Optimal Vertical Alignment Analysis for Highway Design

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Abstract: Critical length of grade control, fixed-elevation points, and nonoverlapping of horizontal and vertical curves are three common requirements in the vertical alignment design of roads. These three forms of constraints are, however, usually not addressed in the conventional road alignment optimization analysis because of the complexity in considering them in the mathematical formulation and solution of the problem. This paper illustrates that the artificial intelligence technique of genetic algorithms can be adopted to handle these three forms of constraints effectively. The formulation of the genetic-algorithm computer program and the method of solution are explained. The validity of the optimization algorithm is verified against a dynamic programming solution. Examples are presented to illustrate the application of the genetic-algorithm program to problems involving critical length of grade requirements, fixed-elevation control, and nonoverlapping of horizontal and vertical curves. These three constraints were found to have significant effects on the computed optimal alignments and the associated construction costs.

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Introduction

Vertical alignment determination is a major element of highway design that has important implications on road construction costs, traffic operations, vehicle fuel consumption, driving maneuverability, and safety. In addition, it also has major environmental implications with respect to disruption of natural landform and soil conservation. The constraints and requirements, many of which are conflicting in nature, have made the design of vertical alignment a rather complicated problem. The need for optimization analysis in the selection of a desirable vertical alignment has long been recognized. It has been a topic actively studied by researchers since the 1960s, when the advent of computer made theoretical optimization techniques practicable analytical tools for solving engineering problems.

Many different optimization techniques have been applied by researchers for vertical alignment analysis. These include liner programming (Schacke 1972); quadratic programming (Calogew 1973); various methods of search, such as direct search, random search, and gradient search (Haymon 1970); state parametrization (Goh et al. 1988); and more recently genetic algorithms (GAs) (Jong 1998). It is observed that all these models have provided alignment designs to meet vehicle operational requirements of safety sight distances and maximum grade control. However, merely meeting safety sight distances and the maximum grade requirements is inadequate. A vertical alignment design is not complete without incorporating in the analysis the critical length consideration and the nonoverlapping control of horizontal and vertical curves. A different optimal vertical alignment design will be obtained in an optimization analysis when these considerations are included.

Fixed-elevation control points are another common requirement in real-life projects that present difficulties in conventional mathematical optimization analyses. Such controls are necessary in built-up areas and at intersections with existing highways and bridges. Inclusion of the critical length consideration, fixed-elevation control points, and nonoverlapping of horizontal and vertical curves greatly increases the degree of difficulty in problem formulation and optimization analysis of vertical highway alignment design. This paper describes an optimization algorithm that addresses these three additional considerations along with the requirements of maximum grade and safety sight distances. The GA optimization technique is adopted in this study. Numerical examples are presented to show that significantly different optimal alignments are obtained with the additional considerations.

Problem Description

Besides presenting the development of GA formulation for solving the general vertical highway alignment problem, it is an aim of this study to illustrate the need to include in the analysis the three additional considerations highlighted in the preceding section. For the purpose of comparison and easy demonstration, a problem solved by Fwa (1989) using dynamic programming is analyzed in this paper. The three additional considerations were not considered in the dynamic programming solution by Fwa.

Fwa (1989) performed a preliminary construction cost analysis for a proposed four-lane highway connecting an industrial town to a residential area with a population of 50,000. The horizontal alignment of the proposed highway has been fixed. The total horizontal distance was 5,875 m. The cost items considered were the

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Table 1. Construction Cost Data for Example Problem

Cost item	Value
Earthwork filling cost	S$10.00 per m^3
Earthwork cutting cost	
Depth >1.5 m	S$10.00 per m^3
1.5–3.0 m	S$14.40 per m^3
3.0–4.5 m	S$18.20 per m^3
4.5–6.0 m	S$25.00 per m^3
6.0–7.5 m	S$30.00 per m^3
>7.5 m	S$50.00 per m^3
Pavement construction cost	S$80.00 per m^2

Note: S$ represents Singapore dollars (S$1 is approximately U.S. $0.6).

earthwork costs of cutting and filling, and the pavement construction costs. These cost data are summarized in Table 1. Land acquisition costs were not included. Solutions were provided for different constraining conditions under the objective function of minimizing the total sum of earthwork and pavement construction costs.

