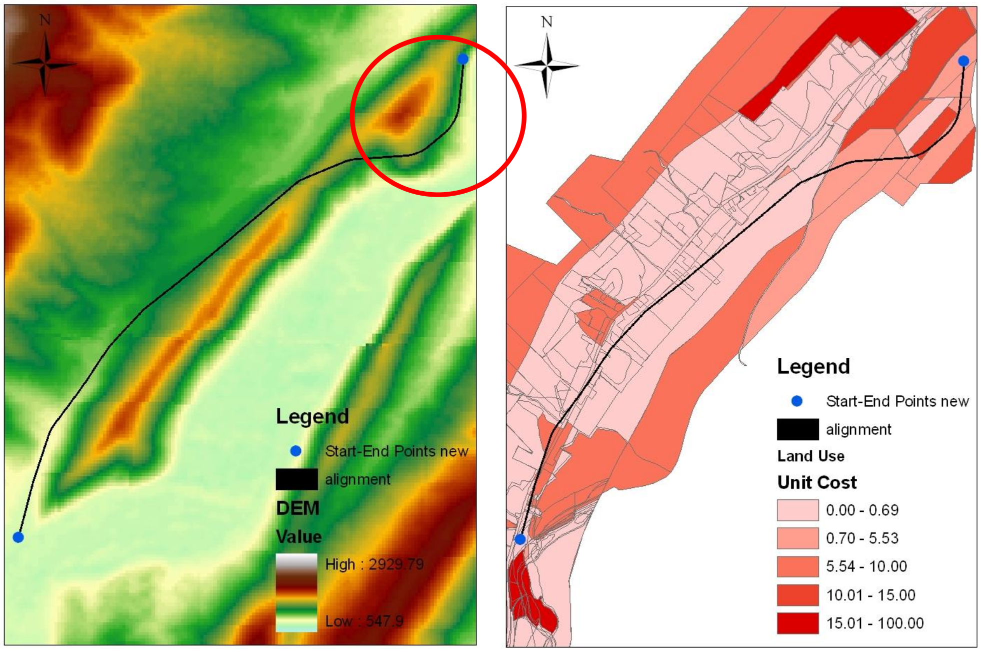
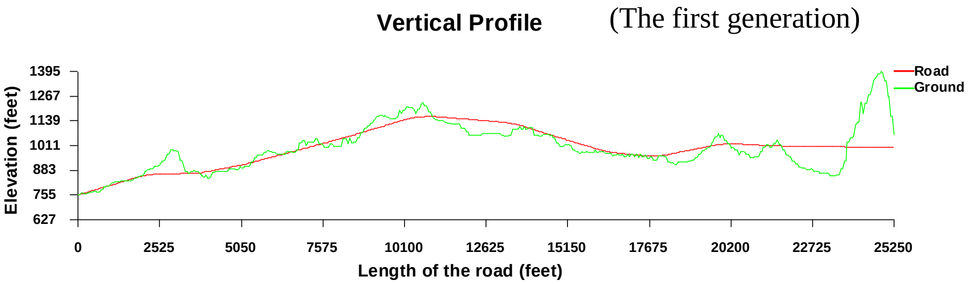


Figure 5-6 Horizontal Alignment Generated by the Improved HAO Model

Figure 5-7 compares the vertical alignment at the first generation (upper graph) and the final vertical alignment after searching for 300 generations. As shown in the upper graph, the alignment elevation does not match with the ground elevation very well, which may lead to high cut and fill volumes, and high earthwork cost. However, the final vertical alignment indicates the road alignment follows the ground profiles in order to minimize the earthwork cost.



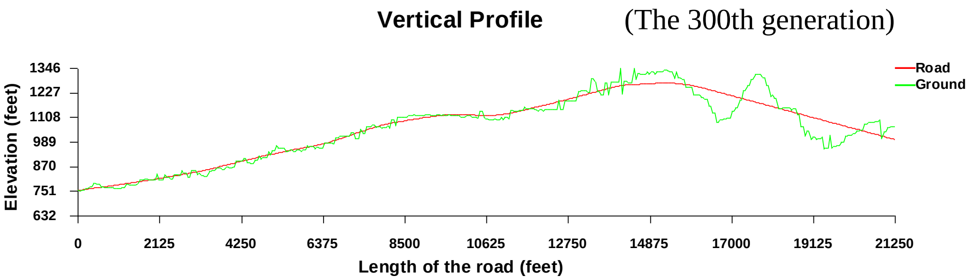


Figure 5-7 Vertical Alignment of the Improved HAO Model

The objective function consists of several cost components, including right-of-way cost, earthwork cost, length-dependent cost, accident cost, penalty cost, vehicle operating cost, travel time cost and environmental cost. Table 5.2 presents the detailed breakdown of the costs. The percentages of each cost component in the model objective function value are shown and analyzed in Figure 5-8.

Total Length (feet)		21267 4.03 (miles)
Total Cost (million $)		233.91
Agency Cost (million $)	Right-of-way Cost	1.75
	Length-dependant Cost	12.76
	Earthwork Cost	128.53
	Location penalty Cost	0
	Horizontal penalty Cost	0
	Length of Vertical Curve Penalty	0
	Gradient Penalty Cost	0

	Cross Structures Cost	0
	Bridge Cost	0
User Cost (million $)	Accident Cost	8.64
	Travel time Cost	15.12
	Vehicle operating Cost	28.61
Environmental (million $)	Environmental impacts Cost	38.49

Table 5-2 Cost Calculation of the Newly Improved HAO Model

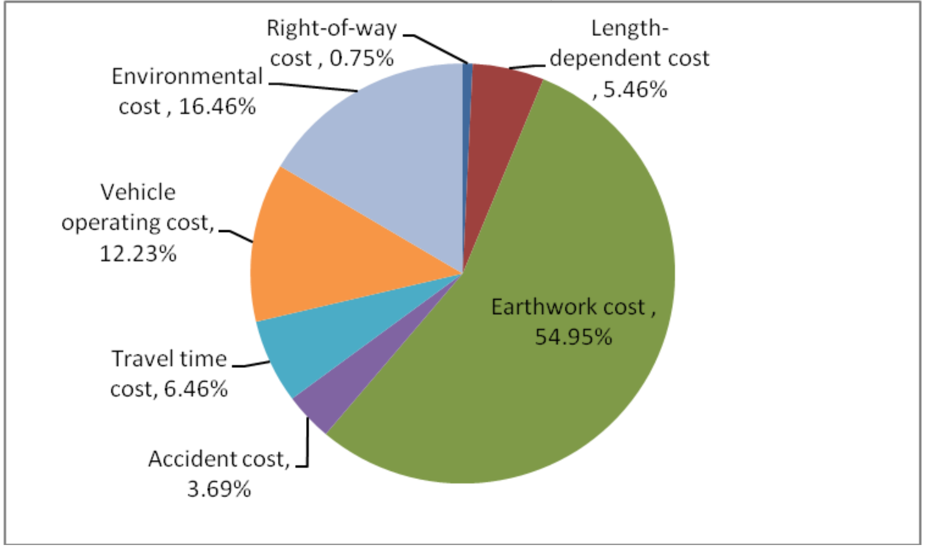


Figure 5-8 Percentages of Each Cost Component

The optimization results indicate that the dominant cost in the case study is the earthwork cost. The net present value of the earthwork cost is $ 128.53 million, which constitutes about 55% of the total cost. The user costs, which include accident cost, travel time cost and vehicle operating cost, are about 22.4% of the total cost.

The accident cost (about 17% of the user cost) is estimated based on the IHSDM model, which has been tested in different studies, and proved to be a reliable model.

The earthwork cost per mile varies depending on the location. A mile of road through mountains may cost hundreds times more than the one on flat ground. The average earthwork cost in the case study is $16 million per lane mile when lane width is 10.6 feet and shoulder width is 8 feet.

