Highway Alignment Optimization Incorporating Bridges and Tunnels

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Abstract: A three-dimensional highway alignment optimization methodology is developed that automatically determines whether and where bridges or tunnels are preferable to embankments or deep cuts, respectively. This is done by comparing the optimized costs of such alternatives. The data for detailed computations of earthwork, right-of-way, vehicle operation, user time, and other costs are obtained from a geographic information system (GIS) for each alternative alignment considered. The alignment optimization process relies on a genetic algorithm developed for this problem. Two example studies implemented in an artificial study area with a real GIS show that by modeling bridges and tunnels we can improve the reliability and adaptability of highway alignment optimization as well as find more practical solutions than otherwise.

DOI: 10.1061/(ASCE)0733-947X(2007)133:2(71)

CE Database subject headings: Bridges, highway; Tunnels; Alignment; Geographic information systems; Algorithms.

Introduction

Bridge and tunnel options as substitutes for embankments and deep cuts are difficult to examine in an automated optimization process for highway alignments due to topographic and land-use complexities. These issues are often faced by highway planners, designers, and bridge engineers in highway agencies and pose a challenging task. A multitude of factors, such as structures, topography, socioeconomics, land-use patterns, operating costs, user time, safety, environment, and community concerns, increase the problem's complexity. These are considered with different degrees of emphasis and levels of detail at different stages in alignment optimization. Typically, these processes for highway alignments have required much time and effort from highway agencies, planners, engineers, and affected residents. Imprecise assessment of bridge and tunnel locations may cost billions of dollars when projects have to be delayed and rescoped. Some examples of such projects include Boston's central/artery tunnel, Northern Virginia's mixing bowl, and Maryland's Intercounty Connector.

Several mathematical and computer models (OECD 1973; Shaw and Howard 1982; Fwa 1989; Jong 1998; Jong et al. 2000; Jha 2000; Kim 2001; Jong and Schonfeld 2003; Jha and Schonfeld 2004; Jha et al. 2006) have been developed for optimizing highway alignments. These optimization methods can save considerable time and cost compared to traditional manual methods yet previously did not incorporate the options of bridge and tunnel construction. There are certainly some circumstances where bridge or tunnel construction is more economical than fills or cuts, especially in mountainous areas, yet while culverts are also alternatives to bridges and fills, we have deferred their analysis.

Characteristics of Bridges and Tunnels

Bridge Characteristics

When bridges dominate the associated alignments, the following arguments by Barker and Puckett (1997) are generally true: "a bridge is the key element in a transportation system for three reasons: (1) it controls the capacity of the system; (2) it is the highest cost per mile of the system; and (3) if the bridge fails, the system fails." Although various bridge types may be considered, we focus here on the steel and concrete composite girder type, which accounts for most U.S. highway bridges (Barker and Puckett 1997).

On a particular highway alignment, we should consider when a bridge may be preferable to fills. There should be an economic break-even point between fills and bridges, depending on various site-specific characteristics. In this study, the break-even point is determined and used to evaluate alignment alternatives. Of course, bridges are sometimes the only practical option, as for example, for crossing rivers. Other important bridge characteristics affecting highway alignments include radii of bridges, span lengths, number of spans, number of piers, and heights of piers. Bridges need not be straight: having horizontal and vertical curvatures, they are considered parts of alignments.

Tunnel Characteristics

Among many tunnel elements, the most important factors for highway tunnels are ventilation for pollutants and consequent ad-

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Note. Discussion open until July 1, 2007. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on July 9, 2003; approved on May 22, 2006. This paper is part of the ***Journal of Transportation Engineering***, Vol. 133, No. 2, February 1, 2007. ©ASCE, ISSN 0733-947X/2007/2-71–81/$25.00.

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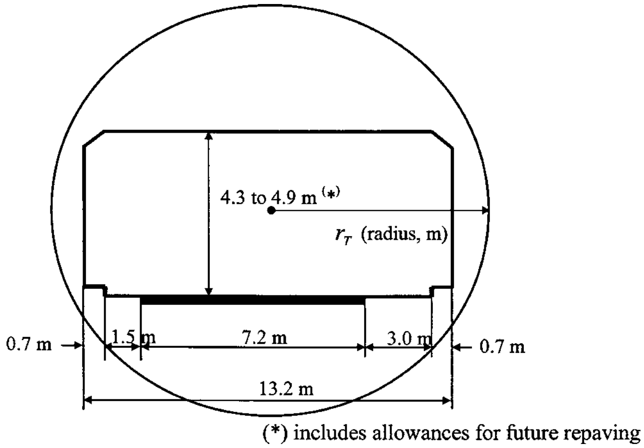

Fig. 1. AASHTO typical desirable cross section and clearances for two-lane tunnel

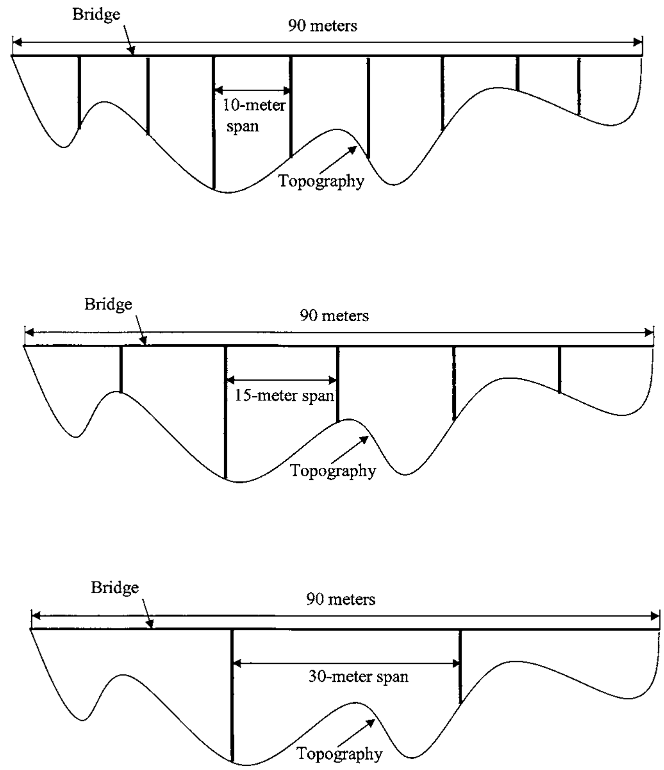

Fig. 2. Equally spaced piers for example bridge using integer numbers of equal spans

justment of the air supply and exhaust, lighting for safety and ensuring maximum appropriate speeds, fire safety provisions for providing refuge from a raging fire or deadly smoke, elaborate traffic surveillance and control systems coordinated with the other system for protected egress of motorists in the event of a fire and access for firefighting personnel, and soil types for earthwork and construction (King and Kuesel 1996). These elements are functions of several characteristics of tunnels. Many tunnel characteristics affect their costs, among them, those that affect highway alignments, such as cross sections, clearances, horizontal alignments, and grades.

