3D Highway Alignment Optimization for Brookeville Bypass

by

Dr. Paul Schonfeld, Professor
Min Wook Kang, Graduate Assistant

Department of Civil Engineering
University of Maryland at College Park

and

Dr. Manoj Kumar Jha, Assistant Professor

Department of Civil Engineering
Morgan State University

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Executive Summary

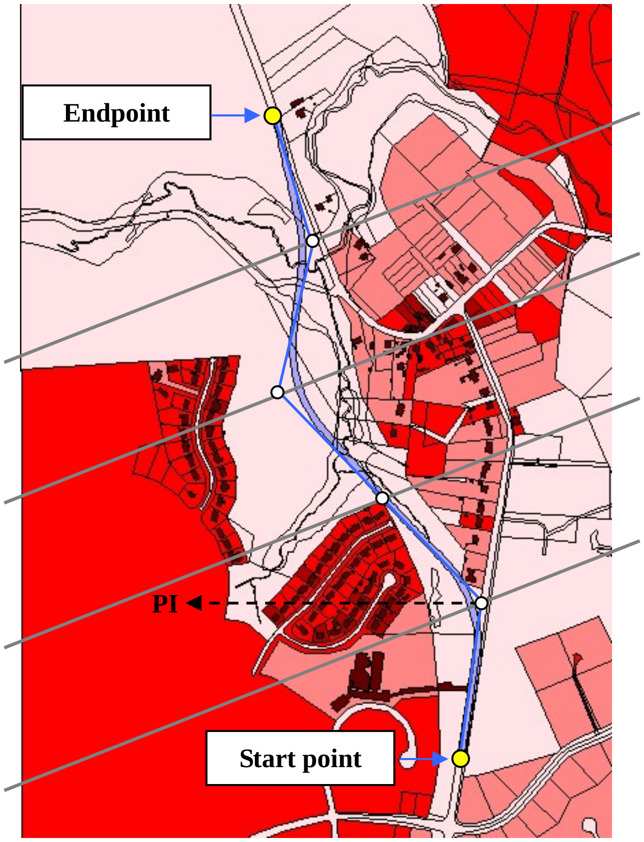
Research Objective and Scope

This study applies the previously developed Highway Alignment Optimization (HAO) model to the MD 97 Bypass project in Brookeville, Maryland. The objective of this study is to demonstrate the applicability of the HAO model to a real highway project with due consideration to issues arising in real world applications. In this report, we demonstrate the sensitivity of optimized alignments to various user-specified input variables, such as the number of points of intersection (PI's), tradeoff values for the environmental sensitive areas, grid size for elevation, design speed, and cross-section spacing. We expect that the optimized results from the HAO model will be compared with those obtained through conventional manual methods by the Maryland State Highway Administration (SHA). In addition, this report should be helpful in familiarizing readers with the nature and capabilities of the HAO model.

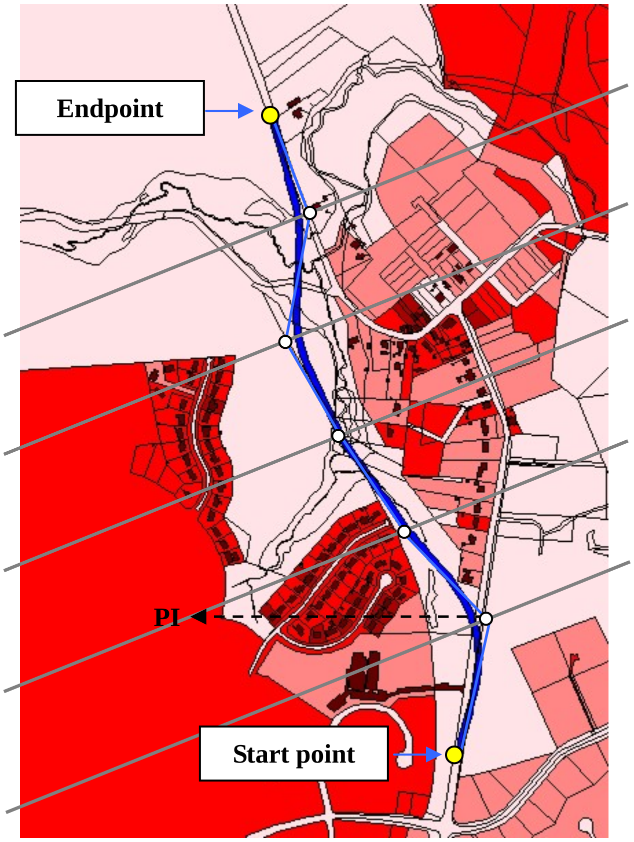
Result Summary for Optimized Alignments

Through the HAO model application to the Brookeville Bypass project, its practical applicability to real highway projects was ensured by obtaining specific road design information for optimized alignments. The analysis results indicate that (1) alternatives which reflect various user preferences can be found easily with the HAO model and (2) the HAO model provides practical results for highway engineers to use in identifying and refining their design. Figure 1 presents optimized alignments obtained by specifying four to seven PI's, but otherwise similar input data.

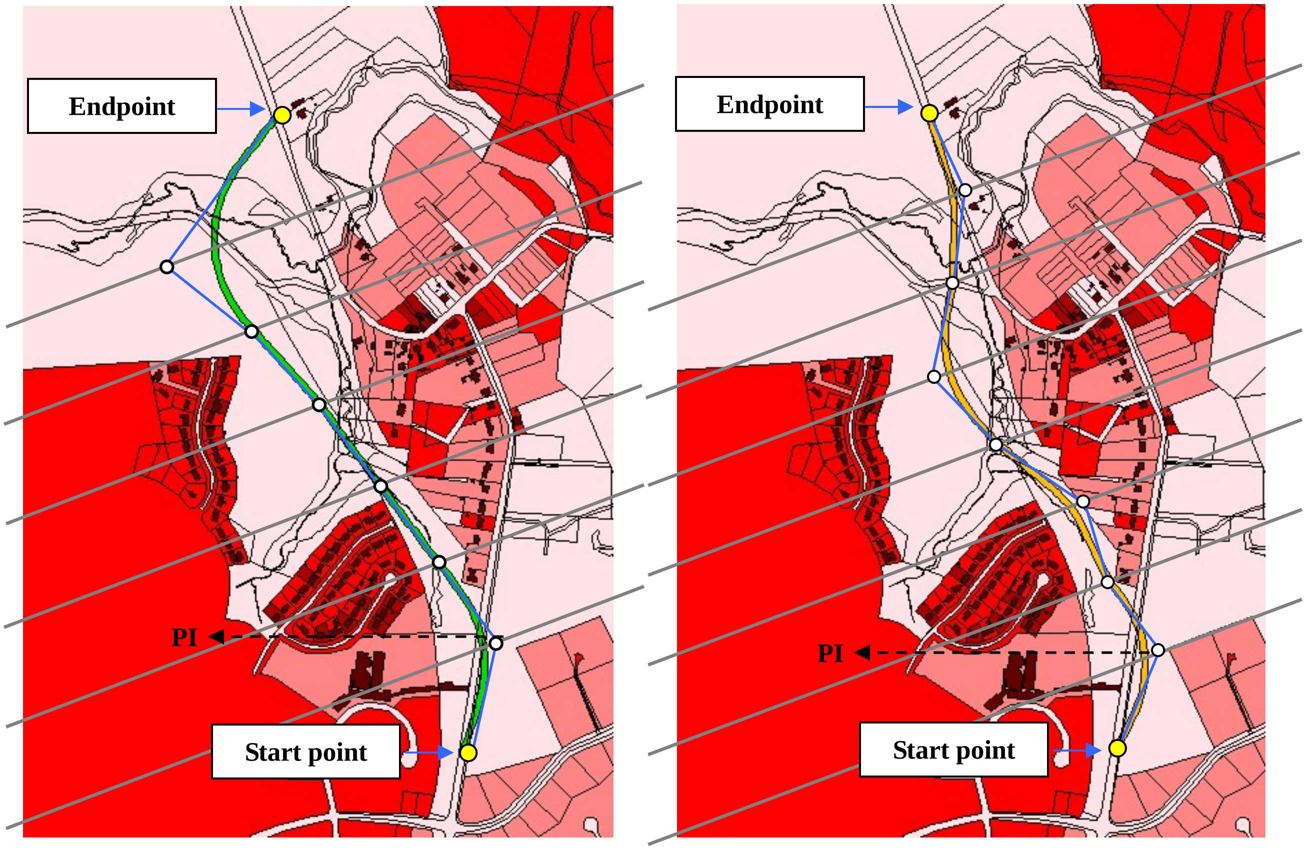
As shown in Figure 1, all four alternatives mainly occupy Montgomery County's reserved area and Reddy Branch Park as hardly affecting Longwood Community Center, wetlands, and properties in Brookeville Historic District. The start and end points of the proposed alignments are located on MD 97 (Georgia Avenue) in Brookeville. The X, Y, Z coordinates of the start and end points are (1295645, 548735, 470), (1294512, 552574, 407) respectively and the shortest distance between these two points is about 4,000 feet. The proposed alignment is assumed to be a two lane road with 40 feet width (11 feet per lane and 9 feet per shoulder, as shown in Figure 13) with 50 mph design speed. The cross-section spacing, which determines the precision of earthwork computations, is assumed to be 40 feet. The only crossing type considered for the proposed alignment with the existing Brookeville Road was grade separation. The input data values used for the four optimized alignments in Figure 1 as well as most others are summarized in Table 14. Tradeoff land values, which are used to represent the relative values of different types of land use characteristics in the study area, are presented in Table 13.



(a) Optimized Alignment A with 4PI's



(b) Optimized Alignment B with 5PI's



(c) Optimized Alignment C with 6PI's **(d) Optimized Alignment D with 7PI's**

Figure 1. Optimized Alignments with Different Number of PI's

Table 1 summarizes the results for the four optimized alignments (A to D) in Figure 1 and the optimized alignment E, which is presented in Figure 2. The search was conducted over 300 generations, during which about 6,500 alignments were evaluated for each optimized alignment. Thus, to obtain the one optimized alignment, approximately 22 alignments were evaluated in each of 300 generations. A desktop PC Pentium IV 3.0 GHZ with 512 MB RAM were used to run the model and evaluate the possible alignments. It took about 4.5 to 6.5 hours of computation time for 300 generations because the Brookeville study area is fairly complex and has numerous properties (about 650 geographical entities).

Table 1. Result Summary for Optimized Alignments A to E

Optimized alignment		**A**	**B**	**C**	**D**	**E**
Number of PI's		4	5	6	7	5
Initial construction costs ($)		5,148,404	4,629,708	5,956,983	5,220,679	7,436,002
Length of the optimized alignment (ft)		4,251.88	4,194.00	4,499.26	4,314.88	5,099.88
Computation time (hr)		4.41	4.68	4.95	5.01	6.07
Environmental impact						
Socio-economic resources	Affected residential area (sq.ft.)	305.96	0	0	0	5.56
	Residential relocations (no.)	0	0	0	0	0
	Affected Community Center (sq.ft.)	152.38	0	0	0	134.23
	Affected properties in Historic Districts (sq.ft.)	0	0	0	0	0
	Affected Montgomery County reserved area (sq.ft)	4,1896.1	45,295.9	45,286.0	45,260.0	42,522.0
	Affected existing roads (sq.ft)	39,152.1	29,609.1	17,037.6	25,227.4	36,012.8
Natural resources	Affected wetlands (sq.ft)	0	0	0	0	0
	Affected floodplains (sq.ft)	23,259.8	17,260.3	16,689.7	14,883.5	21,040.3
	Affected streams (sq.ft)	690.5	777.6	634.9	610.7	697.0
	Affected parkland in Historic Districts (sq.ft)	11,662.2	20,109.9	9,231.7	18,336.5	5,492.1
	Affected parkland (sq.ft)	35,061.6	24,882.6	55,461.0	30,658.7	57,228.1

As shown in Table 1, none of the five alternatives requires any residential relocations or significantly affects environmentally sensitive areas. In addition, the first four alternatives, which have the same start and end points, have similar alignment lengths. Although all five alignments seem acceptable, optimized alignment B seems the most preferable since its initial construction cost is the lowest ($ 4,629,708) of the five and it hardly affects the sensitive areas. It should be noted here that the initial construction cost in Table 1 is underestimated. The reason is that the initial construction cost mainly consists of right-of-way, length-dependent, bridge, and earthwork cost; i.e., other costs required in road construction (such as landscape architecture cost, traffic signal strain poles cost, etc.) and other contingency costs are not included. Other detailed model outputs for optimized alignment B (such as costs breakdown of total, earthwork cost per station point, and coordinates of the alignments), which are automatically recorded with during program runs, are introduced in APPENDIX C.

The input data values in Table 2, which were used for optimized alignment B, were employed as baseline inputs (the most preferable among the four alignments) to conduct sensitivity analyses regarding other major factors (such as grid size and design speed). Based on the baseline inputs, different values for each factor were applied for each sensitivity analysis. Detailed results for such analyses are presented in Chapter 3.4.

The sensitivity analysis regarding grid size indicates that the HAO model may produce unreliable earthwork estimates if the grid sizes are too large, since terrain elevation estimates may then be too rough. The analysis of sensitivity to design speed shows that the HAO model satisfies horizontal design constraints very well and creates longer smooth horizontal curved sections for higher design speeds. In analyzing sensitivity to tradeoff values for environmentally sensitive areas, parklands were considered in an example case aimed at reviewing how the importance of the sensitive areas affects alignments. To do this, we used the penalty cost as the tradeoff value (as discussed in Chapter 2.4). As expected, the results shows that the parklands area affected by the proposed alignments increases as the penalty on the parklands decreases, given that the penalty on the other sensitive areas remains fixed.

Figure 2 presents optimized alignments B and E. As stated previously, optimized alignment B was obtained with the baseline input values from Table 2. The other optimized alignment, E, was obtained by changing the baseline coordinates of the endpoint to (1295645, 548735), while keeping the other input values fixed.

Other optimized alignments, which were obtained through the analyses of sensitivity to various major input parameters, are shown in Figures 21 through 27.

Table 2. Baseline Values for Major Input Parameters

Key factors	Baseline value
Number of PI's	5
Grid size	40 ft * 40 ft
Design speed	50 mph
Cross-section spacing	40 ft
Tradeoff value for the parklands	$100 \times X$[1]
Start and End points (X, Y)	Start point: 1295645, 548735
	Endpoint: 1294512, 552574
Unit length-dependent cost	400 $/ft
Crossing type with the existing roads	Grade Separation

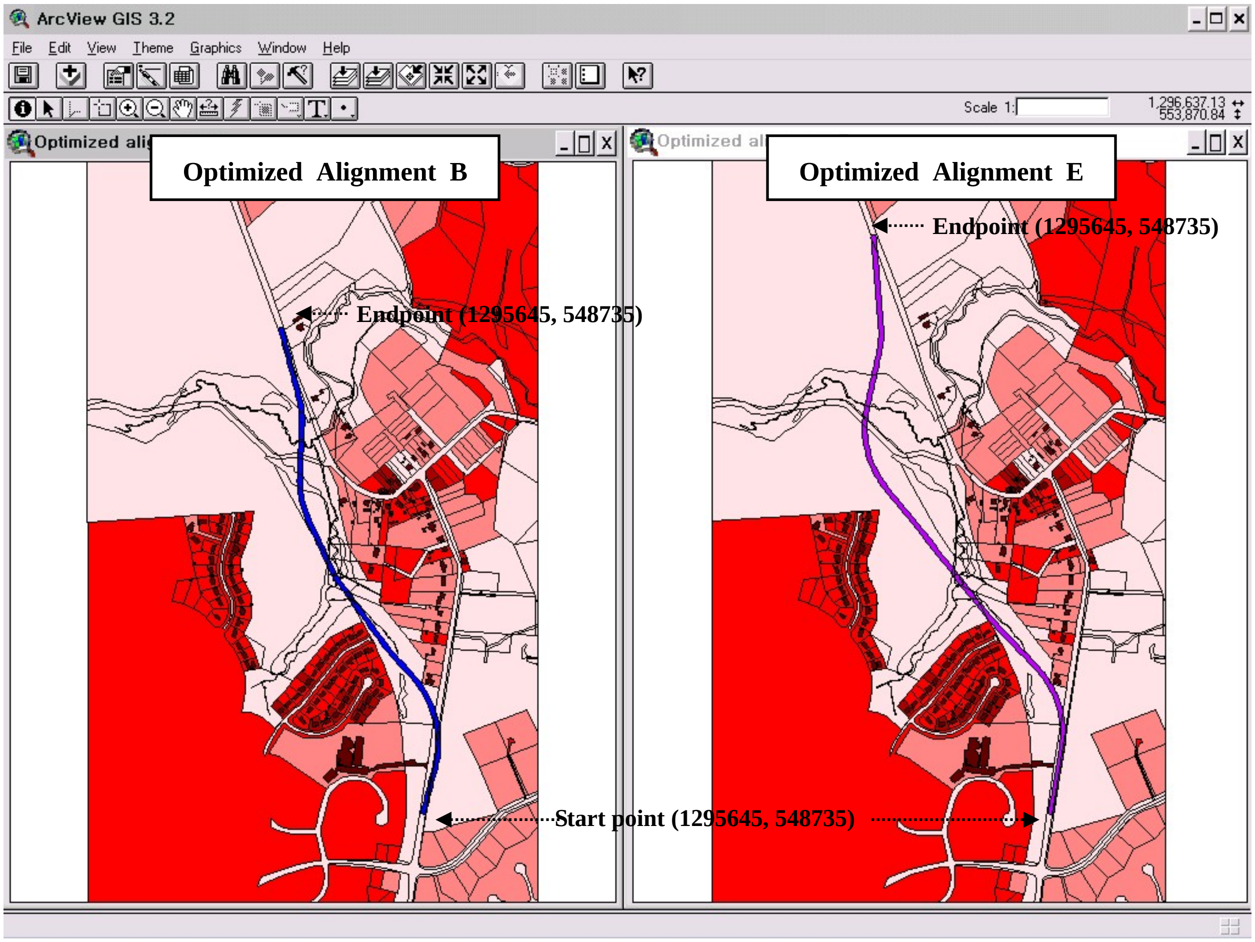


Figure 2. Two Different Optimized Alignments with Different Endpoints

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[1] X=14 $/sq.ft.: Maximum unit cost for land in the Brookeville study area

Recommendations

Throughout the HAO model application to the Brookeville Bypass project, it has been shown that the HAO model can quickly evaluate various alignments which reflect various user preferences, and optimize with precision. Furthermore, some desirable enhancements have been identified that would improve the HAO model. The following are some issues to be considered in the future in order to enhance the model's capabilities.

1. Location and number of points of intersection (PI's)

   It is recommended that the number of PI's should depend on the complexity of the search space and the PI's should be randomly distributed according to the geographic complexity of the study area.

2. Computation efficiency

   In order to reduce model computation time, it is recommended that a prescreening process be added. This process will be used to quickly eliminate undesirable alignments (for example, alignments which have small horizontal curve radii that violate AASHTO standards) during the search process, before detailed evaluations are made.

3. Bridge analysis

   The vertical clearances between the alignment and water levels should be considered in analyzing bridge, through some hydrologic analysis during the search process.

4. Crossing types with existing roads

   The current HAO model can handle limited crossing types with the existing road (including grade separation, 4-leg intersections, and diamond interchanges). The introduction of additional crossing types, such as roundabouts and 3-leg intersections should overcome this limitation.

Chapter 1: Introduction

1.1: Project Background

Project Area

SHA is conducting project planning on the MD 97 Brookeville Bypass project in the area of Brookeville, Maryland. The project area is located near the town of Brookeville in Montgomery County, approximately ten miles south of I-70 and three miles north of MD 108 and listed on the National Register of Historic Places as a Historic District. MD 97 is an arterial highway providing a direct north-south route between the Pennsylvania state line and Washington D.C., which serves commuter traffic traveling through Carroll, Howard, and Montgomery Counties *(12)*.

Project Issues and Purpose

According to the previous study for Brookeville Bypass project of SHA and FHWA (*12*), three issues are relevant in the project area. Table 3 summarizes the project needs in Brookeville area. There are safety concerns, since the crash rate in Brookeville (1996 to 1999) exceeds the statewide average crash rate. MD 97 is a two-lane undivided roadway with little to no shoulder and its right-of-way width is not constant within the project area. In addition, due to irregularly posted speed limits and limited sight distance, travel speed in the project area is also variable. There are no exclusive turn lanes along the MD 97 in the project area. According to the growth forecast in the previous study (*12*), it is expected that planned residential development in the Brookeville area and to the north will generate increased traffic.

The purpose of Brookeville Bypass project is to remove the increasing traffic volumes from the town of Brookeville, improve traffic operation and safety on existing MD 97, and preserve the historic character of the town.

Table 3. Issues Regarding MD 97 in the Brookeville Project Area

	Issues
Access	No access control No exclusive turn lanes
Safety	Inconsistent roadway width Irregular speed limit Limited sight distance Inconsistent travel speed High crash rate above the statewide average
Traffic	Expected traffic volume increasing
Socio-Environmental	All traffic is currently routed through a historic district

1.2: Previous Model Development

Our research team has worked extensively on the development of the Highway Alignment Optimization (HAO) model since 1996. Table 4 provides an overview of the previous model developments. Three Ph.D. dissertations (*17, 18, 19*) have been published on the topic.

Table 4. Chronological Sequence of our Highway Alignment Optimization Work

Work Description	Publication (full citation included in References)
Preliminary 3-D Highway Alignment Optimization (i.e., simultaneous optimization of horizontal and vertical alignments) with Genetic Algorithms (GAs) and Geographic Information Systems (GISs)	Jong, Jha, and Schonfeld (2000)
Right-of-Way Cost Analysis	Jha and Schonfeld (2000a)
Integrating GAs and GISs	Jha and Schonfeld (2000b)
Preliminary Consideration of Intersections and Bridges	Jha (2001)
Using Computer Visualization in conjunction with GAs and GISs	Jha, McCall, and Schonfeld (2001)
Planar Interpolation for Estimating Earthwork Cost	Kim, Jha, Kim, and Son (2002)
Applying Swarm-Intelligence for Alignment Optimization	Jha (2002)
Criteria-Based Decision Support System and Trade-Off Analysis	Jha (2003)
Maintenance Cost Formulation	Jha and Schonfeld (2003)
Local Optimization of Intersections and Interchanges along with Bridges and Tunnels	Kim, Jha, and Schonfeld (2004a); Kim, Jha, Lovell, and Schonfeld (2004b);
Optimization within Narrow Bounds and in Mountainous Terrain	Jha and Schonfeld (2004)
Preliminary Consideration of Demand of the Region	Jha and Kim (2004)
Stepwise GAs for Improving Computational Efficiency	Kim, Jha, and Son (in press)
A Comprehensive Textbook for Intelligent Road Design, including 3-D Alignment Optimization with GAs and GISs	Jha, Schonfeld, Jong, and Kim (forthcoming)

An overview of completed HAO work is provided next.

