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A highway alignment optimization model using geographic information systems

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Abstract

Highway alignment optimization based on cost minimization requires comprehensive formulation of costs sensitive to alignment and development of efficient solution algorithms. The complexity of the applicable cost functions severely limits the search algorithms that can be employed. Recently, genetic algorithms, which can search very effectively through complex spaces with huge numbers of local optima, have been successfully developed for highway alignment optimization. However, in order to solve real-world problems the optimization algorithms should work directly with a Geographic Information System (GIS) which stores relevant geographic information, such as land boundaries, environmentally sensitive regions, and topographic data. This paper presents a model for highway alignment optimization that integrates a GIS with genetic algorithms, examines the effects of various costs on alignment selection, and explores optimization in constrained spaces that realistically reflect the limits on road improvement projects. The paper integrates several previously published developments and adds some new analysis approaches. A real-world problem using a GIS database for Maryland is solved using the proposed method. An example using an artificial map to investigate the effectiveness of the proposed model in mountainous terrain is also demonstrated. The results indicate that travel-time cost, which is often neglected by highway agencies in selecting alignments, significantly affects the alignment optimization. Computation time increases significantly with the number of properties affected by each alignment. The model can optimize alignments in mountainous terrain or regions with very complex geography.

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1. Introduction

The development of automated models for optimizing highway alignments is very challenging. It requires capturing all sensitive and dominant costs, developing efficient solution algorithms, and working with real Geographic Information System (GIS) maps. A dominating cost is one which generally accounts for a relatively high percentage of the total cost. A sensitive cost is one which varies significantly with design features. A dominating cost is not necessarily a sensitive cost. For example, in vertical alignment optimization vehicle operating costs are dominant but not sensitive to design changes since vehicle descents roughly compensate for climbs provided no steep ascents or descents are involved. A number of costs are considered for highway construction by the highway agencies of which the most significant are right-of-way and construction (including earthwork and pavement) costs. Highway alignment optimization models (Jong, 1998; Jha, 2000) seek to optimize highway alignments by minimizing total cost. Since decisions are not solely made based on cost minimization, tradeoffs among various cost components may have to be explored based on their relative significance.

A good highway alignment optimization model should have the following characteristics (Jong, 1998): (1) consider all dominating and sensitive costs, (2) formulate all important constraints, (3) yield a realistic alignment, (4) be able to handle alignments with backward bends, (5) simultaneously optimize horizontal and vertical alignments, (6) find globally or near globally optimal solution, (7) have an efficient solution algorithm, (8) have a continuous search space, (9) consider intersection, interchange, bridge, and tunnel costs, (10) automatically avoid inaccessible regions, and (11) be compatible with a GIS. A number of classical optimization methods (Howard et al., 1968; Thomson and Sykes, 1988; Shaw and Howard, 1981, 1982; OECD, 1973; Turner and Miles, 1971; Turner, 1978; Athanassoulis and Calogero, 1973; Parker, 1977; Trietsch and Handler, 1985; Trietsch, 1987a,b; Hogan, 1973; Nicholson et al., 1976) such as calculus of variation, dynamic programming, numerical search, linear programming, and network optimization have been employed for highway optimization). Most of these methods lacked one or more of the above mentioned characteristics of a highway alignment optimization model. Moreover, most of these methods neglect some costs which are difficult to represent as explicit functions of decision variables. Some of these methods unrealistically require the cost functions to be linear or at least smooth.

Genetic algorithms (Jong, 1998; Jong and Schonfeld, 2003) have been proved to be effective in optimizing highway alignments, especially due to their effectiveness in simultaneously optimizing horizontal and vertical alignments by exploring a better solution through successive generations while exploiting the entire search space without getting stuck in local optima. These algorithms can simultaneously optimize horizontal and vertical alignments and can work directly with real GIS maps for real-world applications while generating a smooth and continuous alignment (i.e., an exact alignment rather than a corridor). However, the users may use separate procedures for vertical alignment optimization such as the one suggested by Trietsch and Handler (1985) and only use genetic algorithms for horizontal alignment optimization. This might reduce computation time but restrict the objective function to proven convex forms, while a genetic algorithm approach for both horizontal and vertical alignment optimization allows the use of more realistic cost functions, including unsmooth ones.

The genetic algorithms developed by Jong (1998), and Jong and Schonfeld (2003), relied on manual inputs and worked only with artificial maps. They were not sufficient for real-world problems where thousands of land parcels with complex environmental features must be analyzed. To solve real-world problems while considering complex land and environmental features, highway optimization algorithms should work with a GIS that stores all geographic information of interest. Jha and Schonfeld (2000a) integrated genetic algorithms with GIS using specialized dynamic link libraries enabling dynamic communication during optimal search. While such integration allows direct use of real maps and databases, it significantly increases the computation time. That increase is primarily attributable to: (1) spatial analyses required in the GIS computing environment, (2) numerous geographic entities (such as land parcels, environmentally sensitive regions, and existing highway networks) in the search space, and (3) numerous alignment alternatives to be evaluated by the genetic algorithms. Jha (2000) shows that the computation time increases with the number of geographic entities (i.e., land parcels, streams, roads, etc.) in the

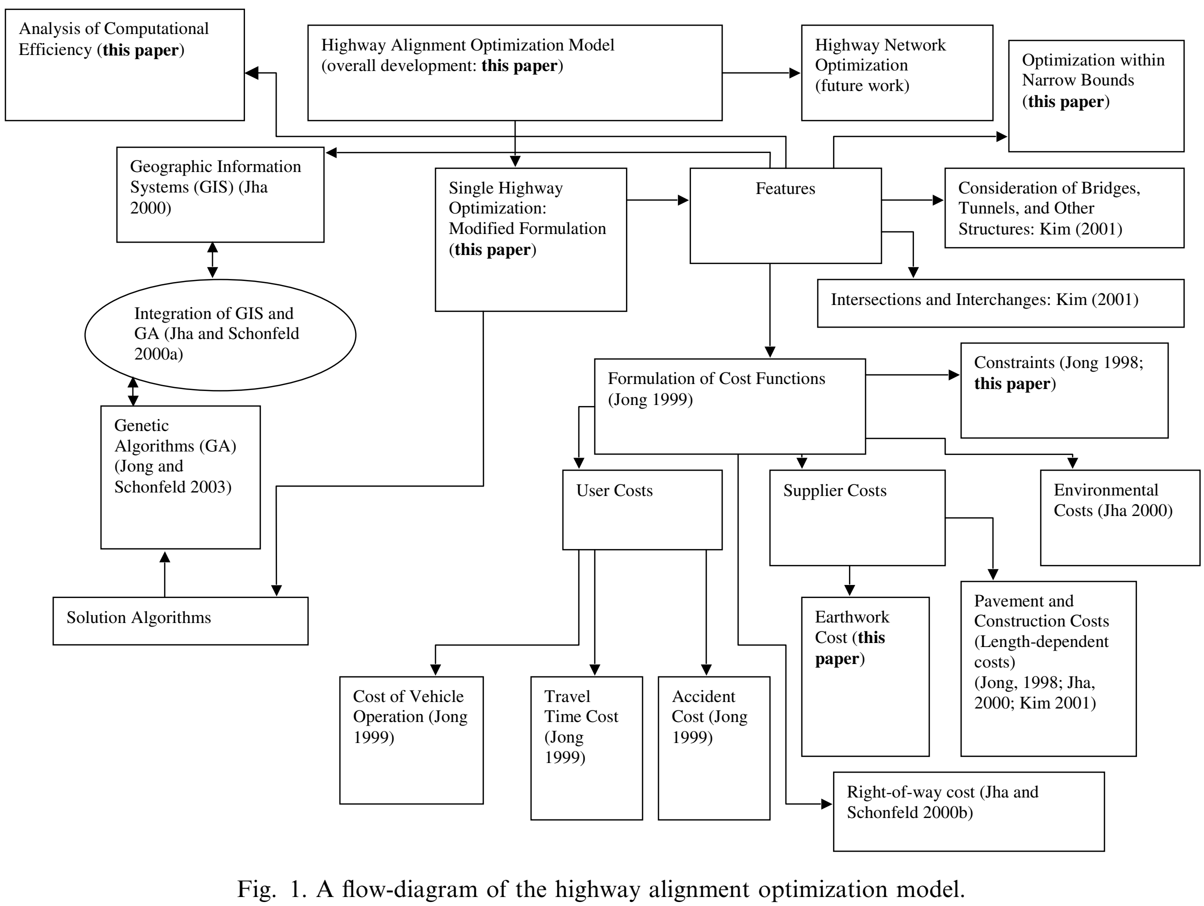


Fig. 1. A flow-diagram of the highway alignment optimization model.

search space. That time increases linearly for up to 100,000 entities, after which it increases with approximately the 1.2 power of the number of entities.

The present work extends the methods developed in Jong (1998) and Jong and Schonfeld (2003) to a more practical highway optimization model which can work with GIS databases and maps. A comprehensive formulation of major costs emphasizing those that are sensitive to geography is developed. The effects of a constrained search space on computing efficiency and the relative significance of various cost components are also explored. It should be noted that the authors have studied the highway alignment optimization problem since 1996 and published several papers on it, each offering some distinct contribution. The current paper is a comprehensive paper integrating previously developed methods (Jha and Schonfeld, 2000a,b; Jong and Schonfeld, 2003) for optimizing highway alignments with specially-tailored genetic algorithms (Jong and Schonfeld, 2003), based on detailed and mathematically unrestrictive functions (Jong and Schonfeld, 1999), and using geographic information extracted from a GIS (Jha and Schonfeld, 2000a). This paper presents the comprehensive highway alignment optimization model and also covers several significant issues which are novel and have not been previously published, including: (1) a comprehensive formulation of the earthwork cost and penalties for floodplain and wetland constraints; (2) analysis of the effects of problem size on computational burden, especially when connected to a GIS database; and (3) optimization within tight bounds in restricted spaces. Fig. 1 shows a flow-diagram of the highway alignment optimization model; it shows numerous subproblems that tie into the comprehensive model developed here. Some of them are covered in our previous publications, while others still require further research. The figure provides an overview of the novelty of the current work and its relations to our previous publications.