Methods of Optimization Analysis

Choice of Optimization Techniques

The traditional theoretical optimization techniques require the problem to be formulated mathematically. This requirement presents a severe limitation in applying the techniques to solve the vertical alignment problem. In a real-life highway design problem, not all constraints and requirements can be easily quantified mathematically. Varying ground conditions from one road segment to another and special discrete controls or constraints at specific points make mathematical modeling by the conventional optimization techniques extremely difficult. The very large number of feasible vertical alignment solutions in a typical highway design problem also renders most conventional optimization techniques unsuitable for practical applications of road alignment analysis.

A relatively new optimization technique known as genetic algorithms (GAs) was adopted for the present study to overcome the problems described in the preceding paragraph. GAs are an artificial intelligence optimization tool formulated on the basis of mechanics of natural selection and natural genetics. They are different from traditional optimization techniques in a few important aspects. GAs offer great flexibility in problem formulation as they do not require any information on differentiability, convexity, or other auxiliary properties. GAs handle a pool of feasible solutions in each cycle of search, enabling the search to reach out to a much larger solution space than is possible by conventional search methods. GAs employ probabilistic transition rules to move from one pool of solutions to another. This introduces perturbations to move out of local optima and allows it to work with problems that have disjointed solution spaces.

Genetic-Algorithm Optimization Analysis

In the GA solution process, a set of solutions, known as the parent solution pool, is first selected randomly. A pool of solutions, known as the offspring solution pool, is then generated from the initial a parent solution pool. A new pool of parent solutions is formed from the initial parent pool and the offspring pool by selecting the best solutions. This process is repeated to obtain better solutions. It is stopped when negligible differences are observes between the successive pools of solutions. Readers are referred to the work by Goldberg (1989) and Holland (1975) for the theoretical basis and operations of the technique.

For the purpose of comparison, the same vertical and horizontal grid system as adopted in the dynamic programming solution (Fwa 1988) is used in the present GA analysis. The input ground profile and the final computed road alignment are each represented by a series of line segments passing through one grid point on each vertical grid line. The spacing of vertical and horizontal grid lines of 0.25 and 62.5 m, respectively, were used. These spacings were found by the earlier dynamic programming analysis to have produced sufficiently accurate solutions. The GA solutions developed in this study had also verified this finding. The decision variables are therefore the positions of the road alignment on all the vertical grid lines.

Genetic-Algorithm Formulation

The GA computer program developed is able to handle the following five types of constraints: (1) maximum allowable gradient; (2) vertical curvature constraints to meet sight distance requirements; (3) fixed-elevation control points anywhere along the length of the route analyzed; (4) critical length control of vertical gradients; and (5) nonoverlapping of horizontal and vertical curves. The GA program can accommodate different objective functions specified by the user. The examples presented in this paper are based on the objective function of minimizing the total construction cost comprising earthwork and pavement construction costs.

Constraints Representation

Gradient Control

Gradient control is a traffic operational requirement to ensure smooth vehicle movement. The maximum allowable gradient is a function of design highway speed, as well as the types of vehicles included in the design traffic stream. This constraint of gradient was dealt with in the formulation by the following inequality:

$$|Y_i - Y_{i-1}| \leqslant Gd \quad i=2,3,...,N \tag{1}$$

where Y_i=road alignment level at grid line i; G=maximum allowable gradient; d=horizontal distance between two successive grid lines; and N=total number of vertical grid lines. In the GA optimization analysis, each generated offspring solution was checked against this inequality requirement and classified accordingly as feasible or infeasible solution.

Vertical Curvature Constraints

Curvature requirements were achieved by considering the magnitude of algebraic change in gradient between two consecutive line segments. In accordance with the recommendations of the American Association of State Highway and Transportation Officials (AASHTO 1990), the absolute value of gradient change, g, which was derived from considerations of highway safety, aesthetics, and comfort of ride, were specified separately for crest and sag vertical curves as follows:

