Using GIS and Genetic Algorithm in Highway Alignment Optimization

Chan Weng Tat and Fan Tao

***Abstract*—Optimizing highway alignments is a difficult combinatorial problem from highway engineering. The problem is to find an alignment connecting two given end points such that the alignment incurs minimal total costs. From past experience, it has been found that the two critical success factors in the optimizing of highway alignments are a good search algorithm, and an efficient and accurate way to calculate the total costs of the highway. The genetic algorithm (GA) is a good choice as a search algorithm as its stochastic nature and global search characteristic enables the GA to find high quality solutions even for complex problems. The solution for an accurate cost model may lie with the use of the Geographic Information System (GIS). GIS can spatially represent both the physical, natural and socio-economic features of the region of the alignment. Furthermore, the spatial analytical capabilities of the GIS provide valuable inputs to the highway alignment optimization. This paper describes an integrated model that combines the capabilities of the GA and the GIS to optimize the highway alignments.**

***Keywords*—Highway, Genetic Algorithms, Geographic Information System**

I. INTRODUCTION

For a proposed new highway, one of the first design tasks is to determine the three-dimensional (3D) highway alignment. Let $S=(x_S, y_S, z_S)^T$ and $E=(x_E, y_E, z_E)^T$ denote the coordinate vectors of the start point and the end point respectively. The basic requirement of the highway alignment task is to identify the most economical alignment connecting the start and end points subject to a set of design constraints and operational requirements.

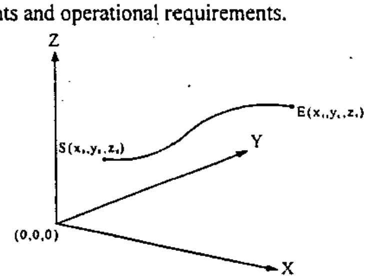

Figure 1 A typical three-dimensional highway alignment

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A. Cost component

Previous studies [Winfrey, 1968; OECD, 1973; Wright, 1996] have shown that alignment sensitive costs used in the design can be categorized as either supplier costs or user costs (see Table 1).

TABLE I
COST COMPONENTS IN HIGHWAY DESIGN

Classifications		Examples
Supplier costs	Length-dependent cost	Construction and maintenance cost
	Location-dependent cost	Right-of-way and environmental cost
	Earthwork cost	Cut, fill, and mass-haul cost
User costs	Vehicle operating cost	Fuel consumption, vehicle wear and tear cost
	Travel-time cost	Vehicle hours times unit value of time
	Accident cost	Estimated accident rates times unit accident cost

B. Design constraints and operational requirements

There are numerous design constraints and operational requirements relevant to the design of the highway alignment. These specifications have developed over a long period of time and are often codified into national codes of practice and design guidelines / manuals; an example of which is the [AASHTO, 1990]. Various aspects covered by these specifications are discussed below.

1) *Traffic consideration*

A basic premise in highway design is that it should cater to the behavior of all road users. Annual average daily traffic (AADT), design hour volume (DHV), traffic composition and design speed are some of the important traffic parameters.

2) *Horizontal alignment*

The horizontal alignment of a highway is conceived as a series of straight lines (tangents), circular curves and spiral transition curves. The most important constraints on the horizontal alignment are:

- Minimum radius, and
- Sight distance on a curve.

3) *Vertical alignment*

The vertical alignment of a highway is conceived as a series of straight lines joined by parabolic curves. The most important constraints on the vertical alignment are:

- Maximum gradient,
- Sight distance on the crest of a vertical curve, and
- Head light sight distance and motorist comfort on the sag of vertical curves.

C. Optimization model for highway alignment

Knowing the objective cost function and the constraints on the highway alignment, it is then possible to formulate a mathematical model to optimize the highway alignment as follows:

Objective function

$$Minimize: C_T = C_N + C_L + C_V + C_U \quad (1)$$

Subject to:

- Horizontal curvature constraints
- Gradient constraints
- Vertical curvature constraints

Where C_T, C_N, C_L, C_V and C_U represent the total costs. location-dependent cost, length-dependent cost. volume-dependent cost and user costs, respectively.

Highway alignment optimization problems have attracted much research interest over the past three decades. However, most of the models published in the literature have been developed to optimize either vertical alignments [Fwa, 1989; Fwa, 2002] or horizontal alignments [Shaw, 1982; Trietsch, 1987]. Models for both the horizontal and vertical alignments simultaneously in 3-D space are rarely found. These models will often neglect some of the cost items and design constraints [Parker, 1977]. Jong (1998) developed a model to optimize both the horizontal and vertical alignments simultaneously using GA. Jha (2000) extended this model by incorporating the use of the GIS to make the calculation of the highway cost more efficient and accurate.