2. Highway costs

For optimizing highway alignment based on cost minimization it is necessary to comprehensively formulate all dominating and alignment sensitive costs. Different types of costs may favor different alignment configurations. For example, costs sensitive to alignment length and vehicle miles of travel tend to favor straighter alignments whereas costs sensitive to locations tend to favor more indirect or circuitous alignments.

2.1. Classification of highway costs

We classify the costs into two broad categories: (1) supplier costs which are directly incurred by highway agencies and (2) user costs incurred by highway users. Penalty costs associated with design violations and formulations of some indirect costs to reduce the impacts to some environmentally sensitive regions are also developed. The supplier costs are further divided in three categories: (a) construction, pavement, and other costs primarily depending upon the length of the alignment, (b) right-of-way costs including those associated with land and environmental impacts as well as impacts to stream and other water conduits, and (c) earthwork costs. The user costs are divided into three categories: (a) travel-time cost, (b) vehicle-operating cost, and (c) accident cost. The penalty costs are associated with the violations of design standards which are primarily considered to allow safe movement of traffic through curved sections and insure adequate sight distance to vehicles crossing through steep vertical curves. The indirect costs associated with environmental damage are considered in order to protect environmentally sensitive regions such as wetlands and floodplains.

Over land, the construction and pavement costs will generally be influenced by soil characteristics, whereas on water construction of bridges will be required, which in turn will depend on water level and bridge-length requirements. The land and structure values as well as land use will drive the right-of-way cost. Earthwork cost will depend on topography. Alignments will tend to be more circuitous through heterogeneous land use or mountainous terrain. Since accident and travel-time costs would significantly increase through circuitous and curved routes, these costs would favor straighter alignments. Topography may also affect vehicle operating cost, although climbs and descents may even out the net vehicle operating cost as long as the gradients are mild.

2.2. Costs sensitive to geography

2.2.1. Right-of-way cost

Here we relate our right-of-way cost formulation to the nature of highway intersections with geographic entities. We consider three common types of intersections: (1) intersections with properties, (2) intersections with water, and (3) intersections with existing roads. Intersections with properties will require additional right-of-way acquisition and assessment of resulting damage to properties. Intersections with water will require bridge construction and intersections with roads will require at-grade intersection, overpass, or interchange construction (depending on the access requirements). The total right-of-way cost, C_R is expressed as

$$C_R = \alpha C_{R_L} + \beta C_{R_S} + \gamma C_{R_H} \tag{1a}$$

$$\alpha, \beta, \gamma = 0 \text{ or } 1; \quad \alpha + \beta + \gamma = 1 \tag{1b}$$

$$\alpha = 1 \text{ for land}, \quad \beta = 1 \text{ for water}, \quad \text{and} \quad \gamma = 1 \text{ for roads} \tag{1c}$$

where C_{R_L}, C_{R_S}, and C_{R_H} are right-of-way costs associated with property, water, and highway intersections respectively. α, β, and γ are integer constants. A list of symbols is provided in Table 1.

2.2.1.1. Intersection with properties. Formulation of C_{R_L} is quite complex due to the difficulty in handling shapes of land parcels and estimating damage caused to the properties. Jong's (1998) algorithm for right-of-way cost computation can only handle land parcels of rectangular shapes, since it cannot be applied to non-convex shapes. Moreover, it only considers fractions of properties actually taken by the alignment being evaluated and ignores effects of usability of remainder pieces of land parcels. Also, problems of realistic size with complex geographic features and huge numbers of land-parcels require working directly with a GIS.

Jha and Schonfeld (2000b) provide a comprehensive formulation of C_{R_L} based on usability of remainder pieces of lands resulting due to intersection. Since partial taking of lands may affect overall value of properties (depending on the nature of the intersection), they analyze right-of-way cost based on the compactness of remainder pieces. Fig. 2 shows how an alignment leaves unused land pieces after intersection. In most cases the damage to leftover properties significantly exceeds the costs of sections actually taken by the alignment. Thus, C_{R_L} can be expressed as

$$C_{R_L} = C_{Rd} + \mu C_{Ru} \tag{2}$$

Table 1
List of symbols

Notation	Description	Units
α	Binary integer used in right-of-way cost computation	
α_1	Binary integer used in earthwork cost computation	
$\alpha_0, \alpha_2, \alpha_3$	Positive coefficients used in computing gradient penalty	
β	Binary integer used in right-of-way cost computation	
β_1	Binary integer used in earthwork cost computation	
$\beta_0, \beta_2, \beta_3$	Coefficients used in computing penalty due to the violation of vertical curve length	
γ	Binary integer used in right-of-way cost computation	
γ_1	Binary integer used in earthwork cost computation	
$\gamma_0, \gamma_2, \gamma_3$	Coefficients used in computing floodplain damage from highway alignments	
μ	Binary integer used in computing right-of-way cost for property intersection	
η	Binary integer used in computing right-of-way cost for road intersection	
η_0, η_1, η_2	Coefficients used in computing wetland damage from highway alignments	
A	Fractional area of properties due to alignment intersection	m^2
A_c	Cross-sectional area of a cut section	m^2
A_f	Cross-sectional area of a fill section	m^2
A_l	Area of floodplains or wetlands taken by the alignment	m^2
A_p	Total floodplain area	m^2
A_t	Total cross-sectional area for a transition section in computing earthwork cost	m^2
A_{tc}	Cut cross-sectional area for a transition section in computing earthwork cost	m^2
A_{tf}	Fill cross-sectional area for a transition section in computing earthwork cost	m^2
A_w	Total wetland area	m^2
C_A	Accident cost	$
$c_c(i)$	Penalty cost imposed on the ith curve along the alignment	$
C_D	Travel-time cost	
C_E	Earthwork cost	$
C_F	Fuel cost	$
$C_{F_{ik}}$	Value of the fraction of the ith property taken by the alignment in zone k	$
C_H	Haul cost	$
C_L	Length-dependent cost	$
C_O	Operator (agency) cost	$
C_P	Total penalty cost	$
C_{Pf}	Floodplain penalty	$
C_{Pg}	Gradient penalty	$
C_{Pm}	Penalty due to the violation of vertical curve length	$
C_{Pw}	Penalty due to wetland damage	$
C_R	Total right-of-way cost	$
C_{Rd}	Damage to land parcels due to alignment intersection	$
C_{R_L}	Right-of-way cost when the alignment intersects properties	$
C_{R_H}	Right-of-way cost when the alignment intersects highways	$
C_{R_S}	Right-of-way when the alignment intersects water	$
C_{Rn}	Right-of-way cost for intersection construction	$
C_{Ro}	Right-of-way cost for overpass construction	$
C_{Rt}	Right-of-way cost for interchange construction	$
C_{Ru}	Damage to structures due to alignment intersection	$
C_T	Total cost	$
C_U	Total user cost	$
C_u	Unit cost of properties	$
D_c	Width term used in the cut portion of transition sections	m

Table 1 (*continued*)

Notation	Description	Units
D_f	Width term used in the fill portion of transition sections	m
g	Gradient	
G_{max}	Maximum gradient	
H	Height terms used in computing cut and fill cross-sections	m
K_c	Unit cut cost	$\$/m^3$
K_f	Unit fill cost	$\$/m^3$
L	Highway section length	m
L_m	Minimum length of vertical curve	m
L_v	Vertical curve length	m
m_c	Cut slope	
m_f	Fill slope	
P	Perimeter of land parcels	m
W_{d1}	Width term used in computing cross-sectional area	m
W_{d2}	Width term used in computing cross-sectional area	m
W_P	Traveled portion width	m
W_r	Alignment width on overpass	m
W_S	Shoulder width	m
X	Area of the smallest land-parcel for a zone	m^2
X'	Minimum vertical clearance for overpasses	m
x_L	Lower limit on the x-coordinate of decision variables	m
x_P	x-Coordinate of decision variables	m
x_U	Upper limit on the x-coordinate of decision variables	m
y_P	y-Coordinate of decision variables	m
y_U	Upper limit on the y-coordinate of decision variables	m
z_L	Lower limit on the z-coordinate of decision variables	m
z_P	z-Coordinate of decision variables	m
z_U	Upper limit on the z-coordinate of decision variables	m

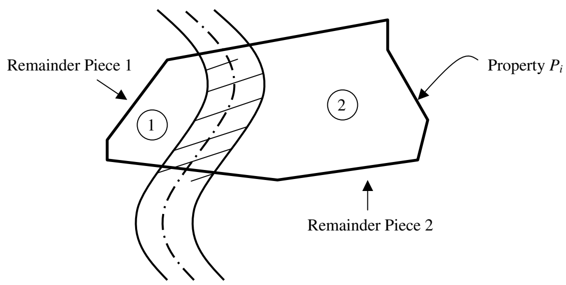


Fig. 2. Remainder property pieces as a result of alignment intersection.

where C_{Rd} and C_{Ru} represent damages to land parcels and structures (in dollars), respectively. μ is a binary integer valued at 1 if the land parcel contains a structure, or zero otherwise. The values of damages to land parcels and structures depend on how they are intersected by the alignment as well as by other factors, such as changes in land use pattern after the construction of the new highway and number of trips generated. The land use generally depends on the zoning established by the local jurisdictions. It is unlikely that the zoning will change after the construction of the highway. For example, if a property is zoned "residential," it should probably remain residential after the construction of the highway. The zoning should influence number of trips attracted to the new highway. The after value may be correlated to the number of trips or the annual vehicle miles of travel (AVMT) on the new highway. The damage to properties may be correlated to their area, unit cost, and cost of structures on them. Jha and Schonfeld (2000b) formulated the after value of properties based on the manner in which they are affected by the new highway. If the ith property is intersected by the alignment to be evaluated, then C_{Rd} is expressed as

$$C_{Rd_{ik}} = \left\{ \begin{array}{ll} (C_{F_{ik}} + \sum_j A_{ijk} \times C_{uik}) & \text{if } A_{ijk} < X_{ik} \text{ and } \frac{A_{ijk}}{P_{ijk}^2} < Y_{ik} \ \forall j \in n \\ C_{F_{ik}} & \text{otherwise} \end{array} \right\} \tag{3}$$

where

$C_{F_{ik}}$ value of the fraction of the ith property taken by the alignment in zone k
A_{ijk} area of the jth fraction of the ith property in zone k
C_{uik} unit cost of the ith property in zone k
P_{ijk} perimeter of the jth fraction of the ith property in zone k
X_{ik} $\min(A_1, A_2, \ldots, A_m)$
Y_{ik} $\min\left[\left(\frac{A}{P}\right)_1, \left(\frac{A}{P}\right)_2, \ldots, \left(\frac{A}{P}\right)_m\right]$
m number of properties in the analyzed section
A_i area of the ith property in the analyzed section
P_i perimeter of the ith property in the analyzed section

2.2.1.2. Water crossings. Crossings of rivers and other bodies of water will require construction of bridges, for which a formulation is provided in Jha (2001).