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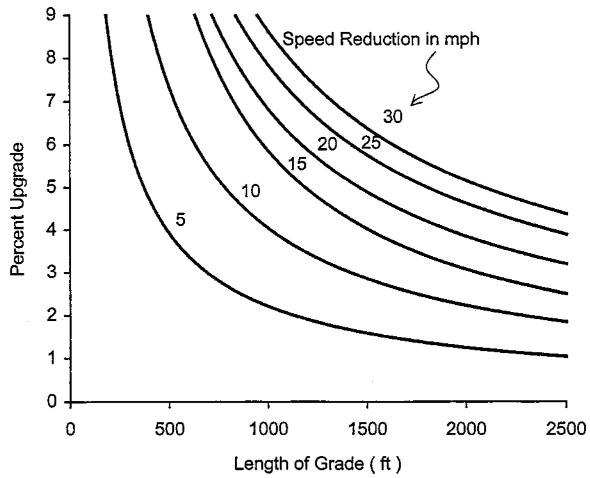

Fig. 1. Critical lengths of grade for design (AASHTO 1990); note: For 300 lb/hp truck at 55 mi/h entering speed 1 mi/h=1.6 km/h; 1 ft=0.305 m; 1 lb/ph=0.454 kg/hp

- For crest vertical curve

$$g \leqslant 405/(2S-L) \quad \text{when} \quad L \leqslant S \tag{2}$$

$$g \leqslant 405L/S^2 \quad \text{when} \quad L > S \tag{3}$$

- For sag vertical curve

$$g \leqslant (122+3.5S)/(2S-L) \quad \text{when} \quad L \leqslant S \tag{4}$$

$$g \leqslant (122+3.5S)/L/S^2 \quad \text{where} \quad L > S \tag{5}$$

where g=absolute algebraic difference in gradient (%); L=length of vertical curve (m); and S=sight distance (m). The sight distance S, is a function of design speed, vehicle type, and roadway gradient. The allowable gradient change, g, would therefore vary with the geometric parameters selected by the designer. These curvature constraints were handled in the GA solution in the same manner as for gradient control discussed in the preceding section. For the example problems analyzed in this paper, the design speed of 50 mi/h (approximately 80 km/h) was adopted. The corresponding sight distance was obtained in accordance with the recommendations by AASHTO (1990).

Fixed Point Control

Control points of fixed levels are commonly encountered in real-life highway alignment design. The levels of the start and end points of a new highway are typically fixed. Intermediate fixed-level control points are needed where a new highway intersects existing roads. There are also instances where the elevations of the new road have to be fixed due to vertical clearance requirements or constraints imposed by the surrounding features. Fixed point controls can be easily accommodated in the GA formulation by simply assigning fixed values to the decision variables representing the levels of these fixed points.

Critical Length of Grade

The critical length of grade requirements specified by AASHTO (1990) are adopted in this study. These requirements are shown in Fig. 1. The input parameter to be specified by the user is the allowable speed reduction. With each trial selection of highway alignment, the computer program computes the critical length of grade in accordance with the procedure outline in AASHTO (1990) for different types of vertical curves. A trial highway alignment is considered infeasible if it does not meet the critical length of grade given in Fig. 1. It is important to note that this critical length of grade control must be satisfied in both directions of travel for the highway alignment examined.

Nonoverlapping of horizontal and vertical curves

Based on safety consideration, AASHTO (1990) recommends that pronounced vertical curves should not be introduced at or near a sharp horizontal curve. This requirement of nonoverlapping of horizontal and vertical curves was accommodated in the present analysis by imposing the following constraints:

$$X_{H1} - H_{V2} \geqslant X_d \quad \text{or} \quad X_{V1} - X_{H2} \geqslant X_d \tag{6}$$

where X_{H1} and X_{H2} are the X coordinates (i.e., horizontal distance measured along the central line of the horizontal alignment) of the start and end points, respectively, of the horizontal curve; X_{V1} and X_{V2} are the X coordinates of the start and end points, respectively, of the vertical curve in question; and X_d is the preselected distance that separates the end point of one curve to the start point of the other curve. In the present analysis, X_d, was taken to be 100 m.