Methodology

Highway alignment optimization (HAO) seeks to identify the alignment (both horizontal and vertical alignments should be simultaneously obtained) connecting two end-points (Figure 3) that best satisfies stated objectives and constraints. Theoretically, the HAO problem can have an infinite number of alternatives to be evaluated. In previous applications *(2, 10)* the optimization problem was formulated as a cost minimization problem in which cost functions were non-differentiable, noisy and implicit. Thus, the need for fast and efficient search algorithms to solve such a problem is unavoidable.

A trade-off analysis, which was first explored in 2003 *(6)* suggested that a set of near-optimal alignments (rather than a single optimal alignment) should be presented based on varying degrees of land and environmental impacts.

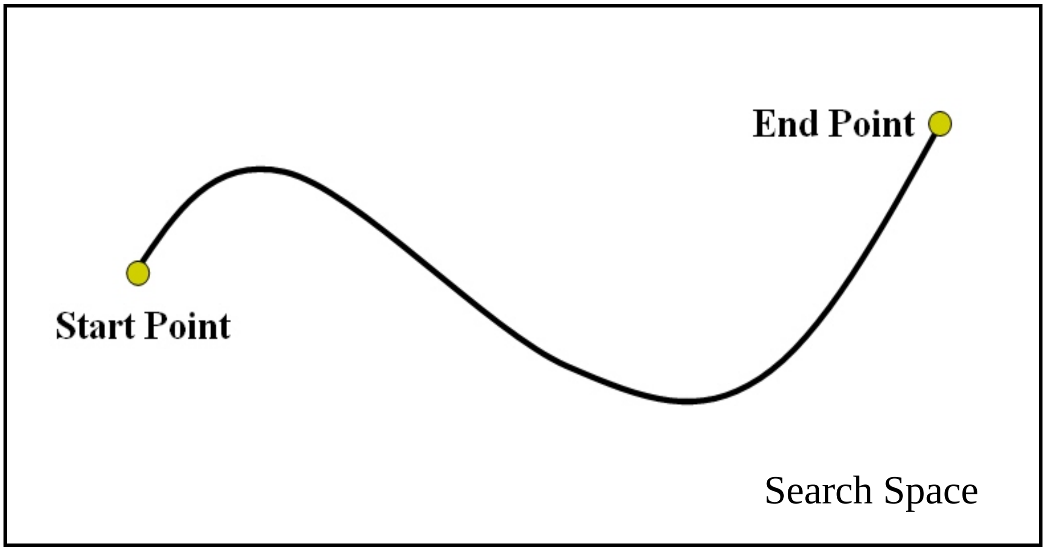

Figure 3. Highway Alignment Optimization Problem

As shown in Table 5, seven search methods have been found in the literature on alignment optimization. Except for genetic algorithms (*2*), all those methods have some critical defects when applied to the highway alignment optimization problem. Table 6 summarizes these defects.

Table 5. Studies on Highway Alignment Optimization

Target for optimizing	Types of approach	References
Horizontal alignment	Calculus of variations	Wan (1995), Howard et al. (1968), Thomson and Sykes (1988), Shaw and Howard (1981 &1982)
	Network optimization	OECD (1973), Turner and Miles (1971), Athsanassoulis and Calogero (1973), Parker (1977), Trietsch (1987a &b)
	Dynamic programming	Hogan (1973) and Nicholson et al. (1976)
	Genetic algorithms	Jong et al. (2000), Jong and Schonfeld (2003)
Vertical alignment	Enumeration	Easa (1988)
	Dynamic programming	Puy Huarte (1973), Murchland (1973), Goh et al. (1988) and Fwa (1989)
	Linear programming	ReVelle, et al. (1997) and Chapra and Canale (1988)
	Numerical search	Hayman (1970), Goh et al. (1988), Robinson (1973), Fwa (1989) and MINERVA (OECD, 1973)
	Genetic algorithms	Jong et al. (2000) and Jong and Schonfeld (2003)
Horizontal and vertical alignment simultaneously	Dynamic programming	Hogan (1973) and Nicholson et al. (1976)
	Numerical research	Chew et al. (1989)
	Two-Stage ptimization	Parker (1977) and Trietsch (1987a)
	Genetic algorithms	Jong et al. (2000) and Jong and Schonfeld (2003)

Table 6. Weaknesses of the Existing Highway Alignment Optimization Methods

Methods	Defects
Calculus of variations	• Requires differentiable objective functions • Not suitable for discontinuous factors • Tendency to get trapped in local optima
Network optimization	• Outputs are not smooth • Not for continuous search space
Dynamic programming	• Outputs are not smooth • Not suitable for continuous search space • Not applicable for implicit functions • Requires independencies among subproblems
Enumeration	• Not suitable for continuous search space • Inefficient
Linear programming	• Not suitable for non-linear cost functions • Only covering limited number of points for gradient and curvature constraints
Numerical search	• Tendency to get trapped in local optima • Complex modeling • Difficulty in handling discontinuous cost factors

Genetic Algorithms for Optimal Search

Genetic Algorithms (GAs) have been proven to be very effective for highway alignment optimization problems (*2, 10*) since they can effectively search in a continuous search space without getting trapped in local optima. Goldberg (1989) states four important distinctions of GAs over other search methods:

(1) GAs work with a coding of the parameter set, rather than the parameters themselves.

(2) GAs search from a population rather than a single point.

(3) GAs use payoff (objective function) information, rather derivatives or other auxiliary knowledge.

(4) GAs use probabilistic transition rules, rather than deterministic rules.

In addition it is found that GAs are highly efficient for searching in a large solution space. Specialized GAs have been developed for HAO by Jong (*2, 10*). The unique requirements in applying GA's are to formulate the encoded solutions and develop problem-specific operators.

HAO Formulation

As shown in Fig. 1, it is assumed that the start and end points are given. The points of intersections ($P_i's$) are assumed to fall along the orthogonal cutting lines (planes for the 3-dimensional case) passing through intermediate points placed at equally spaced intervals between the start and end points. The $P_i's$ are first connected with straight lines; curves are then fitted to connect straight lines (see, Figure 4 and 5). The curve radius is calculated using the AASHTO (2001) design criteria. Thus, the problem reduces to finding the $P_i's$, which are treated as the optimized decision variables.

In Figure 4, C_i and T_i denote points of curvature and points of tangency, respectively. For notational convenience, we further denote $T_0 = P_0 = S$ and $C_{n+1} = P_{n+1} = E$ as the start and end points of the alignment.

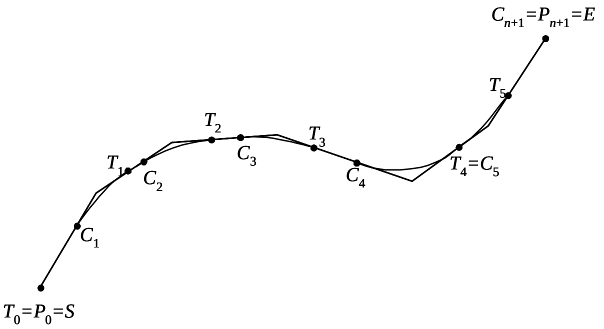

Figure 4. A 2-D Alignment Construction: A Case of 5 Points of Intersection

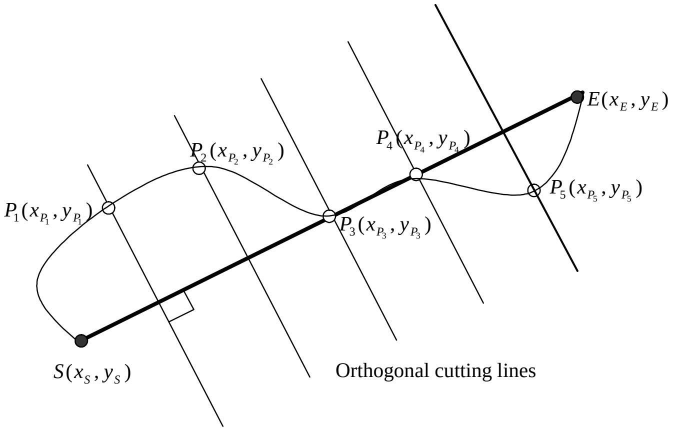

Figure 5. An Example of Points of Intersections, Tangency and Curvature

Genetic Encoding of Alignment Alternatives

Each P_i's is determined by three decision variables, namely its X, Y and Z coordinates *(2, 10).* For an alignment represented by n points of intersections, the encoded chromosome is composed of $3n$ genes. Thus, the chromosome is defined as:

$$\Lambda = [\lambda_1, \lambda_2, \lambda_3, ..., \lambda_{3n-2}, \lambda_{3n-1}, \lambda_{3n}] = [x_{P_1}, y_{P_1}, z_{P_1}, ...x_{P_n}, y_{P_n}, z_{P_n}] \qquad (1)$$

where: Λ = chromosome

λ_i = the i^{th} gene, for all $i = 1,.......,3n$

$(x_{P_i}, y_{P_i}, z_{P_i})$ = the coordinates of the i^{th} point of intersection, for all $i = 1,......., n$

Genetic Operators

The genetic operators employed are problem-specific (*2, 10*). Each operator is designed to work on the decoded points of intersection rather than on individual genes. Extensive tests are conducted to ensure that these operators assist in obtaining precise and efficient solutions.

The Highway Alignment Optimization Problem Formulation

To describe highway alignments (or centerlines of highways), a parametric representation is useful (*13, 14, 15*). In the proposed method, a smooth and continuous alignment is explored in a given solution space. Boldface capital letters will be used to denote vectors in space. Let $\mathbf{P}(u)=[x(u),y(u),z(u)]^T$ be a position vector along the alignment L, where $u=\frac{\int_0^u \|\mathbf{P}'(t)\|dt}{\int_0^1 \|\mathbf{P}'(t)\|dt}$ and $\|\mathbf{P}'(u)\|=\sqrt{(x'(u))^2+(y'(u))^2+(z'(u))^2}$. Basically, $\mathbf{P}$ is parameterized by u, which represents the fraction of arc length traversed to that point. If L is an alignment connecting $\mathbf{S}=[x_S,y_S,z_S]^T$ and $\mathbf{E}=[x_E,y_E,z_E]^T$, then the position vector $\mathbf{P}(u)$ must satisfy $\mathbf{P}(0)=\mathbf{S}$, and $\mathbf{P}(1)=\mathbf{E}$. $\mathbf{P}(u)$ must also be continuous and continuously differentiable in the interval $u\in[0,1]$.

The model formulation includes: (1) an objective function, and (2) constraints. The objective function is usually a total cost function (C_T) having five main components (user cost (C_U), right-of-way cost (C_R), length-dependent cost (C_L), earthwork cost (C_E), and structure cost (C_S)) as explained in Eq (2).

$$\underset{x_{P_1},y_{P_1},z_{P_1},\ldots\ldots,x_{P_n},y_{P_n},z_{P_n}}{\text{Minimize}} \quad C_T=C_U+C_R+C_L+C_E+C_S \tag{2}$$

$$\text{subject to} \quad x_O\le x_{P_i}\le x_{\max}, \quad \forall\, i=1,\ldots\ldots,n \tag{2a}$$

$$y_O\le y_{P_i}\le y_{\max}, \quad \forall\, i=1,\ldots\ldots,n \tag{2b}$$

where (x_O,y_O) = the X, Y coordinates of the bottom-left corner of the study region (Figure 6)

(x_{P_i},y_{P_i}) = the X, Y coordinates of points of intersections, P_i

$(x_{\max},y_{\max})$ = the X, Y coordinates of the top-right corner of the study region (Figure 6)

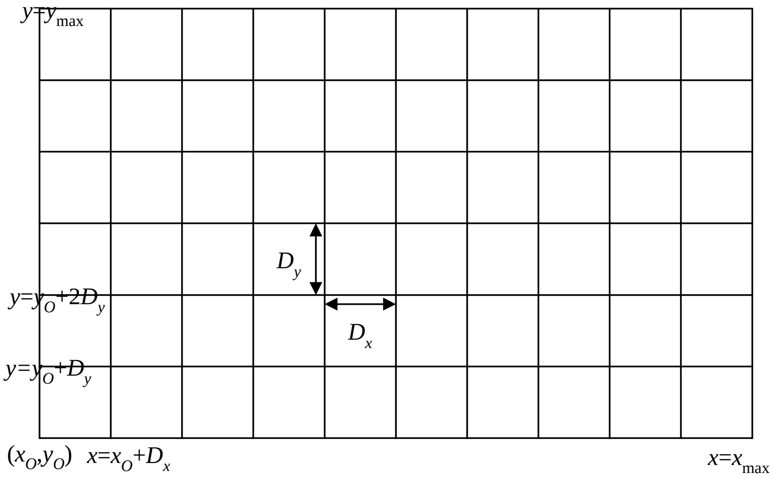

Figure 6. An Example of Study Area for Alignment Optimization

Basically, the costs have to be formulated as functions of the PI's, which are treated as the optimized decision variables.

There are also many design and operational constraints to be met in alignment optimization. Among those, the minimum length of vertical curves, gradient, sight-distance, and environmental constraints are important ones, which are sufficiently formulated and considered in the model.

The user costs, which consist of travel–time cost, vehicle operating cost, and the accident cost (*10*, *16*) are suppressed from the objective function in this HAO application. Thus, the objective function used in this study is $C_T = C_R + C_L + C_E + C_S$. The right-of-way cost is calculated from the cost of the land area taken by the alignment and damage to the properties, based upon a digitized map (*8*). The length-dependent cost varies the length of the proposed alignment and mainly consists of costs for pavements, substructures and superstructures (such, as barriers) on the road. The earthwork cost is calculated based on the actual ground elevation of the study area.

Integrated GA-GIS Model

An integrated model that combines GIS and optimization based on GA is used for HAO. In this integrated model, dynamic data exchange *(9)* occurs during optimal search since many tasks, such as cost calculations, environmental impact assessment, and optimal search are shared between GIS and GA. GIS is primarily used for map processing, right-of-way cost and environmental constraint calculations. The GA-based optimization component is used for (1) random generation of alignment, (2) earthwork, pavement, and construction cost calculations, (3) penalty calculations of design criteria and environmental constraints, and (4) optimal search. A number of user-specified input parameters are needed to initiate the optimal search, including limit of search space, start and end points of the proposed alignment, alignment width, terrain elevation, cut and fill costs, maximum allowable super-elevation, and criteria for stopping the search (Refer to Table 14).

Model Output

The model output includes the optimized horizontal and vertical alignment and optimized objective function (i.e., cost). Several measures of effectiveness, such as numbers of home and business displacements and areas of affected floodplains and wetlands, are also obtained. Cost breakdowns by locations and categories are also obtained.

Trade-Off Analysis

In order to perform the trade-off analysis *(6)* the solutions obtained with genetic algorithms at intermediate generations are saved. The promising alternatives with varying degrees of environmental effects and costs are then extracted and a set of alignments depending on user preferences are presented as final solutions.

Future Work

A list of desirable future research tasks is provided in Table 7 below.

Table 7. Critical Issues for Future HAO Research (not in any priority order)

Item #	Critical Issues for Future HAO Research	Explanation
1	Developing a sophisticated GIS with automated data processing and digital map creation	The current HAO model requires a digital GIS map. Thus, numerous data processing and manual digitization is required in creating such a map, which is very time consuming and limits model applicability to large-scale projects.
2	Automation in the process of deciding the suitable number of PI's and the spacing between them.	The number of PI's is now specified by users and they are equally spaced in the current HAO model. The suitable number of PI's and the spacing between them will depend on the complexity of the search space.
3	More sophisticated bridge characteristics	The bridge module introduced by Kim et al. (2004 a&b) requires improvements. Key questions such as penalties for violating minimum bridge clearance, selection of cost-effective bridge types, pier locations, and optimal placement of bridges should be addressed.
4	Hydrologic and geotechnical analysis	The roadside drainage and slope stability will depend on hydrologic and geotechnical characteristics, which should be addressed. Hydrologic analysis should also determine the locations, dimensions, and costs of bridges and culverts.
5	Noise analysis and mitigation	Noise levels in the residential neighborhoods should be minimized.
6	Future land use and development	Changes in future land use patterns should be considered.
7	Variable road-widths, number of lanes, and speed limits	In the current model the road width and speed-limit are still fixed. It is possible to drop some lanes and pick up additional lanes along a highway resulting in varying widths. Similarly, speed-limits may vary along a highway.

Item #	Critical Issues for Future HAO Research	Explanation
8	Variable cut and fill slopes and consideration of retaining walls for road stability	In our current model cut and fill slopes are assumed to be fixed. In reality, they will depend on soil characteristics. Retaining walls may sometimes be preferred to sloped cuts.
9	Minimum buffer from sensitive properties	It may be necessary to specify a minimum buffer between the road and certain properties, such as a school, cemetery, or a historical property.
10	Relocating wetlands	Possibility of relocating wetlands with a provision for compensation multiplier should be investigated.
11	Automatic search for start and end points within specified ranges	Instead of assuming fixed start and end points these may be optimized within desired limits.
12	Roundabout consideration	In addition to intersections and interchanges, roundabouts may also be considered when feasible.
13	Extending single alignment optimization to road network	Instead of a single highway a network of roads may have to be optimized.
14	Computational Efficiency	When connected to a GIS the model is relatively slower since computational time increases due to extensive spatial analysis required in GIS. The computation time depends on map density, problem-size, search generations, processor speed, and computer memory. In a current project, with the latest desktop PC Pentium IV 3.0 GHz with 512 MB RAM, 300 generations of search in 8,400 x 3,600 sq. ft. space containing 650 geographic entities (i.e., land parcels, historic sites, wetlands, parks, floodplains, each represented as a geographic entity) it took about 4.5 to 6.5 hours to search for 300 generations requiring about 6,500 candidate alignment evaluations.

Chapter 2: Data Preparation

Three major data preprocessing works (horizontal and vertical map digitization and tradeoff in map representation) were conducted before evaluating possible alignments with the HAO model. Figure 7 presents the procedure used in applying the HAO model to the Brookeville Bypass project. Details on each data preparation process are described in the following sections.

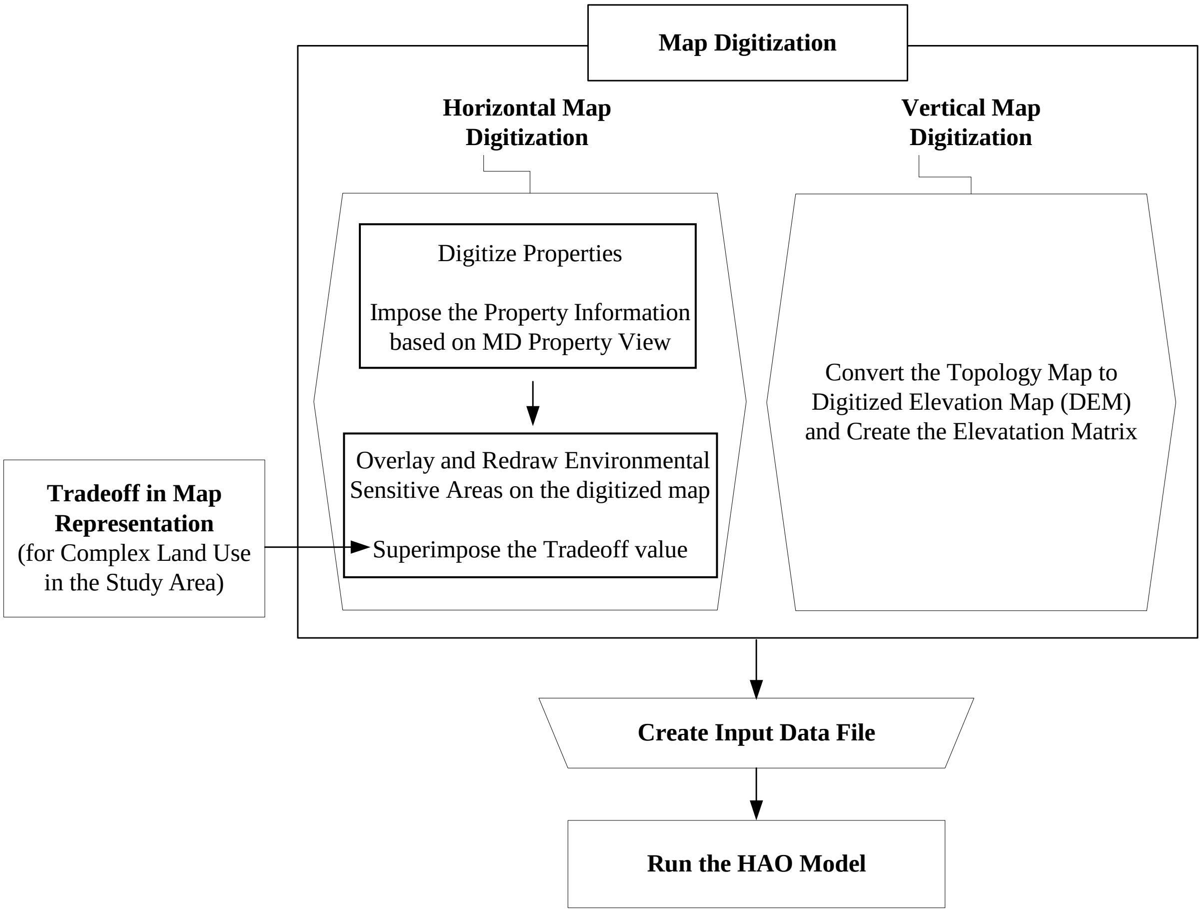

Figure 7. Procedure of the HAO Model Application

2.1 Estimated Working Time

To reduce working time for preparing geographical information, a study area was defined around in the town of Brookeville. Maryland’s GIS database (MD Property View 2003) and the Micro-station base maps for Brookeville area (from SHA) were used to construct the study area. Property boundaries for the study area, including environmentally or socio-economically sensitive regions, were digitized with the Micro-station base map and associated geographic databases containing relevant information (such as, land area, zoning, and land cost) of the study area are referred from MD Property View. Thus, the study area became the search space of the HAO model application. As shown in Table 8, the data preparation time for the HAO application in the Brookeville Bypass project was about 250 person hours. Most of that time was spent on the map digitization work for the study area. Model computation time varies depending on input parameters (mainly generation number) and the complexity of land use in the study area.