2.2.1.3. Intersection with roads. The right-of-way cost associated with road intersections, C_{R_H} is expressed as

$$C_{R_H} = \sum_{i=1}^{n} C_{Rn_i} + \sum_{j=1}^{m} \eta (C_{Ro_j} + C_{Rt_j}) \tag{4}$$

where C_{Rn_i} is the cost associated with the ith intersection construction and C_{Ro_j} and C_{Rt_j} are costs associated with jth overpass and interchange constructions, respectively. η is a binary integer which has a value of 1 where overpasses or interchanges are used, or a value of 0 where at-grade intersections are provided. Generally, intersections with arterial streets will be at-grade, whereas for intersections with freeways, overpasses and interchanges will be necessary. Formulations for intersection and overpass costs are provided in Jha (2001) and Kim (2001). Since a precise computation of interchange cost would depend on detailed design decisions made after the basic alignment selection, it is neglected in this analysis.

2.2.2. Earthwork cost

There are two popular methods for computing earthwork cost: (1) the average-end area method and (2) the trapezoidal method. While the trapezoidal method provides better precision, it increases computational burden. For planning stage evaluations the average-end area method is sufficient. The trapezoidal method may be suitable at the detailed design level when better precision is required after alignment corridor has been identified. Cross-sectional profiles under cut and fill conditions are considered here in more detail than Jong (1998). The earthwork cost, C_E can thus be expressed as

$$C_E = C_H + 0.5\sum_{i=1}^{n}[\alpha_1 K_{ci} s A_{ci} L_i + \beta_1 K_{fi} A_{fi} L_i + \gamma_1 (K_{ci} s A_{tci} + K_{fi} A_{tfi}) L_i] \tag{5}$$

$$\alpha_1, \beta_1, \gamma_1 = 0 \text{ or } 1; \quad \alpha_1 + \beta_1 + \gamma_1 = 1 \tag{6a}$$

$$\alpha_1 = 1 \text{ for cut section}, \quad \beta_1 = 1 \text{ for fill section}, \quad \text{and} \quad \gamma_1 = 1 \text{ for transition section} \tag{6b}$$

where

C_H total haul cost, i.e., cost of moving earth between adjacent cut and fill sections to balance overall earthwork volume

n total number of highway sections

K_{ci}, K_{fi} unit cut and fill costs (\$/m^3) for the ith cut and fill sections, respectively

L_i length of the ith highway section (m)

s swell or shrinkage factor

$A_{ci}, A_{fi}, A_{tci}, A_{tfi}$ cross-sectional areas at the ith section under cut, fill, transitional cut, and transitional fill conditions, respectively.

The formulation for C_H is available in Jha (2000). The horizontal highway sections are tangents connected by circular curves. The vertical tangents are connected by parabolic curves. These choices of vertical and horizontal curves are not inherent to this modeling approach based on genetic algorithms. Alternative curves, such as the splines as presented in Trietsch (1987a) might be substituted. Jong (1998) describes in detail the representation of alignments used here. The determination of cut, fill, and transition sections is based on difference in terrain and road heights at regular intervals, which is user-specified. Since the terrain elevation is needed for computing earthwork cost the precision of the computation will depend on the availability of realistic terrain elevation data at a much finer level. Actual elevation data however, can only be obtained through actual surveys, which may be very expensive. Therefore for crude evaluations one may use interpolation to get the elevations of intermediate points if elevations at sparsely located points were known. However, if there was a major break on the earth's surface such as the existence of a mountain, the interpolated elevation data may not be reliable. Therefore, care should be taken in using the right elevation data by examining the characteristics of the search space. The elevation data may be obtained from various sources such as the US Geological Survey or the National Geodetic Survey.

The cross-section profiles under cut, fill, and transition sections are shown in Figs. 3–5, respectively. The total areas under different scenarios are computed by summing the trapezoidal sections as shown in these figures. The end area for a cut section, A_{ci} can be expressed as

$$A_{ci} = \left\{ \left(\frac{H_{1i}+H_{2i}}{2} \times W_{P_i}\right) + \left(\frac{H_{2i}+H_{3i}}{2} \times W_{S_i}\right) + \left(\frac{H_{3i}+H_{4i}}{2} \times W_{d1_i}\right) + \left(\frac{H_{4i}+H_{5i}}{2} \times W_{d2i}\right) + \left(\frac{H_{5i}^2}{2 \times m_{ci}}\right) \right\} \tag{7}$$

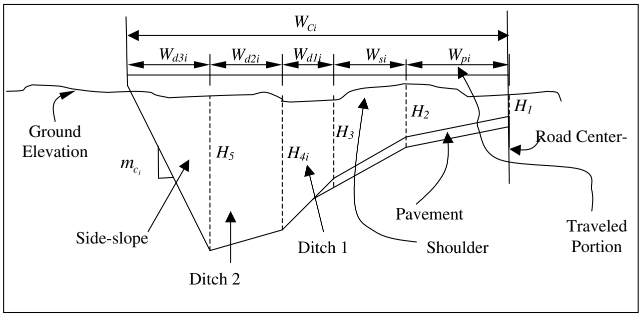


Fig. 3. Cut cross-section.

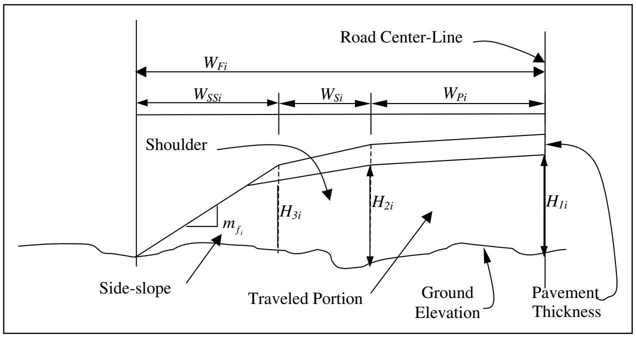


Fig. 4. Fill cross-section.

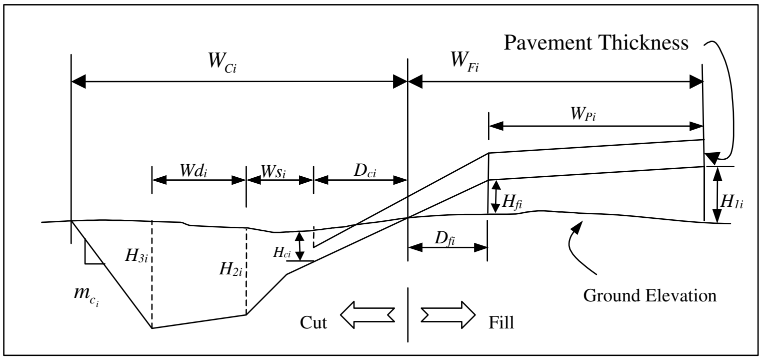


Fig. 5. Transition cross-section (both cut and fill).

The end area for a fill section, A_{fi} can be expressed as

$$A_{fi} = \left\{ \left(\frac{H_{1i} + H_{2i}}{2} \times W_{P_i} \right) + \left(\frac{H_{2i} + H_{3i}}{2} \times W_{S_i} \right) + \left(\frac{H_{3i}^2}{2 \times m_{fi}} \right) \right\} \tag{8}$$

The end area in case of transition from a fill to a cut transition, A_{ti} can be expressed as

$$A_{ti} = A_{tfi} + A_{tci} \tag{9}$$

where A_{tfi} and A_{tci} are the cut and fill areas in transition which can be expressed as

$$A_{tfi} = \left\{ \left(\frac{H_{1i} + H_{fi}}{2} \times W_{P_i} \right) + \left(\frac{H_{fi} \times D_{fi}}{2} \right) \right\} \tag{10}$$

$$A_{tci} = \left\{ \left(\frac{H_{ci} \times D_{ci}}{2} \right) + \left(\frac{H_{ci} + H_{3i}}{2} \times W_{S_i} \right) + \left(\frac{H_{2i} + H_{3i}}{2} \times W_{d_i} \right) + \left(\frac{H_{3i}^2}{2 \times m_{ci}} \right) \right\} \tag{11}$$

In Eqs. (7), (8) and (11) m_{c_i} and m_{f_i} represent side-slopes of cut and fill sections, respectively.

2.3. Constraints

Penalty cost functions are imposed to avoid design violations and satisfy other constraints. Constraints are applied for two important geometric design features: maximum gradient and minimum vertical curve length. These constraints are imposed to generate a smooth and continuous alignment for safer movement of traffic at specified design speeds in accordance with AASHTO (1994) standards. It should be noted that the model automatically constrains the horizontal radius based on the user-specified design speed. Moreover, sight-distance restrictions are also considered on vertical curves (as in Jong, 1998).