Objective Function

The objective function was to search for the vertical alignment that minimized the total construction cost comprising earthwork and pavement construction costs. It can be expressed mathematically as follows:

$$\text{Min} \sum_{k=0}^{N-1} [C_1(U_{1k}) + C_2(U_{2k})] \tag{7}$$

where C_1 and C_2 represents the unit costs of earthwork and pavement, respectively, as given in Table 1. U_{1k} is the volume of earthwork required for the line segment k bounded by grid lines k and $k+1$; while U_{2k} is the area of pavement construction for the same line segment. The computations of U_{1k} differentiates cut and fill volumes. For cases where cut and fill are involved in different portions of a line segment, their respective volumes are computed accordingly. Pavement construction cost within a line segment is a function of pavement design, which is assumed to be fixed in this example problem as implied by the constant unit pavement cost in Table 1. The GA formulation allows for different pavement designs and hence different unit pavement costs along the length of the highway. This is realistic, as pavement construction cost in an actual project will vary with the soil condition.

Genetic-Algorithm Solution Process

Problem Representation and Solution Space

In the GA representation, the solution to the problem is presented as a string of cells. Each cell contains a value that defines the elevation of the road alignment on a vertical grid line. The number of cells in the solution string structure is therefore equal to the total number of vertical grid lines of the problem, which is given by N in Eq. (1). Next, it is necessary to identify the width of solution space above and below the horizontal axis of the pro-

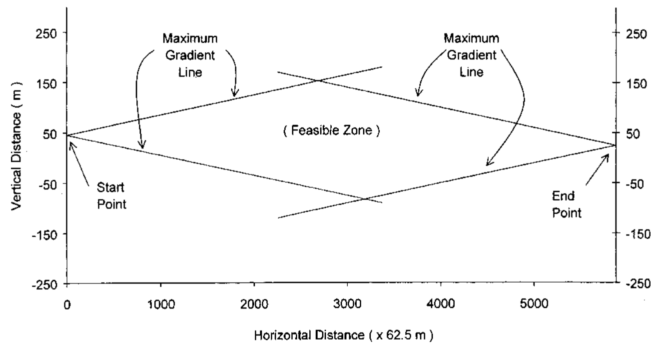

Fig. 2. Envelope of feasible zone subject to maximum allowable gradient

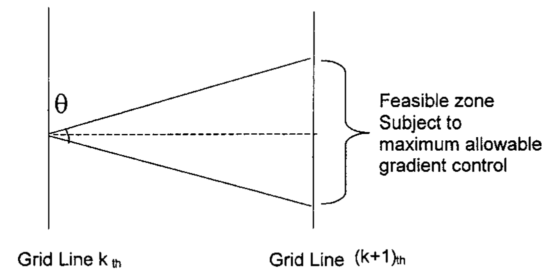

Fig. 3. Illustration of shooting ray method

posed highway. An intuitive method would be to define a band along the axis sufficient to envelop all practical solutions. For instance, in the present example problem, a 110 m space above and below the horizontal axis would appear to be a reasonable choice. Unfortunately, this is not a good choice from the computation point of view. With vertical divisions at 0.25 m intervals, there are 881 points on every vertical grid line, each representing a possible solution point of highway alignment on this grid line. As the elevations of th two points are known, the total number of possible solutions is equal to $(881)^{N-2}$, where N is the total number of grid lines. For the example problem with N equal to 95, the number of solutions given by $(881)^{93}$, or 7.63×10^{273}, is indeed a very big number. A trial run using this solution space has shown that the convergence was slow and was not guaranteed.

Instead of the horizontal axis, an improved representation is to use the ground profile as the reference to define the solution space; that is, the elevation profile of computed alignment is defined with respect to the elevation of the ground surface. This offers a logical choice in vertical alignment analysis, since nay large deviation of the computed alignment from the ground profile would incur high cutting or filling costs. This would cut down the zone width of the solution space by half or more. However, this reduction of solution search space was still found inadequate in this study to improve the convergence for the example problem.

Since GA rely on random generation of solutions in the search for the optimal answer, it is important that the problem search space be defined properly. To ensure that the optimal highway alignment is computed efficiently in the solution process, a sufficiently small and well defined solution space needs to be identified. This is achievable by means of a two-stage search space determination process. First, from each of the two end points, a positive and a negative maximum gradient line are drawn. An enclosed space is formed by the four lines, as shown in Fig. 2. This enclosed space presents the feasible solution region for the problem, because any point that falls outside it would violate the maximum gradient constraint. The determination of this feasible solution region is significant because it greatly facilitates the generation of an initial parent solution pool for the initialization phase of the GA solution process.