Fig. 1 illustrates the AASHTO (2001) typical desirable cross section and clearances for a two-lane tunnel with two 3.6 m lanes, a 3.0 m right shoulder, a 1.5 m left shoulder, and a 0.7 m curb or sidewalk on each side. The roadway width may be differently distributed to either side if needed to better fit the dimensions of the tunnel approaches. The vertical clearance for the desirable section is 4.9 m for freeways and 4.3 m for other highways.

If curves are required along tunnel sections, the minimum radius is determined by stopping sight distances and acceptable superelevation in relation to design speed. Where shoulders are narrow, horizontal sight distance may be restricted by the proximity of the tunnel sidewall; usually, passing distances do not apply.

Upgrades in tunnels carrying heavy traffic are preferably limited to 3.5% to reduce ventilation requirements. For long two-lane tunnels with two-way traffic, a maximum grade of 3% is desirable to maintain reasonable truck speeds; for downgrade traffic, 4% or more is acceptable; and for lighter traffic volumes, grades up to 5 or even 6% have been used for economy's sake (King and Kuesel 1996).

Cost Functions for Bridges and Tunnels

Bridge Cost Functions

According to bridge engineering conventions (O'Connor 1971; Meiarashi et al. 2002; Mitsuru et al. 1988; Fagan and Phares 2000), bridge costs are usually classified into those for superstructure and substructure. Both cost components are functions of the number of spans, span lengths, types, materials, pier heights, and topography. There is no simple formula for estimating bridge costs based on all these variables; only theoretical linear functions for superstructure and substructure costs based on one variable—span lengths—are available from the literature (O'Connor 1971).

Our extensive literature search on the Engineering Village II and Transportation Research Information System (TRIS) databases did not reveal any bridge cost formulation as a function of the bridge characteristics relevant for alignment optimization, such as number of spans, span lengths, types, and materials. However, numerous articles [such as Meiarashi et al. (2002); Mitsuru et al. (1988); Fagan and Phares (2000)] address life-cycle cost analysis of different highway bridges as well as cost-effective measures for bridge repair and rehabilitation. The linear functions for superstructure and substructure costs noted in O'Connor (1971) are based on simply supported composite (steel and concrete) girder bridges. Once the type, material, and length of a bridge are set, the estimated bridge costs depend mainly on (1) how many piers (substructures) are selected; and (2) where those piers are located. These two factors are interrelated in optimizing bridges.

In bridge engineering, continuity is considered a major factor in optimizing pier locations or span lengths. Continuity considerations favor equal or at least gradually varying spans. This study uses a simple approach for estimating bridge costs based on such continuity considerations. The following example shows how the number of piers or span lengths for bridges can be optimized. Suppose that we consider a highway bridge which is 90 m long. To maintain continuity (that is, equal spans), we should divide the 90-m length by some integer, for example, 3, 6, or 9, resulting in 30-, 15-, or 10-m spans, respectively, as shown in Fig. 2. Based on configurations in Fig. 2, we can compute the total bridge costs for each case based on the given number of piers and span lengths (the details are explained later). This approach is pursued numerically until the span is optimized, as shown in Fig. 3. (There is no

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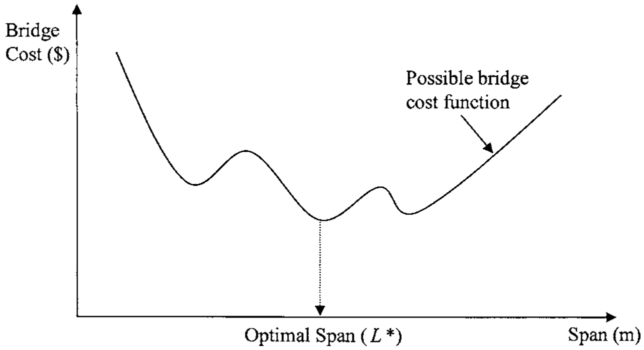

Fig. 3. Graphical representation of bridge span optimization

guarantee that the bridge cost function is convex. Local optima may exist when a bridge is relatively long and the terrain under it is unsmooth.)

Since this study is not intended to fully optimize bridges, some limited but acceptable number of trials is envisioned. It is notable that the search space has just one dimension, the span. A 2D extension of this problem might add an optimizable variable for locating the first pier.

To estimate bridge costs, linear cost functions for superstructure and substructure developed by O'Connor (1971) are adopted. For the superstructure costs (C_U^B), Eq. (1) can be used

$$C_U^B = (a_1 + a_2 L) \tag{1}$$

where L=span length and the coefficients are differentiated by a girder spacing. Please note that the above formula can be easily replaced in our model if another relationship is available in the literature.

Eq. (2) shows that costs (C_L^B) per foot-width of substructure for variable pier heights increase linearly with span

$$C_L^B = (a_3 + a_4 L) \tag{2}$$

The coefficients in Eq. (2) differ for different pier heights.

Tunnel Cost Functions

The characteristics affecting small tunnel costs include lengths, cross sections, clearances, horizontal alignments, and grades. Based on these characteristics, this study formulates both earthwork costs and additional costs for small tunnels. Earthwork costs account for lengths, cross sections, and clearances, while additional costs account for remaining characteristics and factors. For estimating earthwork costs, typical desirable cross sections and clearances for a two-lane highway tunnel configuration shown in Fig. 1 are considered. This study uses the tunnel radius (r_T, m) since tunnels are usually excavated with circular cross sections. Therefore, the tunnel earthwork costs (C_E^T) are

$$C_E^T = \pi K_T L_T (r_T)^2 \tag{3}$$

where K_T=tunnel earthwork unit cost per cubic meter (\$/m^3) and L_T=tunnel length (m).

The tunnel earthwork cost function shown in Eq. (3) is a linear function of tunnel length. However, the other costs for ventilation, lighting, fire safety, surveillance, and traffic controls may not be captured with a linear function of tunnel length.

Cost functions for estimating additional tunnel costs (C_a^T) are difficult to obtain from previous studies. We may then rely on existing databases for each affecting factor from which some functional forms can be developed. This study does not develop cost functions for those factors. Here, a quadratic function of tunnel length is introduced for preliminary analysis, to allow for factors such as ventilation, lighting, fire life safety provisions, and traffic control systems that have a more than linear effect on tunnel costs

$$C_a^T = \alpha_1^T (L_T)^2 + \alpha_2^T (L_T) + \alpha_3^T \tag{4}$$

It is important at this point to remember that the optimization processes for highway alignments should involve both dominating and sensitive cost items (OECD 1973). For the preliminary alignment optimization, the effects of tunnel excavation costs may dominate the other cost items such as ventilation, fire safety, and surveillance.

Moreover, for normal operations, naturally ventilated and traffic-induced ventilation systems are considered adequate for relatively short tunnels [less than 180 m (600 ft)] with low traffic volumes (Bendelius 1996). Also, in most cases a lighting system is not required inside tunnels of less than 45 m (150 ft) (Mowczan 1996), and fire safety provisions and traffic control systems may not be deployed for short two-way rural highway tunnels. In this study, it is assumed that tunnel construction costs are mainly based on tunnel excavation costs; additional tunnel costs in Eq. (4) are only applied when the tunnel length exceeds 180 m.