Penalties are also used to limit environmental impacts on floodplains and wetlands. The total penalty cost, C_P is expressed as

$$C_P = C_{Pg} + C_{Pm} + C_{Pf} + C_{Pw} \tag{12}$$

where C_{Pg} and C_{Pm} are total penalties due to gradient and vertical curve length violations. C_{Pf} and C_{Pw} are penalties to constrain damages to floodplains and wetlands, respectively. Let C_{pg_i} denote the penalty cost for violating gradient constraint at the ith tangent. Then C_{pg_i} is expressed as

$$C_{pg_i} = \begin{cases} \alpha_0 + \alpha_2(|g_i| - G_{\max})^{\alpha_3} & \text{if } |g_i| > G_{\max} \\ 0 & \text{otherwise} \end{cases} \quad \forall i = 0, \ldots, n \tag{13}$$

where α_0, α_2 and α_3 ($\alpha_3 > 1$) are user-specified coefficients. The total penalty cost for violating gradient constraints is then obtained by adding the individual penalty costs at each tangent:

$$C_{Pg} = \sum_{i=0}^{n} C_{pg_i} \tag{14}$$

Similarly the penalty cost for violating the minimum length of vertical curve, C_{pm_i} at the ith vertical curve is specified as

$$C_{pm_i} = \begin{cases} \beta_0 + \beta_2(L_{m_i} - L_{v_i})^{\beta_3} & \text{if } L_{v_i} < L_{m_i} \\ 0 & \text{if } L_{v_i} \geqslant L_{m_i} \end{cases} \quad \forall i = 1, \ldots, n \tag{15}$$

where β_0, β_2 and β_3 ($\beta_3 > 1$) are user-specified coefficients. The total penalty in this case is also obtained similarly to Eq. (14). In order to discourage the alignment from crossing through environmentally sensitive regions penalties varying with the magnitudes of violations are specified as follows:

$$C_{pf_j} = \gamma_0 + \gamma_2 \left(\frac{A_{l_j}}{A_{p_j}} \right)^{\gamma_3} \tag{16}$$

where
C_{pf_j} penalty associated with the intersection of the jth floodplain
$\gamma_0, \gamma_2, \gamma_3$ user-specified coefficients
A_{l_j} intersected area of the jth floodplain
A_{p_j} total area of the jth floodplain

$$C_{pw_k} = \eta_0 + \eta_1 \left(\frac{A_{l_k}}{A_{w_k}} \right)^{\eta_2} \tag{17}$$

where
C_{pw_k} penalty associated with the intersection of the kth wetland
η_0, η_1, η_2 user-specified coefficients
A_{l_k} intersected area of the kth wetland
A_{w_k} total area of the kth wetland

Obviously, high values of the coefficients in Eqs. (16) and (17) can act as soft constraints that discourage the use of floodplains and wetlands for highway alignments.

3. The optimization problem

Our highway alignment optimization problem is to find an alignment that minimizes overall cost, subject to constraints. In our problem the horizontal alignment is represented as a combination of tangent sections and circular curves. The vertical alignment is represented as a combination of tangent sections and parabolic curves. The coordinates of intermediate points through which the alignments cross are treated as decision variables. For this purpose, first a number of orthogonal cutting lines (for horizontal alignment) or planes (for vertical alignment) are constructed at equally spaced intervals between the given end points (see Fig. 6). Those lines are orthogonal to the line connecting the start and end points. (For 3-D alignments, we consider orthogonal cutting planes.) The intermediate points lie somewhere along these cutting lines (or planes). While the precision of alignment thus generated depends on number of intermediate points, additional points increase the computation burden. The optimization problem is thus formulated as

$$\min_{x_{P_1}, y_{P_1}, z_{P_1}, \ldots, x_{P_n}, y_{P_n}, z_{P_n}} \quad C_T = C_O + C_U + C_P \tag{18}$$

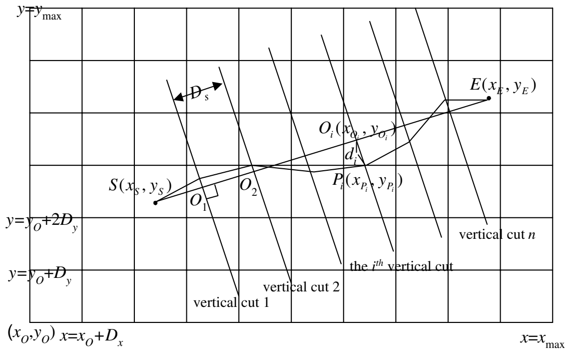
$$\text{s.t.} \quad x_L \leqslant x_{P_i} \leqslant x_U \quad \forall i = 1, \ldots, n \tag{19a}$$

$$y_L \leqslant y_{P_i} \leqslant y_U \quad \forall i = 1, \ldots, n \tag{19b}$$

$$z_L \leqslant z_{P_i} \leqslant z_U \quad \forall i = 1, \ldots, n \tag{19c}$$

$$|g_i| \leqslant G_{\max} \quad \forall i = 1, \ldots, p \tag{19d}$$

$$L_{v_i} \geqslant L_m \quad \forall i = 1, \ldots, p \tag{19e}$$



Notation key:

$S(x_S, y_S)$, $E(x_E, y_E)$: start and end points

$O_i(x_O, y_O)$: Point where $\overline{SE}$ intersects i^{th} vertical cut

(x_O, y_O), $(x_{\max}, y_{\max})$: limits of the search space (or analysis section)

(D_x, D_y) : width and height of the rectangular cells contained in the search space. When using real GIS map these cells represent land parcels with actual shapes (which may be irregular)

D_s : spacing of the vertical cuts

d_i : distance between O_i and the i^{th} Point of Intersection (PI), $P_i(x_{p_i}, y_{p_i})$.

Fig. 6. Alignment representation for a two-dimensional case.

where C_T is total cost (\$), C_O, C_U, and C_P are operator, user, and penalty costs (in dollars), (x_L, y_L, z_L) and (x_U, y_U, z_U) are lower and upper limits on the decision variables (x_{P_i}, y_{P_i}, z_{P_i})'s. n and p are the number of intermediate points and vertical curves, respectively. Eqs. (19a), (19b) and (19c) impose upper and lower limits on the decision variables and Eqs. (19d) and (19e) limit the maximum gradient and minimum vertical curve length.

3.1. The curve fitting process

The above formulation only considers solutions expressed in terms of Point of Intersection (PI) coordinates (x_i, y_i, z_i)'s. Circular horizontal curves and parabolic vertical curves are then fitted. Horizontal transition curves (e.g., splines or cubic spline functions) may be added later, when such models are refined for more detailed design applications.

The curve fitting process follows immediately after the series of Points of Intersection and resulting tangents between those points are obtained. The curve lengths at adjacent intersection points may be interdependent. Ideally, a tangent section must be long enough to accommodate the required curve lengths based on design standards. However, for any given set of intersection points, some tangent lengths may be insufficient. If a tangent is too short, the curve lengths at both ends must be reduced to preserve a continuous alignment. To make the best use of all tangent sections, the curves are inserted from the two ends of the most insufficient tangent. This procedure (Jong, 1998) is repeated until the curves are inserted at all intersection points. The resulting alignments are always smooth and continuous, but may not satisfy design constraints. Appropriate penalties, imposed as discussed earlier, serve to guide the search toward better alignments that satisfy those constraints.

Alternative curve modeling approaches may be explored for more detailed design. Thus, Trietsch (1987a) uses parametric cubic spline function for horizontal curves and regular (non-parametric) cubic spline functions for vertical curves.

The operator and user costs are expressed as

$$C_O = C_R + C_L + C_E \tag{20a}$$

$$C_U = C_D + C_V + C_A \tag{20b}$$

where C_R, C_L, C_E, C_D, C_V, and C_A are right-of-way, length-dependent (including construction and pavement), earthwork, travel-time, vehicle-operation, and accident cost, respectively. C_R and C_E are computable using Eqs. (1a) and (5), respectively. C_L is unit length-dependent cost ($/m) times total alignment length. Unit length-dependent cost is assumed to be user-specified.

3.1.1. Formulation of user costs

As noted earlier three types of user costs are considered in our model: travel-time, vehicle-operation, and accident. These costs are computed as a function of alignment variables, which can be found in Jha et al. (2001) and Jong (1998). The fuel-cost constitutes major portion of the vehicle-operation cost (Jong, 1998) formulation of which is given as

$$C_F = [C_F^B(\overline{G}, L_n, \overline{V}_{pp}, \overline{V}_{pn}, \overline{V}_o) + C_F^B(-\overline{G}, L_n, \overline{V}_{pp}, \overline{V}_{pn}, \overline{V}_o)]\left[\frac{\mathrm{e}^{(r_t-\rho)n_y} - 1}{r_t - \rho}\right] \tag{21}$$

where C_F is the net present worth of total fuel consumption cost ($), ρ is the assumed interest rate (decimal fraction), C_F^B is the fuel consumption cost for traffic in one direction in the base year ($/year), $\overline{G}$ is the grade of road section (%), L_n is the total length of the alignment (m), $\overline{V}_{pp}$ is the average running speed in the peak period and prevalent direction (km/h), $\overline{V}_{pn}$ is the average running speed in the off-peak period (km/h), $\overline{V}_o$ is the average running speed in the peak period and non-prevalent direction (km/h), r_t is the annual growth rate of Annual Average Daily Traffic (AADT), and n_y is the analysis period. The travel-time cost is computed as

$$C_D = c_B^T(L_n, \overline{V}_{pp}, \overline{V}_{pn}, \overline{V}_o)\left[\frac{\mathrm{e}^{(r_t-\rho)n_y} - 1}{r_t - \rho}\right] \tag{22}$$

where C_V is the net present value of total travel-time costs ($). The term $c_B^T(L_n, \overline{V}_{pp}, \overline{V}_{pn}, \overline{V}_o)$ is the total travel-time cost for two-way traffic in the base year formulation for which is available in Jong (1998). The accident cost is computed as

$$C_A = \sum_{i=1}^{n} c_c(i) + \frac{1}{5}\left[\frac{(1+\rho)^5 - 1}{\rho(1+\rho)^5}\right]\sum_{k=1}^{n_k}\left[\frac{1}{(1+\rho)^{5(k-1)}}\sum_{j=1}^{n} A_{kj}\right]U_c \tag{23}$$

where A_{kj} is the total number of accidents on the jth curve in the kth 5-year period, $c_c(i)$ is the penalty cost imposed on the ith curve along the alignment ($), n is the number of curves along the alignment, n_k is the number of 5-year periods in the analysis, U_c is the average costs per accident ($/accident, and ρ is the interest rate. The penalty cost, $c_c(i)$ is specified as

$$c_c(i) = \begin{cases} b(R_i - R_{\min})^2 & \forall R_i < R_{\min} \\ 0 & \text{otherwise} \end{cases} \tag{24}$$

where b is the penalty parameter which is user specified, R_i is the radius of the ith horizontal curve, and $R_{\min}$ is the minimum radius. Detailed formulations of the various terms in Eqs. (21)–(24) are available in Jha et al. (2001) and Jong (1998).