Table 8. Estimated Working Time[2]

Tasks			Working time
Data preparation time	Horizontal map digitization	Digitize properties	50 hrs
		Impose property Cost	80 hrs
		Tradeoff in map representation	95 hrs
	Vertical map digitization	Create DEM matrix	20 hrs
	Create an input data file		7 hrs
Model computation time on Pentium IV 3.0 GHZ with 512 MB RAM			4.5~6.5 hrs for 300generations

For horizontal map digitization, Micro-station base maps which store boundaries of environmentally sensitive areas, such as wetlands, floodplains, and historic resources were used to digitize properties in the study area of Brookeville. This task took about 50 hours. After

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[2] The estimated work time includes much trial and errors; thus, it should decrease with experience.

this task, the property cost was imposed to the digitized properties based on MD Property View. A relatively long time (approx. 80 hours) was spent on this step because we manually imposed property information on the digitized map from MD Property View. After the previous two steps, superimposition of tradeoff values for the existing sensitive regions in the study area was applied on the digitized map. This step was quite lengthy, requiring approximately 95 hours.

For vertical map digitization, we obtained a Micro-station contour map for Brookeville from the SHA, and converted it to a Digitized Elevation Map (DEM) that provides elevations with grid a base. This task took about 20 hours; however, it should be noted that if the projection of the Micro-station base map and that of MD Property View are same, the working time for vertical map digitization would be reduced to just using the DEM file for the Brookeville area from the web site http://data.geocomm.com/dem/demdownload.html.

2.2: Horizontal Map Digitization

The purpose of horizontal map digitization is to reflect complex land uses in the study area on the GIS digitized map and to obtain detailed right-of-way costs for the proposed alignments. Horizontal map digitization mainly consists of two steps (See Figure 7). For this project, we first digitized properties of the study area and next imposed the associated property information to the previously digitized properties. After this step, the environmentally sensitive areas (such as wetlands and historic sites) were overlaid and redrawn onto the digitized map. Tradeoff values for the different land use characteristics were then superimposed.

Digitizing properties

For horizontal map digitization, we first digitized properties in the Brookeville study area using the Arc View GIS 3.2 software. In this step, each property was regarded as a polygon, which can retain property information as its attributes. Next, the property information, such as land value and land use characteristics were imposed on the digitized properties based on MD Property View.

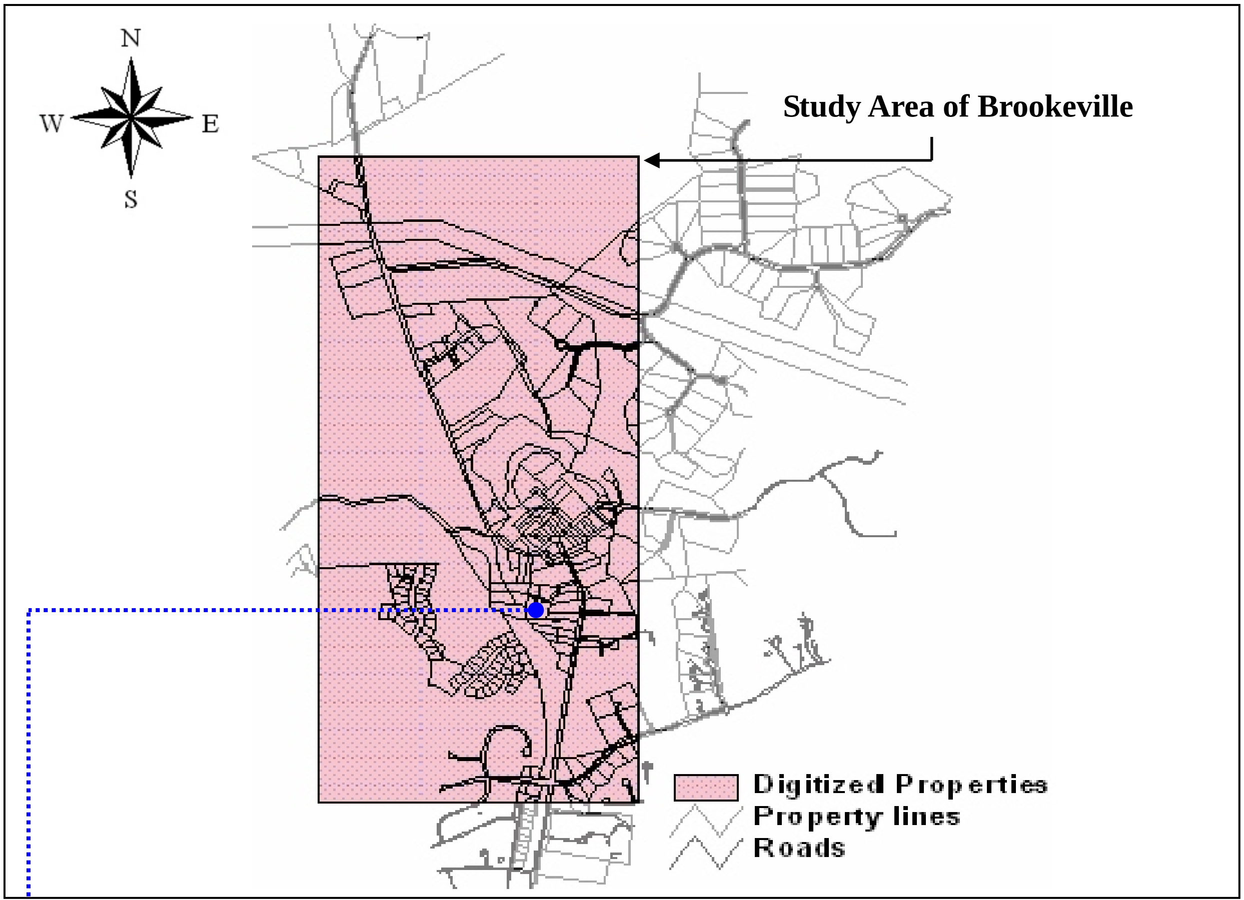

Figure 8. Digitized Property Cost Map

Table 9. Property Information

Segment number[1]	Parcel ID #	Perimeter (ft)	Unit Cost ($/sq. ft)[3]	Area (sq. ft)	Land use
.	.	.	.	.	
.	.	.	.	.	
54111	85	1075.362	6.2349	53987.121	Historic District
.	.	.	.	.	
.	.	.	.	.	

---

[3] Based on MD Property View

Figure 8 shows a digitized map on which the real property information is assigned. The information assigned on the map includes parcel ID number, perimeter, unit cost, and area of each property (See Table 9). It is noted here that the unit cost is obtained simply by dividing the property value by its area.

Among these attributes, unit cost ($/sq.ft.) is mainly used for alignment evaluation. Right-of-way cost, length of alignment, and the area taken by the proposed alignments is computed based on the unit cost.

As shown in Table 9, we also imposed land use type and segment number, which is recorded on MD Property View, to the digitized properties. In fact, these attributes are not used in model computation; however, they may help in reducing other working times, such as in superimposing tradeoff values on critical areas and updating property information from the MD Property View.

Overlay and redraw environmental issued areas

In order to consider the existing control areas, such as environmentally or socio-economically issued regions to the HAO model application, we overlaid and redrew the control areas on the previously digitized map.

The existing land use in the study area of Brookeville is a combination of various land use types. Figure 9 presents various land use type of the study area in Brookeville. The land use type of the study area is represented as 10 different land use characteristics on the digitized map; structures (houses and other facilities), wetlands, residential areas, historic places, streams, park with Historic District, parklands, floodplains, existing roads, and other properties.

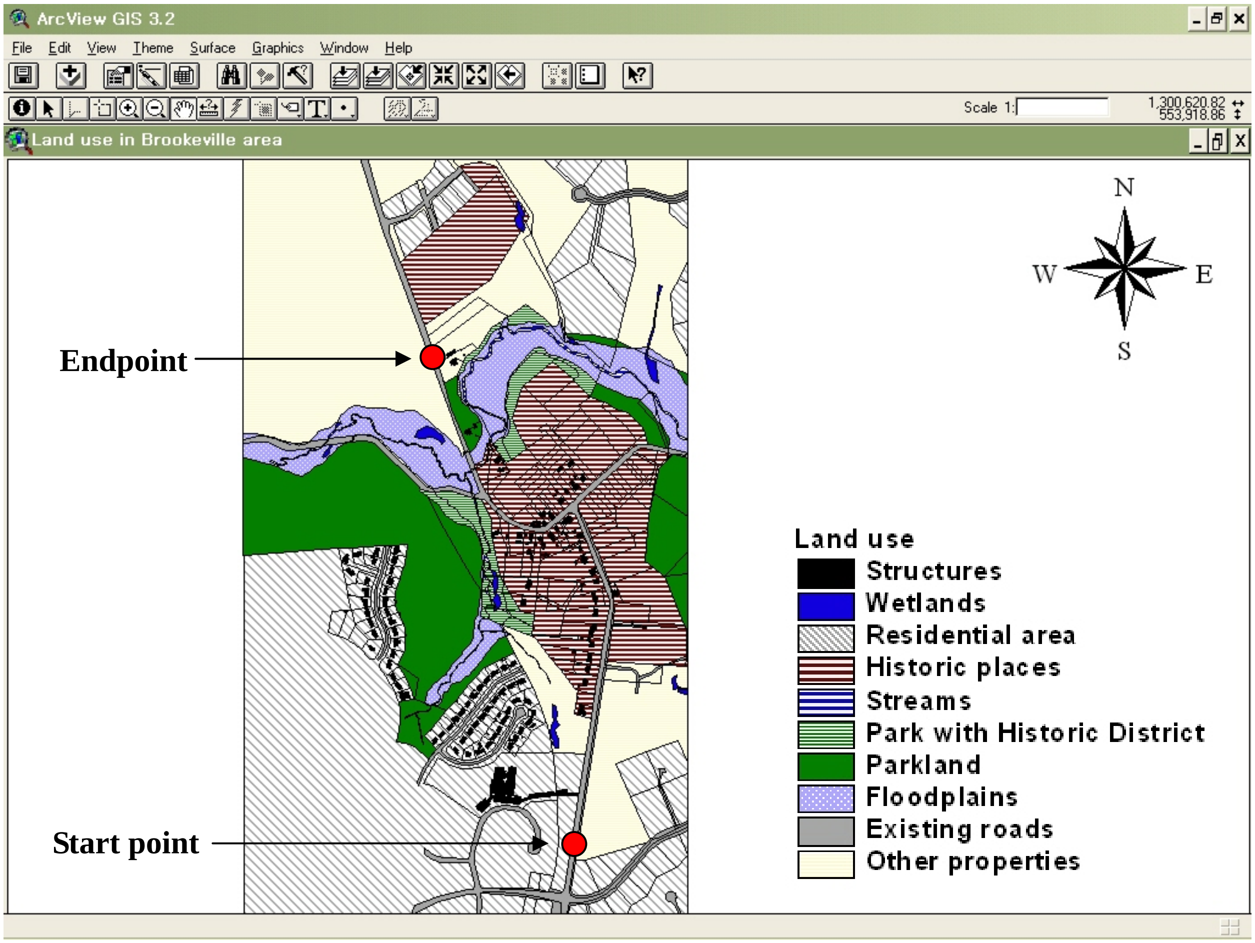

Figure 9. Land Use of the Study Area in Brookeville

As shown in Figure 9, the study area comprises about 650 geographic entities (including land, structures, road etc.) with given start and end points of the proposed alignment. The search space (690 acres) includes primarily residential areas (203.4 acres), historic sites (73.3 acres), parkland (67.4 acres), and floodplains (30.9 acres).

Figure 10 presents real property cost in the Brookeville study area. The unit property cost for land ranges from 0 to 14 $/sq.ft. and structure costs (such as houses and public facilities costs) ranges from $36,100 to $1,162,200. The darker land parcels have higher unit costs.

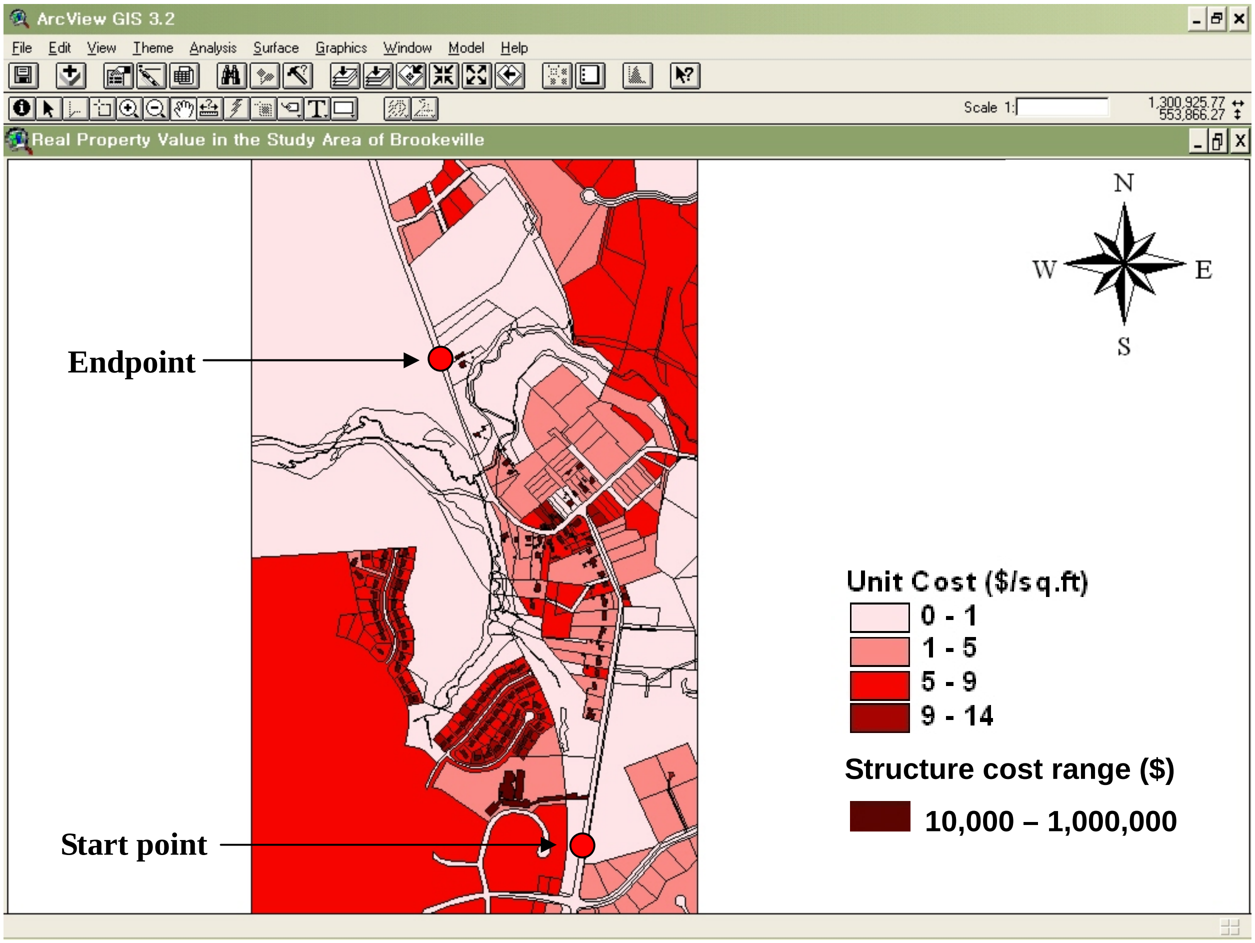

Figure 10. Real Property Value of the Study Area

2.3: Vertical Map Digitization

In the HAO model the earthwork cost of the proposed alignment was calculated based on an elevation matrix. Thus, preparation of the elevation matrix for the study area was required. We converted the Microstation contour map for Brookeville to a Digitized Elevation Map (DEM) using Arc View GIS 3.2. Figure 11 shows the ground elevation of the study area.

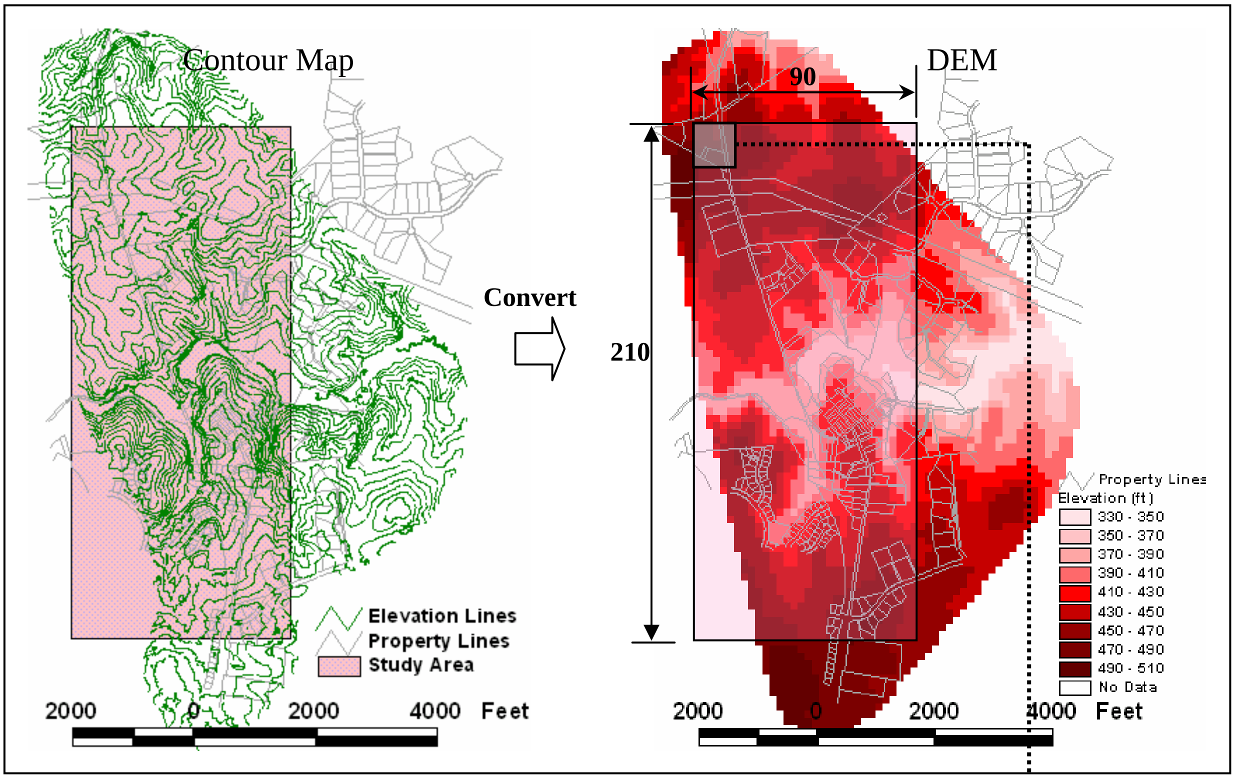

Figure 11. Ground Elevation of the Study Area in Brookeville

Table 10. Sample Grid Evaluations for the Study Area (90*210 grids)

	1	**2**	**3**	**4**	**5**	**. . .**	**90**
1	470	470	468	464	461	. . .	432
2	470	470	469	465	461	. . .	434
3	470	470	470	465	460	. . .	435
4	470	470	468	463	460	. . .	437
5	472	470	466	461	460	. . .	439
:	:	:	:	:	:	:: :	:
210	403	396	390	395	399	. . .	**464**

The elevation range in the Brookeville area is 330 to 510 feet. The darker areas represent higher elevations. As shown in Figure 11, floodplains and parklands near in the floodplain exist in low elevation areas while Historic District is located in relatively high elevation sites (Also see Figure 9).

The elevation of the study area is represented as a matrix of 90*210 grids in Table 10. Each grid cell is 40 feet * 40 feet, representing approximately 0.04 acres. The selected grid size significantly influences to the earthwork cost calculation.

2.4: Tradeoffs in Map Representation for Environmental Issues

When considering roadway construction in a given project area, various geographically sensitive regions (such as historic sites, creeks, public facilities, etc.) may exist. These control areas should be avoided by the proposed alignment and to the extent, its impact to these regions should be minimized.

Based on the previous Brookeville study by SHA and FHWA *(12)*, we categorized residential properties, the Longwood Community center, Historic districts, and wetlands as environmentally primary sensitive areas that should not to be taken by the new alignment if at all possible. In addition, parklands, floodplains, and streams were considered environmentally secondary sensitive areas, i.e., to the extent possible their impact should be minimized next to the primarily sensitive area. This requires expressing different implicit cost levels for various environmental factors into the GIS based evaluations, practically. It should be noted that parklands, floodplains, and streams are located between the given start and end points; furthermore, these areas are unavoidably taken by the proposed alignment.

Table 11. Types of Control Areas in the Brookeville Study Area

Type	Control areas	Characteristics
Type 1	Wetlands Historic places Residential areas Site of Community center Structures (Houses, Public Facilities, etc.)	The control area that the proposed alignment can avoid
Type 2	Streams Floodplains Parklands	The area that the proposed alignment cannot avoid

Table 11 shows two different types of control areas in the Brookeville study area with respect to their land use characteristics; (1) the control area that the proposed roadway alternatives can avoid, (2) the area that the proposed alternatives cannot avoid. Type 1 areas include wetlands, historic places, residential areas, Community Center, and other structures. Type 2 areas consist of streams, parklands and floodplains, which are unavoidably affected by the alignments.

To properly reflect these relevant environmental and socio-economic issues on the GIS map representation, careful tradeoff property values for the different land use types are required, since these values are significantly able to affect the resulting alignment. Thus, penalty costs for type 1 areas should be much higher than that for type 2, since type 1 areas have primary (i.e., stronger) environmental regions to be avoided whereas type 2 areas contain only secondary regions.