II. HIGHWAY ALIGNMENT OPTIMIZATION MODEL

Genetic algorithm is evolutionary methods motivated by the principles of natural selection and "survival of the fittest". The GA performs a multi-directional search by maintaining a population of potential solutions and encourages information formation and exchange between these directions [Michalewiz, 1996]. GA is stochastic algorithms that can be used to find approximate solutions for complex problems. The problems usually have a search space that typically is much too large to be searched by means of enumerative methods.

GA work with an evolving set of solutions (represented by chromosomes) called the population. Solutions from the current population are taken and used to form a new population to replace the current population. This is motivated by expectation that the quality of solutions in the new population will be better than that in the previous one. Solutions are selected to form new offspring according to their fitness. The fitter they are, the more chances these solutions will have to be selected. The basic steps of the GA are as follows:

*Step*1: Determine a genetic representation for potential solutions to the problem.

*Step*2: Generate an initial population of candidate solutions.

Step3: Compute the fitness of each individual.

Step4: Select individuals from the parent population according to their fitness.

*Step*5: Apply both the crossover and mutation operators to each selected individual to form the offspring population.

*Step*6: If a pre-specified stopping condition is satisfied, stop the algorithm; otherwise, return to step 3.

The general GA framework just described is usually customized to each particular type of optimization problem. We propose the following GA model for the highway alignment optimization problem. The piecewise straight line $\overline{SE}$, which connects the start point S and the end point E, is line in 3D space. The projection of $\overline{SE}$ onto the XY plane becomes the horizontal alignment. We complete the horizontal alignment by adding a curve with a fixed radius (for example, we can use the minimal radius according to AASHTO [Jong 1998]) at each point of intersection in the horizontal alignment. The projection of the 3-D line onto the surface orthogonal to the XY horizontal plane containing the horizontal alignment determines the vertical alignment. Adding fixed length parabolic curves to the vertical intersection points completes the vertical alignment. We can therefore determine the 3-D alignment of the highway by using a series of spatial piecewise straight lines.

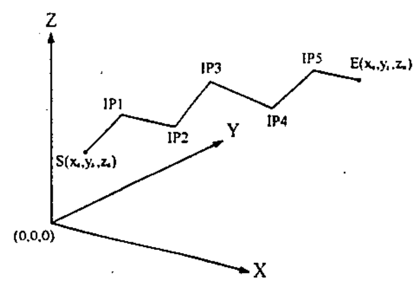

Figure 2 Basic model for the 3-d highway alignment

Other details of the GA model for the optimization of highway alignment are as follows:

A. Representation of the problem

Each intersection point is determined by three decision variables, namely the X, Y, and Z coordinates. For an alignment represented by n intersection points, the chromosome is composed of 3n genes. Thus, the chromosome is defined as:

$$V = (\lambda_1, \lambda_2, \lambda_3, \ldots\ldots, \lambda_{3n-2}, \lambda_{3n-1}, \lambda_{3n})$$
$$= (x_1, y_2, z_3, \ldots\ldots, x_n, y_n, z_n)$$

where: V =chromosome

λ_i=the i[th] gene, for $i = 1,\ldots\ldots,3n$

(x_i, y_i, z_i)=the coordinates of the i[th] intersection point, for $i = 1,\ldots\ldots,n$

B. *Initialization of the population*

We assume that no prior knowledge about the optimal solutions is available. The initial population is randomly generated within the search area in order to get a variety of individuals in the population. However, if we have a good idea about promising solutions, we can encode these as individuals to be included in the initial population [Jong, 1998]. We suggest three variations in the choice of intermediate intersection points when forming the initial population:

1) points of intersection that lie randomly on the straight line connecting the start and end points;
2) points of intersection that lie randomly within the search area with elevations that are as close as possible to existing ground elevations;
3) *points of intersection that lie randomly within the search area but with randomly chosen elevations.*

C. *Fitness evaluation*

Fitness is an index to show the adaptability (goodness) of a chromosome (solution) to the problem. The fitness of a chromosome V, denoted by $f(V)$, is simply defined as the total cost plus the penalties. Adding a penalty term is one of the methods to avoid constraint violation during the evaluation progress [Michalewiz, 1996]. Chromosomes with lower cost mean that they have more opportunity to be selected to reproduce offspring, and vice versa. A penalty is added to the objective function in order to decrease the "goodness" of infeasible chromosomes. The fitness of each chromosome is:

$$f(V) = C_N + C_L + C_V + C_U + \sum P_i \tag{2}$$

where: $f(V)$ =the fitness of chromosome

C_T, C_N, C_L, C_V and C_U are the same as equation (1)

$\sum P_i$ = the sum of all the penalties of the chromosome.