The second stage of the search space determination process makes use of a so-called "search angle method." For each point selected on a grid line k during the solution process, a search angle subtending from the selected point is defined as shown in Fig. 3. The length of grid line $(k+1)$ covered by the search angle is the feasible space for the next point to be selected on grid line $(k+1)$. The magnitude of the search angle is fixed in accordance with the maximum gradient requirement. This method has reduced the search space substantially for an efficient solution process.

Choice of Genetic-Algorithm Parameters

Two GA operations, namely crossover and mutation operations, were employed in the solution process. The following two methods of applying these operations were evaluated: (1) applying mutation only to strings that did not undergo crossover; and (2) allowing strings to undergo both crossover and mutation. It was found that there were negligible differences in the answers obtained by the two procedures. Method (2) was adopted in this study, and the mutation and crossover rates used were 0.03 and 0.55, respectively.

Another important GA parameter is the parent population size. A total of 10 pool sizes were studied for the example problem, ranging from 100 to 1,000 in increments of 100. Improvements in the final solution were observed as the pool size increased, until a pool size of 600 was reached. Negligible differences were found for pool sizes larger than 600. Hence, a pool size of 700 was adopted for the example problem. The offspring pool size was selected to be 630, which was equal to 90% of the parent pool size. These 630 offspring solutions together with the best 70 solutions of the parent pool formed the next parent pool. With these parameters, it was found that the objective function value of the best solution generated improved relatively rapidly in the initial 150 iterations. The rate of improvement decreased thereafter and began to level off after about 400 iterations. The rate of improvement decreased thereafter and began to level off after about 400 iterations. For all the problems analyzed in this study, convergence was reached before 500 iterations.

Handling of Infeasible Solutions

Infeasible solutions with constraint violations were generated in each generation of the offspring pool as GA searched for new solutions. This was unavoidable and not totally undesirable in the solution search process that repeatedly probed different sectors of the solution space. This search capability helped the solution process to move out of local optimums. Infeasible solutions, however, needed to be weeded out as the solution process proceeded. Otherwise, the speed of convergence might be affected. There existed different methods of handling infeasible solutions. In the present problem, the method of constant static penalty function was found to be effective. As the objective function value was of the order of $\$1.5\times 10^7$, a penalty of $\$1\times 10^7$ was added to the objective function value of a solution for every constraint violated. For instance, if a solution violated the maximum gradient at one location and the vertical curvature constraint at three loca-

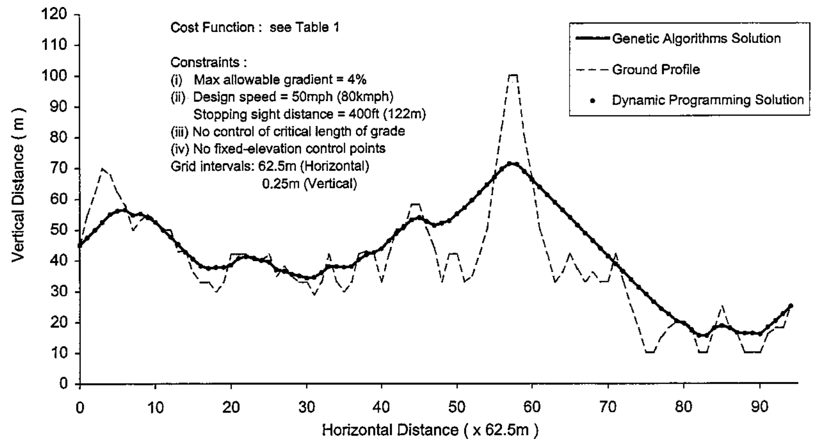

Fig. 4. Comparison of dynamic programming and genetic algorithm solutions

tions, the total penalty added would be $\$4\times10^7$. In other words, a higher penalty value was added to a solution with a greater number of constraint violations.

