A GENETIC ALGORITHM APPROACH TO A 3D HIGHWAY ALIGNMENT DEVELOPMENT

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Abstract: This paper reports for the possibility of developing a genetic algorithm (GA) based technique model to optimize highway alignment. It suggests a novel technique to optimize a highway alignment in a three dimensional space. The technique considers station points to simultaneously configure both horizontal and vertical alignment rather than considering the existing conventional principles of design which deals with both alignments in two different stages and uses horizontal intersection points (HIP), vertical intersection points (VIP), tangents (T), curve radii (R), deflection angles (Δ), grade values (± g %), and horizontal and vertical curve fittings to depict the horizontal and vertical alignments. The proposed method is expected to produce a global optimal or near optimal solution and also to reduce the number of highway alignment design elements required and consequently reduce the constraints imposed on alignment planning and design. The results obtained have good merits and encourage further investigations for better solutions.

1 INTRODUCTION

Highway alignment development aims to connect two terminal points at minimum possible cost subject to the design, environmental (natural features and air pollution), economical, social, and political constraints. The final alignment selection will also be affected by the public view points and decision makers' policy. The most common cost components that can be considered are construction, maintenance, location, earthwork, environmental, and user costs. The weight of each component is affected by the user and/or designer preferences and/or the purpose that the alignment is built for.

All these compenents and parameters must be considered together. However an alignment that makes one of the parameters optimal will rarely, if ever, make all optimal. The problem of developing and selecting an optimum alignment is therefore very complex but very important.

1.1 The Conventional Approach

In conventional highway design projects, highway engineers and planners select several candidates as alternative solutions and evaluate their suitability for the region's environment until coming up with the most suitable one (Wright and Ashford, 1998). Horizontal and vertical alignments are considered apart from each other and the vertical one is optimized based on the 'best' selected horizontal one. This process starts by fixing several horizontal intersection points (HIP). The number of the HIPs may depend on the length of the highway, natural and manmade features, and the topography. The successive HIPs are then connected by lines thus forming a horizontal piecewise linear trajectory. These lines are called tangents and the deflections in direction between successive tangents at HIPs are called Deflection angles. Later on and in a separate procedure horizontal circular or spiral curves are fitted at each HIP location to form the proposed horizontal alignment. This alignment then undergoes an evaluation process to know whether it suits the environment or not. The evaluation may take the form of cost consideration, damage to environment, and socio-economic issues subject to several design constraints that are imposed on the alignment. This process, through numerous iterations, is repeated and should continue until finding the most suitable one.

In a different process the vertical alignment is selected using the same concept as for the horizontal alignment. First, the elevations along the selected horizontal alignment are determined to form the natural ground elevation profile (NGE). Later on, to

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generate the alignment grade line, several vertical intersection points (VIPs) are fixed and interconnected successively to form a vertical piecewise linear trajectory. The number of VIPs is mainly affected by the variations in ground elevations. Parabolic curves are then fitted at VIPs to depict the vertical alignment. The vertical grade line of the alignment is then evaluated based on the design requirements and the amounts of earthwork for both cut and fill sections. The process will continue repeatedly until finding the most suitable one.

The selection of the final alternative alignment is accomplished by focusing on the detailed design elements. HIPs, deflection angles, curve radii, VIPs, tangents, grade values, and sight distances are among the design elements of highway alignment in 3D. Most of these design elements are constrained by standard limits described by such documents as the Design Manual for Roads and Bridges (DMRB, 1992-2008) and AASHTO design standards (AASHTO, 1994).

As the two processes are considered apart from each other, the generated alignment likely represents a local optimum rather than a global one. This approach takes into account many design elements and, at the same time, neglects numerous possible solutions due to non simultaneous consideration of both alignments. This process is also very expensive in terms of time.

Researchers have tried to speed up the process of highway alignment planning and design and to find better solutions. Attempts have been done to optimize either horizontal or vertical or both simultaneously. Calculus of variations by Shaw and Howard (1982), numerical analysis by Chew et al (1989), linear programming by Easa (1988), and genetic algorithms by Jong (1998), Fwa et al. (2002), and Tat and Tao (2003) are some of the techniques that have been used. The work done by Jong (1998) has also been extended to incorporate more cost components, GIS integration, and to formulate the model to handle the problem as a multi objective problem. All these can be seen in (Jong and Schonfeld, 1999) (Jha and Schonfeld, 2000) (Maji and Jha, 2009). It should be noted that all these studies are based on the conventional design principles of highway alignment design which consider HIP, VIP, tangents, and curve fittings.

Since its introduction, despite the extreme development in computers and highway surveying field instruments technologies (e.g. total station), highway engineers and planners are still using the same convensional design approach. None of the studies has exploited the technology development to explore the possibility of changing some ideas imposed on highway alignment planning and design. A question arises here, do we still need to keep the same planning and design approach or do we need to change to reflect technology development? That is the question that this study seeks to answer.

1.2 The New Approach

This study introduces a novel technique for alignment optimization. It suggests optimizing simultaneously the horizontal and vertical alignment of a highway through *station points*. Station points as points along the centre line of alignment, which are defiend by their X, Y, and Z coordinates, are used to define the alignment configuration. This research study is inspired by the fact that any generated alignment by whatever method will finally consist of a series of station points and it will be implemented on the ground depending on those station points. Figure 1 shows the difference in alignment generation and configuration between the traditional and proposed method.