D. *Genetic operators*

The reproductive chance of each individual is determined by its fitness; an individual with a lower total cost will have a higher probability of being selected to reproduce offspring. There are many methods to select chromosomes and allocate reproductive chances including roulette wheel selection, Boltzman selection, tournament selection and ranking selection. We recommend ranking selection because it can avoid both the pre- convergence in early generations and random search in later generations.

Some members of this new population undergo reproduction by means of crossover and mutation to form new solutions. Crossover combines the features of two parent chromosomes to form two offspring, while mutation arbitrarily alters one or more genes of a selected chromosome to create a new chromosome.

GA has been proven to be very useful in highway alignment optimization [Jong, 1998]. The use of the GA can overcome some of the drawbacks in other optimization methods. However, it is difficult to calculate the highway cost using conventional methods. GIS can spatially represent the location of mountains, plains, rivers and other useful geographical characteristics of the highway search area; it can therefore provide valuable inputs for the computation of cost in highway alignment optimization.

III. Cost Evaluation Model

The GIS is a computer-based system that is used for geospatial data input storage, management, analysis and presentation [Tor, 1999]. GIS can help capture, store, analyze, and display geographical information. The spatial characteristics of geographic entities stored in a GIS allow precise calculations of areas or volumes [Laurin, 1992]. An attribute is a defined characteristic of an entity, such as the type of a bridge, the size of a lake, the land use type of the existing land, or the wetness of soil. Highway alignment optimization needs to calculate the total cost of the highway, which includes location-dependent costs, length-dependent costs, user costs and volume costs. It is very hard to calculate these costs efficiently and accurately using conventional methods. GIS seems to be a very useful tool for this purpose, and this is just beginning to be appreciated by researchers [Jha, 2000; Jha, 2001].

There are some preparative tasks prior to using a GIS to calculate costs. The main task is map digitization to capture the geometric extents and attributes of geographical features relevant to highway alignment. Another task is the creation of a surface elevation model in order to determine the X, Y and Z coordinates of any given point on the map.

The GIS assists in the projection of individual alignment intersection points onto the horizontal and vertical planes to determine the horizontal and vertical alignments, as well as the calculation of various costs associated with these two alignments.

A. *Length-dependent cost*

The total length-dependent cost can be represented as follows:

$$C_L = U_L \times L \tag{3}$$

where: C_L = total length-dependent cost ($)

U_L = total unit length-dependent cost ($/m)

L = total length of the alignment (m)

The total unit length-dependent cost U_L can be expressed as:

$$U_L = U_P + U_M \tag{4}$$

where: U_P = unit pavement cost ($/m)

U_M = unit maintenance cost ($/m)

The unit pavement and maintenance costs are user specified. The GIS can calculate the total length of the alignment and thus determine the total length-dependent cost.

B. Volume cost

The surface elevation model can be used to determine the position of the design elevation relative to the existing ground along designated points of the chosen alignment. The ground profile perpendicular to the alignment can also be determined from the surface elevation model. The GIS can be used to determine the cut-and fill necessary to adapt the ground profile to the desired elevation and cross-section. A typical cross section is shown below:

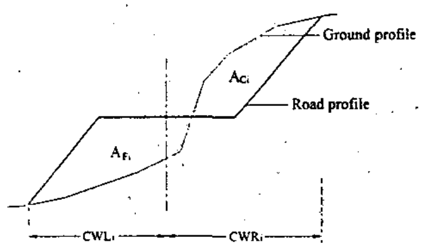

Figure 3. Typical cross section

This can be extended to determine the volume of earthworks required. Among the most commonly used methods for earthwork volume estimation are the Average End Area Method and the Prismoidal Method. We use the Average End Area Method because it is simple and most commonly used in real engineering projects. Average End Area Method assumes that the earthwork volume between two consecutive cross-section is the average of their areas multiplied by the distance between them:

$$V_{Fi} = l_i \times (\frac{A_{Fi} + A_{Fi+1}}{2}) \quad (5)$$

$$V_{Ci} = l_i \times (\frac{A_{Ci} + A_{Ci+1}}{2}) \quad (6)$$

wher: V_{Fi} = the fit volume between two cross sections (m^3)

V_{Ci} = the cut volume between two cross sections (m^3)

A_{Fi} and A_{Fi+1} = fill areas of two cross sections (m^2)

A_{Ci} and A_{Ci+1} = cut area of two cross sections (m^2)

l_i = distance between two cross section (m)

The total volume cost can be represented as follows:

$$C_V = U_{Fill} \times \sum V_{Fi} + U_{Cut} \times \sum V_{Ci} \quad (7)$$

where: U_{Fill} and U_{Cut} = unit cost of fill and cut volume ($\$/m^3$)

During the calculation of the area of each cross section, we need calculate two other useful quantities: CWL_i and CWR_i. These represent the left and right construction width of the ith station point (as shown in figure 3). These two quantities are important in the calculation of the location-dependent cost of the right-of-way corridor.