The annual vehicle operating cost (5-year period) is $28.6 million, which constitutes 12% of the total cost. The computation in the newly improved HAO model is based on the vehilce horsepwower and fuel consumption rate, as shown in equations 3.27 and 3.28. This method replaces Jong's (1998) model in the existing HAO model, which is the function of road grade and vehicle speed. The comparision of results generated by the new model and Jong's approach is shown in Figure 5-9. The comparision indicates that the vehicle operating cost estimated with the two approaches are quite different. The cost estimated by Jong's method is much samller than the result calculated by the new model. One of the reasons is that Jong's model only considers the fuel consumption cost, while the new method includes fuel consuption, maintenance, tire wear, and vehicle depreciation costs.

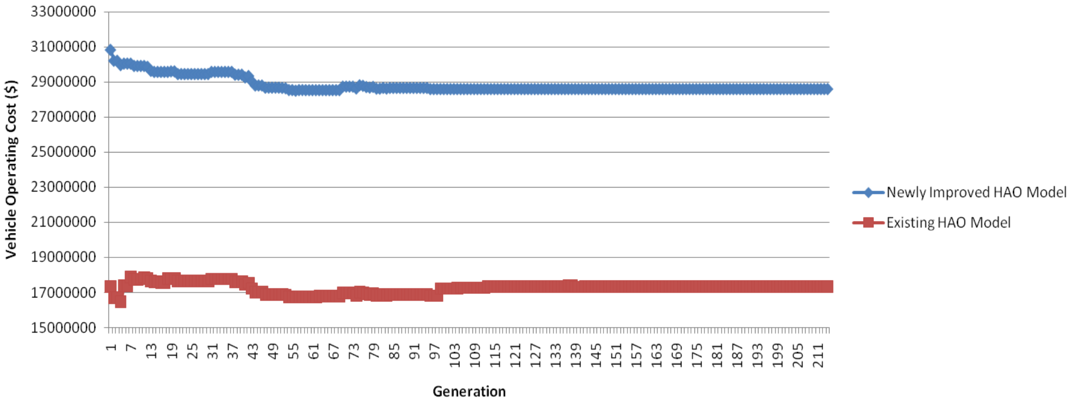


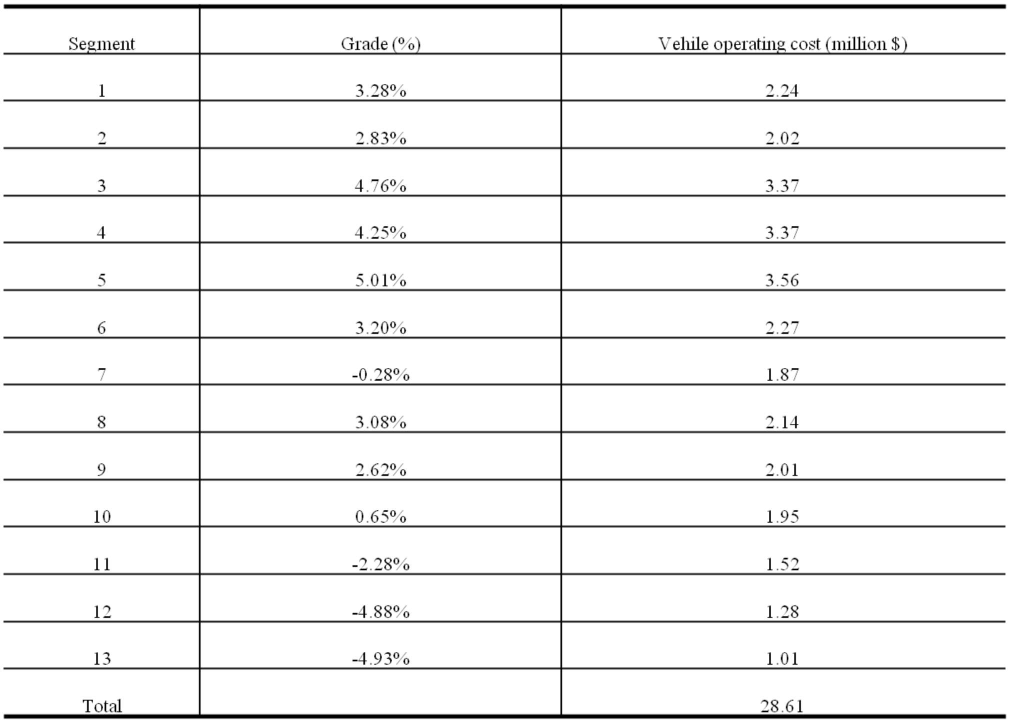
Figure 5-9 Comparison of Vehicle Operating Cost for Existing and New Improved HAO Model

A mannual calculation is performed to test if the vehicle operting cost is estimated correctly by the new model. There are 2 endpoints and 12 IP points, and thus there are13 horiziontal alignment segments conneting these 14 points. The vertical profiles of the 13 segments after searching for 300 generations are given in Table 5-3.

IP	Z Value (feet)	Difference in Z (feet)	Horizontal Alignment Length (feet)	Grade (%)
Start point	754.5932			
		56.7443	1730.177945	3.28%
1	811.3375			
		47.4798	1676.801017	2.83%
2	858.8173			
		72.9412	1532.882308	4.76%
3	931.7585			
		65.6168	1543.759402	4.25%
4	997.3753			
		76.3837	1523.792702	5.00%
5	1073.759			
		49.333	1541.480863	3.20%
6	1123.092			
		-4.326	1535.27237	-0.28%
7	1118.766			
		47.265	1535.085125	3.08%
8	1166.031			
		40.251	1533.678483	2.62%
9	1206.282			
		10.854	1675.609695	0.65%
10	1217.136			
		-47.478	2085.542761	-2.28%
11	1169.658			
		-74.881	1535.161689	-4.88%
12	1094.777			
		-94.121	1908.985621	-4.93%
End point	1000.656			

Table 5-3 Average Grade of Each Segment

Other varialbes required for calculating the vehicle operating cost are listed in Table 5-1. The operating costs of each segment are calucated based on equations 3.27 and 3.28. The results are given in Table 5-4. As Table 5-4 shows, the total vehicle operating cost calculated manually is the same as the output of the HAO model, which is $28.61 million. This result indicates that the vehicle operating cost function in the newly improved HAO model is coded correctly.



Segment	Grade (%)	Vehile operating cost (million $)
1	3.28%	2.24
2	2.83%	2.02
3	4.76%	3.37
4	4.25%	3.37
5	5.01%	3.56
6	3.20%	2.27
7	-0.28%	1.87
8	3.08%	2.14
9	2.62%	2.01
10	0.65%	1.95
11	-2.28%	1.52
12	-4.88%	1.28
13	-4.93%	1.01
Total		28.61

Table 5-4 Manual Calculation of the Vehicle Operating Cost

The environmental cost is estimated by calculating the vehicle emissions cost. The pollutants considered here are NO_x, CO, SO_x and PM_{10}. The emission cost is $38.49 million, which constitutes 16.5% of the total cost. This magnitude indicates that the environmental cost cannot be neglected in highway alignment optimization.

If the vehicle emission is incorporated in the objective function, then the HAO model is expected to optimize the highway alternatives with less emission cost. A test is performed to examine the effects of environmental cost component on highway alignment and emission reduction. Two scenarios are designed. The environmental cost is included in the objective function in the first scenario, while it is excluded in the section scenario. The cost in the first scenario can be got form the model output directly, and is calculated manually based on the equations 3.34 and 3.35 in the second scenario. Table 5-5 shows the comparison between the environmental costs in the two scenarios. It can be seen from the Table 5-5 that the emission cost increases from $38.49 million to 41.95 million, with an increase rate is 9%. Therefore, if the environmental cost component is designed and coded correctly, the incorporation of environmental cost in the objective function is able to yield alignment solutions with reduced vehicle emissions.