Table 12. Order of Magnitude of Penalty Costs

Type of Control Areas	Level	Magnitude[4]	Control Areas	Tradeoff Value ($/sq.ft.)
Type 2	1	100 × X	Floodplains, Parklands, Park with Historic Districts	1,400
Type 2	2	1000 × X	Streams	14,000
Type 1	3	10,000 × X	Historic sites, Residential sites, Community center sites	140,000
Type 1	4	100,000 × X	Wetlands	1,400,000

Table 12 presents the order of magnitude of penalty costs for the various types of control areas. We developed a guideline for the penalty costs based on the maximum unit land cost[5] (14 $/sq.ft.). The idea is to eliminate impacts on type 1 areas and minimize those on type 2 areas, and to encourage the alignments to take other properties (e.g., Montgomery County's reserved areas and existing roads in this study area). For this purpose, we discriminated between type 1 and type 2 areas by assigning 140,000 $/ sq.ft. for type 1 areas and 1,400 $/ sq.ft. for type 2 areas (i.e., the penalty to type 1 areas are 100 times higher than for type 2). In addition, we particularly differentiated wetlands among type 1 areas by assigning a considerably higher cost (1,400,000$/ sq.ft.) since we assumed that wetlands are the most sensitive areas the proposed alignment must avoid. For the same reason, we distinguished streams from type 2 areas by assigning relatively high unit cost (14,000 $/ sq.ft).

It is noted that the tradeoff values presented in Table 12 were successful in minimizing the control area taken by the proposed alignment.

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[4] X=14 $/ sq.ft: Maximum unit cost for land in the study area of Brookeville

[5] Range of unit land cost for the study area is 0-14 $/ sq.ft (See Figure 10)

Table 13. Unit Land Cost Finally Assigned to the Different Land Uses

Group	Land Use	Unit Cost ($/sq.ft)	Note
1	Other properties	0 - 14	Real value
2	Existing roads	0.025	Assumed
3	Floodplains, Parklands, Park with Historic Districts	1,400	Penalty
4	Streams	14,000	Penalty
5	Historic resources, Sites of Residential, and Community Center	140,000	Penalty
6	Wetlands	1,400,000	Penalty
7	Structures (Houses, Public facilities, etc.)	36,100-1,162,200 ($)	Real value

Table 13 presents the list of unit costs, which were finally assigned to the properties for the HAO application in Brookeville Bypass project. As stated earlier, these unit costs were mainly used to calculate right-of-way cost, length of alignment, and the area taken by the proposed alignment.

Unit costs for group 1 and structure costs for group 7 are extracted directly from MD Property View. On the other hand, unit costs for group 3 to 6 are the tradeoff values from Table 12. These costs were used to avoid taking the control areas, if possible, for the proposed alignments. It is noted here that we assumed the unit cost of the existing roads to be very small (0.025 $/sq.ft.).

Figure 12 shows a tradeoff search space of the study area with the unit land cost in Table 13.

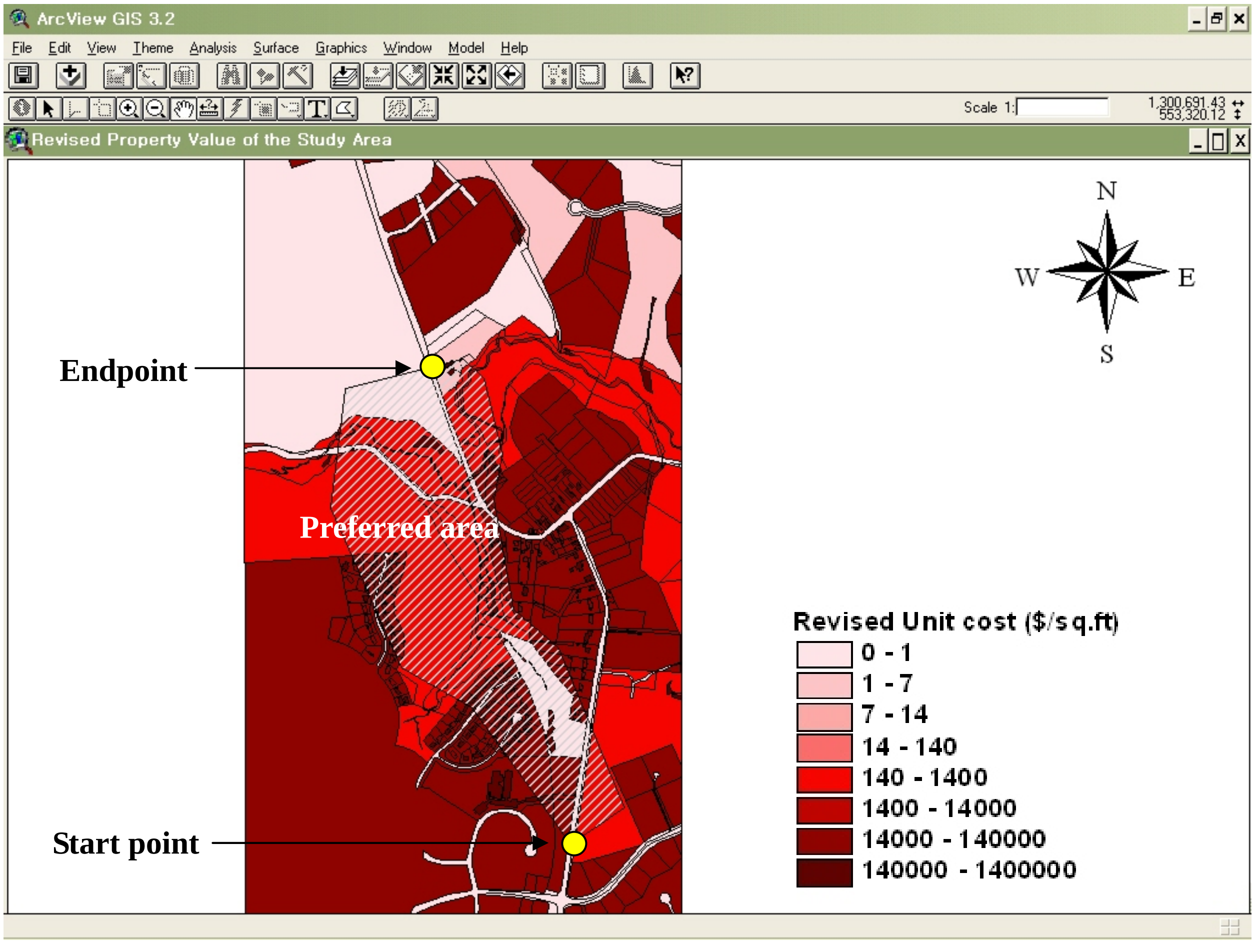

Figure 12. Tradeoff Search Space for Brookeville

Chapter 3: Results

3.1: Input and Output for Optimized Alignments

To conduct highway alignment optimization with the HAO model, users have to pre-specify some input values, such as proposed alignment width and design speed. Since the optimized alignment varies depending on these inputs, users should carefully determine the input variable values.

We specified the start and end points of the proposed alignments to (1295645, 548735, 470) and (1294512, 552574, 407) as a default on the south and north sections of MD 97 in Brookeville, respectively (see, Figure 12). The Euclidean distance between the start and end points is about 4,000 feet. The design speed was set at 50 mph. The distance between station points, which are used as earthwork computation unit in the HAO formulation, is assumed to be 40 feet. The cross section of the proposed alignment is assumed to represent a 2 lane road with 40 feet width (11 feet for lanes and 9 feet for shoulders, as shown in Figure 13).

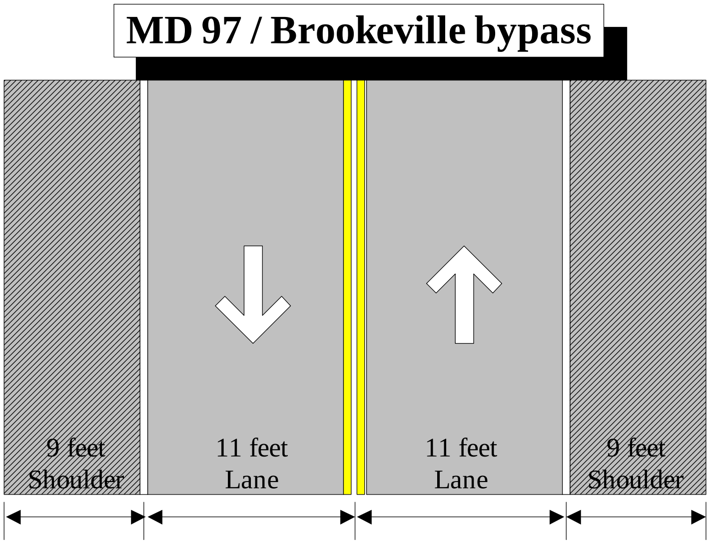

Figure 13. Cross Section of the Proposed Alignment

Grade separation was the only crossing type of the proposed alignment with the existing Brookeville Road, considered in this analysis. Various user specifiable input variables required in the highway alignment optimization process are described in left hand side of Table 14 (note that only the shaded values are actual values). As previously mentioned, the unit construction costs, such as unit cut and fill costs and length dependent costs are user-specifiable. Based on the pre-specified unit costs, the total cost is computed (refer to page 16).

Table 14. Baseline Inputs Used in Sensitivity Analysis to # of PI's

Input variables	Value
# of Intersection points (PI's)	4 to 7
Proposed alignment width	40 ft, 2 lane road (11 for lane, 9 for shoulder)
Design speed	50 mph
Maximum super-elevation	0.06
Maximum allowable grade	5 %
Coefficient of side friction	0.16
Longitudinal friction coefficient	0.28
Location of start and end points (X,Y, Z)	(1295645, 548735, 470), (1294512, 552574, 407)
Distance between station points	40 ft
Fill slope	0.4
Cut slope	0.5
Earth shrinkage factor	0.9
Unit cut cost	35 $/cubic yard
Unit fill cost	20 $/cubic yard
Cost of moving earth from a borrow pit	2 $/cubic yard
Cost of moving earth to a fill	3 $/cubic yard
Unit length-dependent cost[6]	400 $/ft
Crossing type with the existing road	Grade separation
Terrain height ranges	330 ~ 510 ft
Unit land value in the study area	0 ~ 14 $/ sq.ft.
Unit cost of existing road	0.025 $/ sq.ft.
Unit bridge cost	10,000 $/sq.ft.

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[6] Length-dependent cost mainly consists of pavement cost and sub and super structure (e.g. barrier and median) costs on the road

The input values presented in Table 14 were used for analyzing sensitivity to the number of PI's. These values were also used for sensitivity analyses to the other major key parameters as the baseline values presented in Chapter 3.4.

Detailed results for the optimized alignments, such as costs breakdown of total, earthwork cost per station, and coordinates of all evaluated alignments are provided as HAO model outputs. These results are automatically recorded in different files during program runs. In addition, environmental impacts for the optimized alignment can also be summarized using Arc View's attribute table after program terminates. Available output results from the HAO model application presented in Table 24 of APPENDIX A.

3.2: Description of Optimized Alignments

Four optimized alignments are produced here by using the HAO model to optimize the Brookeville project with different numbers of PI's. It is assumed that all the four alternatives have the same start and end points and cross the Brookeville Road with grade separation. They mainly dominate Montgomery County's reserved area and Reddy Branch Park without affecting any residential property and Brookeville Historic District. Optimized alignments A, B, C, D have 4, 5, 6, and 7 PI's, respectively. Figure 14 shows horizontal alignments of these four alternatives on the Brookeville property cost map. As shown in Figure 14, rights-of-way for all four alignments seem to be similar; however, it is noted that detailed results (such as initial construction cost, environmental impact, and road elevation of each alignment) are quite different, as shown in Table 15 and Figures 16 to 19.

Other optimized alignments, which were obtained by changing major input parameters based on the baseline inputs in Table 14, are presented in Chapter 3.4.

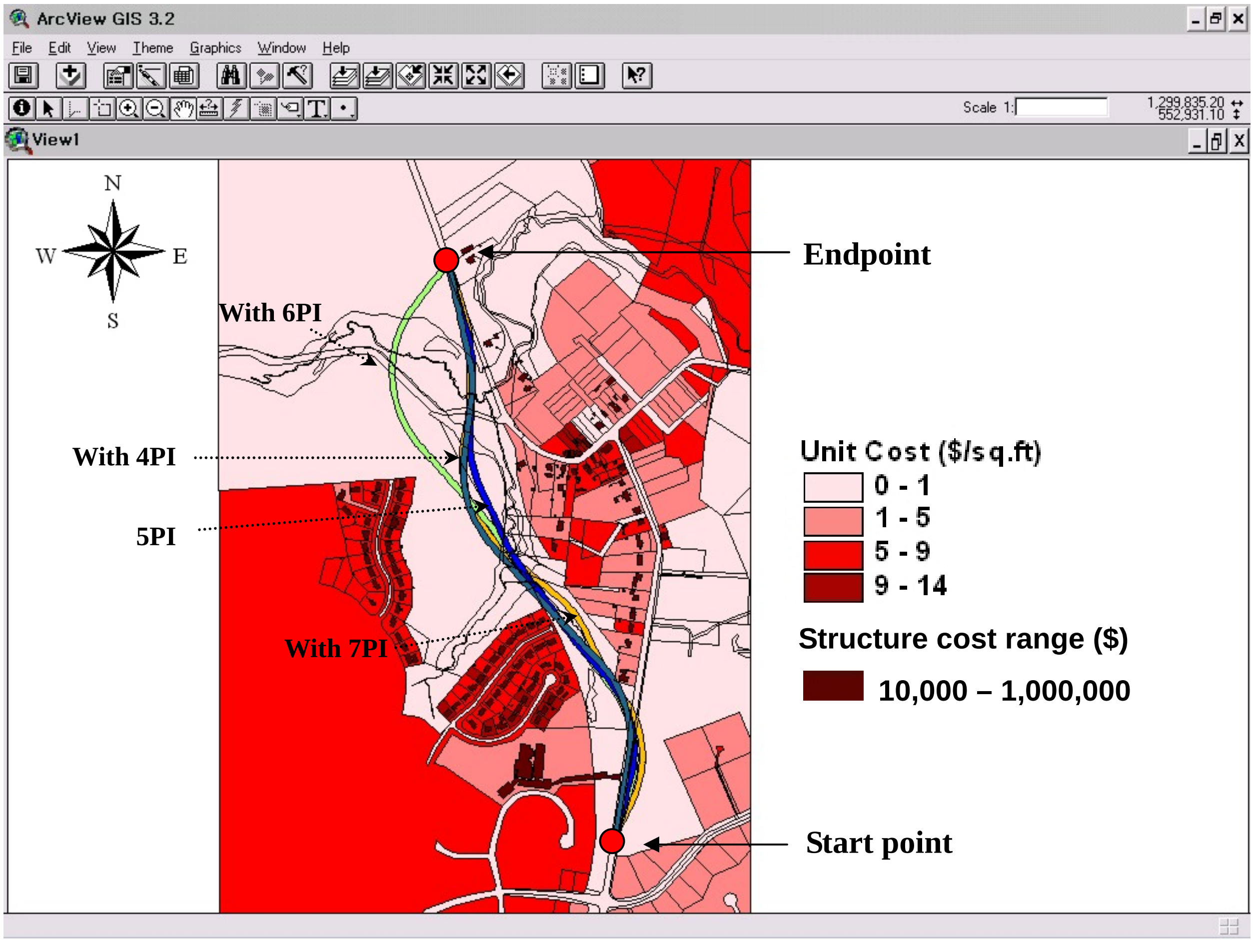


Figure 14. Optimized Horizontal Alignments with Different Number of PI's

3.3: Sensitivity of Optimized Alignments to the Number of PI's

Optimizing (roughly) the number of PI's is quite desirable in applying the HAO model, mainly to reduce the number of curved sections. Moreover, the solution quality (such as the impact of the proposed alignment to the sensitive area and its right-of-way) and computation efficiency of the HAO model differ depending on this number. Therefore, a sensitivity analysis was conducted in this study to explore the preferable number of PI's between 4 and 7. More than 8 PI's were not considered in this analysis to avoid too many horizontal curves. Table 15 shows the result summary for the sensitivity analysis. Initial construction cost, environmental impacts, length, and model computation time for four different optimized alignments are presented here. The search was conducted over 300 generations, during which about 6,500 alignments were evaluated for each case. A desktop PC Pentium IV 3.0 GHZ with 512 MB RAM was used to run the model. It took a considerable time (about 4.5 to 6.5 hours) to run through 300 generations because the Brookeville study area is quite complex with many properties (about 650 geographical entities). As shown in Table 15, none of the four alternatives require any residential relocation and all have similar alignment lengths. Among the four alternatives, the initial construction cost is lowest for optimized alignment B ($ 4,629,708) and highest for optimized alignment C ($ 5,956,983). In terms of environmental impact, the sensitive areas taken by the alignment B (63,030 sq.ft. for total) are also the lowest although the differences are not great among the four alignments. For type 1 areas, which were previously defined as environmentally primary sensitive regions, optimized alignment A with 4 PI's affects relatively large amounts of type 1 areas compared to those of the other three alternatives. Alignment A affects 484.34 sq.ft. of type 1 areas (305.96 sq.ft. for residential area and 152.38 sq.ft. for Longwood Community Center); on the other hand, the other three optimized alignments hardly affect type 1 areas (i.e., less than 1 sq.ft.). A detailed environmental impact summary for optimized alignments A to D is presented in APPENDIX B. In terms of computation efficiency, Table 15 shows that model computation time increases slightly when the number of PI's increases from 4 to 7. It seems that model computation time is not significantly affected by the number of PI's. However, it should be noted that computation time still increases with the number of PI's since additional PI's generate additional horizontal and vertical curved sections. For instance, the HAO model with 20 PI's requires over 10 hour computation time with the same inputs shown in Table 14. Thus, the HAO users should keep in mind that more PI's can increase computation burdens significantly.

Table 15. Sensitivity to Number of PI's

Optimized alignment	# of PI's	Initial construction costs ($)	Environmental impact				Length (ft)	Computation time (hr)
			The control area taken by alignments (sq.ft.)			Residential relocation (No.)		
			Type 1	Type 2	Sum			
A	4	5,148,404	458.34	70,674.2	71,132.6	0	4,251.88	4.41
B	5	4,629,708	0	63,030.4	63,030.4	0	4,194.00	4.68
C	6	5,956,983	0	82,017.4	82,017.4	0	4,499.26	4.95
D	7	5,220,679	0	64,489.3	64,489.3	0	4,314.88	5.01

It should be noted that the initial construction cost in Table 15 is systematically underestimated. This cost mainly consists of right-of-way, length-dependent, bridge, and earthwork cost; i.e., other costs required in road construction (such as drainage landscape architecture cost, traffic signal strain poles cost, etc.) and contingency cost are not included. It should be noted that penalty costs (tradeoff values) for the control areas taken by optimized alignments are not included in the initial construction cost (i.e., the penalty costs are subtracted from the objective function value)[7].

Figure 15 implies changes in objective function value over successive generations for four different optimized alignments. As shown in Figure 15, most of the improvement is found in the early generations, i.e., there is no great improvement of the objective function after about 60 generations. This indicates that the HAO model can provide reliable (though not optimized results) results quite quickly. It is noted here that the objective function value of optimized alignment A is relatively higher than those of the others. This is because alignment A affects type 1 areas more than those of others, so that more penalties are added to its objective fuction.

---

[7] The initial objective function used in this study is $C_T = C_R + C_L + C_E + C_S$ and the estimated initial construction cost is $C_T = C_R + C_L + C_E + C_S - C_{penalty}$. (Refer to HAO formulation on page 16.)