Incorporating Cost Functions into Genetic Algorithms

This section describes algorithms devised for incorporating the developed cost functions (Kim 2001) into genetic algorithms (GAs) previously developed for highway alignment optimization (Jong et al. 2000; Jong and Schonfeld 2003; Jha and Schonfeld 2004). These GAs are specially adapted from classic GAs for highway alignment optimization. An extensive discussion of the applicability of GAs for highway alignment optimization is provided in Jong and Schonfeld (2003); therefore, only a brief overview is provided here. We should note, however, that GAs are especially suited for optimization problems with numerous local optima and are easily adaptable to parallel processing.

In these specialized GAs, the problem (alignment optimization) is treated as the environment and a set of possible solutions to the problem is treated as the population. Each alignment in the population is encoded into a string representation called a chromosome. At each generation, the individuals (alignment alternatives) then compete with each other for reproducing offspring according to their "fitness" (i.e., minimum cost in this study) to the environment (the problem) by applying genetic operators (such as crossover or mutation). Through successive generations, the most adapted alignments should survive and influence future generations, whereas poor alternatives should become extinct. The population will finally converge to a near-optimal solution. Detailed discussions of GAs are available in Goldberg (1989) and Michalewicz (1996).

At least seven search methods for alignment optimization have been considered: GAs, calculus of variations, network optimization, dynamic programming, enumeration, linear programming, and numerical research. Among them, the six methods other than GAs have some critical weaknesses for highway alignment optimization, in which cost functions are nondifferentiable, noisy, and implicit (e.g., user costs cannot be calculated until alignments are finally determined). Goldberg (1989) states four important dis-

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tinctions of GAs over other search methods: GAs (1) work with a coding of the parameter set, not the parameters themselves; (2) search from a population rather than a single point; (3) use payoff (objective function) information, not derivatives or other auxiliary knowledge; and (4) use probabilistic transition rules, not deterministic rules. Despite the above advantages, it is notable that GAs do not always find an absolute global optimum and are not the best search algorithms for all problem types, but rather can be considered very effective approaches for finding near-optimal solutions relatively quickly.

The objective function used in this study integrates elements of the objective functions developed by Jong (1998) and Jha (2000) with bridge and tunnel cost functions developed in the previous sections:

$$\underset{d_1,d_2,\ldots,d_n}{\text{Minimize}} \quad C = C_R + C_P + C_U + C_E + C_U^B + C_L^B + C_E^T + C_a^T \tag{5a}$$

subject to

$$d_{iL} \le d_i \le d_{iU}, \quad \text{for all } i = 1, \ldots, n \tag{5b}$$

where C=total cost (\$); C_R=right-of-way cost (\$); C_P=pavement cost (\$); C_U=user cost including fuel consumption, travel time, and accident costs (\$); C_E=alignment earthwork cost (\$); C_U^B=bridge superstructure cost (\$); C_L^B=bridge substructure cost (\$); C_E^T=tunnel excavation cost (\$); C_a^T=additional tunnel cost (\$); and d_{iL} and d_{iU}=lower and upper bound of the ith decision variable.

For incorporating bridge and tunnel costs into total alignment cost functions, precision is helped by locating as many stations on a new alignment as possible, subject to reasonable limits on computing time. In this study, 6 m (20 ft) is used as the station length. We must also determine the critical elevation differences for bridge (tunnel) construction, at which those become preferable to fills (cuts). Unfortunately, it is very difficult to predetermine optimal elevation differences since the critical elevation differences are functions of the associated earthwork volumes as well as the lengths of bridges and tunnels. Thus, the relation between earthwork volumes and lengths of bridges or tunnels does not have a closed form. However, vertical clearances should be maintained for bridges and tunnels. This study uses 4.5 m of elevation differences between an alignment (road) and the ground as the threshold for constructing bridges or tunnels. In other words, bridges (tunnels) are considered if a road elevation is 4.5 m higher (lower) than the ground elevation. Then, the algorithms determine the lengths of bridges (tunnels) for finally selecting the preferable (less costly) choice between bridges (tunnels) and fills (cuts).

Ground and Road Elevations

In the proposed HAO model (Jha et al. 2006), ground elevations for the analysis section are assumed to be available from site survey of CADD/elevation maps (Kang et al. 2006). The GA randomly generates a 3D alignment at each search stage, and thus at any given search generation, ground and road elevations are known that are necessary to perform bridge/tunnel analysis. Since the model relies on exogenously available terrain and lake/creek elevations, the results are as good as the supplied elevations. The algorithm for combining bridges and tunnels with original genetic algorithms are as follows:

Step 1: Set as many stations on a new alignment as computationally feasible (6 m station gap in this study).

Step 2: Find the stations at which bridges and tunnels are preferable. If elevation differences exceed vertical clearances (4.5 m), save those stations as candidates for bridge or tunnel construction, depending on the sign of elevation difference.

It is worth noting that unless road cross sections are as wide in tunnels as elsewhere, some additional accident costs should be included in the evaluation.

Step 2.1: Discard any alignment through creeks, rivers, and lakes that violates the high water level constraint, ϵ_w. Thus, if any station's road elevation is not above ϵ_w ($z_r \le \epsilon_w$), the alignment is infeasible. Also, assign large right-of-way costs to any alignment through environmentally sensitive properties.

Step 2.2: Find stations for bridges and tunnels.

- Step 2.2.1: Find stations for bridges: If ($z_g > 0$ and $z_r - z_g > 4.5$ m) or ($z_g = 0$ or $z_r - z_g > 0$), save ($z_r - z_g$) and the station number for bridge construction.
- Step 2.2.1: Find stations for tunnels: If ($z_g > 0$ and $z_g - z_r > 4.5$ m), save ($z_g - z_r$) and the station number for tunnel construction.

Step 2.3: Obtain the lengths of bridges and tunnels using the saved station number in step 2.2. This step only applies when the lengths equal or exceed the user specified length which, in this study, is set at 100 ft.

Step 2.4: Estimate the costs of bridges and tunnels.

- Step 2.4.1: Bridge costs
  - a. Find an optimal span length using the method developed in the previous section.
  - b. Estimate superstructure costs and substructure costs based on the optimal bridge span and lengths using the cost functions.
  - c. Estimate the total bridge cost using Eqs. (1) and (2).
- Step 2.4.2: Calculate tunnel costs using Eqs. (3) and (4).