C. Location-dependent costs

The construction buffer on each side of the horizontal alignment can be obtained by connecting the most extreme construction points between consecutive stations (as shown in Figure 4). This construction buffer can be overlayed on a land use layer to identify the land parcels affected by the construction buffer. Doing so enables the calculation of the total land area affected by construction of the highway alignment and the associated cost of the buffer:

$$C_N = \sum A_i \times C_{Ni} \quad (8)$$

where: C_N = location-dependent cost (\$)

C_{Ni} = unit cost of land type i ($\$/m^2$)

A_i = total area of land type i within the construction buffer (m^2)

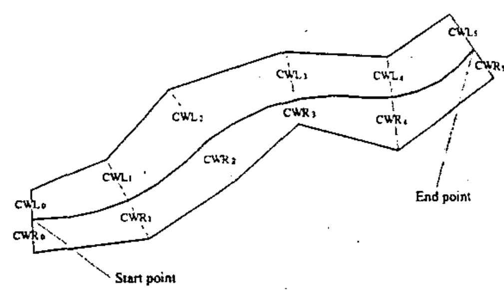

Figure 4. Construction buffer of the alignment

D. User costs

The user cost considered here are the vehicle operating, travel time, and accident costs. The definition of these costs is as follows:

$$C_U = \sum C_F + \sum C_T + \sum C_A \quad (9)$$

where: C_U = total user costs

C_F, C_T and C_A = fuel consumption cost, travel time cost and accident cost respectively.

Jong [1998] shows how to calculate these costs.

IV. INTEGRATED MODEL

We have outlined both the highway alignment optimization model based on the GA and the cost evaluation model based on the use of the GIS. Combining a GIS with the highway optimization model requires both to be integrated in such a way that there is a continuous and automated exchange of inputs and outputs between the GA and the GIS. Figure 5 is a flow diagram depicting the coordination of task execution and exchange of information between the GA and GIS.

V. CONCLUSION

Optimizing the highway alignment is complex and difficult engineering problem. One of the challenges in this problem is the computation of the total costs of the highway alignment efficiently and accurately. By digitizing the relevant maps and creating a surface elevation model, we can use the GIS to calculate the total costs of the highway alignment.

Another basic consideration is the choice of a search algorithm to be used to search for an optimal solution. Genetic algorithms (GA) are stochastic algorithms that can be used to find approximate solutions for complex problems and it has found to be a very efficient tool to solve this problem. Integrating the GIS and the GA for the highway alignment problem allows one to take advantage of the strengths of each technique in the search for optimal or nearly optimal highway alignments.

VI. FUTURE WORKS

This paper proposes a methodology that integrates Genetic Algorithms and Geographic Information Systems for highway alignment optimization using a total cost minimization objective. The methodology has yet to be applied to the design of a real highway design, and research to refine and implement the methodology is still in progress. However, the methodology differs from previous work by Jha (2000) and Jong (1998) as follows:

- The number of segments and intersection points used in the horizontal and vertical alignment problems need not be the same; each problem can use the number of segments that best suits the characteristics of the problem.
- Furthermore, the number of intersection points of the proposed horizontal highway alignment need not be fixed but can vary depending on the terrain condition.
- The horizontal highway alignment is composed of straight line segments joined by circular arcs; the radius of these circular arcs need not be fixed (as is the case for alignments reported in previous work) but can be variable depending on the terrain condition.

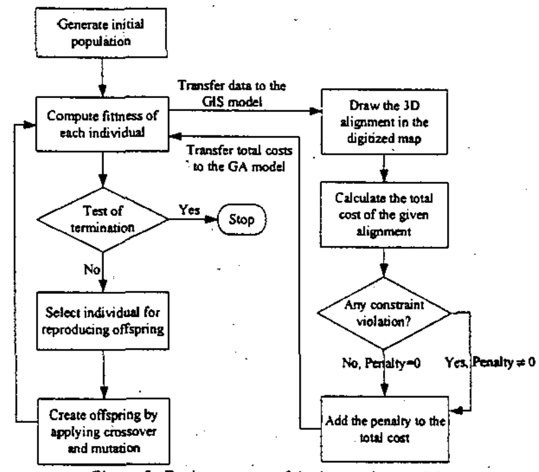

Figure 5. Basic structure of the integrating model

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