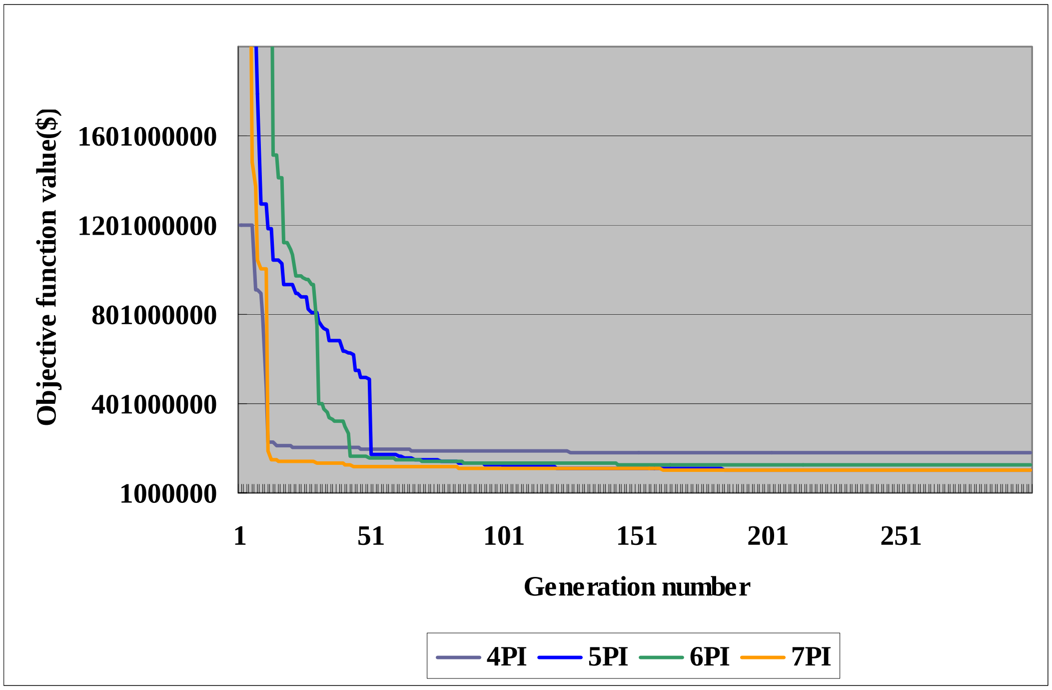
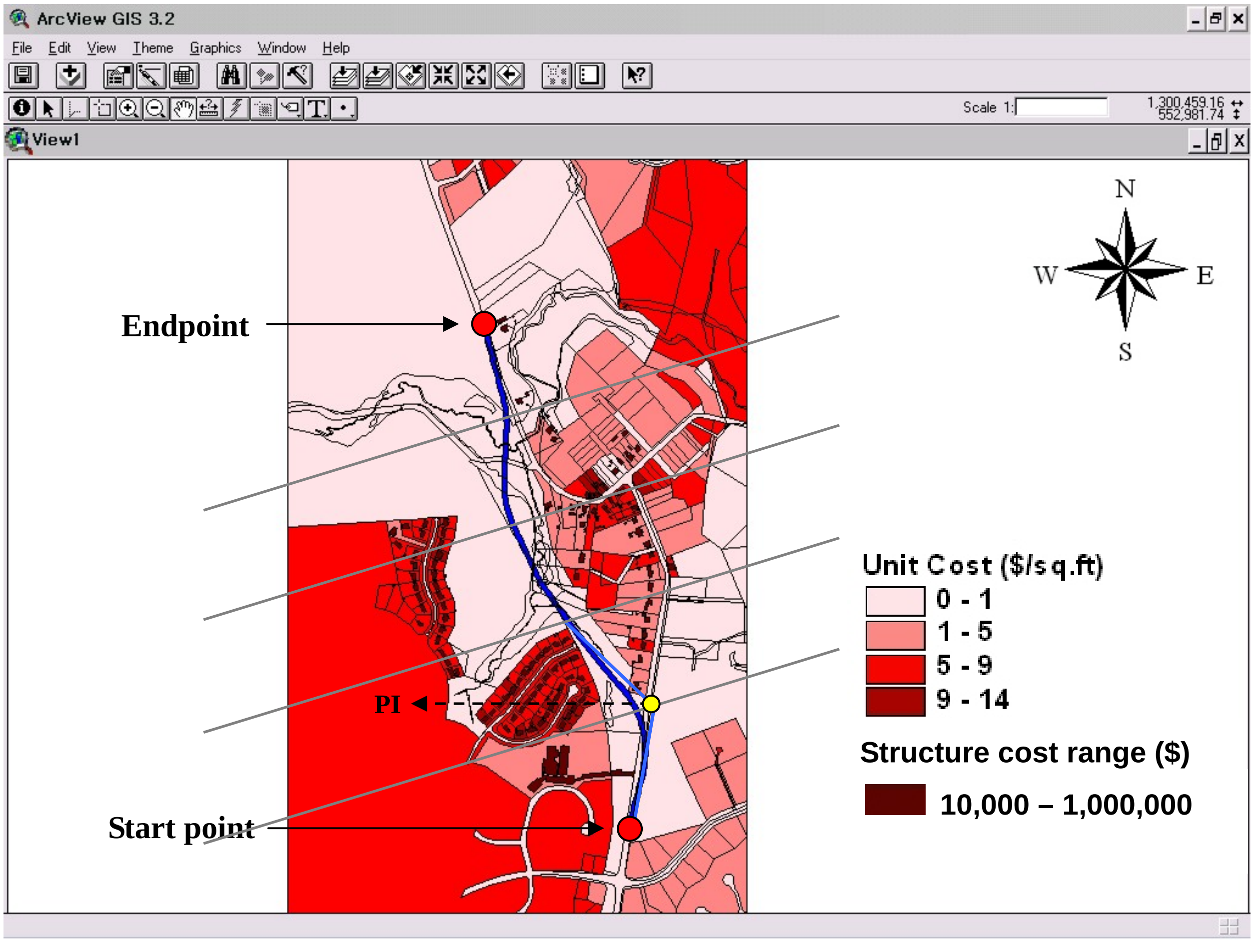
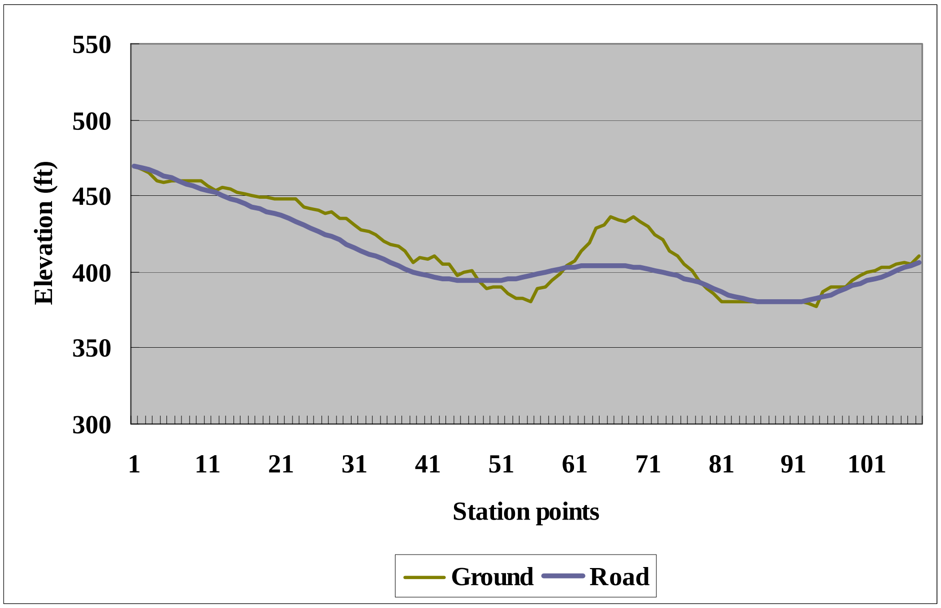


Figure 15. Changes in Objective Function Value over Successive Generation

Figures 16 to 19 show horizontal and vertical optimized alignments A to D. As stated previously, the horizontal alignments of all four alternatives are quite similar without affecting any wetland and structure; moreover, they do not require any land use change. Only alignment A affects a very slight residential area (305.96 sq. ft.) and the Longwood Community Center (152.38 sq. ft.). In addition, they use parklands and floodplains while minimizing the areas taken by them. These four optimized alignments have circular curves that satisfy the American Association of State Highway and Transportation Officials (AASHTO) minimum radius requirement (*11*) for safe movement of traffic at the specified design speed (50 mph). Various output details for optimized alignment B, such as cost breakdown for net total construction, environmental impact summary, coordinates, the information of horizontal and vertical curvatures, and earthwork volume per station are presented in the APPENDIX C.

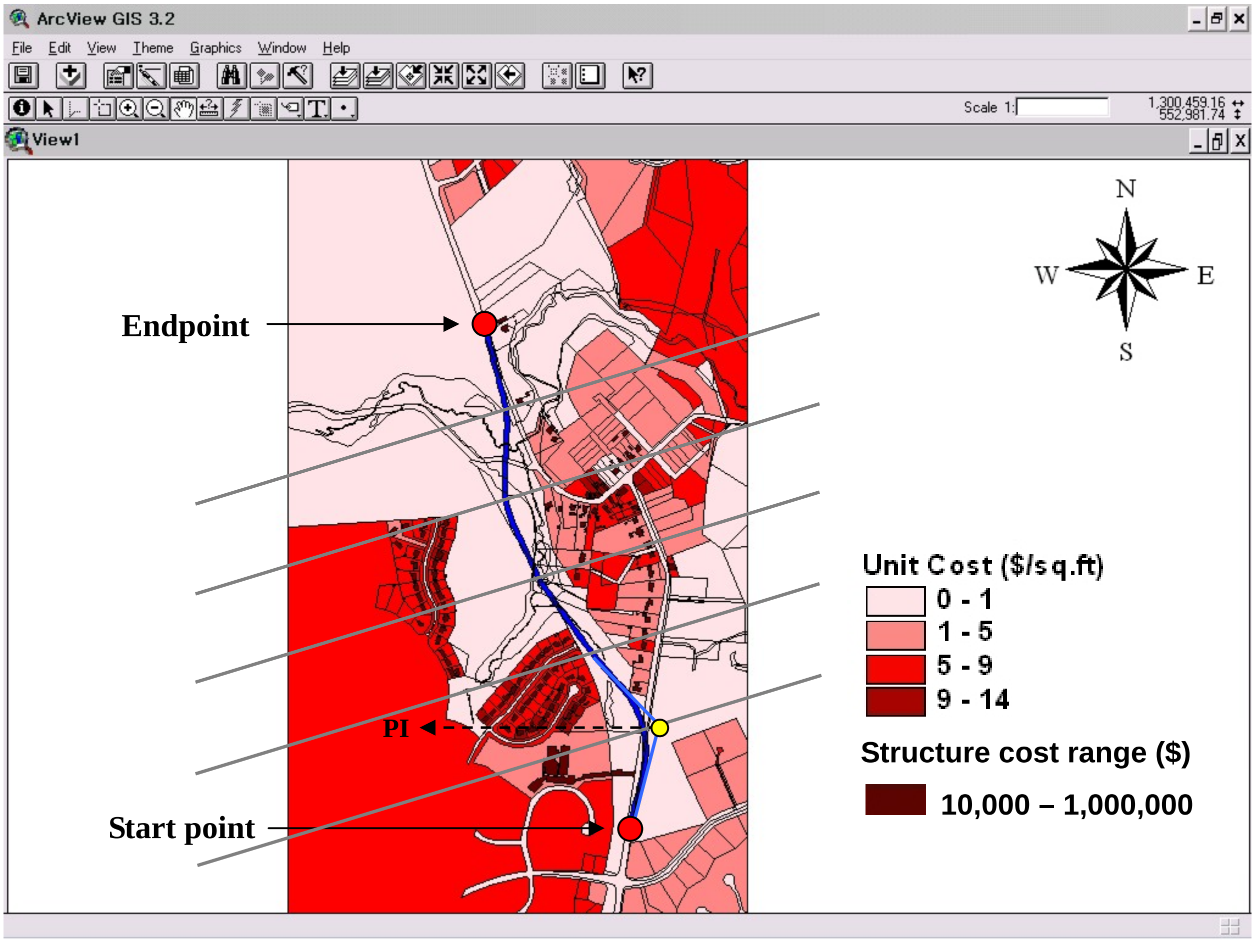


(a) Horizontal Alignment for A

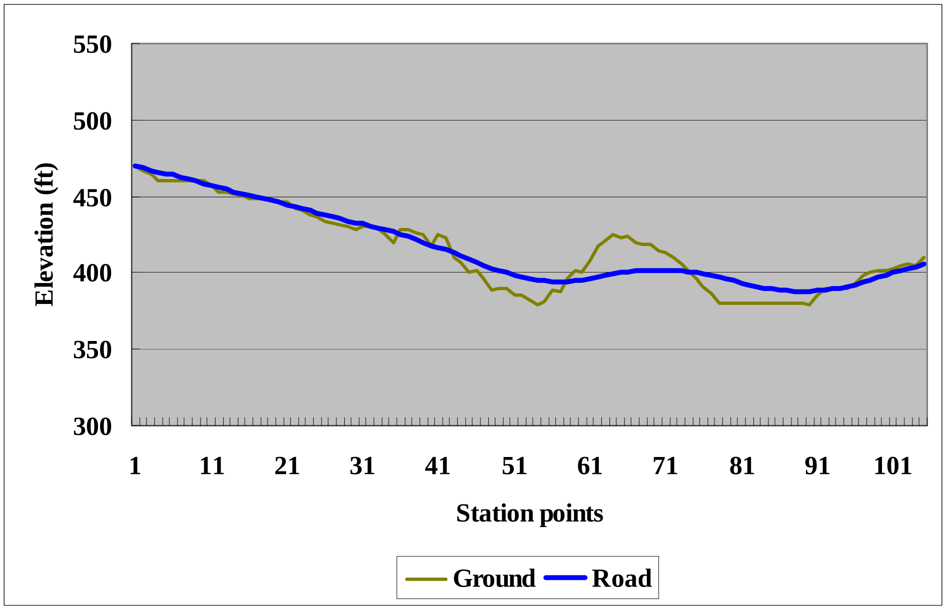


(b) Vertical Alignment for A

Figure 16. Optimized Alignment A with 4PI's

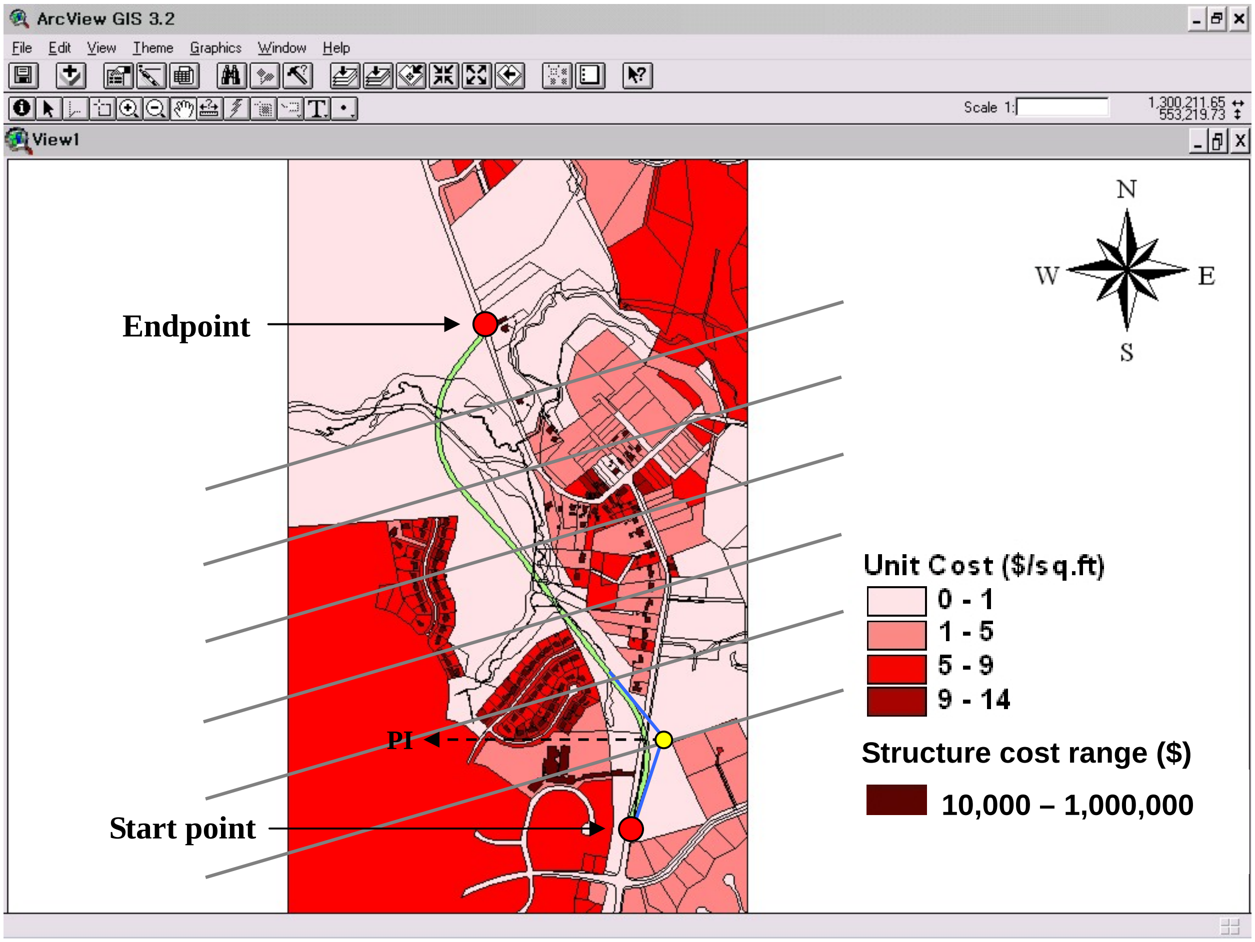


(a) Horizontal Alignment for B

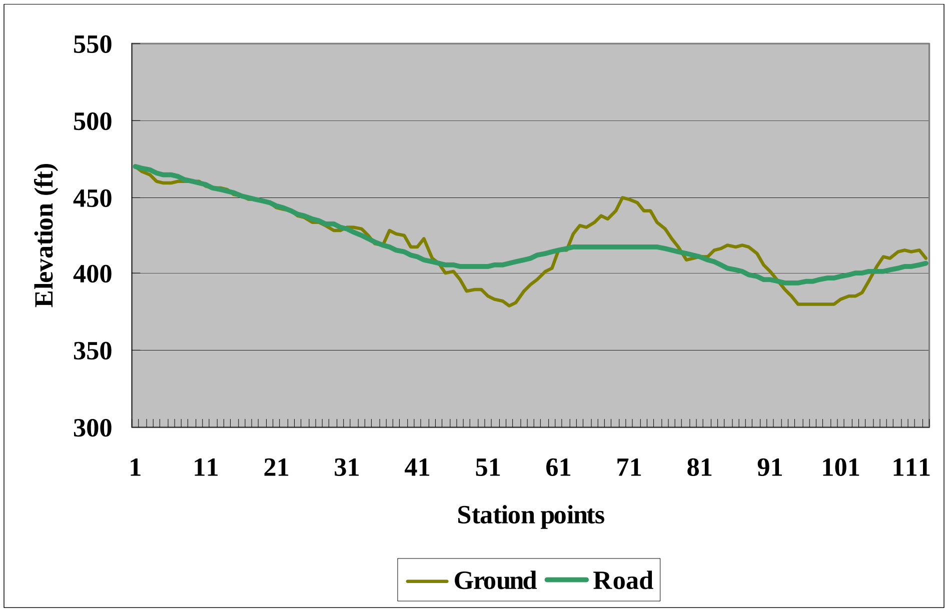


(b) Vertical Alignment for B

Figure 17. Optimized Alignment B with 5PI's

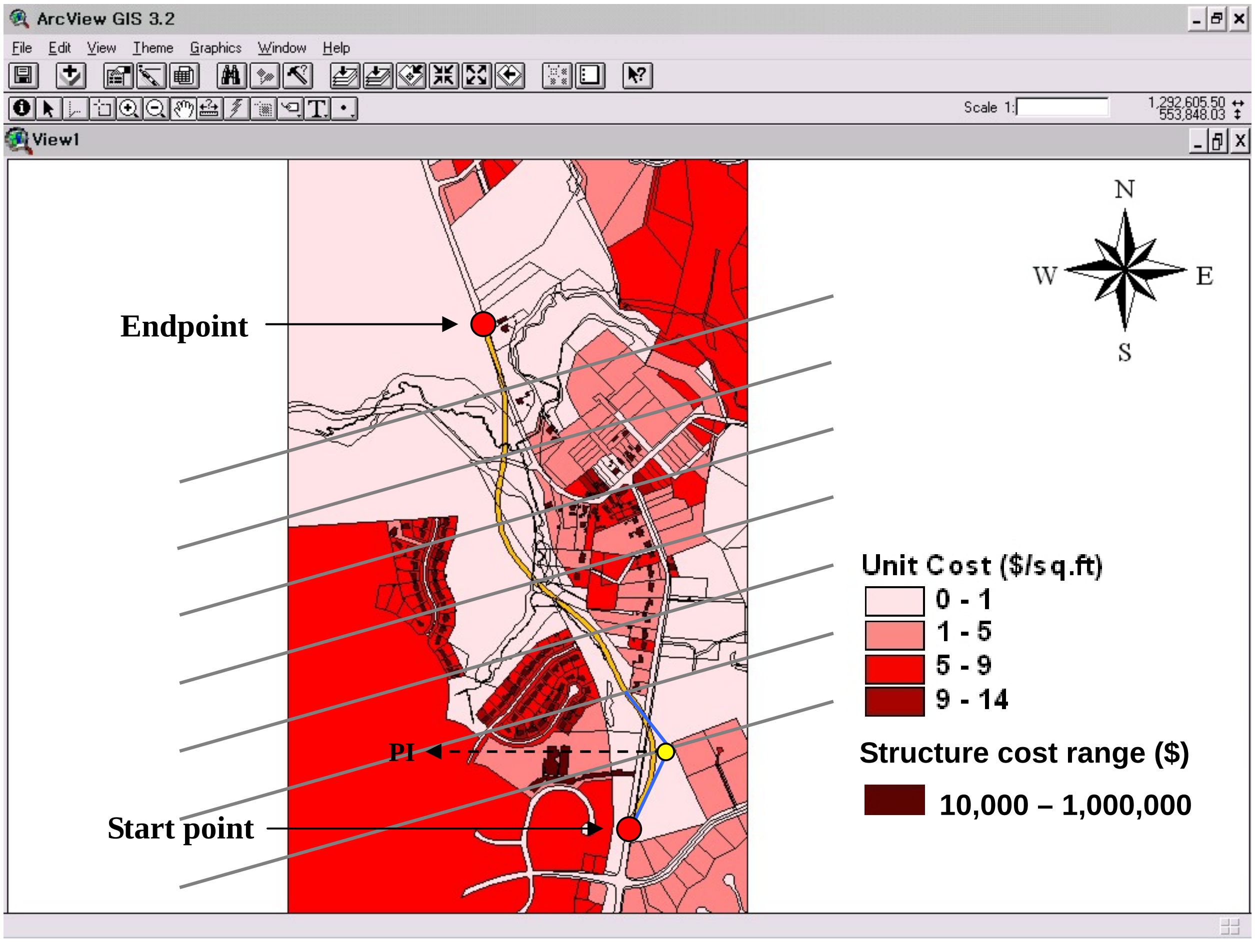


(a) Horizontal Alignment for C

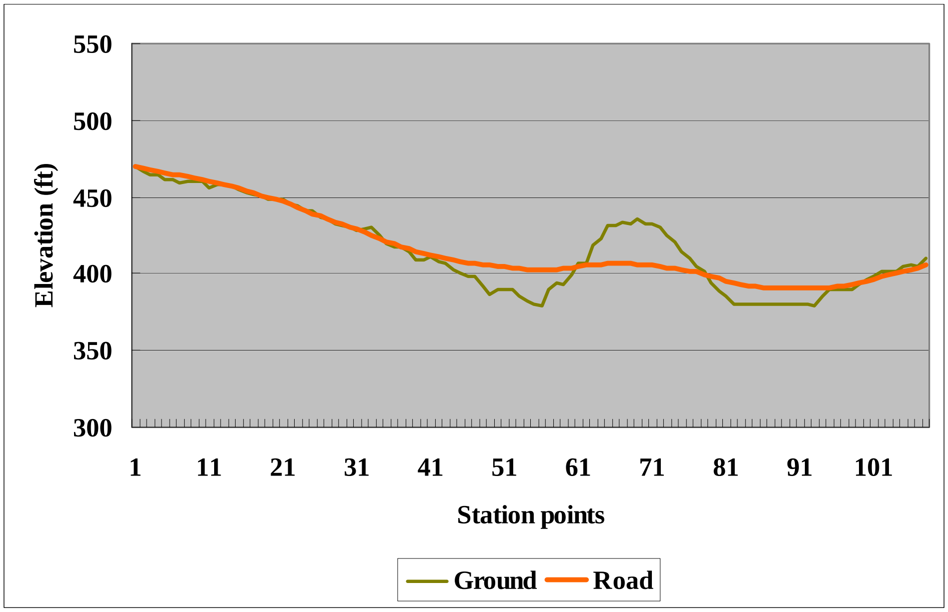


(b) Vertical Alignment for C

Figure 18. Optimized Alignment C with 6PI's



(a) Horizontal Alignment for D



(b) Vertical Alignment for D

Figure 19. Optimized Alignment D with 7PI's

3.4: Sensitivity to Other Major Input Parameters

This chapter presents sensitivity to other major input parameters of the HAO model (such as grid size, design speed, cross-section spacing, etc) besides number of PI's. To check the influence of these factors on the solution quality, several sensitivity analyses were conducted based on optimized alignment B, which is preferable in a previous sensitivity analysis. Input data values, used for optimized alignment B (shaded in Table 16), were employed as default values for each sensitivity analysis, and two different input values for each major input factor were applied for each sensitivity analysis. For instance, to check the sensitivity to grid size, 80ft *80ft and 120ft*120ft grids were also used, given that other factors' values (shaded) remain fixed.