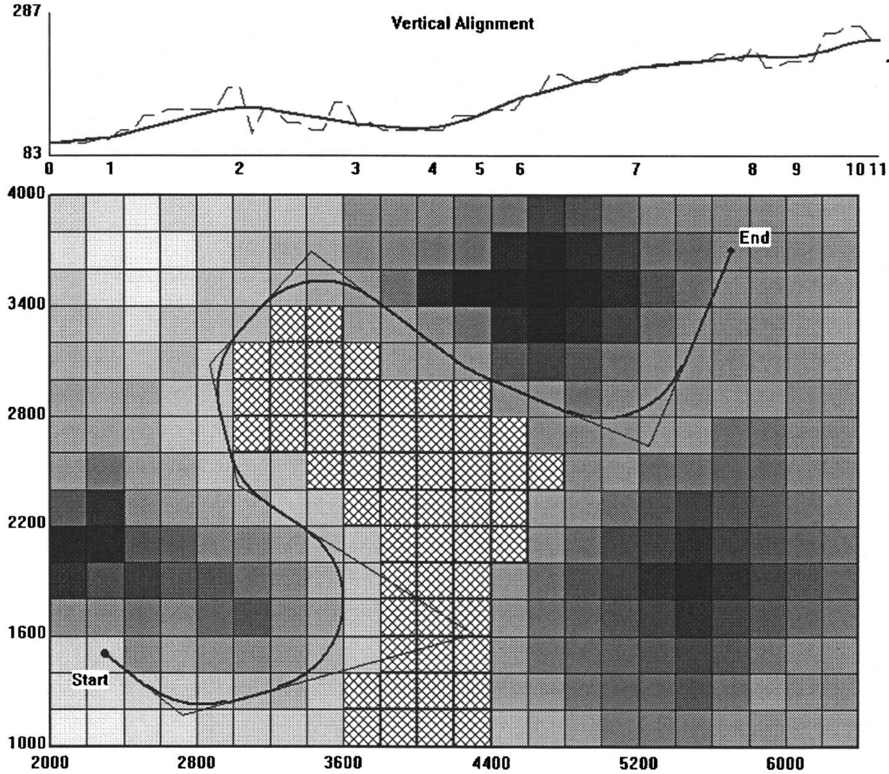
Step 2.5: Calculate earthwork costs for stations where bridges and tunnels are not considered. For precisely estimating earthwork costs, planar interpolation is applied (Kim and Schonfeld 2001).

Step 3: Return the total costs.

- Step 3.1: If no bridges and tunnels are considered, return pure earthwork costs.
- Step 3.2: If a new alignment hits environmentally sensitive areas, return the assigned earthwork costs using a large unit cost in step 2.1.
- Step 3.3: If a new alignment consists of at least one bridge or tunnel, return the bridge and tunnel costs summed up with earthwork costs for stations where cuts and fills are applied.

Case Study

To illustrate modeling processes of bridges and tunnels in alignment optimization, one artificial study area and a real GIS map are used. Fig. 4 shows an artificial study area where darker cells represent higher elevations. The hatched area represents a lake. Jong (1998) obtained the best solution at generation 1,999. (2,000 generations were run in 25 s on a desktop PC with 1 GHz CPU speed and 261 MB RAM.) That solution costs approximately \$27.8 million. In it, bridges and tunnels are precluded by assign-



Generation #	Objective
1971	27821056
1972	27821056
1973	27821056
1974	27821056
1975	27821056
1976	27821056
1977	27821056
1978	27821056
1979	27821056
1980	27821056
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1999	27821056
2000	27821056

(Note: The first column values on the right represent the search generation in genetic algorithms and the second column values represent objective function (total cost) in dollars)

Fig. 4. Best solution found by Jong (1998) for artificial study area (used with permission)

ing a high right-of-way value (approximately 50 times higher than other cells) to the lake.

The artificial study area in Fig. 4 is then used without changing the high unit right-of-way cost of the lake to check how the developed cost functions and algorithms for modeling bridges and tunnels search for a solution. When incorporating the modeling processes for bridges and tunnels, a completely different solution (Fig. 5) is found at generation 1,802, which costs $22.45 million. Computations take 2 min and 43 s, which is 6.5 times longer than Jong's 25 s.

The new alignment has two tunnels and one bridge. As shown in the upper part of Fig. 5, new vertical alignment exhibits less emphasis on balancing earthwork volumes than in Fig. 4. This results in a straighter vertical alignment with steadier grades and less vertical curvature, which improves safety. Since alignments are significantly changed when incorporating bridges and tunnels, differences of total costs stem from many cost components such as right-of-way, pavement, and user costs and not just from the newly added bridge and tunnel costs, which are approximately $7.7 million (34% of the total costs). Table 1 shows the comparative cost breakdown for the two solutions. It is observed that solutions with significantly different costs and locations are obtained when bridges and tunnels are considered in alignment optimization models.

Since the unit right-of-way cost over the lake of Figs. 4 and 5 was assigned a deliberately high value, the solutions obtained are not supposed to cross the lake. For sensitivity analysis, the following example decreases this unit cost to allow a solution to cross the lake. This unit cost is now decreased from 50 to 5 times compared to the non-lake cells. From the new right-of-way cost of the lake, a changed solution is obtained (Fig. 6), which is straighter horizontally as well as vertically. The new alignment includes three tunnels and two bridges. This solution results from the mountainous topography of the study area and the advantages of a straight alignment which can greatly decrease user costs (by 55% of the solution in Fig. 7 and by 28% of the solution in Fig. 5).

The new optimized solution is obtained after 2,000 generations and costs $22.1 million. (In Fig. 6, the optimized objective function values seem unchanged from generations 1,971 to 2,000. However, comparisons are based on floating numbers rather than on integers.) Its computation time is 12 min and 44 s, which is 4.7 times longer than that of example in Fig. 4. This longer computation time is attributable to the shorter distance between station points (i.e., more station points on the alignment). To sensitively detect the effects of bridge and tunnel lengths, it is desirable to consider more stations. In this example, a 6 m (20 ft) distance between stations is employed instead of the 60 m (100 ft) used in the previous two cases. These many stations practically initiate more earthwork computations during the program run in addition to the computation time for bridge and tunnel cost estimation. Table 2 shows fractions of each cost item for this solution.

The optimized alignment in Fig. 6 has two bridges. For Bridge 2, which is 177 m (590 ft) long, the spans are optimized. To preserve the continuity of spans, integer numbers of piers and equal span lengths are considered. Also, a high-water level flooding constraint (ϵ_w=6 m) is applied. Table 3 and Fig. 7 illustrate