Environmental Cost (million dollars)	Scenario 1	Scenario 2	Changes
	38.49	41.95	9%

Table 5-5 Effects of Environmental Cost Component on Environmental Cost Reduction

In addition, the horizontal penalty, length of vertical curve penalty and gradient penalty cost are all zero, which means the optimized alignment satisfies all the design constraints, which are horizontal curvature, gradient and minimum length of vertical curves (vertical sight distance).

The right-of-way cost is estimated by multiplying the area (feet^2) of land use taken by alignment with the unit cost (\$/ft^2). The fraction of area taken by alignment of each land use parcel is calculated in the GIS module. Most alignment segments are located in residential areas, and avoid floodplains and protected areas. Table 5-6 presents the areas of different land use types impacted by the alignment and the corresponding right-of-way cost.

	Area (feet^2)	Cost ($)
Total	723358.12	1753506.26
Residential	303325.02	1003452.00
Protected Forest	420033.10	750054.26
Commercial	0	0
Cropland	0	0
Floodplains	0	0
Deciduous Forest	0	0

Table 5-6 Area taken by Alignment and the Right-of-way Cost

It is also noted that among all the cost components, the user cost and environmental cost together account for almost 39% of the total cost. However, most highway agencies only consider the agency cost, without considering the user and environmental cost in the highway construction projects. Therefore, the choice of an appropriate objective function is very important. The goodness test for the best solution is given in Section 5-4.

5.3 Goodness Test for the Best Solution

Although both the horizontal and vertical alignment found by the proposed HAO model seem reasonable, the goodness of the solution should still be tested and demonstrated, since a genetic algorithm cannot guarantee finding the globally optimal solution. Therefore a statistical experiment is designed to test the goodness of the best solution found by the HAO model. The experiment is initiated by generating solutions randomly, and calculating their objective values. 20,000 observations are representative and independent of each other. The best object value is \$1,053 million, while the worst solution yields an objective value of \$34,259 million. The sample mean is \$9,566 million and the standard deviation is \$5,127 million. The descriptive statistics and the distribution of random sample are presented in Table 5-7, and Figure 5-10. The optimized solution found by the proposed algorithm, which is \$233.91 million is also shown in Figure 5-10.

Variable	Min	Max	Mean	Standard Deviation
Random Search	1,053	34,259	9,566	5,127
Model	233.91			

Table 5-7 Comparison of Solutions Found by Random Search and HAO Model (unit: \$ million)

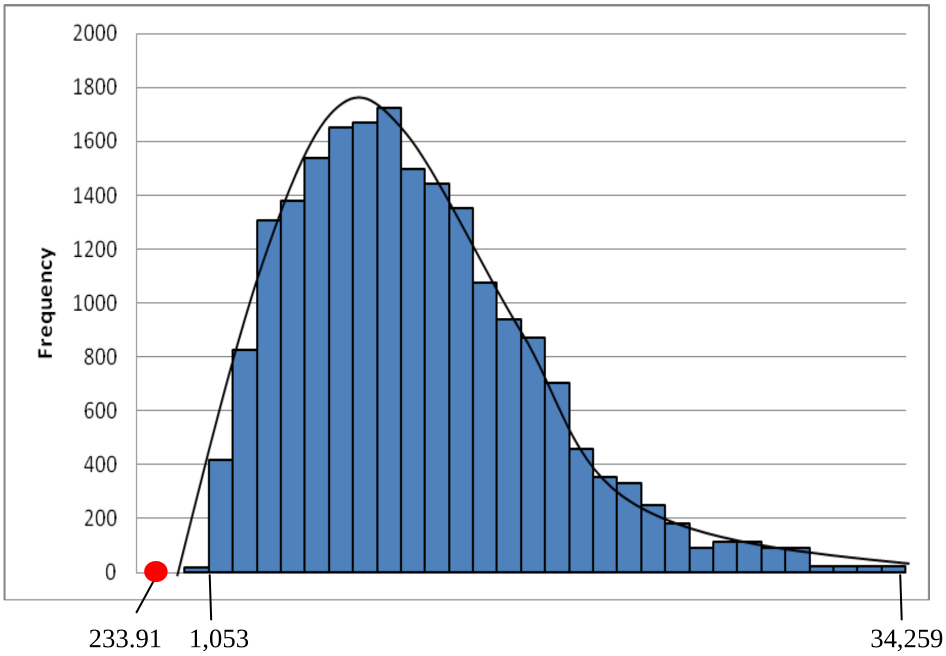


Figure 5-10 Distribution of Objective Function Values (unit: $ million)

The results show that the offset (minimum value) of the sample distribution is $1,053 million, which is much higher than the best solution ($233.91 million) found by HAO model. It indicates that the optimized solution found by the proposed algorithm is remarkably good when compared to other possible results.

5.4 Sensitivity Analysis

5.4.1 Sensitivity to Model Objective Function

This analysis tests how the HAO model satisfies different objective functions, in order to evaluate the effects of each cost component on alignment optimization results. Three scenarios are designed to evaluate how different cost components affect optimization results. The input parameters for all three scenarios are the same. The three scenarios are:

Scenario 1: $C = C_{\text{right-of-way}}$

Scenario 2: $C = C_{\text{agnecy}}$

Scenario 3: $C= C_{\text{agency}} + C_{\text{user}} + C_{\text{environment}}$

It is expected that the algorithm with only right-of-way cost as the objective function generates the alignment which is able to avoid all the areas with high land costs. However, the alignment might also cross the high elevation area, with large gradient and sharp curves since the agency costs and user costs are excluded in the objective function. The alignment using agency cost as objective function is expected to have sharper curves and larger gradient to minimize earthwork cost and length-dependent cost than the one generated combining agency cost and user cost in the objective function. Moreover, the road is expected to be very close to the ground to decrease earthwork cost. The outputs of Scenario 3 should have smoother and longer curves since the HAO model seeks to reduce all the user costs, and most user costs, e.g. vehicle operating cost, can be decreased with smaller gradients and a smoother alignment.

The horizontal alignments are presented in Figure 5-11, while the vertical alignments are shown in Figure 5-12. According to Figure 5-11, Alignment 1 succeeds in skirting all the high land cost areas, while Alignments 2 and 3 affect some high-cost areas. However, Alignment 1 is the longest one. A possible reason could be that agency and user costs are excluded in Scenario 1. Hence the model fails to reduce the alignment length, in order to decrease the agency and user costs. It also can be seen from Figure 5-11 that the Alignment 3 is smoother than Alignments 1 and 2 since a smoother alignment and longer curves are able to decrease the user costs, while in Scenario 2 the algorithm only considers the agency cost, and generates sharp curves and steep gradient to only reduce earthwork cost and length-dependent cost.

Figure 5-12 shows the three vertical alignments. The vertical alignment is improved successfully after running for 300 generations in both Scenarios 2 and 3. However, there is still considerable difference between the ground and the alignment elevation in Scenario 1 since the objective function in Scenario 1 is not able to consider the topography of the study area, but only the land values. Both vertical Alignments 2 and 3 adhere closely to the ground, in order to minimize the earthwork cost. The alignment results conform to expectations and reveal no real surprises. This sensitivity analysis shows that decision makers should consider using different objective functions or weighting factors in one objective function to reflect different concerns. For instance, even if Alignment 1 has the longest road, if the decision maker is more concerned with minimizing protected land and floodplain impacts, the first alignment should be preferred.