Table 16. Analysis of Sensitivity to Other Major Input Parameters

Type of sensitivity analysis		Value		
Sensitivity to grid size		40 ft * 40 ft	80 ft * 80 ft	120 ft *120ft
Sensitivity to design speed		50 mph	40 mph	60 mph
Sensitivity to cross-section spacing		40 ft	30 ft	60 ft
Sensitivity to penalty cost for parklands		100×X	50×X	10×X
Sensitivity to Start and End points	Start point (X, Y)	1295645, 548735	1295750, 549400	1295645, 548735
	Endpoint (X, Y)	1294512, 552574	1294690, 552069	1294244, 553285
Sensitivity to unit length-dependent cost		400 $/ft	300 $/ft	200 $/ft
Sensitivity to crossing type with the existing roads		Grade Separation	Interchange (Diamond)	Intersection (4-leg)

Sensitivity to grid size

Figure 20 shows that the HAO model produces different optimized alignments depending on the grid size. As shown in Table 17, all three cases show striking differences in earthwork cost calculation; the earthwork cost significantly increases with rough grid size. This indicates that the HAO model may produce unreliable earthwork estimates if the gird sizes are too large, since terrain elevation estimates may then be too rough. Thus, a fine grid size is recommended in order to estimate earthwork cost more precisely.

Sensitivity to design speed

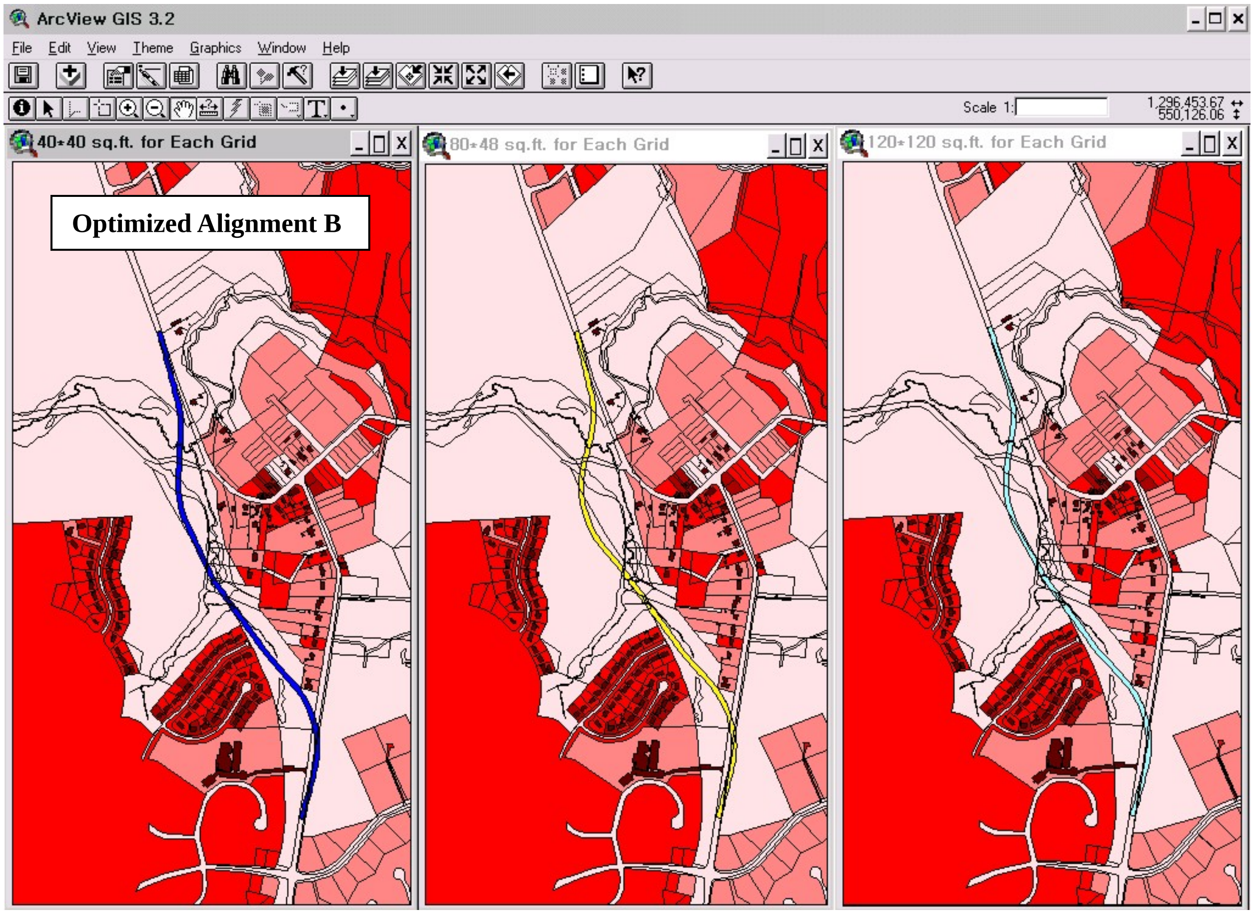
Table 18 and Figure 21 show that the HAO model satisfies horizontal design constraints very well as creating smooth horizontal curved section for higher design speed. As shown in Table 18, the generated minimum curve radius in each optimized alignment gets longer with higher design speed.

Sensitivity to cross-section spacing

Table 19 and Figure 22 present sensitivity to cross-section spacing, which is used as the earthwork computation unit in the HAO model. Table 19 indicates that the earthwork cost and alignment length can be varied depending on the unit cross-section spacing. In the HAO model, the cross-section spacing directly influences the precision of earthwork cost computations. Moreover, the alignment length also is affected by the overall earthwork cost since the HAO seeks to reduce all the considered costs that are affected by the alignment length. In general, however, the variation of earthwork cost due to the differences of cross-section spacing is not significant.

Table 17. Sensitivity to Grid Size

Unit grid size for elevation (ft*ft)	Initial construction cost($)	Earth-work cost($)	Environmental impact		Alignment length (ft)	Computation time (hr)
			The type 1 areas taken by alignments (sq.ft.)	Residential relocation (No.)		
40*40	4,629,708	1,819,516	0	0	4,194.00	4.68
80*80	6,177,558	3,029,621	0	0	4,261.00	5.04
120*120	6,315,492	3,415,125	0	0	4,223.43	4.63

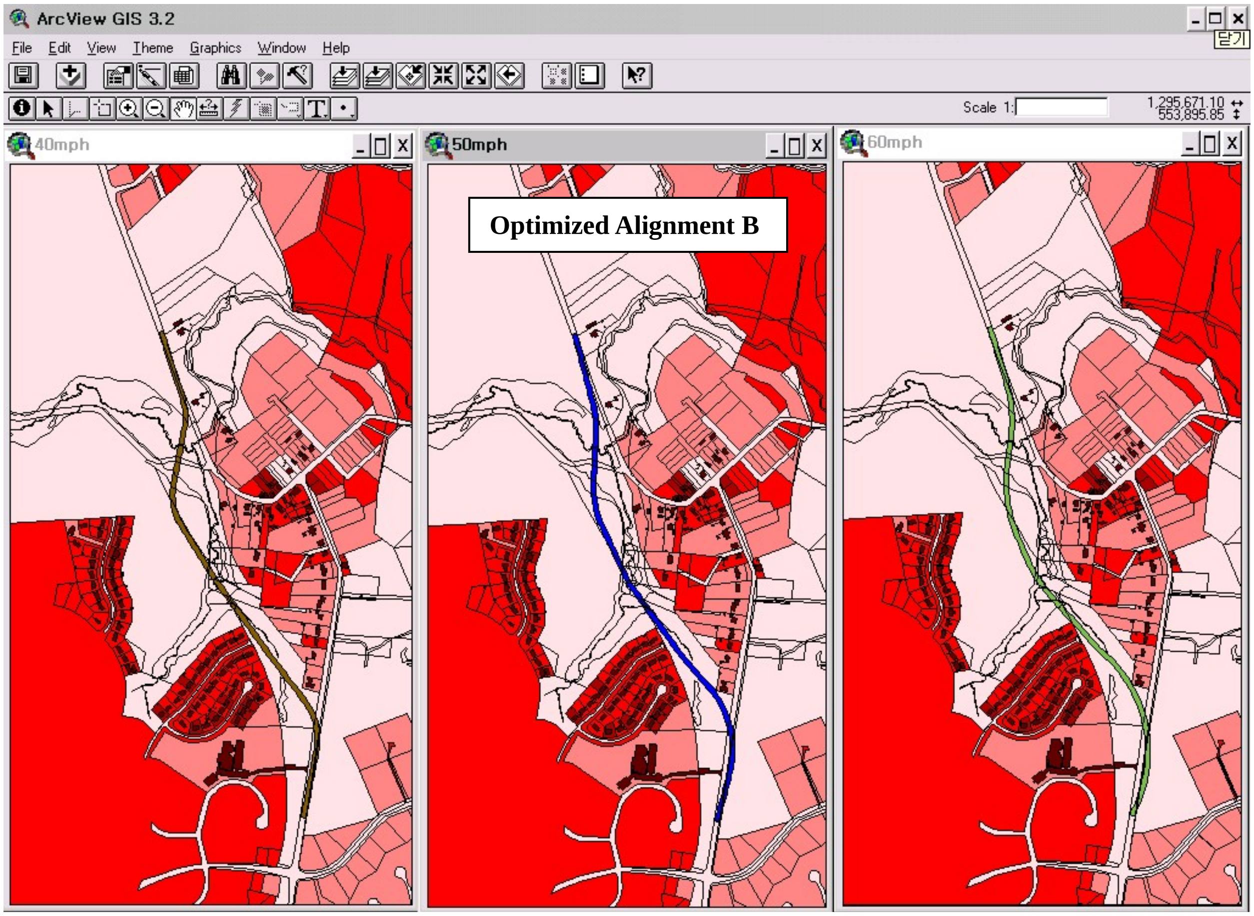


90*210 Grids (40ft*40ft for each) **45*105 Grids (80ft*80ft for each)** **30*70 Grids (120ft*120ft for each)**

Figure 20. Alignments Optimized with Different Elevation Grid Size

Table 18. Sensitivity to Design Speed

Design speed (mph)	Initial construction cost($)	Minimum curve radius (ft)	Environmental impact		Alignment length (ft)	Computation time (hr)
			The type 1 areas taken by alignments (sq.ft.)	Residential relocation (No.)		
40	4,821,618	485	0	0	4,233.96	4.62
50	4,629,708	758	0	0	4,194.00	4.68
60	4,939,938	1,032	0	0	4,232.22	4.67



40 mph

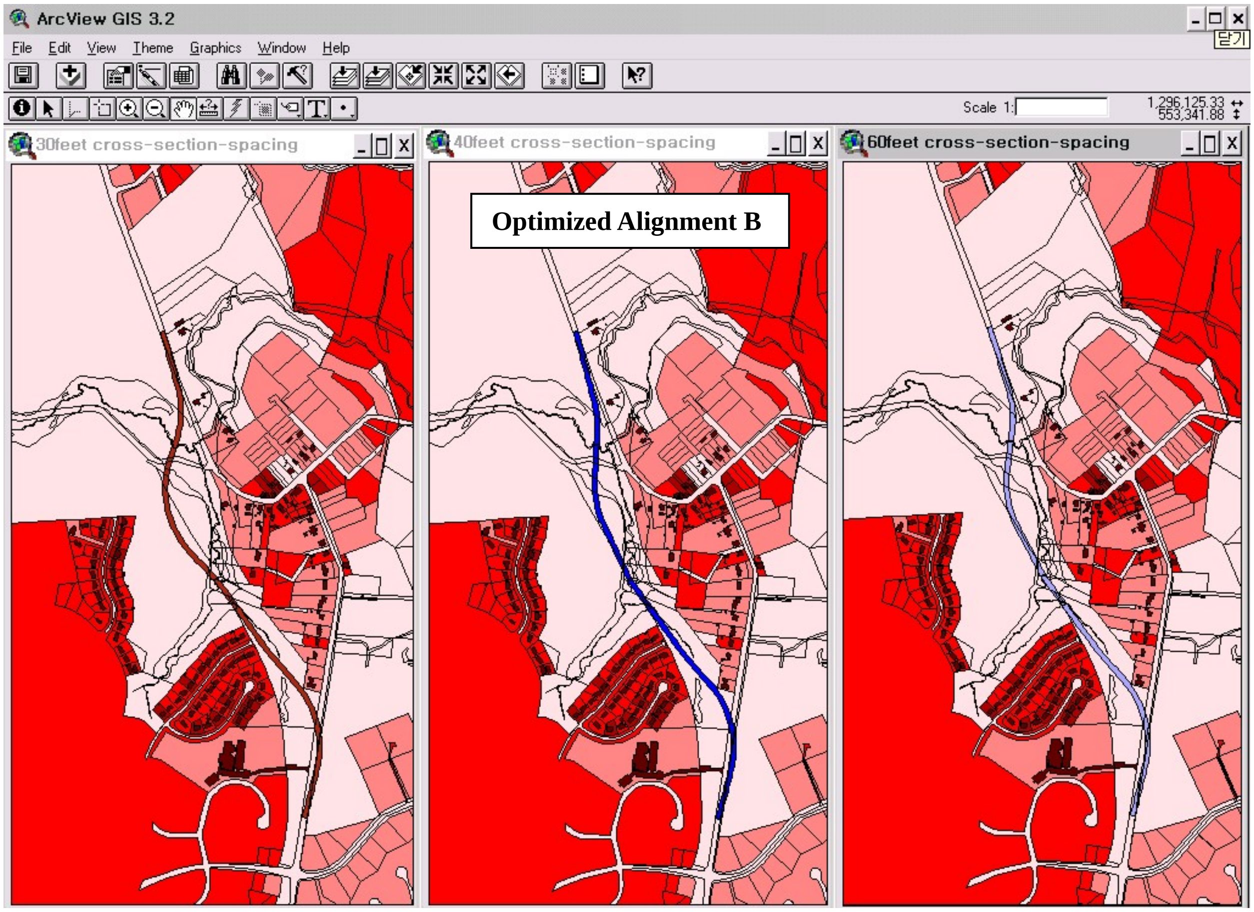
50 mph

60 mph

Figure 21. Alignments Optimized with Different Design Speed

Table 19. Sensitivity to Cross-section spacing

Cross-section spacing (ft)	Initial construction cost ($)	Earthwork cost ($)	Environmental impact		Alignment length (ft)	Computation time (hr)
			The type 1 areas taken by alignments (sq.ft.)	Residential relocation (No.)		
30	4,973,666	1,858,877	0.005	0	4,282.92	4.77
40	4,629,708	1,819,516	0.07	0	4,194.00	4.68
60	4,708,533	1,833,714	0	0	4,211,45	4.64



30 ft 40 ft 60 ft

Figure 22. Alignments Optimized with Different Cross-section spacing

Sensitivity to penalty costs for parklands

To explore the sensitivity of solutions to penalty costs for environmentally sensitive areas, we conducted a sensitivity analysis for parklands as an example case. This is aimed at checking how the proposed alignments vary depending on the penalty cost, which is imposed as the tradeoff value. Suppose that the impacts of the parklands are less significant than those of the floodplains. Then, it may be necessary to assign relatively low penalty costs to the parklands in order to minimize the impacts of the floodplains by the proposed alignment. As shown in Table 20 and Figure 23, the floodplains affected by the proposed alignments decrease with a lower penalty on the parklands, given that the penalty on the floodplains remains fixed at 100 × X (i.e., relatively higher penalty on floodplains); on the other hand, the affected parklands decrease. Here, as stated previously in Table 12, X (14 $/sq.ft.) is the maximum unit cost for land in the Brookeville study.

Among the three alignments in Figure 23, the initial construction cost for the first case is the lowest because the alignment is relatively shorter than the others. Note that there is no difference in unit penalty cost between on the parklands and floodplains in the first case in Table 20; thus, the HAO model seeks to reduce the alignment length as shown on the left side of Figure 23. However, if a decision maker is more concerned with minimizing floodplain impacts, other alignments may be preferred.

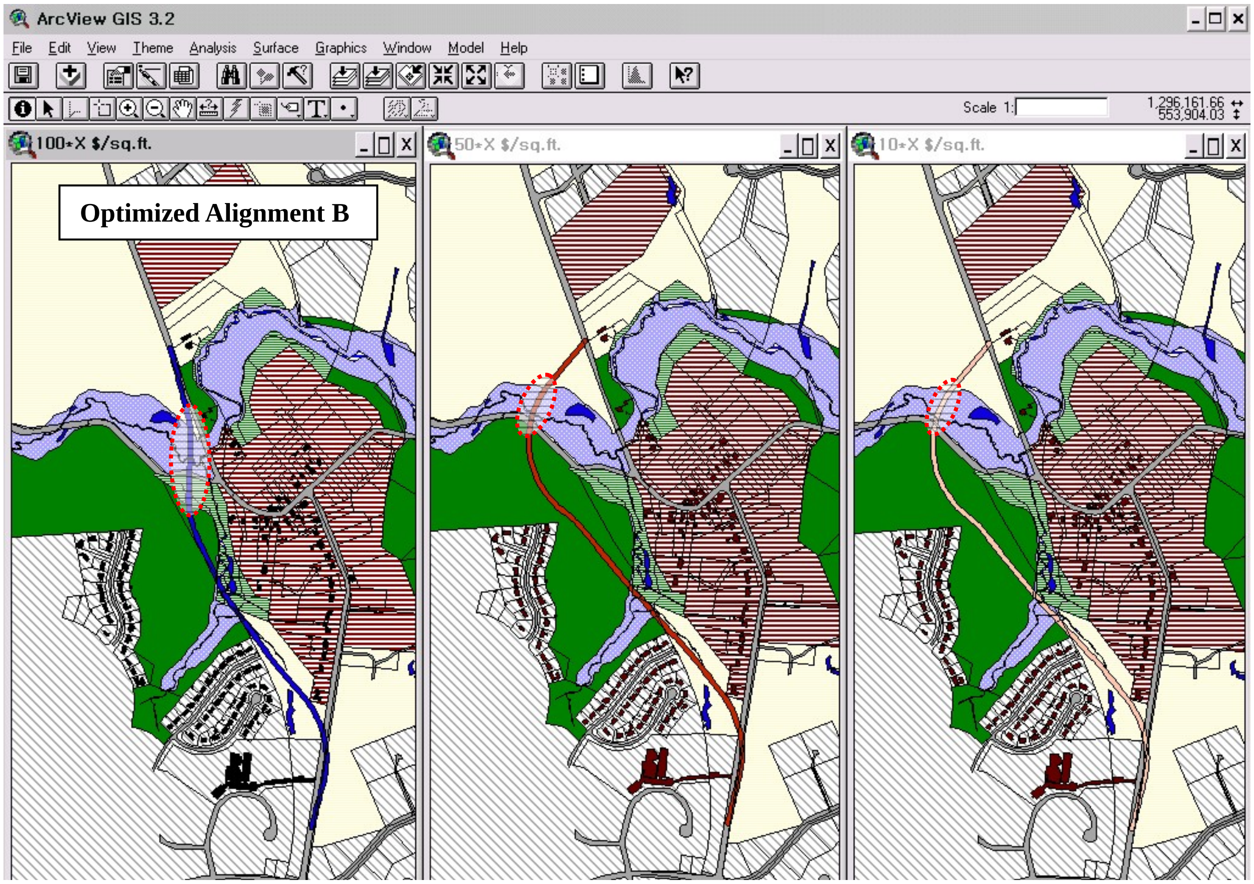
Sensitivity to start and end points

To check the sensitivity of the proposed alignment to different start and end points, we defined another two start and end points on the existing road, MD 97. (See Table 21 and Figure 24.) Although their initial construction costs and environmental impacts differ in terms of the alignment length, the shapes of three alignments do not significantly diverge within the study area. The alignment presented in Figure 25 is optimized alignment E, which is the third case of

Table 21. We considered the alignment E as an alternative of the Brookeville Bypass. An environmental impact summary for optimized alignment E is presented in APPENDIX B.