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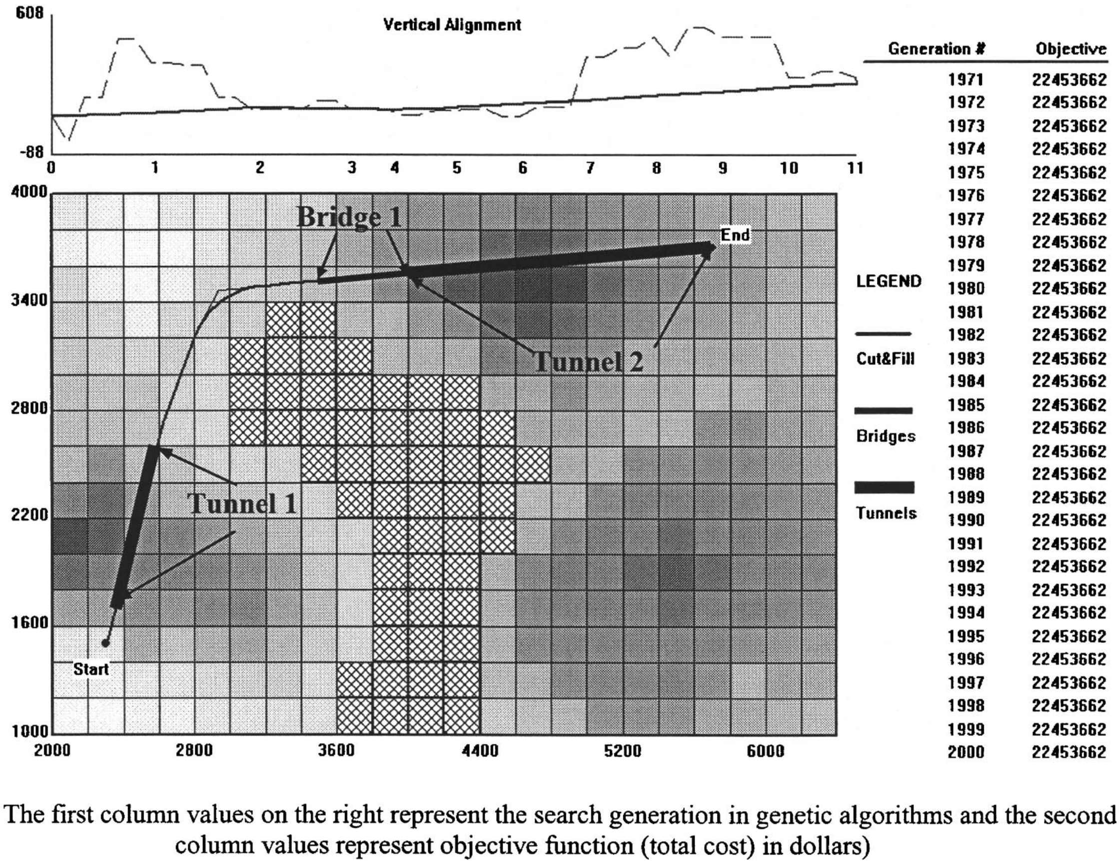

Fig. 5. New solution with bridges and tunnels for artificial study area

how the optimized span is obtained with an integer number of piers. Ten span lengths (7.1 through 88.5 m) are analyzed, using integer numbers of spans from 25 to 2; the optimized span is obtained as 29.5 m, with 5 piers.

Through the new solutions optimized by considering bridges and tunnels, it is notable that the user travel time and accident costs are greatly decreased. This is attributable to the straighter alignments with fewer steep gradients. For instance, the travel time value of \$13.3 million and accidents costs of \$453,000 in Jong's example (Fig. 4) decreased, respectively, by 59% to \$5.4 million and by 63% to \$166,000 in Fig. 6.

The results of the above artificial case study confirm that modeling bridges and tunnels in highway alignment optimization can yield much better (less costly) solutions. For testing the developed methods with a real GIS map, a study area is chosen from Garrett County, Maryland. It contains 90 properties (46 residential, 19 commercial, and 24 agricultural), and most parts of the area are agricultural and includes the Youghiogheny River, which crosses it from north to south, and two two-lane rural highways: White Rock Run and Bishoff Roads. Its area is approximately 0.66 km^2 (0.26 mi^2), unit land costs range mostly from \$0.22/m^2 (\$0.02/ft^2) to \$5.22/m^2 (\$0.47/ft^2), and costs of structure range from \$0.73,000 to \$122,000.

The land use and zoning of the study area were analyzed using the GIS-based desktop electronic property map "MDProperty View." The appraisal costs of properties in the study section ob-

Table 1. Cost Breakdown of Two Solutions Incorporating Bridges and Tunnels

	Jong's solution		New solution modeling bridges and tunnels		
	Costs (×\$1,000)	Fractions (%)	Costs (×\$1,000)	Fractions (%)	Changes in costs (×\$1,000)
Total costs	27,819	(100.00)	22,422	(100.00)	−5,397
Pavement costs	2,530	(9.09)	1,748	(7.79)	−782
Right-of-way costs	4,226	(15.19)	3,380	(15.06)	−846
Vehicle operation costs	1,341	(4.82)	854	(3.81)	−487
User time value	13,291	(47.77)	5,443	(24.25)	−7,848
Accident costs	453	(1.63)	166	(0.74)	−287
Earthwork costs	5,978	(21.49)	3,135	(13.97)	−2,843
Tunnel costs	—	—	6,981	(31.11)	+6,981
Bridge costs	—	—	715	(3.19)	+715

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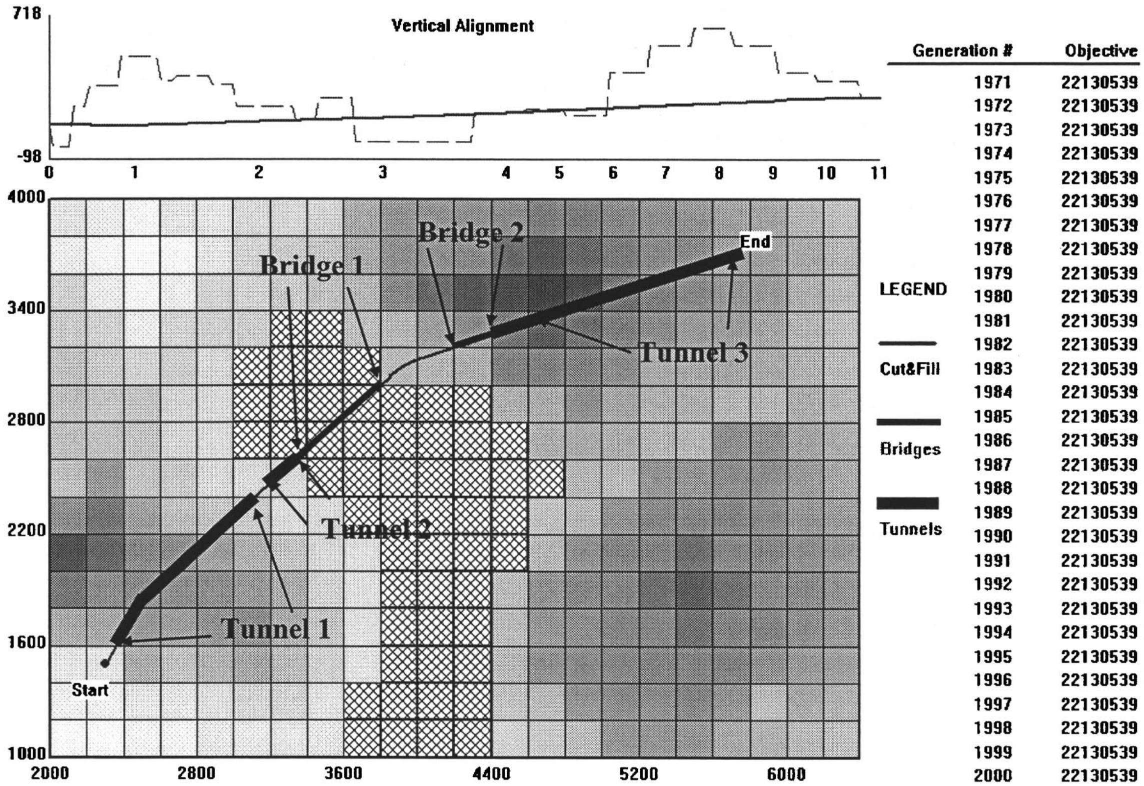