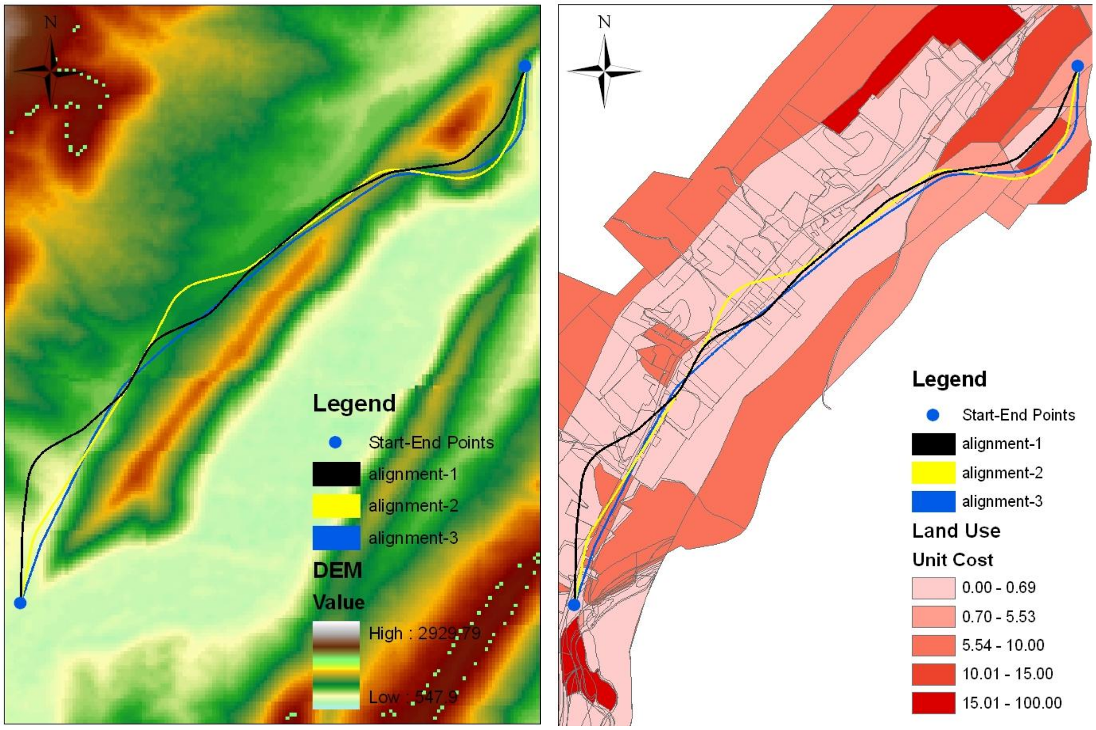


Figure 5-11 Sensitivity of Optimized Horizontal Alignment to Objective Function

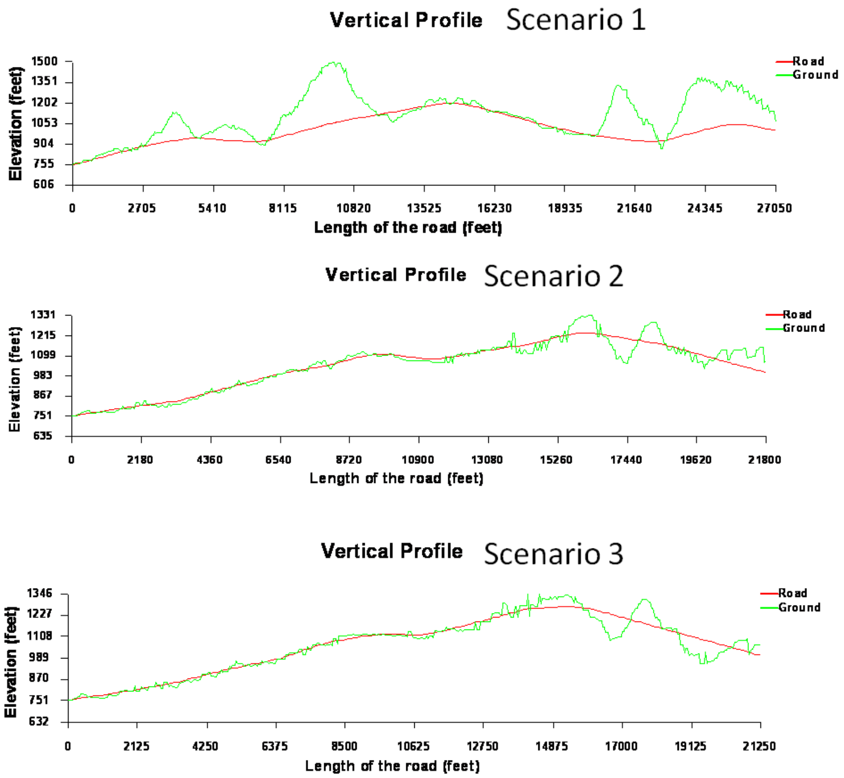


Figure 5-12 Sensitivity of Optimized Vertical Alignment to Objective Function

5.4.2 Sensitivity to Fuel Price

Beyond the objective functions, the sensitivity to other parameters of the HAO model is also examined. The sensitivity to fuel price is tested in this section to demonstrate the effect of vehicle operating cost on alignment optimization. This is aimed at checking how the proposed alignments vary depending on expected fuel price, as well as to assess the effects of vehicle operating cost on alignment. Three scenarios are designed:

Scenario 1: Fuel prices in Dec. 2010

Scenario 2: Fuel prices in April 2011

Scenario 3: Fuel prices increase by 50% compared with Scenario 2

Fuel price is a user specified input parameter in the HAO model, and it is associated with the vehicle operating cost mainly. The fuel prices in three scenarios are given in Table 5-8. The gasoline price per gallon increases 26.97% from 2.993 $/gallon to 3.8 $/gallon since

Dec. 2010 to April 2011, while the diesel price per gallon grows 25.32% from 3.243 $/gallon to 4.064 $/gallon. The fuel prices in Scenario 3 are set to be increased by 50% compared with the prices in Scenario 2.

	Scenario 1 (December 2010)	Scenario 2 (April 2011)	Scenario 3 (Increased by 50%)
Gasoline ($/gallon)	2.993	3.8	5.7
Diesel ($/gallon)	3.243	4.064	6.096

Table 5-8 Fuel Prices in Three Scenarios

The horizontal alignments for all three scenarios are displayed in Figure 5-13 to investigate the differences in the alignment configuration. All three horizontal alignments are designed in the low land cost areas successfully. Moreover, it can be seen from the left graph in Figure 5-13 that the horizontal alignments are almost the same in a relatively flat area. However, in the hilly area, as highlighted in Figure 5-13, the horizontal alignments with higher fuel price are smoother, with longer curves. The reason for such alignment results is that sharper curvatures increase the fuel consumption. The vehicle operating cost increases with higher fuel price. The algorithm therefore seeks to reduce the vehicle operating cost by designing smoother and longer curves, at the expense of increased earthwork.