Analysis of Solutions

Genetic-Algorithm versus Dynamic Programming Solutions

To verify the solutions obtained by the GAs developed in this study, a comparison was made with a dynamic programming solution. The dynamic programming solution was obtained for the example problem with cost data of Table 1. The allowable maximum gradient was 4%, and the vertical curvature constraints were as specified in Eqs. (2)–(5). Not included in this dynamic programming problem were the fixed level control points, the constraint of critical length of grade, and nonoverlapping control of horizontal and vertical curves. The GA computer program described in this paper was applied to solve this problem. For the given horizontal grid intervals and the vertical divisions adopted in the example problem, there is a unique optimal solution, which is the dynamic programming solution plotted in Fig. 4. Verification runs using the GA program developed led to the same final optimal solution, as shown in the same figure. This provided the needed verification of the validity of the GA computer code before the study proceeded to solve for cases involving the constraints of fixed elevation control points, critical lengths of grade, and nonoverlapping of horizontal and vertical curves.

Effect of Critical Length of Grade

The critical grade length constraint is governed by the maximum speed differential between passenger cars and heavy vehicles for smooth and safe traffic operations. The speed differential is caused by speed reductions of heavy vehicles during their upslope climb. In this study, the length of grade control in accordance with AASHTO requirements as shown in Fig. 1 was adopted. The smaller the allowable truck speed reduction is, the more stringent the control on the requirement of the length of grade. To illustrate the impact of critical grade length consideration, the example problem was solved for three different speed reductions (i.e., different critical grade lengths). The three different reductions were 5, 10, and 15 mi/h (approximately 8, 16, and 24 km/h, respectively).

Fig. 5 presents the solutions for the three cases of allowable speed reductions together with the baseline case that did not consider the critical length of grade requirement. As expected, the

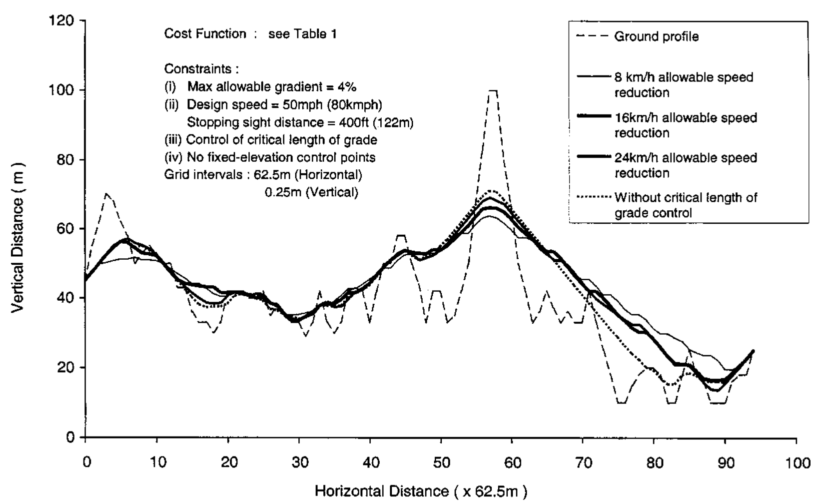

Fig. 5. Optimal road alignment with critical length of grade consideration

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Table 2. Increses in Construction Cost due to Road Alignment Changes Caused by Critical Length of Grade Control

Allowable speed reduction	Construction cost (S$)	Percent increase from baseline case (%)
No limit (baseline case)	1.635×10^7	—
15 mi/h (24 km/h)	1.869×10^7	14.3
10 mi/h (16 km/h)	2.005×10^7	22.6
5 mi/h (8 km/h)	2.342×10^7	43.2

baseline case being the least constrained shows comparatively the highest conformance to the ground profile. A lower degree of conformance to the ground profile is observed when the critical length of grade requirement is introduced. As the allowable speed reduction was reduced, which was equivalent to tightening the critical length of grade requirement, more deviations from the ground profile occurred. The case of 5 mi/h (approximately 8 km/h) reduction, which had the most stringent critical length of grade requirement in Fig. 5, displayed the highest deviations from the ground profile.

The construction costs for the four cases analyzed are summarized in Table 2. The imposition of the critical length of grade controlled to an increase of total construction cost. As explained in the preceding paragraph, larger deviations from the ground profile occurred as a more stringent critical length of grade control was imposed. This led to higher volumes of cut and fill, and hence higher construction costs. As can be seen from Table 2, for the present example, the increase of construction cost from the baseline case ranged from 14.3%, for the case of 15 mi/h (24 km/h) allowable speed reduction, to 43.2%, for the case of 5 mi/h (8 km/h) allowable speed reduction.