(Note: The first column values on the right represent the search generation in genetic algorithms and the second column values represent objective function (total cost) in dollars)

Fig. 6. New best solution for artificial study area

tained from MDProperty View ranged from \$20,000 to \$122,000. These are total property values, not per-meter values, and simply mean that the lowest cost of a house (structure) in the study area was \$20,000 and the highest cost was \$122K. Fig. 8 shows available topography of the study area; note that a hill is evident in the middle of the area.

Suppose that we construct a new two-lane road connecting two existing roads at two specified end points. We can clearly envision that a solution should have at least one bridge. Fig. 9 shows the best alignment successfully obtained by applying the developed methods to the study area after 50 generations.

Computation took 7,419 s (approximately 2 h and 3 min). Since data transfers occur between the optimization module operating in the "C" environment and the cost (especially right-of-way) estimation module operating in the GIS environment, extensive linkage and data transfer time was required.

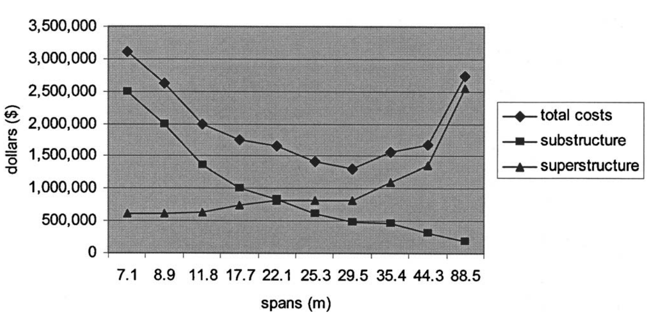

Fig. 7. Optimized span for Bridge 1

The optimized alignment has two bridges and two tunnels. Fig. 10 shows tunnel 1 and bridge 1 of Fig. 9 in detail. The alignment is shown from station zero (its start point) through station 41. Tunnel 1 is 60 m (200 ft) long between stations 9 and 19, with 6 m (20 ft) between stations, followed by bridge 1, which is 66 m (220 ft) long (stations 20 through 31). Between tunnel 1 and bridge 1, a 6 m (20 ft) gap is found. The differences between road and ground elevations of Tunnel 1 and Bridge 1 are found to be approximately 30 m (100 ft) each. The costs for Bridge 1 and Tunnel 1 are \$369,000 and \$559,000, respectively (Table 4); \$2.1 million and \$967,000 are estimated if fills and cuts are employed for Bridge 1 and Tunnel 1 (side slopes of 2.5:1 for fills and 2:1 for cuts are employed). This result justifies construction of Tunnel 1 and Bridge 1. The span of Bridge 1 is optimized at 22.5 m (75 ft),

Table 2. Cost Breakdown for New Best Solution

	Costs ($\times$\$1,000)	Fractions (%)
Total costs	22,131	(100.00)
Pavement costs	1,517	(6.86)
Right-of-way costs	3,960	(17.89)
Vehicle operation costs	748	(3.38)
User time value	4,565	(20.63)
Accident costs	98	(0.44)
Earthwork costs	2,304	(10.41)
Tunnel costs	6,981	(31.55)
Bridge costs	1,958	(8.85)

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Table 3. Optimized Span and Cost Breakdown for Bridge 1, Considering a High-Water Constraint

Number of spans	Span (m)	Total bridge costs (×$1,000)	Substructure costs (×$1,000)	Superstructure costs (×$1,000)	Optimized span (m)	Minimum bridge costs (×$1,000)
25	7.1	3,104	2,490	614	**29.5**	**1,305**
20	8.9	2,622	2,000	622		
15	11.8	1,989	1,359	630		
10	17.7	1,746	1,000	746		
8	22.1	1,657	838	819		
7	25.3	1,424	613	811		
6	**29.5**	**1,305**	**477**	**828**		
5	35.4	1,559	458	1,101		
4	44.3	1,669	310	1,359		
2	88.5	2,732	191	2,541		

and two equal height (60 m, 100 ft) piers are obtained.

Fig. 11 shows a profile for bridge 2 and tunnel 2 of Fig. 9. The stations from 96 through 141 are shown. Cuts are seen from station 96 to station 106 and fills are found between stations 139 and 149. Bridge 2 is 66 m (220 ft) long and Tunnel 2 is 126 m (420 ft) long. The differences between road and ground elevations of Bridge 2 and Tunnel 2 are found to be approximately 18 m (60 ft) and 26.1 m (87 ft), respectively. The span of Bridge 1 is also optimized at 22.5 m (75 ft). The costs for Bridge 2 and Tunnel 2 are $402,000 and $1.17 million, respectively (Table 4); $818,000 and $1.6 million are estimated if fills and cuts are substituted for Bridge 2 and Tunnel 2.

The total highway alignment costs are approximately $12.05 million. Table 4 and Fig. 12 show fractions of the total costs. Since the alignment passes through agricultural properties, right-of-way costs are relatively small for this particular example. Costs for two tunnels and two bridges are $1.73 million (14.37%) and $0.77 million (6.40%), respectively, and user costs ($6.2 million, 52%) account for most of the total costs. Based on the above analysis, the bridges and tunnels obtained on alignments are reasonable and preferable to fills and cuts. Moreover, the optimized solutions and cost estimates indicate that the developed cost functions and algorithms for modeling bridges and tunnels are performing reasonably to produce good solutions.

A sensitivity analysis of tunnels examines the influence of different unit excavation costs and elevation differences at which tunnels become preferable to cuts, since many geologic conditions can be found and different elevation differences can be used, subject to practical and constructional considerations. Since unit tunnel excavation costs vary significantly with soil types, it is desirable to check how different values affect the solutions and cost estimates. The unit cut cost per cubic yard employed for the previous examples was $15. This value is used for the excavation costs of tunnels and normal cut sections. Several excavation unit costs are employed for tunnels while keeping $15 for normal cut sections. To check sensitivity to different excavation unit costs and elevation differences, five scenarios are designed, as shown in Table 5.

The analysis is conducted based on the artificial area used previously in Fig. 6. Figs. 13 and 14 show the results for scenarios 1 and 5 after 2,000 generations. It is clear that the optimized solutions become more circuitous as elevation differences and tunnel excavation unit costs increase. Thus, very large excavation unit costs may be input for tunnels to prevent their use on alignments.