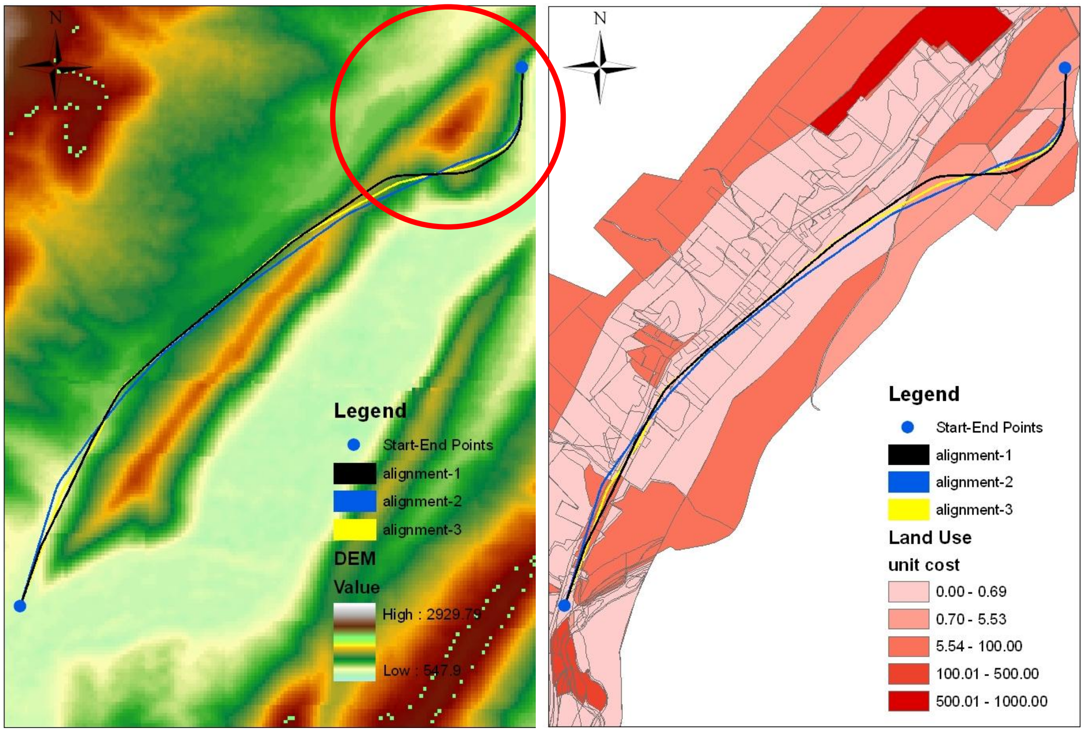


Figure 5-13 Sensitivity of Optimized Horizontal Alignments to Fuel Price

Recall from the table 5-9 and Figure 5-14 that the model outputs for the three scenarios do show a significant difference in objective values. Especially, the vehicle operating cost in Scenarios 2 and 3increase by 14.1%, and 48.6% separately comparing with the operating cost in Scenario 1. Smoother and longer alignments are designed to reduce the operating cost. The alignment lengths keep increasing with higher fuel price. However they requires higher earthwork cost as well. The earthwork cost in Scenarios 2 and 3 increase by 17.5% and 23.1% respectively comparing with the value in Scenario 1. The accident cost and environmental cost don’t show significant differences among all three scenarios. Possible reason is that the smoother curves and grade can reduce both the accident rate and vehicle emissions, however the alignment length increase, which may lead to higher accident rate and emissions as well. The total cost increase with higher fuel prices. Figure 5-14 plots the changes of total cost, vehicle operating cost and earthwork cost over different gasoline prices.

		Scenario 1	Scenario 2	Scenario 3
Total length (feet)		21267.6	21336.1	21531.4
Total cost (million $)		233.90	258.72	275.35
Agency cost (million $)	Right-of-way cost	1.75	1.73	1.72
	Length dependent cost	12.76	12.80	12.92
	Earth work cost	128.53	151.01	158.23
	Location penalty cost	0	0	0
	Horizontal penalty cost	0	0	0
	Length of vertical curve penalty cost	0	0	0
	Gradient penalty cost	0	0	0
	Cross structure cost	0	0	0
	Bridge cost	0	0	0
User cost (million $)	Accident cost	8.64	8.57	8.65
	Travel time cost	15.12	15.06	15.20
	Vehicle operating cost	28.61	32.63	42.51
Environment (million $)	Environmental cost	38.49	36.92	36.21

Table 5-9 Cost Estimated with Different Fuel Prices

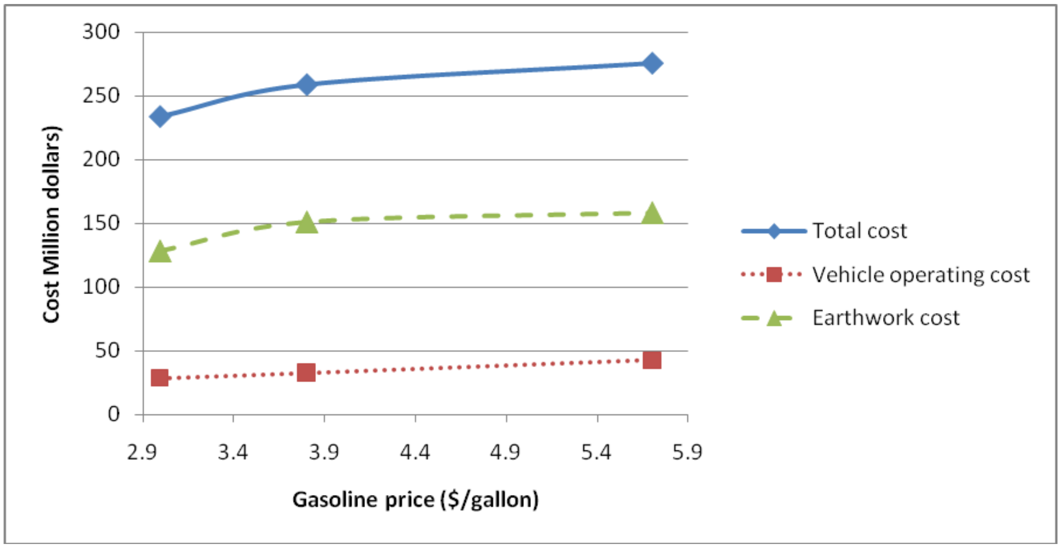


Figure 5-14 Changes of Cost Values with Different Gasoline Prices

5.4.3 Sensitivity to Maximum Allowable Grade

The vertical alignment in hilly area is quite sensitive to the maximum allowable grade. Increases in the maximum allowable grade may decrease the (initial) earthwork cost, but result in shorter vertical curves, which increase fuel consumption and accidents. A sensitivity analysis is designed to test the impacts of different maximum allowable grade on alignment optimization.

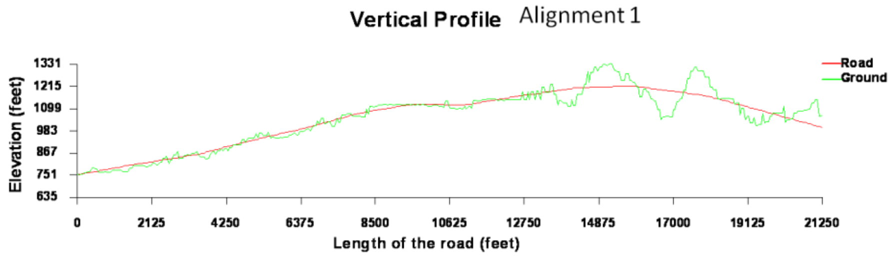
Scenario 1: maximum allowable grade is 5%

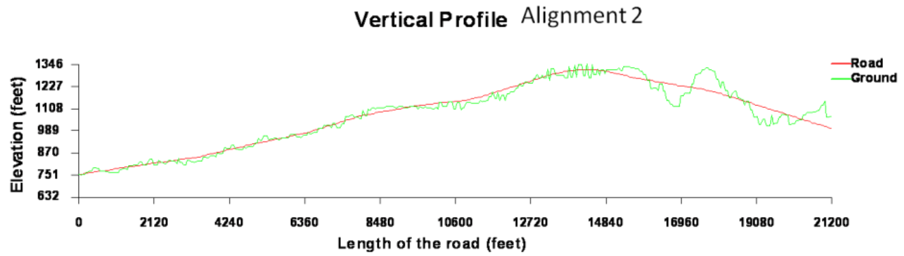
Scenario 2: maximum allowable grade is 6%

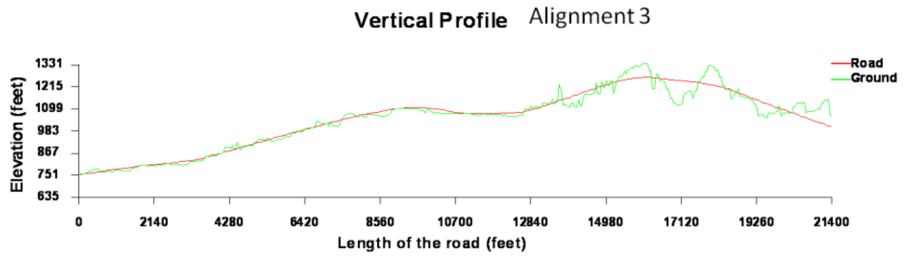
Scenario 3: maximum allowable grade is 7%

Scenario 4: maximum allowable grade is 8%

The vertical alignment results are shown in Figure5-15. It is obvious that the Alignments 3 and 4 have more vertical curvature than Alignments 1 and 2.