Effect of Fixed-Elevation Control Points

Many different forms of fixed-elevation control can be imposed in the analysis of optimal road alignment by the GA computer program developed in this study. Combinations of different forms of fixed-elevation control can be easily handled by the GA program without much difficulty. For illustration, two forms of fixed-elevation control were considered to illustrate their effect on the optimal alignment analysis. The first form consisted simply of points with prespecified fixed elevations, while the second form comprised fixed elevations over specified stretches of the alignment.

Fig. 6 shows the solution of road alignment for a case where two points, A and B, with different fixed elevations were prespecified. The effects of the fixed-elevation control points are apparent when the resulting optimal alignment is compared with the optimal alignment without fixed-elevation points. The differences between the two solutions were largest at the points of fixed-elevation control. Analyses were also made for the cases where only one fixed-elevation point, either A or B, was specified. It was found that the effect on the computed alignment by fixing point B only was limited to within the range of distance between 0 and 30×62.5 m, while the effect of fixing point A only was limited to within the range between 40×62.5 and 80×62.5 m. Table 3 summarizes the construction costs for the three cases. It can be seen that, as the number of fixed-elevation control points increases, higher construction costs will be incurred.

Fig. 7 presents the solution for a case where an elevation control was specified for a stretch of the road alignment. This is designated as Case D in Table 3. From the horizontal distance of 32×62.5 to 40×62.5 m, the surface elevation of the road alignment was not to exceed 35 m. As the maximization process would push the computed road alignment towards the ground surface so as to reduce cutting, it is not surprising to see that the final optimal alignment along the stretch of elevation-controlled road was a level straight section. Case E in Table 3 is one that contains the elevation constraints of Cases A, B, and D. As can be expected, the construction cost of Case E is the highest of all the cases presented in Table 3.

Table 3. Increases in Construction Cost due to Road Alignment Changes Caused by Elevation Control at Specified Locations

Elevation control	Construction cost (S$)	Percent increase from baseline case (%)
No control (baseline case)	1.635×10^7	—
Case A: fixed elevation at Point A	1.972×10^7	20.6
Case B: fixed elevation at Point B	1.756×10^7	7.4
Case C: fixed elevation at Points A and B	2.108×10^7	28.9
Case D: fixed elevation for specified stretch of road (Fig. 7)	1.907×10^7	16.6
Case E: combination of Cases A, B, and D	2.309×10^7	41.2

Effect of Nonoverlapping of Horizontal and Vertical Curves

This constraints was checked for each solution by applying Eq. (6) to every vertical curve of the computed alignment. In the present example, only the vertical curve located between the horizontal distance of 45×62.5 and 50×62.5 m violated the constraint. The change in the optimal alignment from the baseline case is depicted in Fig. 8, in which the original vertical curve is replaced by a simple slope. Compared with the baseline case, the imposition of this constraint caused the optimal alignment to deviate further away from the ground profile and raised the construction cost by 4.2% from S\$$1.635\times10^7$ to S\$$1.704\times10^7$ (S$ Singapore dollars).

Conclusions

The development of an optimization algorithm for road alignment using the artificial intelligence technique of GAs has been described. This optimization technique, which does not require the problem to be represented in full mathematical formulation, is found to offer a flexible analytical tool suitable for incorporating the critical length of grade requirement, nonoverlapping of horizontal and vertical curves, and fixed-elevation control into the vertical road alignment optimization analysis. Any number of points or length of road sections of these constraints can be imposed without causing difficulty in the optimization analysis. These three forms of constraints are important traffic operation and functional requirements in vertical road alignment design, but are difficult to be considered in the conventional optimization techniques. Different answers of optimal road alignment would be obtained when either one of the three constraints or any combi-