Table 20. Sensitivity to Penalty Cost for Parklands

Penalty cost to Parklands ($/sq.ft.)	Penalty to Floodplains ($/sq.ft.)	Initial construction cost ($)	Environmental impact				Alignment length (ft)
			Parklands affected (sq.ft.)	Floodplains affected (sq.ft.)	Type1 areas taken by alignments (sq.ft.)	Residential relocation (No.)	
100 × X	100 × X	4,629,708	24,882.60	32,876.59	0	0	4,194.00
50 × X	100 × X	6,432,767	63,945.00	23,114.76	0	0	4,591.11
10 × X	100 × X	6,193,078	65,722.14	22,584.24	0	0	4,586.74

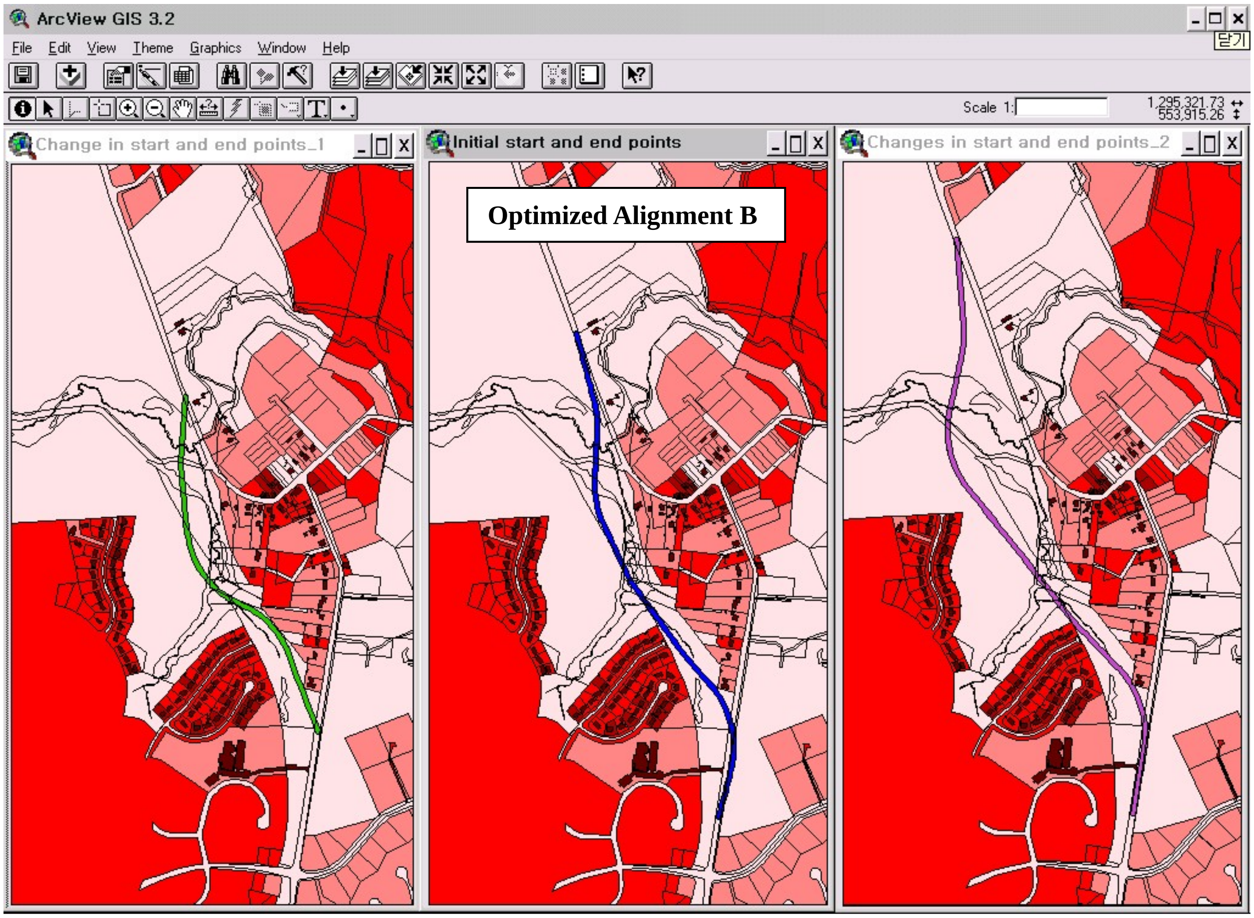


Penalty to Parklands: 100 × X **$/sq.ft.** 50 × X **$/sq.ft.** 10 × X **$/sq.ft.**

Figure 23. Alignments Optimized with Different Parklands Penalties

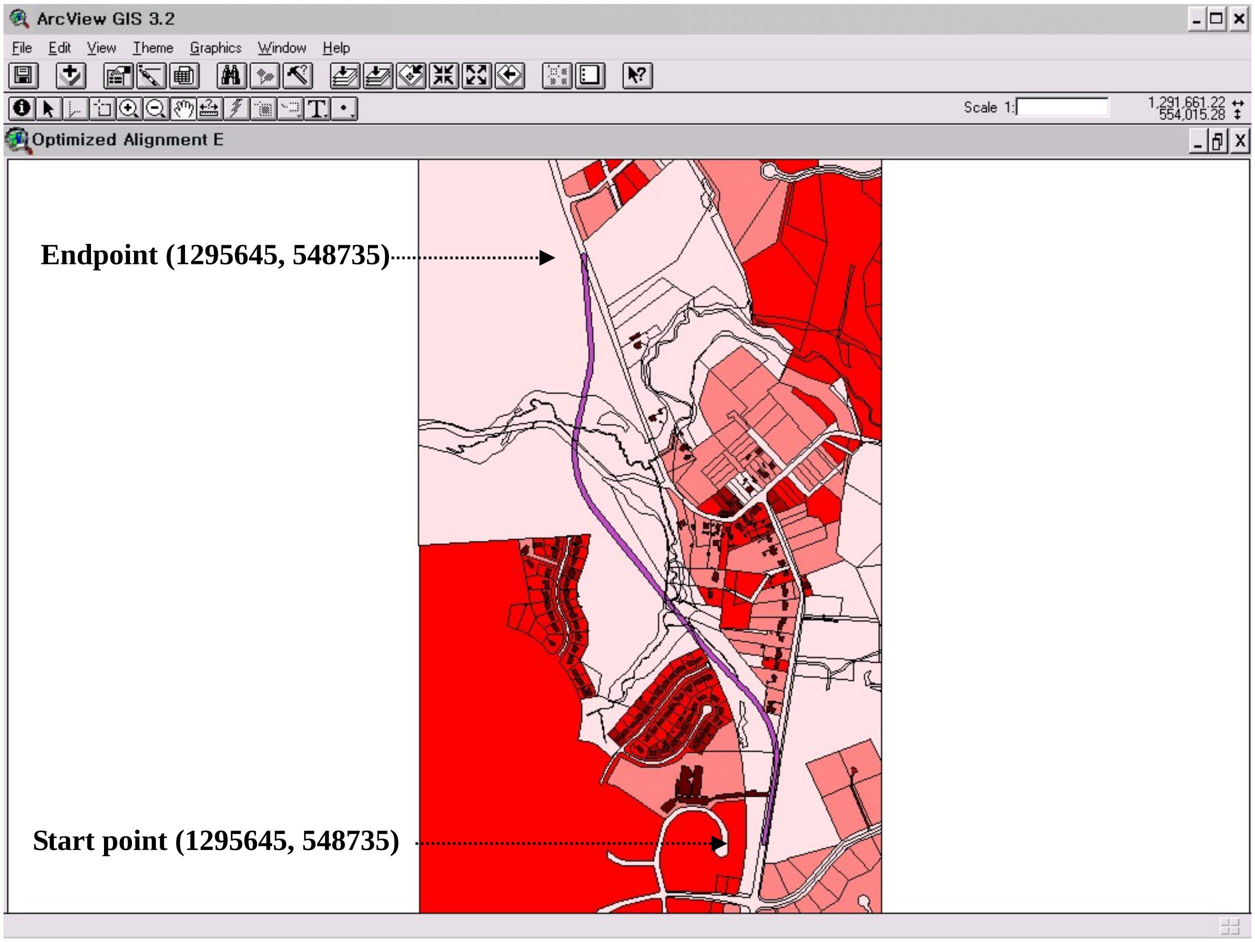
Table 21. Sensitivity to Start and End points

Start Point (X, Y)	Endpoint (X, Y)	Initial construction cost($)	Length-dependent cost ($)	Environmental impact		Alignment length (ft)
				Type 1 areas taken by alignments (sq.ft.)	Residential relocation (No.)	
1295750, 549400	1294690, 552069	4,055,949	1,224,610	72.45	0	3,061.53
1295645, 548735	1294512, 552574	4,629,708	1,677,600	0	0	4,194.00
1295645, 548735	1294244, 553285	7,436,002	2,039,954	423.15	0	5,099.88

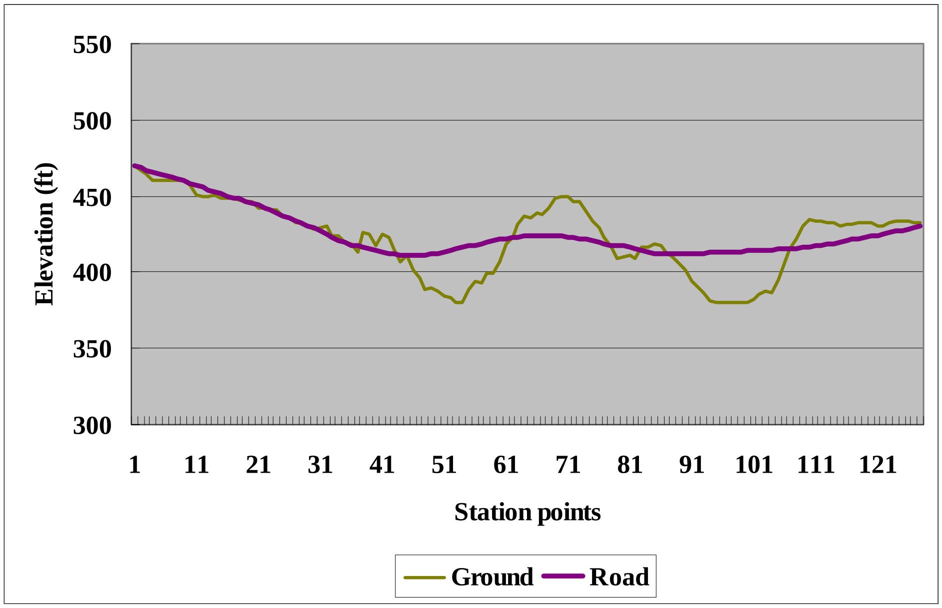


(1295750, 549400), (1294690, 552069) (1295645, 548735), (1294512, 552574) (1295645, 548735), (1294244, 553285)

Figure 24. Alignments Optimized with Different Start and End Points



(a) Horizontal Alignment for E



(b) Vertical Alignment for E

Figure 25. Optimized Alignment E

Sensitivity to unit length- dependent cost

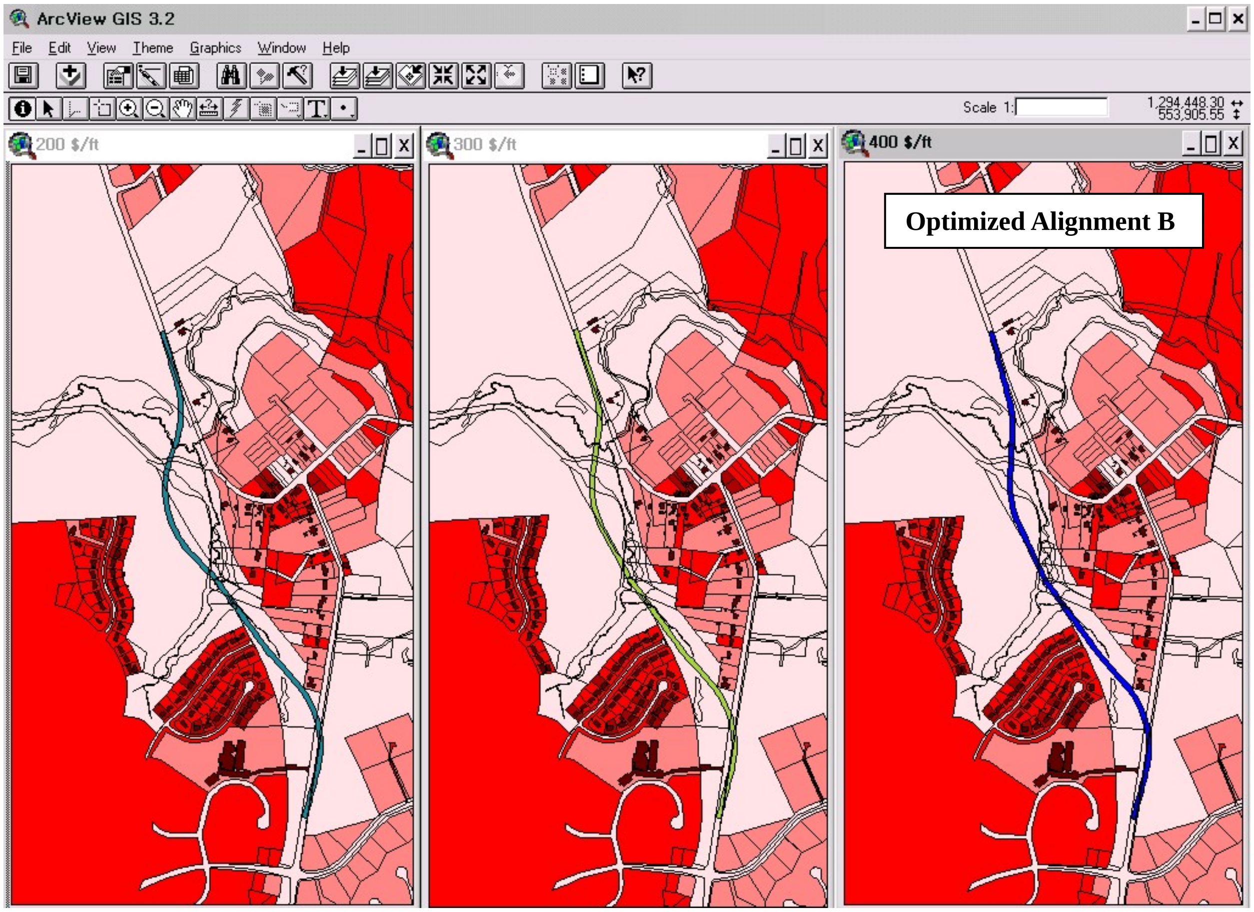
As shown in Table 22 and Figure 26, the alignment length and control areas taken by the proposed alignment differ depending on the pre-specified unit length-dependent cost. It seems that the initial construction cost increases with the higher unit length-dependent cost; however, this is not always true in the HAO model results. This occurs because the HAO model searches for the best alignment while simultaneously considering all the costs involved in the objective function and the tradeoffs in land use complexity in the search space. As shown in Table 22, the initial construction cost of the first case (200$/ft for unit length-dependent cost) is considerably higher than those of the other two (300 and 400$/ft, respectively), although the assigned unit length-dependent cost in the first case is well below than in the others. In fact, it may be expected that the initial construction cost for the second and third cases is considerably higher than for the first. However, since the alignment is longer in the first case than in the other two, many other major costs (such as earthwork cost, right-of-way cost, and bridge cost.) of the first case are higher than those of the others. In addition, the affected control areas in the first case are larger than in the other two. Accordingly, it should be noted that since the detailed output for the optimized alignment can differ depending on the pre-specified unit cost, it is recommended that sensitivity analyses be repeated for the different unit costs.

Sensitivity to crossing type with the existing road

Figure 27 shows optimized alignments, which have different crossing types with the existing roads (Grade separation, Diamond interchange, and 4-leg intersection). As stated previously, all the alternatives analyzed in this study (optimized alignments A to E) are assumed to have grade separation, without being connected with the existing (Brookeville) road.

Table 22. Sensitivity to Unit Length-Dependent Cost

Unit length-dependent cost ($/ft)	Initial construction cost ($)	Earth-work cost ($)	Length-dependent cost ($)	ROW cost ($)	Objective function value ($)	Environmental impact		Alignment length (ft)
						Calculated penalty ($)	Affected areas (sq.ft.)	
200	5,067,434	2,807,870	858,209	31,291	108,095,000	106,527,391	76,090.99	4,291.05
300	4,509,062	2,020,910	1,265,780	27,963	101,435,900	96,367,030	62,738.47	4,219.27
400	4,629,708	1,819,516	1,667,600	28,540	101,760,800	96,607,073	63,030.43	4,194.00

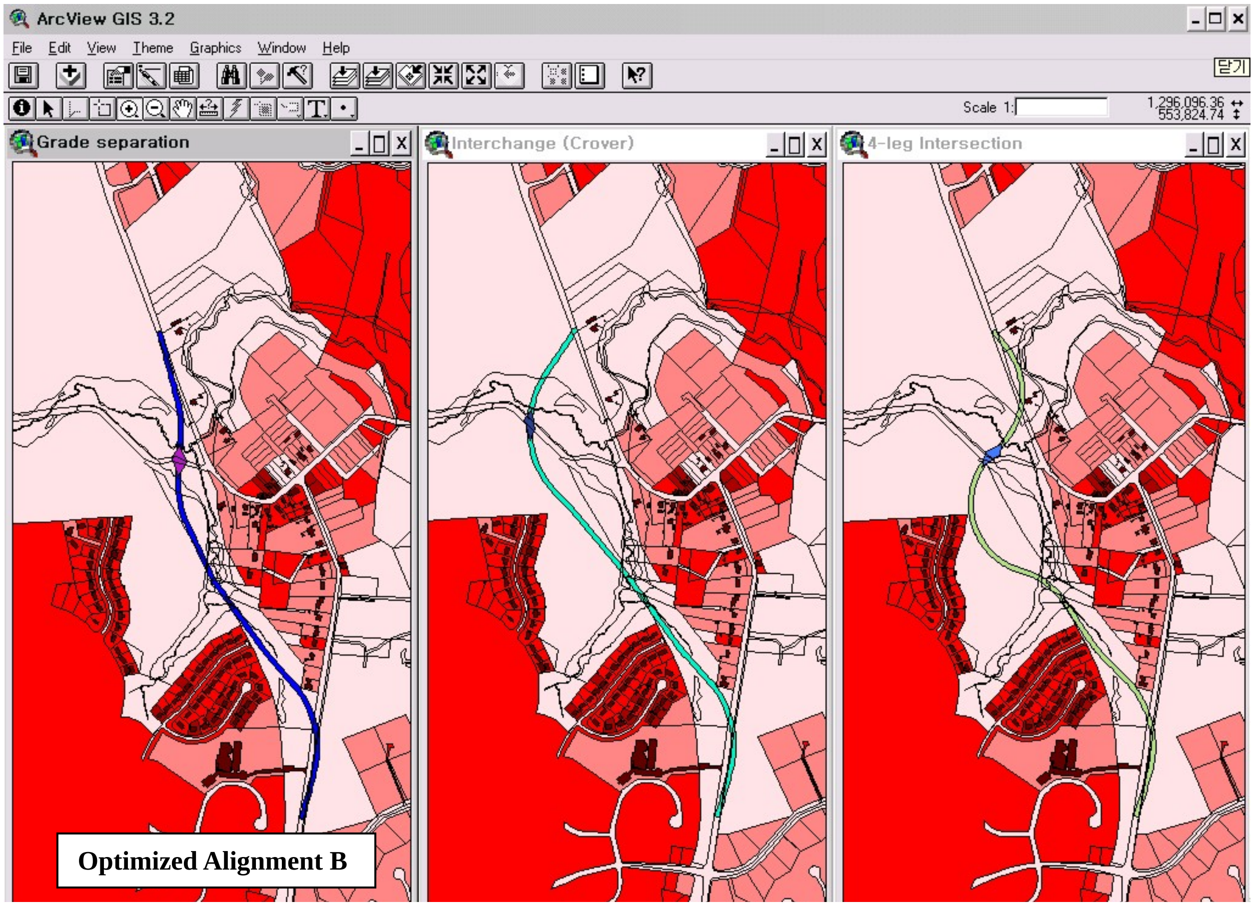


200 $/ft 300 $/ft 400 $/ft

Figure 26. Alignments Optimized with Different Unit Length-Dependent Cost

Table 23. Sensitivity to Crossing Type

Crossing type	Initial construction cost($)	Structure cost ($)							Length-dependent Cost ($)	Alignment length (ft)
		Super structure	Sub structure	Length-dependent[8]	Earth-work[10]	Right-of-way[10]	Bridge	Total		
Grade Separation	4,629,708	12,507	8,141	N/A	N/A	N/A	N/A	20,648	1,667,600	4,194.00
Interchange (diamond)	6,133,663	N/A	N/A	9,928	339,468	2,904	59,404	411,704	1,796,141	4,490.35
Intersection (4-leg)	6,957,770	N/A	N/A	11,809	37,385	2,521	N/A	51,715	1,855,115	4,637.79



Grade Separation **Interchange (Diamond)** **Intersection (4-leg)**

Figure 27. Alignments Optimized with Different Crossing Type with the Existing Road

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[8] These costs are only for access roads not for the main alignment

Chapter 4: Conclusions and Recommendations

4.1: Conclusions

Throughout the application of the HAO model to the Brookeville Bypass project, it has been shown that the HAO model can quickly evaluate the various alignments, which reflect various user preferences, and provide practical information for highway engineers to use in identifying and refining their design.

Several alternatives for the Brookeville Bypass were produced through the tradeoffs in map representation for different types of land use characteristics and through sensitivity analyses to various input parameters (such as number of PI's, grid size, and design speed). The optimized solutions were found without major difficulties and within reasonable computation times. They required only about 4.5 to 6.5 hours, despite the complexity of land use in the study area and the many iterations (over 6,500) that were run.

We expect that the HAO model should perform quite well in the initial road planning stage in finding preferable alternatives; moreover, the optimized results from the HAO model will be used in comparison of those obtained with conventional manual methods. In addition, we hope that this study will be helpful to users in becoming familiar with the HAO model and gaining an appreciation of the model's capabilities.

4.2: Recommendations

Despite its demonstrated capabilities, the HAO model can still benefit from various improvements in order to become more realistic and flexible in use. The following are some issues to be considered in near the future for enhancement of model performance. Several recommendations are offered below for near-term improvements to the HAO model.

1. Location and number of points of intersection (PI's)

The number of PI's is a key input parameter in the precision of the solutions since it affects location of horizontal and vertical curve sections and the calculated cost, especially the earthwork cost. Basically, in dense urban areas and areas with significant variation in the topography, a higher PI density will improve the precision of earthwork costs, whereas in areas with slight variation in topography or land use, fewer PI's will suffice. Therefore, it is recommended that the number of PI's should depend on the complexity of the search space and the PI's should be randomly distributed according to the geographic complexity of the control area.

2. Computation efficiency

In order to reduce computation time, it is recommended that a prescreening process be added. This process will be used to quickly eliminate undesirable alignments (such as alignments which do not satisfy AASHTO standards) early in the search process, before detailed evaluation. We expect this process will reduce the model's computation time, while refining alignments which satisfy all the applicable constraints.

3. Bridge and culvert analysis

Currently, the cost of a bridge is based on (1) width of the water flow that the proposed alignment crosses and (2) the crossing angle between them. However, the vertical clearance the alignment over high water levels is not determined internally within the HAO model. We should connect the HAO to a good hydrologic analysis model, such as

GISHydro, which is one of the Arc View GIS extensions used in Maryland. (It is documented on the http://www.gishydro.umd.edu, website.)

4. Minimize the effects on sensitive areas

In the current HAO model, penalty costs are imposed on environmentally sensitive areas to restrain the model's proposed alignment from affecting them. However, this method has some limitations when (1) several types of sensitive areas exist in the study area (e.g., type 1 and type 2 in the Brookeville project) and (2) a sensitive area can be taken for the alignment up to a certain level. These limitations may be overcome by introducing additional constraints to the HAO formulation, such as lower and upper bounds of allowable areas taken for the proposed alignment.