3.2. Optimal search

Genetic algorithms (GAs) are employed for optimal search. In such GA's an initial population of alignments is randomly generated (Jong, 1998; Jong and Schonfeld, 2003; Jong et al., 2000), which is the first generation. A new generation is formed as less fitted members are replaced with new ones through a selection/replacement scheme. Better fitted members are generally retained and used to create offspring through genetic recombination. A generation terminates after evaluating all members of the population. This process continues through successive generations until improvement in the objective function value becomes negligible. An evaluation of an individual member (i.e., solution of alignment) within a generation is called an *iteration.* Thus a search through 100 generations with 32 iterations in each generation with an initial population of 100 will require the evaluation of 3300 alignments.

3.3. GIS

A GIS is used to assimilate relevant geographic data used for alignment optimization. Some of those include land boundaries, land and structure costs, floodplains, wetlands, and terrain profiles. The GIS is also used to compute the geographic sensitive costs as well as environmental penalty for every intermediate alignment during the search. The genetic algorithm and GIS computing environments thus exchange necessary data during the search. The GIS integration with the genetic algorithms is established using specialized dynamic link libraries discussed at length in Jha (2000) and Jha and Schonfeld (2000a).

3.4. Software development

The genetic algorithms are coded in the "C" programming language. A number of algorithms in the "C" and GIS computing environments are used in the optimization process. The following main tasks are accomplished with these algorithms: (1) random generation of alignments, (2) computation of costs, and (3) application of genetic algorithms for the optimal search. The generation of alignments is quite complex since it requires curve fitting in a way that ensures continuity and smoothness. Jong's (1998) algorithms are employed for this purpose. Cost computations are performed in both "C" and GIS computing environments. The terrain data are made available to the "C" environment from GIS to compute earthwork cost. Jong's algorithm (1998) is employed for obtaining terrain elevation at intermediate locations using interpolation. Jha's (2000) GIS-based algorithm is employed to compute right-of-way cost. The same algorithm is modified to compute the environmental costs. Various procedures used by genetic algorithms for optimization are discussed in Jong (1998).

4. Examples

A number of examples are used to demonstrate the effectiveness of the proposed model. Maryland's GIS database is used to construct some examples. Some artificial maps are also used to construct complex scenarios primarily to examine the performance of the model in mountainous terrain. For assessing the increase in computational burden due to the compactness analysis in computing right-of-way costs, separate cases with and without compactness have been analyzed. Since compactness analysis is primarily performed to assess the usability of land pieces left near alignments we call it usability analysis. The following cases are analyzed below:

1. Total cost optimization with real maps
2a. Right-of-way cost optimization with real maps and usability analysis
2b. Right-of-way cost optimization with real maps without usability analysis
3. Total cost optimization in a constrained search space with real maps
4. Total cost optimization using an artificial map of mountainous terrain

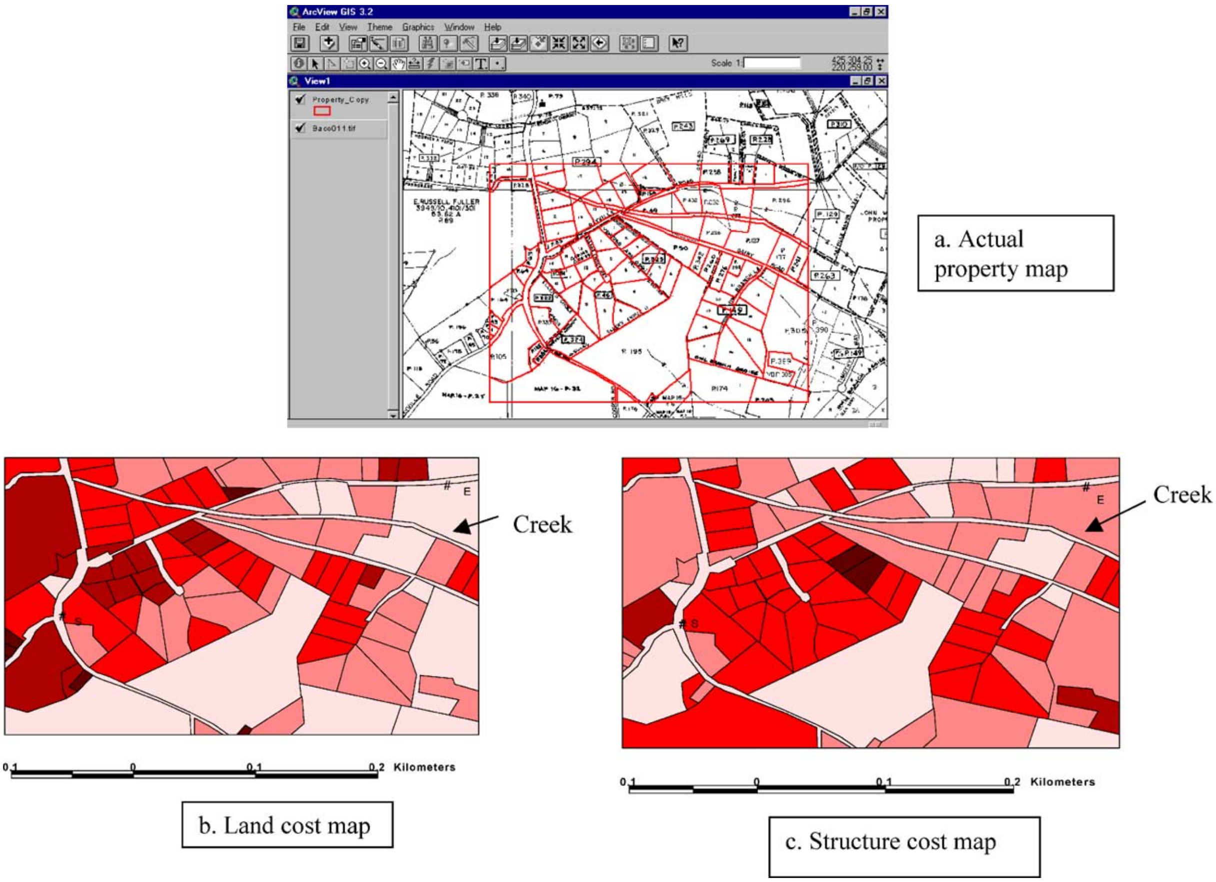
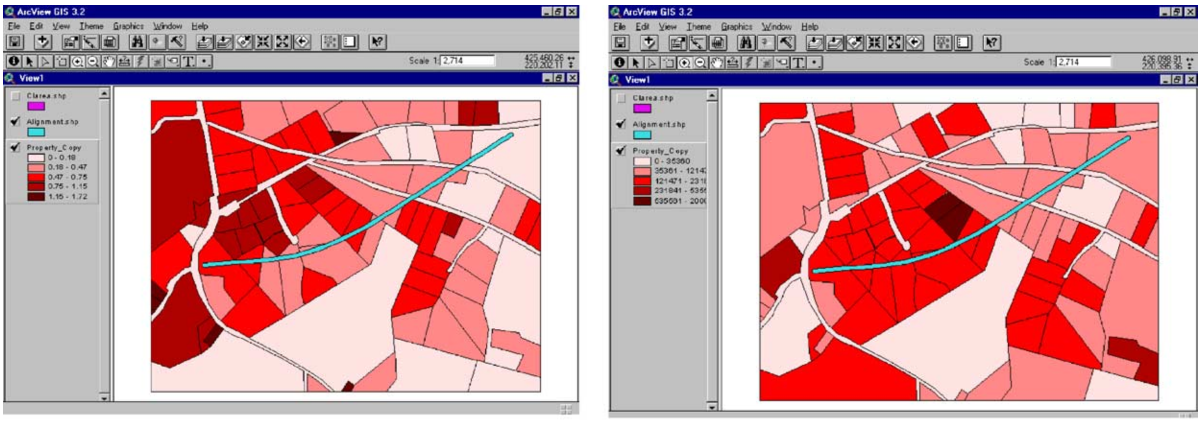


Fig. 7. Search space used in Case 1.

Table 2
Input values for the examples

Input parameters	Value
Total alignment width with shoulders	9.4 m (30 ft)
Design speed	105 kmph (65 mph)
Coefficient of side friction	0.16
Maximum superelevation	0.06
Maximum allowable grade	5%
Unit cost of diesel fuel	0.85 \$/gallon
Unit cost of gasoline	1.25 \$/gallon
Unit accident cost	225283.73 \$/accident
Analysis period	30 years
Interest rate	6%
Annual average daily traffic (AADT)	5000
Traffic growth rate	2%
Value of travel time: passenger cars	\$8.50
Value of travel time: 2A trucks	\$20.00
Value of travel time: 3-S2 trucks	\$23.00
Percent of heavy vehicles	5



a. Land cost map

b. Structure cost map

Fig. 8. Optimized alignment at the 101st generation of Case 1.

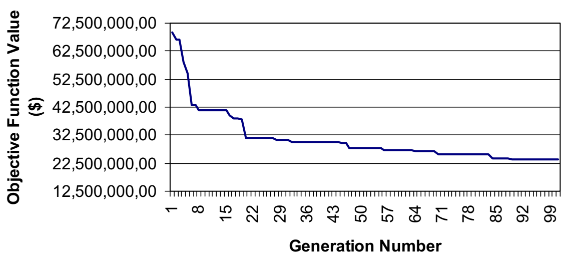


Fig. 9. Changes in objective function value over successive generations for Case 1.