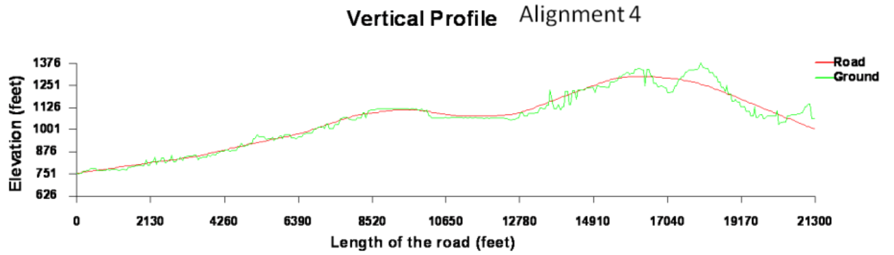


Figure 5-15 Sensitivities of Optimized Vertical Alignments to Maximum Allowable Grade

The objective values estimated with HAO model are presented in Table 5-10. The earthwork cost decreases dramatically with the increases maximum allowable grades. It drops from $128.53 to $68.59 million when the maximum allowable grade increases from 5% to 8%. The earthwork cost is the dominant cost in this highway alignment optimization case study, and the HAO model always seeks to decrease the earthwork cost. The increase in maximum allowable grade enables HAO model to design alignment alternatives with shorter vertical curves to decrease the earthwork cost dramatically. However, it also increases the accident cost, vehicle operating cost, and environmental cost since vehicle speed and horsepower are related with road grade. According to Table 5-10, the increases in accident, vehicle operating and environmental cost are not significant. However, higher vehicle operating cost and environmental cost are expected in reality, since frequent changes of curves and gradients lead to frequent acceleration, deceleration and changes in speed, which consequently increase the accident rate, fuel consumption and emissions. However, the speed in the current HAO model is assumed to be steady in each segment, and not influenced by the changing road geometric features. Therefore the current HAO model underestimates the accident, vehicle operating and environmental costs. Since there is considerable decrease in earthwork cost, the increases in the maximum allowable grade decrease the total cost in this case study.

Maximum Allowable Grade (%)		5	6	7	8
Agency cost (million $)	Earthwork cost	128.53	85.64	79.56	68.59
User cost (million $)	Accident cost	8.64	9.00	9.53	10.04
	Travel time cost	15.12	15.08	15.24	15.15
	Vehicle operating cost	28.61	29.97	30.72	31.64
Environmental cost	Environmental	38.49	40.32	41.12	42.55

(million $)	cost				

Table 5-10 Breakdown of Cost Calculated with Different Allowable Maximum Grade

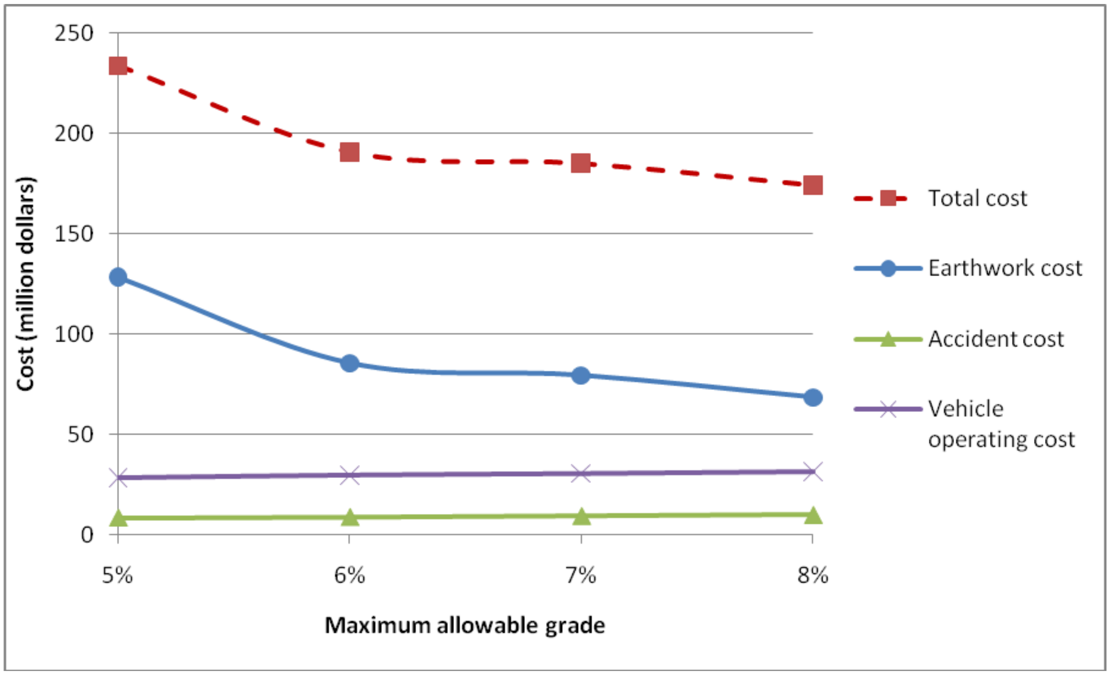


Figure 5-16 Changes of Cost Values with Different Maximum Allowable Grade

Chapter 6: Conclusions and Recommendations

This chapter presents the findings of this research, its conclusion, and some recommendations for future research.

6.1 Summary

The contribution made in this research and the results obtained can be summarized as follows:

6.1.1 Lane Width Optimization

Lane width is one of the most important design parameters and is associated with several cost components in the HAO model. The original HAO model had no ability to optimize the lane width. Newton's method and a finite difference method are employed to find the appropriate lane width, in order to minimize the total cost. For the given inputs in our case study, the optimization algorithm optimizes lane width at 10.6 feet, which yields the minimum total cost of $210.93 million. However, it should be noted that this method cannot guarantee finding the global optimum, and the choice of initial value affects the convergence rate.

6.1.2 More Accurate Operating Cost Estimation

The vehicle operating cost prediction is revised in the new HAO model. The operating cost in the original HAO model only included fuel consumption. However, according to AASHTO, it consists of fuel consumption, maintenance, tire wear and vehicle depreciation. The later three cost components are now incorporated in the vehicle operating cost. Moreover, the fuel consumption in the original HAO model is estimated based on the vehicle speed and road grade. This research improves the fuel consumption prediction by calculating the resistance force and horsepower for running vehicles, and then estimating the fuel consumption based on the fuel consumption rate per horsepower hour. The fuel consumption model is a function of several road geometric features. The relation allows this research to access the impacts of fuel consumption costs for various designs of alignments, as well as to optimize design features in order to minimize fuel consumption cost.

6.1.3 Consideration of Environmental Impacts

The environmental cost in the original HAO model is defined as the cost of taking the environmentally sensitive areas, e.g. floodplain, wetland and historical properties for highway alignment. However, many other environmental impacts, e.g. air pollution, are excluded in the environmental impacts study. This research assesses the environmental cost in terms of vehicle emissions. Three major emission pollutants are studied, which are NO_X, CO, SO_X and PM_{10}. The emission rates are specified per horsepower per hour. The required horsepower for running vehicles is calculated based on vehicle characteristics and road geometry. The environmental cost constitutes 16.46% of total highway alignment cost in the case study, which is a non-negligible component in highway alignment optimization. (The analysis period is 5 years, with 5% annual AADT increase rate, and 3 % interest rate.)