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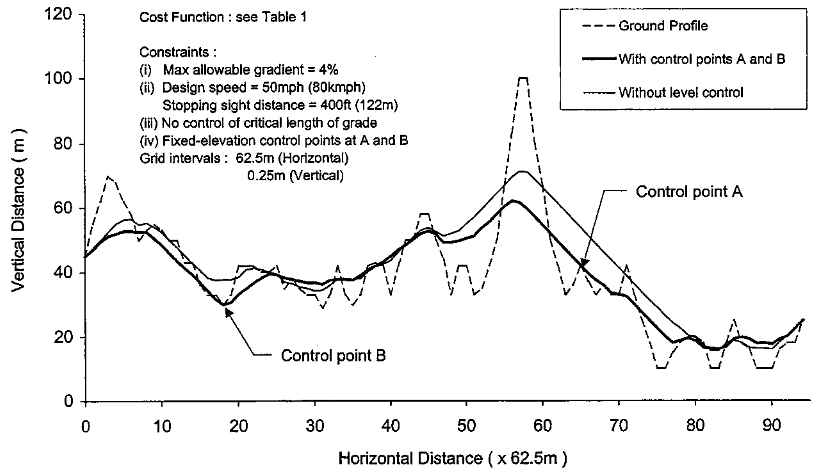

Fig. 6. Optimal road alignment with fixed-elevation control points

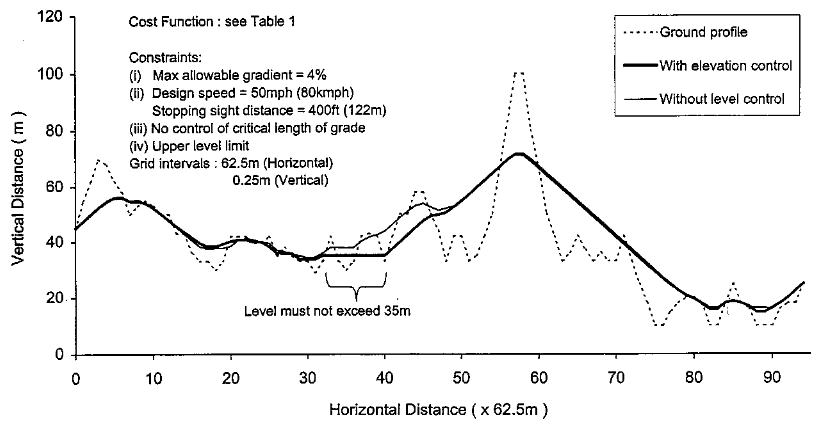

Fig. 7. Optimal road alignment with fixed-elevation control over specified distance

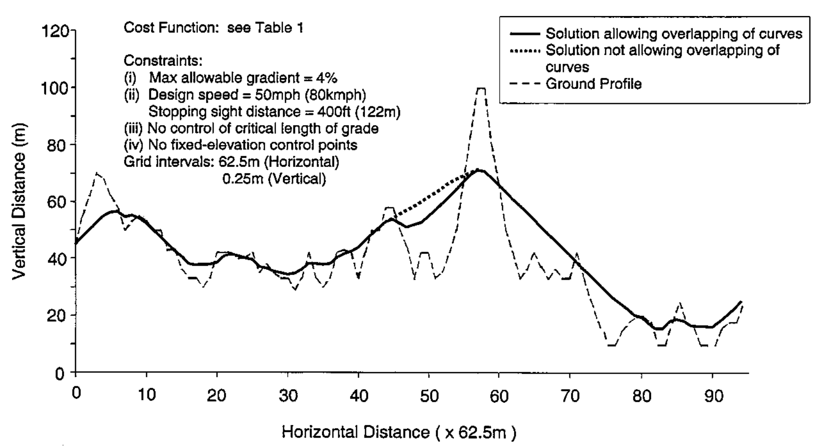

Fig. 8. Optimal road alignment with no overlapping of horizontal and vertical curves

nation of them are included in the analysis. For the example problem studied in this paper, for which the objective function was to minimize construction cost, the consideration of the critical length of grade caused an up to 43.2% increase in the construction cost. The impact of nonoverlapping control of horizontal and vertical curves on construction cost would vary from case to case, depending on the ground profile. The increase of construction cost caused by fixed-elevation control is depending on the elevation difference between the specified fixed point (or road section) and the ground surface. it can be many times more than the effect of critical length of grade control if the elevation difference is large. Working on a workstation with 128 Mb and a hard disk capacity of 2.1 Gb, the time per run for the example problem was about 40 s.

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