4.1. Case 1

A real map from Baltimore County, Maryland is used to obtain an optimized alignment between two given end points using the total user and operator costs as represented in Eqs. (19a) and (19b). The end points lie in a search space (Fig. 7) comprising of about 100 geographic entities (including lands, creeks, and highways). This space represents a section of the GIS database of Baltimore County in Maryland, which is obtained from MDProperty View. MDProperty View (1997) is an ArcView GIS compatible desktop electronic property map which stores property boundaries and associated geographic databases containing relevant information (such as, land area, zoning, and land cost) of Maryland counties. The data values such as land and property costs are routinely updated in MDProperty View.

The search space is primarily a residential area of 1.22 km^2. The terrain height in the search space ranges from 125 to 145 m. Unit land costs range from \$0.22/m^2 to \$18.51/m^2. Land parcels with higher unit costs are shown in dark in Fig. 7. The cost of structures ranges from \$10,900 to \$1.2 million.

The Euclidean distance between the end points is about 332 m. Since the study section only contains minor arterial streets it is only necessary to consider at-grade intersection construction costs when existing streets are intersected by the new alignment. The lane and shoulder widths of the proposed alignment are assumed to be 3.7 m (12 ft) and 1 m (3.3 ft), respectively. The annual average daily traffic (AADT) is assumed to start at 5000 and grow at 2% per year. The design speed is assumed to be 105 kmph (65 mph). The value of travel times for passenger cars, 2A, and 3-S2 trucks are \$8.5, \$20, and \$23, respectively. These values are obtained from AASHTO (1977) data with 1994 updates of the Consumer Price Index (CPI). The 1994 CPI values are obtained from Wright (1996). These and other input values used to run the model are shown in Table 2.

The optimized alignment obtained at the 101th generation is shown in Fig. 8. A total of 3014 alignments are explored in the 101 generations. The optimized alignment has a length of 339.26 m.

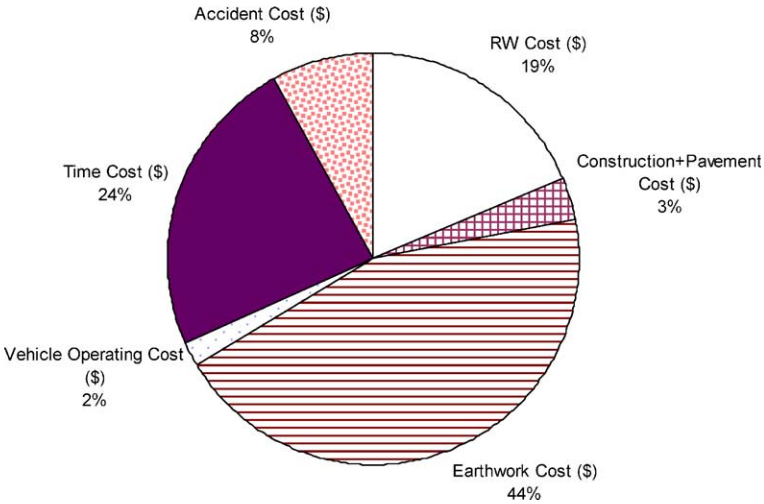


Fig. 10. Cost breakdown for the optimized alignment of Case 1.

Table 3
Case 1 Optimized results

Gen. Num.	Objective function value (total cost – in dollars)	RW cost ($)	Construction + pavement cost ($)	Earthwork cost ($)	Vehicle operating cost ($)	Time cost ($)	Accident cost ($)	Penalty cost_vertical curve ($)	Penalty cost_gradient ($)	Length of horizontal alignment (ft)
1	69,160,098.67	8,340,475.09	1,043,046.79	13,197,210.79	774,345.09	15,109,506.49	22,309,928.58	8,385,585.84	0.00	1400.74
5	54,526,708.43	4,718,957.32	1,046,275.47	17,128,390.19	641,224.10	15,156,277.04	15,642,986.49	192,597.81	0.00	1405.07
10	41,418,403.73	3,732,831.95	924,344.38	18,045,492.45	519,574.27	8,717,121.09	6,985,651.54	2,493,388.04	0.00	1241.33
15	41,372,077.88	3,732,831.95	924,344.38	18,092,379.59	519,365.78	8,690,515.67	6,985,651.54	2,426,988.96	0.00	1241.33
20	31,350,787.78	3,537,587.54	856,115.86	13,208,128.42	468,841.32	6,726,015.01	4,661,001.98	1,893,097.67	0.00	1149.70
25	31,350,787.78	3,537,587.54	856,115.86	13,208,128.42	468,841.32	6,726,015.01	4,661,001.98	1,893,097.67	0.00	1149.70
30	30,778,561.14	3,555,981.47	855,808.22	13,055,825.29	464,745.01	6,372,765.36	5,070,078.06	1,403,357.73	0.00	1149.29
35	29,933,496.64	3,939,914.78	851,608.05	12,996,133.27	462,371.41	6,333,547.59	5,339,217.07	10,704.48	0.00	1143.65
40	29,933,496.64	3,939,914.78	851,608.05	12,996,133.27	462,371.41	6,333,547.59	5,339,217.07	10,704.48	0.00	1143.65
45	29,579,790.70	3,940,389.86	851,615.15	12,100,958.67	464,105.33	6,484,295.39	5,715,888.13	22,538.17	0.00	1143.66
50	27,808,288.62	4,182,670.64	835,290.20	11,940,588.72	454,447.87	6,293,075.46	4,102,215.73	0.00	0.00	1121.74
55	27,808,288.62	4,182,670.64	835,290.20	11,940,588.72	454,447.87	6,293,075.46	4,102,215.73	0.00	0.00	1121.74
60	26,965,286.19	4,750,067.00	839,674.31	8,519,990.60	454,668.23	6,141,315.71	5,485,754.98	773,815.36	0.00	1127.62
65	26,770,875.73	4,335,207.22	833,895.76	11,942,346.50	448,924.07	5,885,915.52	3,324,586.67	0.00	0.00	1119.86
70	25,642,938.31	4,423,982.64	832,298.63	11,065,638.60	444,311.51	5,585,271.31	3,291,435.61	0.00	0.00	1117.72
75	25,642,938.31	4,423,982.64	832,298.63	11,065,638.60	444,311.51	5,585,271.31	3,291,435.61	0.00	0.00	1117.72
80	25,642,938.31	4,423,982.64	832,298.63	11,065,638.60	444,311.51	5,585,271.31	3,291,435.61	0.00	0.00	1117.72
85	24,072,064.60	4,424,002.85	828,797.90	10,623,801.60	443,135.66	5,613,918.65	2,138,407.94	0.00	0.00	1113.02
90	23,984,748.94	4,424,004.78	828,641.25	10,607,891.00	442,989.76	5,608,159.94	2,073,062.20	0.00	0.00	1,112.81
95	23,834,473.17	4,424,198.47	828,358.91	10,578,469.16	442,738.26	5,598,655.71	1,962,052.66	0.00	0.00	1112.43
100	23,796,946.79	4,424,081.21	828,287.35	10,570,712.62	442,669.56	5,595,874.83	1,935,321.23	0.00	0.00	1112.33
101	**23,796,779.24**	**4,424,081.41**	**828,287.46**	**10,570,712.90**	**442,668.61**	**5,595,799.87**	**1,935,228.98**	**0.00**	**0.00**	**1112.33**

Fig. 9 shows the improvement in the objective function through successive generations. The improvements level off after about 80 generations. The total cost of the optimized alignment is about $23.8 million. The earthwork, travel-time, and right-of-way costs together account for 87% of the total cost as shown in Fig. 10. Variations in costs and lengths through successive generations are also reported in Table 3. The higher right-of-way cost is attributed to expensive houses in the study area, which are affected by the alignment. It is noted that the program attempts to obtain a best tradeoff between all costs to minimize overall cost. It is interesting to note that the alignment narrowly avoids expensive houses, as shown in Fig. 8b. In areas with greater right-of-cost variability or with mountainous terrain the optimized alignment would be more circuitous.

4.2. Case 2

Since earthwork, travel-time, and right-of-way costs together account for 87% of the total cost in Case 1, the alignment may not be very sensitive to other costs. Therefore, even after prolonged search not much improvement in other costs would be expected. A relatively higher travel-time

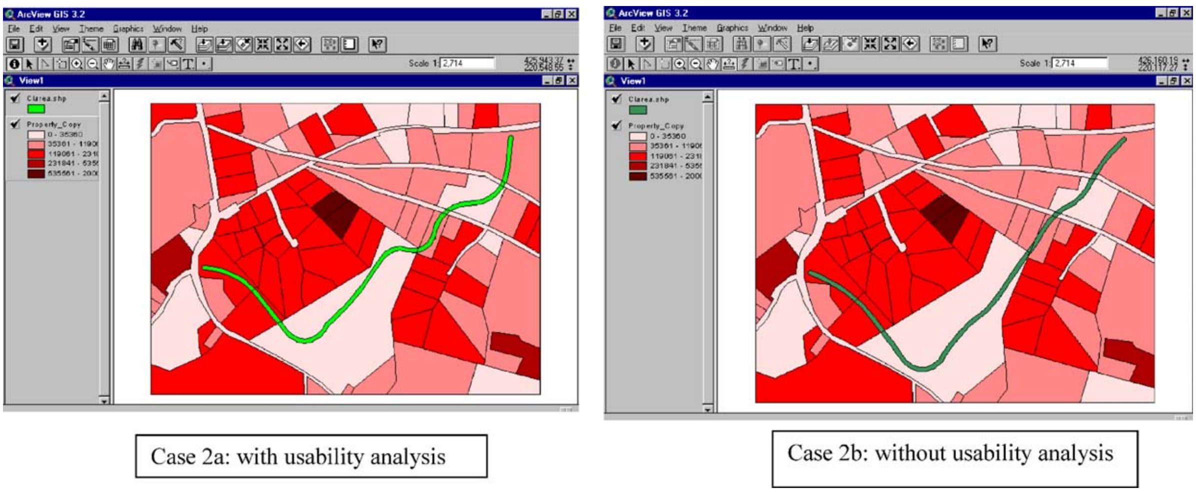


Fig. 11. Optimized solutions when only right-of-way is considered in Cases 2a and 2b.