6.2 Conclusions

6.2.1 Alignment Optimization Results

The objective function for the highway alignment optimization problem consists of agency cost, user cost and environmental cost. The percentage of each cost component varies depending on the study area and input parameters. The case study in Chapter 5 is located in a mountainous area. Hence, the earthwork cost is the dominant cost, which accounts for about 55% of total cost. The user cost constitutes 22.4% of total cost, among which the vehicle operating cost is more than half. In terms of the environmental impacts, the vehicle emissions cost $38.49 million, which is 16.46% of total cost. The road is optimized with small gradients and smooth curves to decrease the user cost and environmental cost. The horizontal alignment in the case study is able to avoid areas with high land use cost and high elevation. Moreover, the vertical alignment result shows that the alignment is close to the ground to minimize earthwork cost. Overall the HAO model yields reasonable and unsurprising results.

6.2.2 Sensitivity Analysis

Three different sensitivity analyses are performed to examine the behavior of the newly improved HAO model. In the first sensitivity analysis, three scenarios are designed with different objective functions. The alignment which only considers the right-of-way cost is able to avoid the expensive areas successfully, but fails to yield an acceptable vertical alignment. The test using the agency cost as the objective function generates a good vertical alignment that closely adheres to the ground elevation. However, the horizontal alignment consists of relatively sharp curves in order to minimize the earthwork cost. Smoother horizontal and vertical curves are designed when both agency cost and user cost are combined in the objective function. This sensitivity analysis indicates the model is quite sensitive to the objective function, and yields reasonable results with different objective functions. Moreover, it should be noted that an appropriate objective function is critical for optimizing alignments in various situations.

Effects of different fuel prices are demonstrated in the second sensitivity analysis. In order to reduce the impacts of fuel price, both horizontal and vertical alignments are designed to be smoother. However, such an alignment increases the earthwork cost. Since the earthwork cost is the dominant cost, the increase in earthwork cost raises the total cost. Overall, the alignment outputs are as expected and show no unexplainable surprises.

Maximum allowable grade is one of the most influential design parameters for alignments in mountainous areas. The third sensitivity analysis explores the alignment changes after increasing the maximum allowable grade from 5% to 8%. The model outputs match expectations. Higher allowable grade reduces earthwork cost. However, it results in higher user costs. The optimization results show the total cost is decreased since the earthwork cost, which is the dominant cost, drops significantly from 128.53 to 98.59 million dollars.

6.3 Recommendations for Future Research

Although the new HAO model performs well in optimizing highway alignments, it can still benefit from various improvements in order to become more realistic and flexible. Possible future enhancements are listed below.

6.3.1. Lane Width Optimization

The lane width optimization problem is solved by using Newton’s method and finite difference methodology in this thesis. The limitation of such methodology is that adequate observations are required to identify the appropriate initial value. However, such calculation is time consuming. Moreover, the search for optimal lane width using Newton’s method and finite difference is repetitive and it cannot guarantee the result is global optimal. A more efficient search method or incorporating the lane width optimization into the alignment optimization using genetic algorithm should be considered in future research.

6.3.2. Environmental Cost Estimation and Analysis

The environmental cost in this research refers to the vehicle emissions cost. It is suggested to also consider the dispersion of the pollutants, and their effects on human health and society. Besides the air pollution, other environmental impacts, such as water pollution and noise, should be included in future research.

6.3.3 Traffic Considerations in Highway Alignment Optimization Model

The traffic volume data has been incorporate in the cost functions, in order to access its impacts on highway alignments. However, more detailed traffic information is required for accurate user cost estimation. For example, the horsepower is a function of vehicle speed, and the speed is affected by the continuously changed road geometric features. However, the speeds in the current HAO model are steady on each segment, which affects the accuracy of horsepower, and consequently decrease the accuracy of fuel consumption and emission. A simulation-based approach may be incorporated in the proposed HAO model for more precise user cost estimation. Moreover, it may benefit the analysis of the geometric effects on vehicle speed. However, one cannot neglect the expected extensive computing load.

APPENDIX A

Converting the 1975 value of travel time per hour to 2010 dollars

Year	CPI [*]	Adjusted CPI	Motorcar ($/mi)	2A Truck ($/mi)	3-S2 Truck ($/mi)
1975	53.825	0.246813756	3	7	8
2010	218.0794167	1	12.15491407	28.36146617	32.4131042

Converting the 2003 vehicle maintenance cost per mile to 2010 dollars

Year	CPI (vehicle maintenance)[*]	Adjusted CPI	Motorcar ($/mi)	2A Truck ($/mi)	3-S2 Truck ($/mi)
2003	195.5916667	0.788822389	3.2	3.7	10.5
2010	247.954	1	4.056679988	4.690536236	13.31098121

Converting the 2003 vehicle tires costs per mile to 2010 dollars

Year	CPI (tires)	Adjusted CPI	Motorcar ($/mi)	2A Truck ($/mi)	3-S2 Truck ($/mi)
2003	101.7166667	0.823408937	0.9	1	3.5
2010	123.5311667	1	1.093017041	1.214463379	4.250621825

Converting the 2003 vehicle depreciation costs per mile to 2010 dollars

Year	CPI (new and used vehicle)	Adjusted CPI	Motorcar ($/mi)	2A Truck ($/mi)	3-S2 Truck ($/mi)
2003	96.49166667	0.993231205	6.2	7.0	8.0
2010	97.14925	1	6.242252526	7.047704465	8.054519389

---

[*] CPI data is accessed from Bureau of Labor Statistics website http://www.bls.gov/cpi

[*] CPI data is accessed from Bureau of Labor Statistics website http://www.bls.gov/cpi/#data, in March 2011

REFERENCES

AASHTO (1997a), "*A Manual on User Benefit Analysis of Highway and Bus-Transit Improvements*", American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO (1997b), "*AASHTO Maintenance Manual for Roadways and Bridges*", American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO (1997c), "*A Policy on Geometric Design of Highways and Streets*", American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO (2004), "*A Guide for Achieving Flexibility in Highway Design*", Washington, D.C.

Martens, M., Comte, S., and Kaptein, N. (1997), "*The Effects of Road Design on Speed Behavior: A Literature Review*", Contract No RO-96-SC.202

Bureau of Public Roads (1964), "*Traffic Assignment Manual*", U.S. Dept. of Commerce, Urban Planning Division, Washington D.C.

CA DOT (1999), "*California Life-Cycle Benefit/Cost Analysis Model*", California Department of Transportation

Chen, J.F, Lee, Y.S. (2006), "*Model for Three Dimensional Highway Alignment*", Journal of Transportation Engineering, Vol. 132, No. 12, pp. 913-920

Chesher, A. and Harrison R. (1987), "*Vehicle Operating Costs – Evidence from Developing Countries*", the International Bank for Reconstruction and Development, The World Bank, Washington, D.C.

Chew, E.P., Goh, C.J., Fwa, T.F. (1989), "*Simultaneous Optimization of Horizontal and Vertical Alignments for Highways*", Transportation Research Part B 23, pp.315 – 329.

EPA (1995), "*Compilation of Air Pollutant Emission Factors Volume 1: Stationary Point and Area Sources*", United States Environmental Protection Agency

EPA (1997), "*Emission Standards Reference Guide for Heavy-Duty and Nonroad*

Engines", United States Environmental Protection Agency, EPA420-F-97-014

EPA (2009), "*Draft Motor Vehicle Emission Simulator (MOVES) 2009*", United States Environmental Protection Agency, EPA-420-B-09-007

FHWA (1997), "*Flexibility in Highway Design*", Federal Highway Administration, FHWA PD-97-062

FHWA (1998), "*Accident Models for Two-Lane Rural Road: Segments and Intersections*", FHWA-RD-98-133

FHWA (2000), "*Prediction of the Expected Safety Performance of Rural Two-Lane Highways*", FHWA-RD-99-207

Fwa, T.F. (1989), "*Highway Vertical Alignment Analysis by Dynamic Programming*", Transportation Research Record, No.1239, Transportation Research Board, Washington, D.C.