Conclusions and Future Work

A 3D highway alignment optimization method is developed that automatically determines whether and when bridges or tunnels are preferable to embankments or deep cuts, respectively. It is clear that bridges and tunnels may be desirable on many highways but have not yet been effectively incorporated into highway alignment optimization processes. The key idea for modeling bridges and tunnels within the context of highway alignment optimization is that there certainly are some circumstances where bridge or tunnel construction is more economical than fills or cuts, especially in mountainous and complex areas. The main objective of the paper is to develop a methodology that selects and optimizes bridge and tunnel constructions in lieu of fills and cuts if they are preferable. An algorithm for this purpose is developed that can work with the previously developed highway alignment

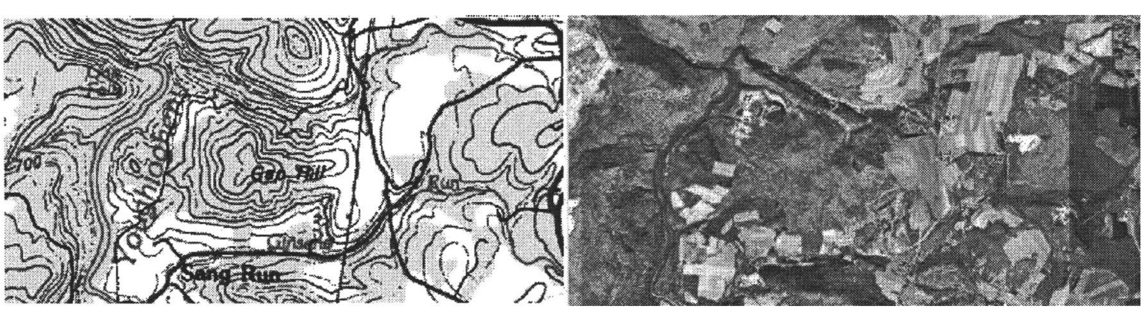

Fig. 8. Topography and aerial photo of study area

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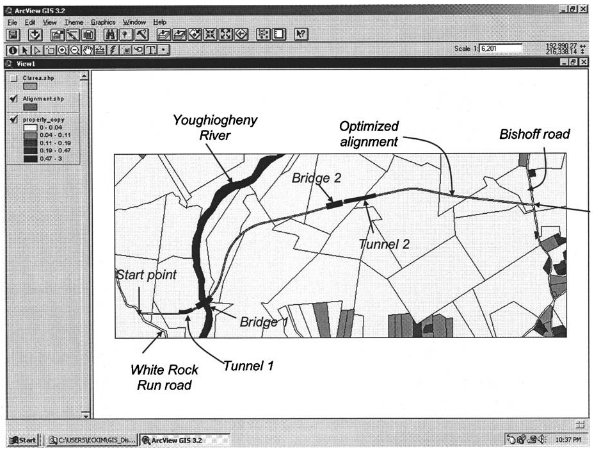

Fig. 9. Optimized solution for Garrett County, Md. example

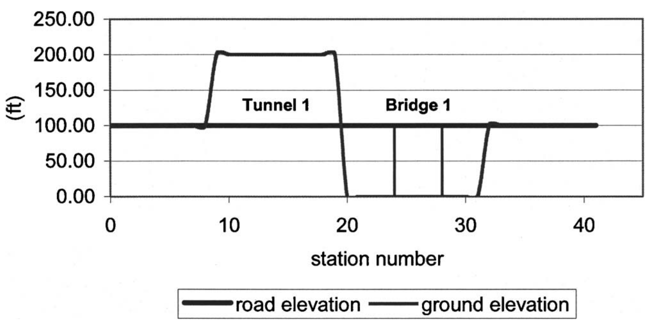

Fig. 10. Zoomed-in profile of Tunnel 1 and Bridge 1 for Garrett County example

Table 4. Cost Breakdown of Optimized Garrett County Solution

		Costs (×$1,000)	Fractions (%)
Total costs		12,049	(100.00)
Pavement costs		1,513	(12.56)
Right-of-way costs		107	(0.89)
Vehicle operating costs		768	(6.37)
User time value		6,245	(51.83)
Accident costs		297	(2.47)
Earthwork costs		616	(5.12)
Tunnel costs	Tunnel 1	559	(4.63)
	Tunnel 2	1,173	(9.73)
Bridge costs	Bridge 1	369	(3.06)
	Bridge 2	402	(3.34)

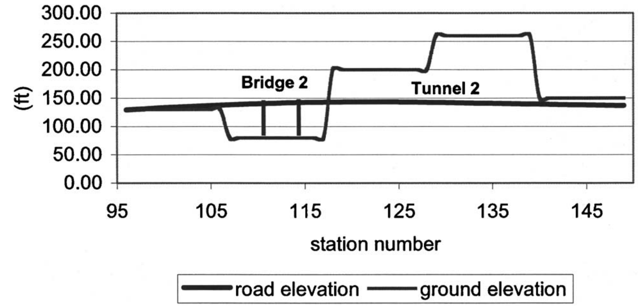

Fig. 11. Zoomed-in profile of Bridge 2 and Tunnel 2 for Garrett County example

optimization algorithm. A detailed bridge cost estimation using additional factors not considered in the analysis can certainly be incorporated in our future works. While culverts are also alternatives to bridges, their modeling is deferred to future extensions. It is shown that cost functions developed for bridges and tunnels can enhance the value and applicability of recently developed highway alignment optimization that previously neglected bridges and tunnel options.

Two example studies implemented in an artificial study area with a real GIS map along with the search for optimized bridge spans and sensitivity analysis of tunnels show that incorporating bridges and tunnels into highway alignment optimization processes produces practical solutions and enhances the scope and reliability of the optimization process.

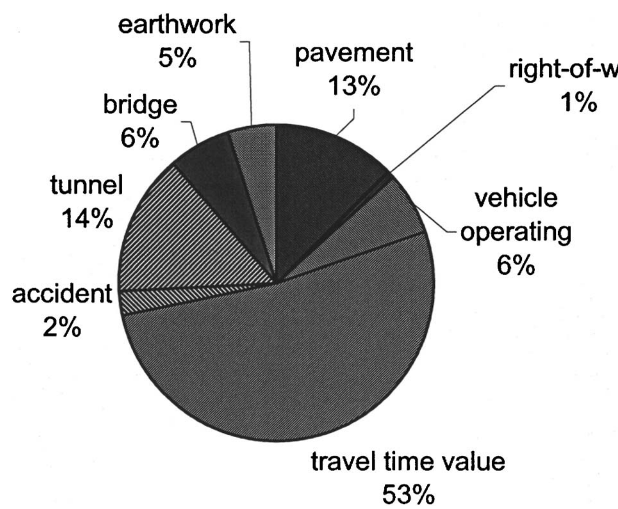

Fig. 12. Fractions for optimized solution for Garrett County example

Table 5. Scenarios for Sensitivity Analysis of Tunnels

Scenarios	Elevation differences between road and ground beyond which tunnels are considered (m)	Tunnel excavation unit cost ($/yd^3)
1	4.5 (15 ft)	30
2	5.4 (18 ft)	60
3	6.3 (21 ft)	120
4	7.2 (24 ft)	150
5	8.1 (27 ft)	250