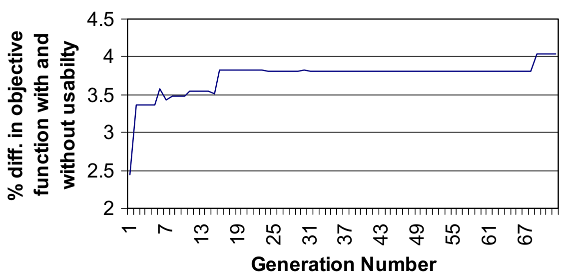


Fig. 12. Percentage difference in objective function with and without usability.

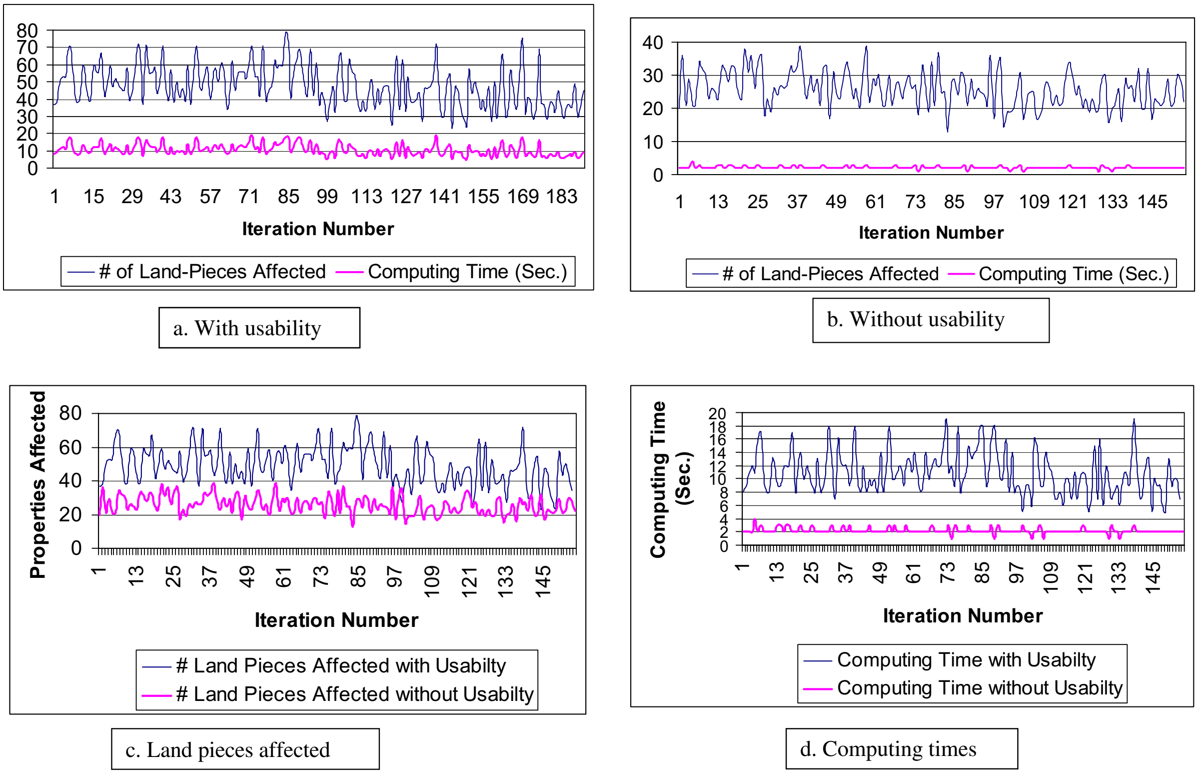


Fig. 13. Computing time and number of land pieces analyzed with and without usability.

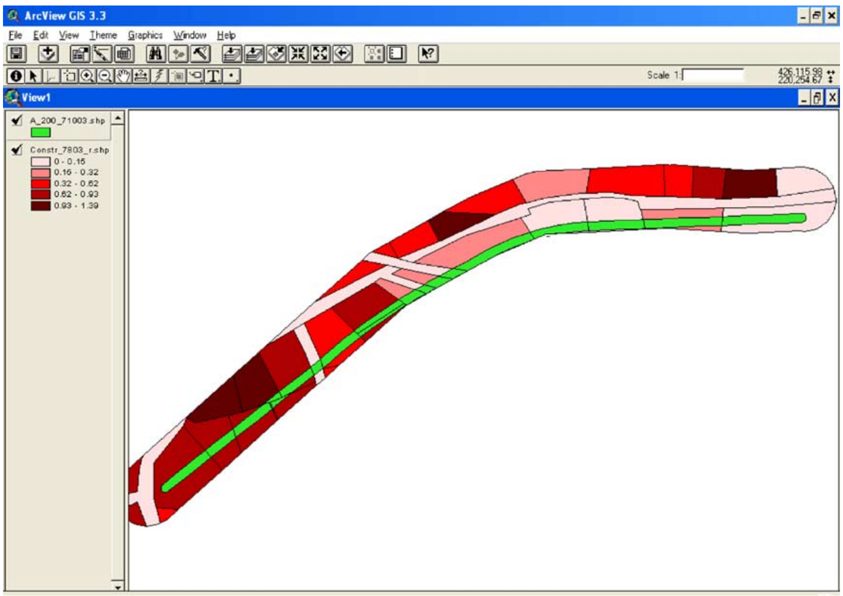


Fig. 14. Optimized alignment at the 101st generation in the constrained search space.

cost tends to straighten and shorten alignments. Here the optimization is based only on right-of-way cost, to explore its effect on alignment selection. The effects of usability analysis (i.e., considering values of leftover property pieces) is also examined. For this purpose Cases 2a and 2b are optimized with and without usability, respectively. The best alignments obtained in the 71st and 54th generations in these cases are shown in Fig. 11. The configurations of the alignments in these cases are slightly different. When usability is considered the algorithm attempts to minimize the number of unused expensive pieces. The lengths of optimized alignments in Cases 2a and 2b are 448.14 and 451.48 m, respectively.

The optimized alignments in Cases 2a and 2b are obtained fairly quickly compared to Case 1, although the algorithm has to search for a while in Case 2a when considering usability. In Case 2a a total of 2132 alignments are explored in 71 generations whereas in Case 2b a total of 1662 alignments are explored in 54 generations. The optimized objective function values in Cases 2a and 2b are \$1.31 million and \$2.21 million, respectively. It is noted that with usability analysis the algorithm attempts to minimize the number of unused pieces while without usability it only considers property fractions taken by the alignment. Usability considerations increase the precision in computing right-of-way cost, but the resulting cost need not be lower. Fig. 12 shows the percentage difference in right-of-way cost obtained in Case 2 with and without usability analysis to be up to 4%. This difference could be higher in dense urban areas with expensive properties.

Since computing time is a significant concern when GIS-based algorithms are used, especially with usability analysis, several results are shown in Fig. 13 to precisely assess it. It is noted that each land piece resulting from alignment intersection has to be separately analyzed when usability

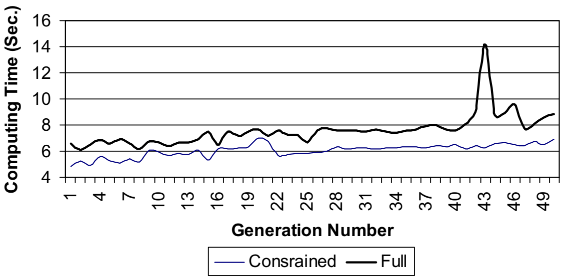


Fig. 15. Computing times with and without constrained search space.

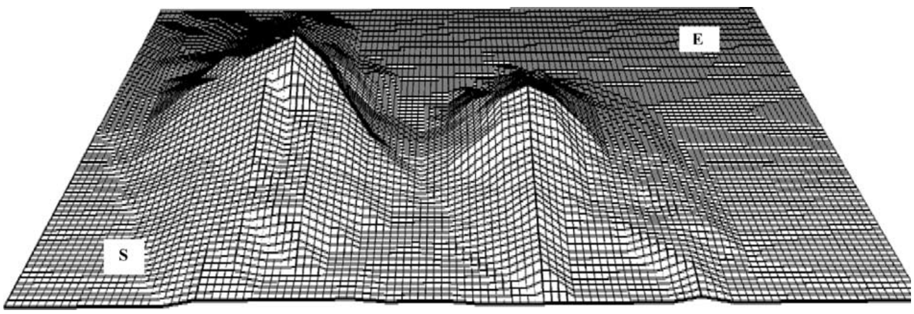


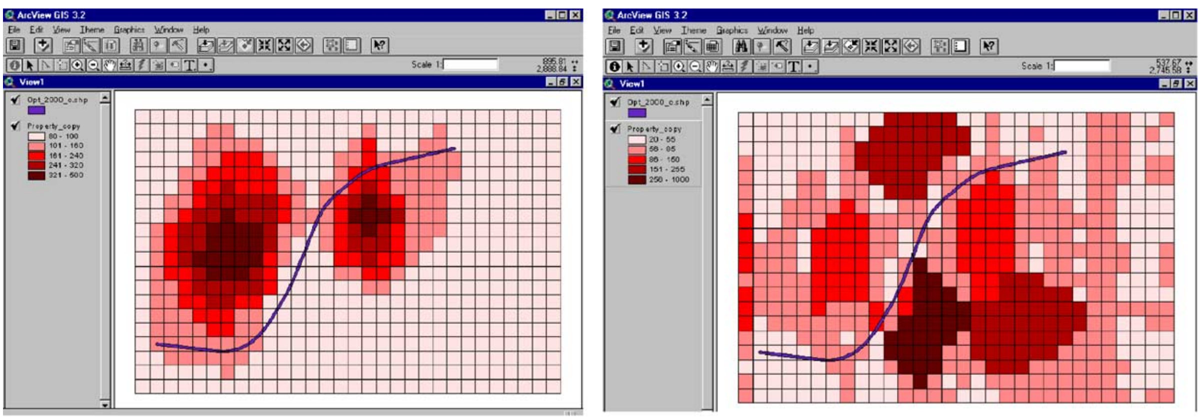
Fig. 16. Elevation map for Case 4.

is considered. Since alignments are randomly generated during the optimal search, computing times can vary depending on number of properties affected by each alignment. Generally, longer alignments with higher map densities (land parcels per unit area) will significantly increase the computing time. Fig. 13a and b show the number of affected land pieces and computing times over successive iterations with and without usability, respectively. It can be seen that computing time per iteration is smaller without usability analysis since fewer slices must be analyzed. Fig. 13c and d compare number of land slices affected and computing times with and without usability analysis. They indicate that with usability analysis up to 89 land pieces must be analyzed, which requires about 20 s on a Pentium III 550 MHz PC with 128 MB RAM. Without usability, the number of pieces to be analyzed stays in the range of 16–36 and the computing time ranges from 1 to 4 s. Therefore, for larger problems faster computers and, possibly, parallel processing would be desirable. It may also be desirable to search in a smaller or constrained space, especially if a road must be located in a narrow fixed corridor. This is explored in the next case.