Goh, C.J., Chew, E.P. and Fwa, T.F. (1988), "*Discrete and Continuous Models for Computation of Optimal Vertical Highway Alignment*", Transportation Research Part B, Vol. 22B, No. 6, pp.399-409

Jha, M. K. (2000a), "*A Geographic Information Systems-Based Model for Highway Design Optimization*", Ph.D. Dissertation, University of Maryland, College Park

Jha, M. K. and Schonfeld, P. (2000b), "*Geographic Information System-Based Analysis of Right-of-Way Cost for Highway Optimization*", Transportation Research Record No. 1719, pp. 241-249.

Jha, M.K., and Schonfeld, P. (2000c), "*Integrating Genetic Algorithms and GIS to Optimize Highway Alignments*", Transportation Research Record No. 1719, pp. 233-240.

Jha, M.K. and Schonfeld, P. (2003), "*Trade-offs Between Initial and Maintenance Costs of Highways in Cross-Slopes*" Journal of Infrastructure System, Vol. 9, pp. 16-25

Jha, M. K. and Schonfeld, P. (2004), "*A Highway Alignment Optimization Model using*

Geographic Information Systems", Transportation Research Part A, Vol. 38, No. 6, pp. 455-481

Jong, J. -C. (1998), "*Optimizing Highway Alignments with Genetic Algorithms*", Ph.D. Dissertation, University of Maryland, College Park

Jong, J.C., Schonfeld, P. (2003), "*An Evolutionary Model for Simultaneously Optimizing Three-dimensional Highway Alignment*", Transportation Research Park B, Vol. 37, pp. 107-128

Kang, M.W, Jha, M.K. and Schonfeld, P. (2006), "*Three-Dimensional Highway Alignment Optimization for Brookeville Bypass*", Transportation Research Board 85th Annual Meeting, Washington DC.

Kang, M.W., Schonfeld P, and Jong J. -C. (2007), "*Highway Alignment Optimization through Feasible Gates*", Journal of Advanced Transportation, Vol. 41, No. 2, pp. 115-144

Kang, M. W. (2008a), "*An Alignment Optimization Model for A Simple Highway Network*", Ph.D. Dissertation, University of Maryland, College Park

Kang, M.W., Schonfeld, P. and Yang, N. (2008b), "*Prescreening and Repairing in a Genetic Algorithm for Highway Alignment Optimization*", Computer-Aided Civil and Infrastructure Engineering, Vol. 24, No. 2, pp. 109-119

Kang M. W., Schonfeld P., and Ning Y. (2009), "*Prescreening and Repairing in a Genetic Algorithm for Highway Alignment Optimization*", Computer-Aided Civil and Infrastructure Engineering, Vol. 24, No. 2, pp. 109-119.

Kim, E. (2001), "*Modeling Intersections & Other Structures in Highway Alignment Optimization*", Ph.D. Dissertation, University of Maryland, College Park.

Kim, E., Jha, M. K., Lovell, D. J., and Schonfeld, P. (2004), "*Intersection Cost Modeling for Highway Alignment Optimization*", Computer-Aided Civil and Infrastructure Engineering, Vol. 19, Issue 2, pp. 136-146.

Kim, E., Jha, M. K. and Son B. (2005), "*Improving the Computational Efficiency of Highway*

Alignment Optimization Models through a Stepwise Genetic Algorithms Approach", Transportation Research Part B, Vol. 39, pp. 339-360

Kim, E., Jha, M.K., Schonfeld, P. and Kim, H.S. (2007), "*Highway Alignment Optimization Incorporating Bridges and Tunnels*", Journal of Transportation Engineering, Vol. 133, No. 2, pp. 71-82

Labi, S. (2006), "*Effects of Geometric Characteristics of Rural Two-Lane Roads on Safety*", Joint Transportation Research Program, Paper 238.

Lamm, R., Guenther, A.K., and Grunwald, B. (1994), "*Environmental Impacts on Highway Geometric Design in Western Europe Based on a Geographical Information System*", Transportation Research Record, Vol. 1445, pp. 54-63

Lee, Y., Cheng, J.F. (2001), "*A Model for Calculating Optimal Vertical Alignments of Interchanges*", Transportation Research Part B, Vol. 35, No. 5, pp. 423-445

Lee, Y., Tsou, Y. R. and Lu H. L. (2009), "*Optimization Method for Highway Horizontal Alignment Design*", Journal of Transportation Engineering, Vol. 35, No. 4, pp. 217-224

Lee, Y., and Cheng, J. F. (2009), "*Optimization Method for Highway Horizontal Alignment Design*", Journal of Transportation Engineering, Vol. 135, No.4, pp. 217-224

Liatsis P., Tawfik H.M. (1999), "*Two-dimensional Road Shape Optimization using Genetic Algorithms*", Mathematics and Computers in Simulation, Vol. 51, No. 1-2, pp.19-31

Maidment, D., Tate, E., and Olivera, F. (1998), "*GIS for Floodplain Mapping in Design of Highway Drainage Facility*", Research Report 1738-4

Maji Avijit, and Jha M. K. (2009), "*Optimization Model of Highway Alignment Based on Multi-objective Evolutionary Algorithms*", Journal of Advanced Transportation, Vol. 43, No. 4, pp. 481-504

Mannering, F. L., Kilareski, W. P., and Washburn, S. S. (2004), "*Principles of Highway*

Engineering and Traffic Analysis", 3rd Edition, John Wiley & Sons, Inc

Menn, C. (1990), "*Prestressed Concrete Bridges*", Springer-Verlag, Wien.

National Cooperative Highway Research Program (NCHRP-a), "*Introduction To StratBENCOST — Strategic Decision Support Tool for Highway Planning and Budgeting*", NCHRP Project 2-18(4), Transportation Research Board, Washington DC

OECD (1973), "*Optimization of Road Alignment by the Use of Computers*", Organization of Economic Co-operation and Development, Paris

Parker, N.A., (1977), "*Rural Highway Route Corridor Selection*", Transportation Planning and Technology, Vol. 3, pp. 247 – 256.

Parsons Transportation Group (2003), "*Relationship between Lane Width and Speed, Review of Relevant Literature*", prepared for the Columbia Pike Street Space Planning Task Force

Polus, A., Liveh,M., and Craus, J. (1984), "*Effect of Traffic and Geometric Measure on Highway Average Running Speed*", Transportation Research Record 960, TRB, National Research Council, Washington, D.C., pp. 34-39

RITA, (2011), "*National Transportation Statistics*", Bureau of Transportation Statistics, U.S. Department of Transportation

Tsunokawa K. and Hoban C. (1997), "*Roads and the Environment A Handbook*", The World Bank, Washington, D.C.

Vey, A.H. & Ferreri, M.G. (1968), "*The Effect of Lane Width on Traffic Operation*", Traffic Engineering, Vol. 38, No. 8, pp. 22-27.

Vogt, A., Bared, J.G.(1998), "*Accident Models for Two-lane Rural Roads: Segments and Intersections*", Publication No. FHWA-RD-98-133

Yagar, S. and Aerde, M. V. (1983), "*Geometric and Environmental Effects on Speed of 2-*

Lane Highways", Transportation Research Part A, Vol. 17, No. 4, pp. 315-325

Zegeer, C.V., Stewart, R., Council, F.M., Reinfurt, D.M., and Hamilton, E. (1992), "*Safety Effects of Geometric Improvements on Horizontal Curves*", Transportation Research Record 1356, TRB, National Research Council, Washington, D.C., pp. 11-19.