5. Crossing types with existing roads

Currently, the HAO model can handle limited crossing types with existing roads (such as, grade separation, 4-leg intersections, and diamond and interchanges). Introduction of additional crossing types, such as roundabout and 3-leg intersection will help overcome this limitation.

We expect that the HAO model will perform even better in optimizing highway alignments with the proposed improvements.

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APPENDIX A

Table 24. Available Output Results

Type of output	Contents	Unit
Costs breakdown for all searched alignments[9]	Earthwork costs (Ethw cost)	$
	Length-dependent costs (Lnth cost)	$
	Right-of-way costs (Lctn cost)	$
	Penalty costs for gradient (Grad cost)	$
	Penalty for vertical curve (Lnvc cost)	$
	Structure cost (Bridge cost)	$
	Alignment length (Length)	ft
Earthwork cost[10] (per station)	Elevation of alignments (Zr)	ft
	Cut volume (E_cutting)	Cubic yard
	Fill volume (E_filling)	Cubic yard
Detailed results for the optimized alignment[11]	PI Index for horizontal and vertical alignment	
	Number of horizontal and vertical curves	No.
	Horizontal curve radius	ft
	Length of vertical curves	ft
Coordinate of the optimized alignments[12] (X, Y)		X,Y coordinates
Environmental impact Summary[13]	Residential relocations	No.
	Affected properties	No.
	Areas affected by the optimized alignment	Sq.ft.

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[9] Recorded on “cost_number.txt and *.out” in working directory

[10] Recorded on “earth.txt” in working directory

[11] Recorded on “*.out” in working directory

[12] Recorded on “intcoord.txt” in working directory

[13] Summarized based on Arc View’s attribute table for the optimized alignment

APPENDIX B

Table 25. Environmental Impact Summary for Optimized Alignments A to E

Optimized alignments		**A**	**B**	**C**	**D**	**E**
Initial construction costs ($)		5,148,404	4,629,708	5,956,983	5,220,679	7,436,002
Length of the optimized alignment (ft)		4,251.88	4,194.00	4,499.26	4,314.88	5,099.88
Socio-economic resources	Affected residential area (sq.ft.)	305.96	0	0	0	5.56
	Residential relocations (no.)	0	0	0	0	0
	Affected Community Center (sq.ft.)	152.38	0	0	0	134.23
	Affected properties in Historic Districts (sq.ft.)	0	0	0	0	0
	Affected MC's reserved area (sq.ft.)	41,896.1	45,295.9	45,286.0	45,260.0	42,522.0
	Affected existing roads (sq.ft.)	39,152.1	29,609.1	17,037.6	25,227.4	36,012.8
Natural resources	Affected wetlands (sq.ft.)	0	0	0	0	0
	Affected floodplains (sq.ft.)	23,259.8	17,260.3	16,689.7	14,883.5	21,040.3
	Affected streams (sq.ft.)	690.5	777.6	634.9	610.7	697.0
	Affected parkland in Historic Districts (sq.ft.)	11,662.2	20,109.9	9,231.7	18,336.5	5,492.1
	Affected parkland (sq.ft.)	35,061.6	24,882.6	55,461.0	30,658.7	57,228.1

APPENDIX C

Detailed Model Outputs for Optimized Alignment B

Table 26. Breakdown of Initial Construction Cost for Optimized alignment B

Cost items	**Costs ($) and Fractions (%)**
Number of PI's	5PI's
Initial construction cost	4,629,708 (100)
Length-dependent cost[14]	1,677,600 (36)
Right of way cost[15]	2,8540 (1)
Earthwork cost	1,819,516 (39)
Grade separation cost[16]	52,402 (1)
Bridge cost	1,051,650 (23)
Alignment Length (ft)	4,194.00

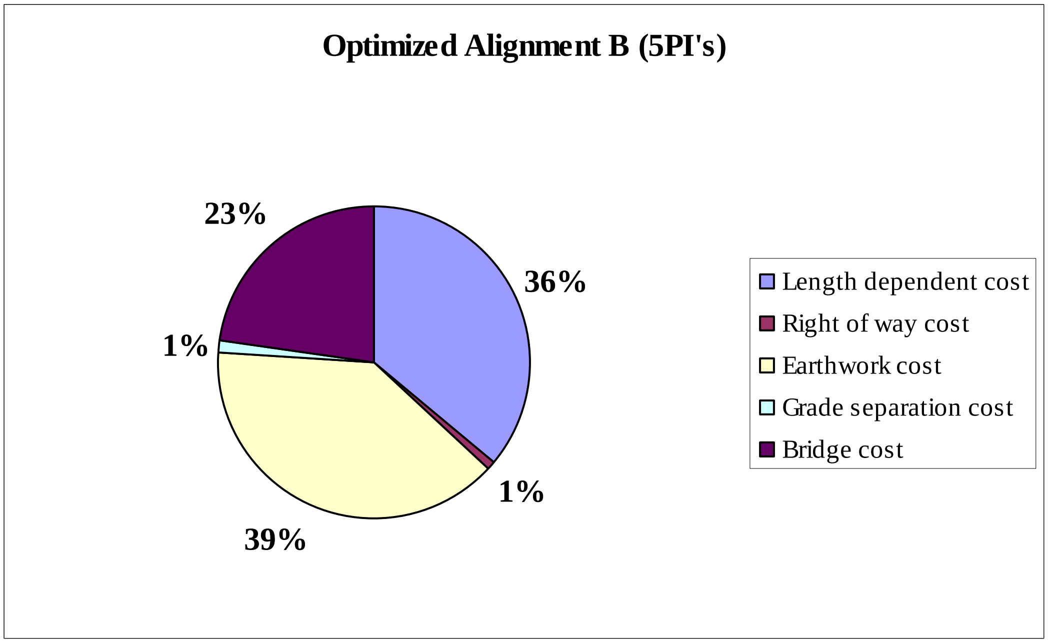

Figure 28. Fraction of Initial Construction Cost for Optimized Alignment B

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[14] Length- dependent cost mainly consists of pavement cost and sub and super structure cost on the road

[15] This value does not include the penalty cost for the affected control areas by optimized alignment B

[16] Grade separation crossing angle to the existing road: 79.9°

Table 27. IP index for Optimized Alignment B

```
Information about the optimal horizontal alignment
IP index         x coordinate         y coordinate       radius
==================================================
  Start        +1.295645e+006    +5.487350e+005    0
       1        +1.295838e+006    +5.494876e+005    758
       2        +1.295353e+006    +5.500400e+005    758
       3        +1.294938e+006    +5.506131e+005    758
       4        +1.294651e+006    +5.512238e+005    758
       5        +1.294682e+006    +5.519286e+005    758
    End        +1.294512e+006    +5.525740e+005    0
==================================================

Information about the optimal vertical alignment
IP index         h coordinate         z coordinate       length    of curve
===========================================================
  Start        +0.000000e+000    +4.700000e+002    0
       1        +7.449635e+002    +4.461491e+002    0
       2        +1.448087e+003    +4.238193e+002    258
       3        +2.155395e+003    +3.896502e+002    555
       4        +2.826530e+003    +4.064500e+002    690
       5        +3.527463e+003    +3.818313e+002    710
    End        +4.194000e+003    +4.070000e+002    0
===========================================================
```

Table 28. Earthwork Details for Optimized Alignment B

Station Points	Road Elevation(ft)	Ground Elevation(ft)	Cut Cost($)[17]	Cumulative Cut volume (cubic yard)	Fill Cost($)[16]	Cumulative Fill volume (cubic yard)
1	470	470	0	0.00	1789	89.45
2	467	469	0	0.00	6329	316.45
3	465	467	0	0.00	15371	768.55
4	460	466	0	0.00	27066	1353.30
5	460	465	0	0.00	35993	1799.65
6	460	464	0	0.00	41639	2081.95
7	460	462	0	0.00	44642	2232.10
8	460	461	713	20.37	44680	2234.00
9	460	460	2225	63.57	44680	2234.00
10	460	458	3365	96.14	44705	2235.25
11	457	457	3365	96.14	47606	2380.30
12	453	456	3365	96.14	52000	2600.00
13	453	455	3365	96.14	54698	2734.90
14	452	453	3365	96.14	56628	2831.40
15	451	452	3365	96.14	59761	2988.05
16	448	451	3365	96.14	63292	3164.60
17	448	450	3365	96.14	64965	3248.25
18	448	448	3365	96.14	65653	3282.65
19	447	447	3505	100.14	65900	3295.00
20	446	446	4937	141.06	65900	3295.00
21	446	444	5567	159.06	66113	3305.65
22	442	443	5567	159.06	67010	3350.50
23	441	442	5567	159.06	69665	3483.25
24	438	441	5567	159.06	73950	3697.50
25	437	439	5567	159.06	80033	4001.65
26	434	438	5567	159.06	88285	4414.25
27	433	437	5567	159.06	97550	4877.50
28	431	436	5567	159.06	106887	5344.35
29	430	434	5567	159.06	116301	5815.05
30	428	433	5567	159.06	123026	6151.30
31	430	432	5567	159.06	124880	6244.00
32	430	430	5567	159.06	125310	6265.50
33	429	429	5567	159.06	128614	6430.70
34	425	428	5567	159.06	139970	6998.50
35	420	427	11455	327.29	140642	7032.10
36	428	425	17881	510.89	140642	7032.10
37	428	424	25461	727.46	140642	7032.10
38	426	422	34341	981.17	140642	7032.10
39	425	420	39608	1131.66	140642	7032.10
40	418	418	39608	1131.66	150378	7518.90
41	425	416	59421	1697.74	150378	7518.90
42	423	415	67468	1927.66	150772	7538.60
43	410	413	67468	1927.66	156599	7829.95
44	407	411	67468	1927.66	171278	8563.90
45	400	409	67468	1927.66	188209	9410.45
46	401	407	67468	1927.66	204899	10244.95
47	396	405	67468	1927.66	235756	11787.80
48	389	403	67468	1927.66	271142	13557.10
49	390	401	67468	1927.66	298795	14939.75
50	390	400	67468	1927.66	330341	16517.05
51	385	398	67468	1927.66	365949	18297.45
52	385	397	67468	1927.66	403650	20182.50
53	382	396	67468	1927.66	451471	22573.55
54	379	395	67468	1927.66	497530	24876.50
55	381	395	67468	1927.66	522068	26103.40

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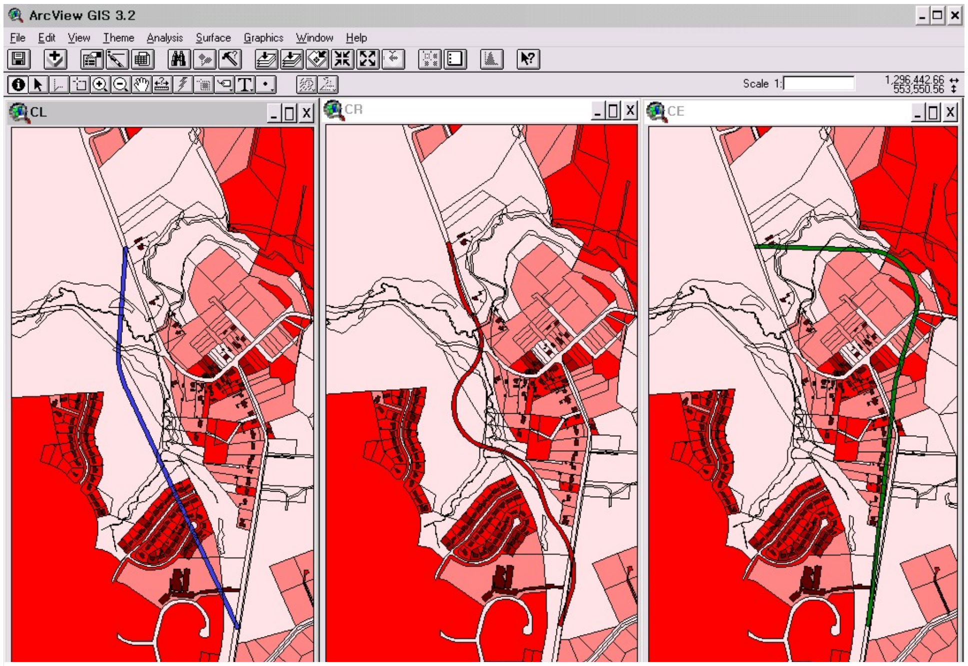
[17] Unit cut cost: 35 $/cubic yard, Unit fill cost: 20 $/cubic yard

Station Points	Road Elevation(ft)	Ground Elevation(ft)	Cut Cost($)	Cumulative Cut volume (cubic yard)	Fill Cost($)[16]	Cumulative Fill volume (cubic yard)
56	389	394	67468	1927.66	534829	26741.45
57	388	394	73412	2097.49	535169	26758.45
58	396	394	82080	2345.14	535169	26758.45
59	401	395	94441	2698.31	535169	26758.45
60	400	395	115002	3285.77	535169	26758.45
61	408	396	162414	4640.40	535169	26758.45
62	417	397	235235	6721.00	535169	26758.45
63	421	398	323702	9248.63	535169	26758.45
64	425	399	411393	11754.09	535169	26758.45
65	423	400	492479	14070.83	535169	26758.45
66	424	400	565125	16146.43	535169	26758.45
67	420	401	624002	17828.63	535169	26758.45
68	419	401	678280	19379.43	535169	26758.45
69	419	401	721787	20622.49	535169	26758.45
70	414	401	754013	21543.23	535169	26758.45
71	413	401	779268	22264.80	535169	26758.45
72	410	401	794158	22690.23	535169	26758.45
73	406	401	800767	22879.06	535169	26758.45
74	402	400	801150	22890.00	538195	26909.75
75	396	400	801150	22890.00	551665	27583.25
76	391	399	801150	22890.00	577139	28856.95
77	387	398	801150	22890.00	620684	31034.20
78	380	397	801150	22890.00	673696	33684.80
79	380	396	801150	22890.00	721991	36099.55
80	380	395	801150	22890.00	764267	38213.35
81	380	393	801150	22890.00	801039	40051.95
82	380	392	801150	22890.00	833251	41662.55
83	380	391	801150	22890.00	861768	43088.40
84	380	390	801150	22890.00	887361	44368.05
85	380	390	801150	22890.00	910722	45536.10
86	380	389	801150	22890.00	932480	46624.00
87	380	389	801150	22890.00	953218	47660.90
88	380	388	801150	22890.00	973884	48694.20
89	380	388	801150	22890.00	996331	49816.55
90	379	388	801150	22890.00	1012253	50612.65
91	385	389	804378	22982.23	1012390	50619.50
92	390	389	805367	23010.49	1012390	50619.50
93	390	390	805462	23013.20	1012622	50631.10
94	390	390	805462	23013.20	1014208	50710.40
95	390	391	806439	23041.11	1014258	50712.90
96	393	392	810579	23159.40	1014258	50712.90
97	398	394	819476	23413.60	1014258	50712.90
98	400	395	829099	23688.54	1014258	50712.90
99	401	397	835909	23883.11	1014258	50712.90
100	401	398	840746	24021.31	1014258	50712.90
101	403	400	846544	24186.97	1014258	50712.90
102	405	401	852866	24367.60	1014258	50712.90
103	406	403	856451	24470.03	1014258	50712.90
104	405	404	861343	24609.80	1014258	50712.90

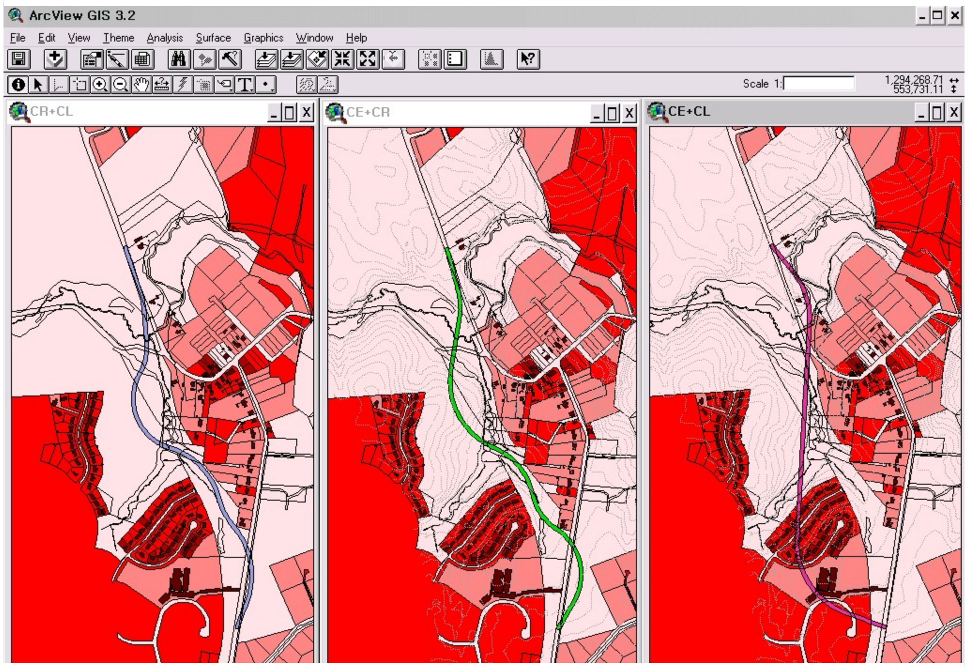
Table 29. Coordinates of Optimized Alignment B

Number	X	Y
1	1295645.000	548735.000
2	1295652.460	548764.058
3	1295659.921	548793.115
4	1295667.381	548822.173
5	1295674.841	548851.230
6	1295682.302	548880.288
7	1295689.762	548909.345
8	1295697.223	548938.403
9	1295704.683	548967.461
10	1295712.143	548996.518
11	1295719.604	549025.576
12	1295727.064	549054.633
13	1295734.524	549083.691
14	1295741.869	549112.777
15	1295748.235	549142.092
16	1295753.435	549171.636
17	1295757.462	549201.363
18	1295760.310	549231.225
19	1295761.974	549261.177
20	1295762.452	549291.171
21	1295761.743	549321.161
22	1295759.847	549351.099
23	1295756.769	549380.939
24	1295752.512	549410.633
25	1295747.083	549440.136
26	1295740.492	549469.401
27	1295732.747	549498.382
28	1295723.862	549527.034
29	1295713.851	549555.312
30	1295702.728	549583.172
31	1295690.511	549610.570
32	1295677.220	549637.463
33	1295662.876	549663.809
34	1295647.500	549689.567
35	1295631.117	549714.696
36	1295613.753	549739.157
37	1295595.434	549762.912
38	1295576.190	549785.924
39	1295556.398	549808.470
40	1295536.601	549831.010
41	1295516.804	549853.551
42	1295497.007	549876.091
43	1295477.210	549898.632
44	1295457.413	549921.172
45	1295437.616	549943.713
46	1295417.819	549966.254
47	1295398.022	549988.794
48	1295378.225	550011.335
49	1295358.808	550034.201
50	1295340.308	550057.815
51	1295322.615	550082.042
52	1295305.022	550106.342
53	1295287.429	550130.642
54	1295269.836	550154.942
55	1295252.244	550179.242
56	1295234.651	550203.542
57	1295217.058	550227.842
58	1295199.465	550252.142
59	1295181.872	550276.442
60	1295164.279	550300.742
61	1295146.686	550325.042
62	1295129.093	550349.342
63	1295111.501	550373.642
64	1295093.908	550397.942
65	1295076.315	550422.242
66	1295058.722	550446.542
67	1295041.129	550470.842
68	1295023.536	550495.142
69	1295005.943	550519.442
70	1294988.350	550543.742
71	1294970.883	550568.132
72	1294954.276	550593.114
73	1294938.670	550618.733
74	1294924.091	550644.950
75	1294910.560	550671.723
76	1294897.756	550698.853
77	1294884.974	550725.994
78	1294872.192	550753.135
79	1294859.410	550780.275
80	1294846.628	550807.416
81	1294833.846	550834.557
82	1294821.064	550861.697
83	1294808.282	550888.838
84	1294795.499	550915.979
85	1294782.717	550943.120
86	1294769.935	550970.260
87	1294757.153	550997.401
88	1294744.371	551024.542
89	1294731.589	551051.683
90	1294719.247	551079.024
91	1294707.992	551106.831
92	1294697.846	551135.061
93	1294688.824	551163.670
94	1294680.942	551192.614
95	1294674.211	551221.847
96	1294668.642	551251.324
97	1294664.244	551280.998
98	1294661.023	551310.822
99	1294658.985	551340.751
100	1294658.132	551370.737
101	1294658.467	551400.733
102	1294659.729	551430.706
103	1294661.059	551460.677
104	1294662.388	551490.647
105	1294663.718	551520.618
106	1294665.048	551550.588
107	1294666.378	551580.559
108	1294667.707	551610.529
109	1294669.037	551640.500
110	1294670.367	551670.470
111	1294671.696	551700.441
112	1294673.026	551730.411
113	1294674.356	551760.382
114	1294675.685	551790.353
115	1294676.984	551820.324
116	1294677.450	551850.319
117	1294676.728	551880.308
118	1294674.820	551910.245
119	1294671.729	551940.084
120	1294667.460	551969.777
121	1294662.020	551999.277
122	1294655.416	552028.539
123	1294647.872	552057.575
124	1294640.239	552086.587
125	1294632.605	552115.600
126	1294624.972	552144.613
127	1294617.339	552173.625
128	1294609.706	552202.638
129	1294602.072	552231.651
130	1294594.439	552260.663
131	1294586.806	552289.676
132	1294579.173	552318.689
133	1294571.539	552347.701
134	1294563.906	552376.714
135	1294556.273	552405.726
136	1294548.640	552434.739
137	1294541.006	552463.752
138	1294533.373	552492.764
139	1294525.740	552521.777
140	1294518.107	552550.790
141	1294512.000	552574.000

APPENDIX D



$C_T = C_L + C_S$ $C_T = C_R + C_S$ $C_T = C_E + C_S$



$C_T = C_L + C_R + C_S$ $C_T = C_L + C_E + C_S$ $C_T = C_R + C_E + C_S$

Figure 29. Alignments Optimized with Reduced Components of the Objective Function[18]

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[18] The initial objective function used in this study is $C_T = C_R + C_L + C_E + C_S$. (Refer to HAO formulation on page 16.)