4.3. Case 3

In order to investigate effects of constrained search space on computing time, which realistically reflect many streetscape and expansion projects, the space used in previous cases for search was reduced as shown in Fig. 14. The optimized alignment obtained at the 101st generation using this reduced space is shown there.

Since a reduced search space is used requiring fewer properties to be analyzed, the solution is obtained much faster since fewer properties and a reduced search space are analyzed. The average computing times per iteration using full and constrained search spaces are compared in Fig. 15, which confirms that they are smaller in the constrained space. It is noted that a saving of about 2 s per iteration results in an overall saving of about 1.7 h in 3024 iterations. In addition to improving computing efficiency, reduced search spaces are in many cases inherently required for certain



a. Elevation map

b. Cost map

Fig. 17. Optimized alignment at the 2000th generation of Case 4.

Table 4
Case 4 Optimized results

Gen. Num.	Objective function value (total cost – in dollars)	RW cost ($)	Construction + pavement cost ($)	Earthwork cost ($)	Vehicle operating cost ($)	Time cost ($)	Accident cost ($)	Penalty cost_vertical curve ($)	Penalty cost_gradient ($)	Length of horizontal alignment (ft)
Straight alignment	252,798,925.69	11,716,081.55	3,738,252.77	215,666,905.46	1,920,596.04	19,757,089.88	0.00	0.00	0.00	5020.21
1	180,164,167.51	18,903,528.56	4,577,505.49	120,278,943.73	2,380,342.25	26,245,414.68	2,147,681.08	5,630,751.71	0.00	6147.27
50	83,914,180.79	11,155,231.85	4,306,779.96	26,940,418.01	2,336,412.72	31,867,619.42	6,560,288.91	747,429.92	0.00	5783.70
100	79,230,785.79	10,999,339.72	4,289,669.11	27,748,343.23	2,277,509.33	27,868,383.25	5,237,119.96	810,421.17	0.00	5760.72
200	75,221,570.09	11,032,899.07	4,301,681.31	24,317,694.68	2,278,308.34	27,544,843.93	4,784,779.59	961,363.17	0.00	5776.85
300	70,364,888.41	11,040,850.20	4,173,546.67	20,881,716.84	2,203,039.74	26,198,685.87	3,948,210.31	1,918,838.78	0.00	5604.78
400	70,364,884.15	11,040,850.32	4,173,546.71	20,881,717.51	2,203,039.74	26,198,684.51	3,948,206.96	1,918,838.40	0.00	5604.78
500	70,364,884.13	11,040,850.32	4,173,546.71	20,881,717.52	2,203,039.74	26,198,684.50	3,948,206.93	1,918,838.40	0.00	5604.78
600	67,780,934.11	10,717,917.55	4,184,284.21	18,621,192.10	2,206,323.14	26,098,369.95	3,610,674.97	2,342,172.20	0.00	5619.20
700	65,032,400.28	10,966,060.25	4,173,541.64	15,355,515.73	2,201,066.37	26,059,990.70	4,278,082.10	1,998,143.49	0.00	5604.77
800	64,000,726.65	10,910,200.03	4,191,530.33	13,798,975.49	2,210,069.10	26,138,313.60	4,861,449.40	1,890,188.70	0.00	5628.93
900	63,471,770.40	11,029,627.71	4,198,985.66	13,456,871.51	2,214,707.64	26,234,494.31	4,657,490.65	1,679,592.92	0.00	5638.94
1000	63,186,459.93	11,201,231.44	4,181,880.61	13,420,781.38	2,206,009.11	26,150,351.00	4,230,625.20	1,795,581.19	0.00	5615.97
1100	63,186,457.09	11,201,229.68	4,181,880.64	13,420,829.05	2,206,009.44	26,150,373.50	4,230,615.36	1,795,519.43	0.00	5615.97
1200	63,186,457.09	11,201,229.68	4,181,880.64	13,420,829.06	2,206,009.44	26,150,373.50	4,230,615.36	1,795,519.43	0.00	5615.97
1300	62,648,626.83	11,076,630.42	4,181,295.41	13,419,897.41	2,205,286.52	26,117,602.82	4,229,198.87	1,418,715.39	0.00	5615.18
1400	62,645,389.01	11,076,634.06	4,181,294.63	13,416,613.54	2,205,286.89	26,117,652.79	4,229,191.29	1,418,715.81	0.00	5615.18
1500	61,935,450.66	11,076,771.75	4,181,013.56	13,026,197.65	2,205,083.64	26,112,032.77	4,228,805.69	1,105,545.60	0.00	5614.81
1600	61,836,986.78	11,076,783.65	4,181,008.85	12,870,759.08	2,205,077.82	26,111,769.14	4,228,783.77	1,162,804.47	0.00	5614.80
1700	61,836,986.71	11,076,783.65	4,181,008.85	12,870,780.88	2,205,077.82	26,111,769.13	4,228,783.77	1,162,782.61	0.00	5614.80
1800	61,737,175.82	11,076,783.67	4,181,008.86	12,811,872.42	2,204,328.31	26,059,149.19	4,228,783.77	1,175,249.60	0.00	5614.80
1900	61,531,755.92	11,076,937.68	4,180,998.66	12,678,908.07	2,205,054.47	26,110,442.50	4,226,623.35	1,052,791.19	0.00	5614.79
2000	**61,531,755.92**	**11,076,937.68**	**4,180,998.66**	**12,678,908.05**	**2,205,054.47**	**26,110,442.50**	**4,226,623.35**	**1,052,791.21**	**0.00**	**5614.79**

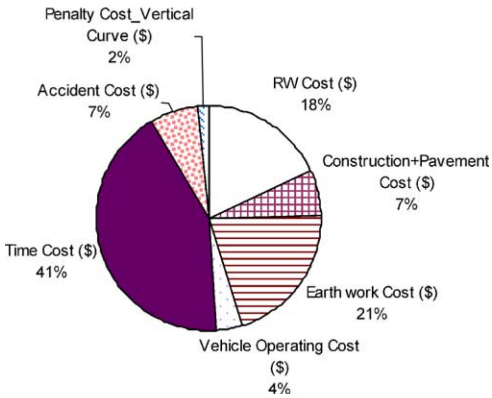


Fig. 18. Cost breakdown of the optimized alignment for Case 4.

highway projects. For example, for certain streetscape or extension projects the alignment must be restricted within certain narrow bounds. The proposed model can yield an efficient solution for such projects.

4.4. Case 4

This case is designed primarily to explore the effectiveness of the model in mountainous terrain. The earthwork and user costs would be quite significant in mountainous terrain due to longer and more circuitous alignments. Fig. 16 shows two mountains in the search space. The start and end points for the search are labeled S and E, respectively. The search space has 600 properties in it with a total area of 24 km^2. For simplicity, the properties are assumed to be of uniform size. The unit land costs range from 20 to 1000 $\$/m^2$. The terrain elevation ranges from 80 to 500 m and the Euclidean distance between the start and end points is 1.53 km. The alignment width and other input values are similar to the previous cases, as shown in Table 2.

The model is run for 2000 generations this time. The optimized alignment obtained at the 2000th generation is shown in Fig. 17. It is separately shown on elevation and cost maps. In Figs. 17a and b the darker shades represent higher elevations and higher land-costs, respectively. It can be seen that the optimized alignment finds its way through lower elevations and inexpensive properties to minimize the overall cost. It narrowly avoids the two mountains in the search space. The optimized results are shown in Table 4 and the cost breakdown is shown in Fig. 18. The total alignment length and cost at the 2000th generation are 1.71 km and $61.5 million, respectively. Fig. 18 indicates that the earthwork and travel-time costs are quite significant due to mountainous terrain and longer alignment. It is noted that the model allows the user to specify the desired optimization type, i.e., optimization of either horizontal alignment or vertical alignment or both.

5. Conclusions

A practical highway optimization model using GIS is developed, which can work with real geographic databases. Several test examples are used to examine the relative effects of various cost types, usability considerations and a constrained search space that realistically reflect the limits on road improvement projects. In addition, the model is also tested in regions with heterogeneous land-use and mountainous terrain. The results demonstrate that there is a considerable tradeoff among various costs used in optimization and care should be taken in using appropriate cost functions. It is also noted that due to the presence of a dominant cost sensitivities of other costs may not be too apparent. The travel-time cost, which may not be of great concern from the supplier's viewpoint, generally tends to be dominating.

While the usability analysis estimates the right-of-way cost quite precisely, it significantly increases computing time. The density of parcels also significantly increases the computing time. It was found that computing efficiency increases when smaller search spaces are used although it only guarantees a local optimal result in that space. For solving larger problems parallel processing and restricting the search spaces are recommended. Also, faster computers should ease the computational burden due to larger problems. A test of 3-D alignment optimization in a complex mountainous terrain shows that the model can find very good solutions in regions with complex topography.

The method presented here is particularly suitable for initial screening of highway alignments. Given sufficiently detailed cost functions and the spatial databases, the method should also be applicable to more detailed alignment optimization.

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