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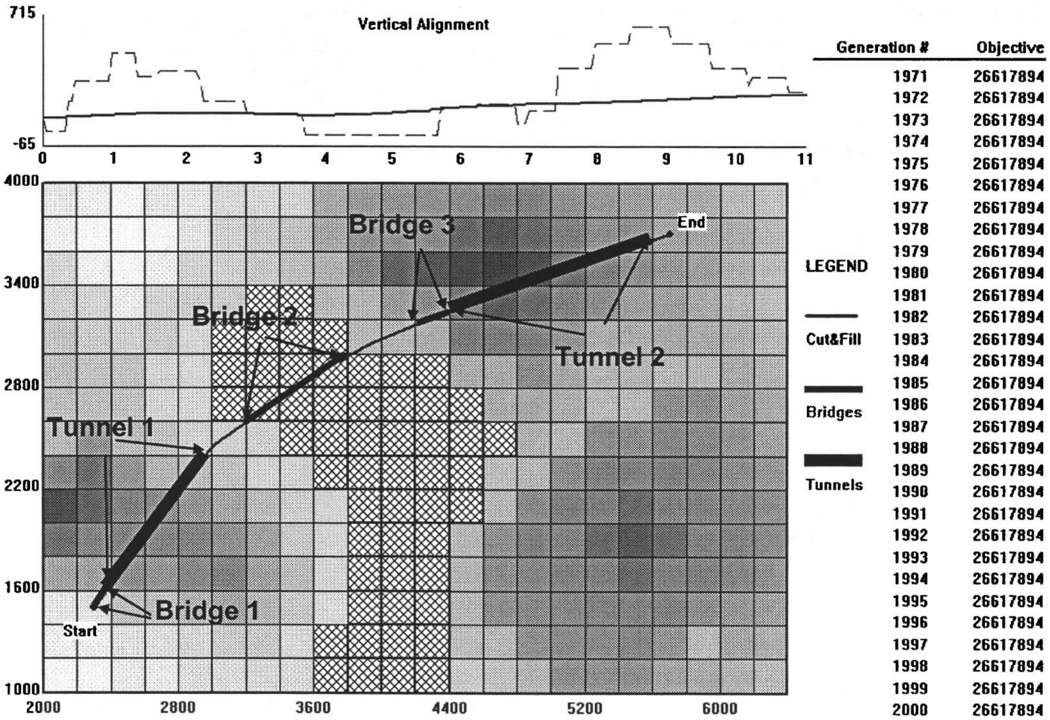
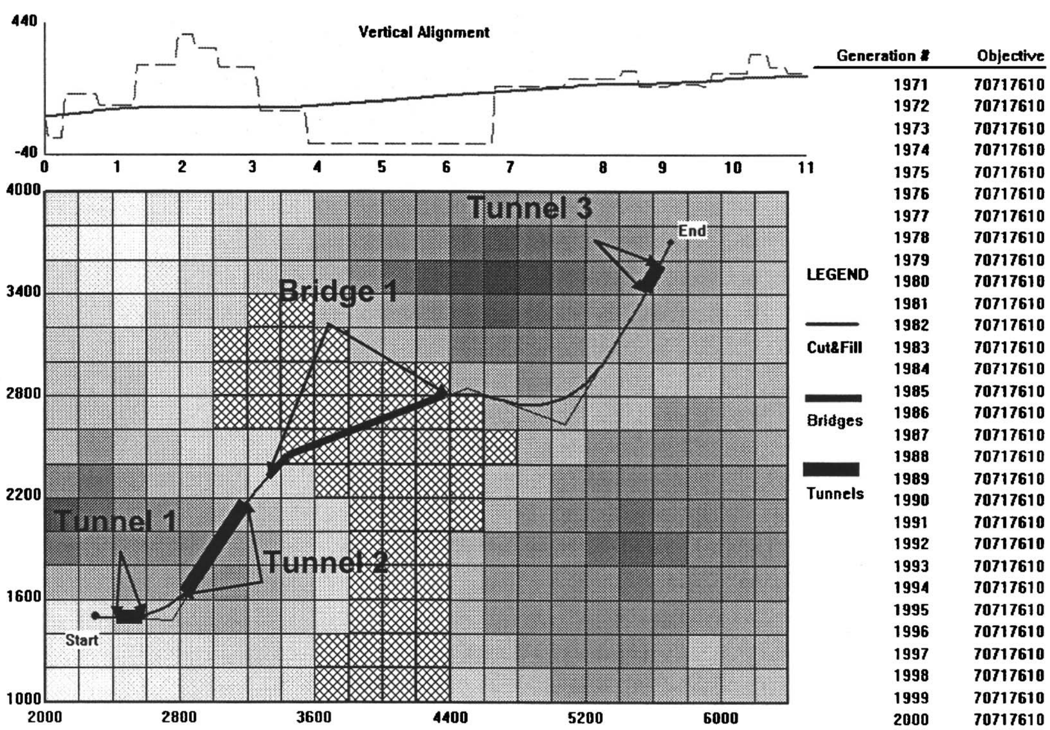


(Note: The first column values on the right represent the search generation in genetic algorithms and the second column values represent objective function (total cost) in dollars)

Fig. 13. Optimized solution (Scenario 1) for sensitivity analysis of tunnels



(Note: The first column values on the right represent the search generation in genetic algorithms and the second column values represent objective function (total cost) in dollars)

Fig. 14. Optimized solution (Scenario 5) for sensitivity analysis of tunnels

Acknowledgments

The writers are thankful for the many valuable comments made by the anonymous reviewers, which enhanced the quality of the paper. This work was partially supported by the Maryland State Highway Administration.

Notation

The following symbols are used in this paper:

a_1, a_2 = coefficients for bridge superstructure cost function;
a_3, a_4 = coefficients for bridge substructure cost function;
C_a^T = additional tunnel cost except tunnel excavation cost;
C_E = alignment earthwork cost;
C_E^T = tunnel excavation cost;
C_L^B = bridge substructure cost;
C_P = alignment pavement cost;
C_R = alignment right-of-way cost;
C_U = alignment user cost;
C_U^B = bridge superstructure cost;
d_{iL}, d_{iU} = lower and upper bound of ith decision variable;
K_T = tunnel earthwork unit cost;
L = bridge length;
L_T = tunnel length;
r_T = radius of tunnel circular cross sections;
z_g, z_r = road and ground elevations at stations;
$\alpha_1^T, \alpha_2^T, \alpha_3^T$ = coefficients for additional tunnel cost function; and
ε_w = high-water constraint.

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