In this study GA, as an evolutionary adaptive search technique (Beasley et al, 1993), is used to perform the search. Some modifications to suit the nature of the problem have been included (Davis 1991; Mitchell 1996).

A variety of studies have proven that GA is an efficient tool for planning and optimization problems. Mathews et al (1999) applied GA to land use planning, Mawdesley et al (2002) used GA for construction site layout in project planning, Ford (2007) used GA for housing location planning, Jong (1998), Fwa et al (2002), Tat and Tao (2003), and Kang (2008) used GA for alignment optimization problems.

2 THE MODEL FORMULATION

2.1 The Study Boundary

The study area is defined and divided into rectangular grid cells usually produced from a GIS model of the area under consideration. The size of the grid cells falls within the user preferences and depends on the desired accuracy. Each grid cell may handle one or more than one average value. In this study two different values are assigned to each cell. Average land unit cost values are used for the alignment location dependent cost calculations while average ground elevations are used to calculate the

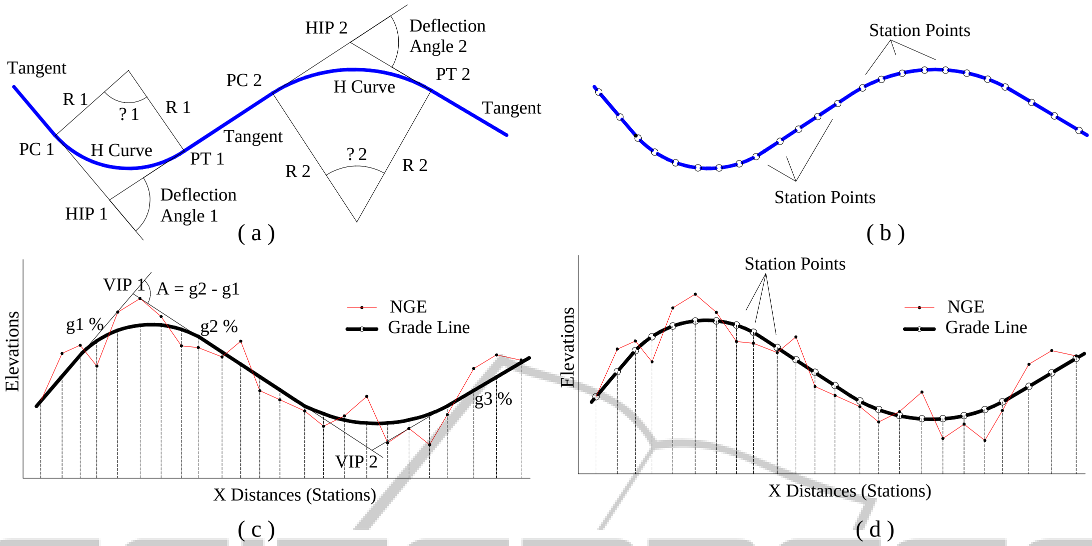

Figure 1: a & c) Horizontal and Vertical Alignment configuration with traditional method, b & d) Horizontal and Vertical Alignment configuration using station points.

earthwork amount of cut and fill. For these purposes, two different matrices are used for each set of data to feed the model during the alignment development process. Figure 2 shows a typical 2D format for a study area:

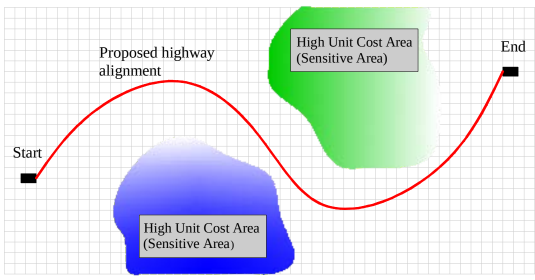

Figure 2: Typical grid format (2D) of a study region.

2.2 The Model Cost Components

The goodness of any alignment is evaluated in terms of cost. The lower the cost, the better will be the solution. In general many costs could be included and the optimum alignment should trade-off among them. In this study, a three dimensional alignment is modelled and tested upon few different cost components which the experiments are based on. These costs are related to:

1. Client or General Costs
   - Length dependent cost (construction costs)
   - Earthwork costs
   - Location costs (environmental costs)
2. User Costs
   - Fuel consumption costs
3. Geometric Design Costs
   - Grade costs
   - Horizontal curvature costs
   - Vertical curvature costs

Other components are also possible for inclusion. The following sections give some details for the incorporated components.

2.2.1 Length Dependent Cost (C_{Length})

This cost directly affects the construction, maintenance, and user costs and therefore it is considered as one of the most influencing factors in highway alignment optimization problems.

Highway alignment construction cost is a function of its length. To calculate this cost, the length of the alignment is multiplied by the unit construction cost as:

$$C_{Length} = L \text{ x Unit Construction Cost} \qquad (1)$$

Where, L is the total length of the alignment. The alignment length is a function of the x and y coordinate of the station points (decision variables).

$$L = \sum_{i=0}^{n-1} \sqrt{(X_{i+1} - X_i)^2 + (Y_{i+1} - Y_i)^2} \qquad (1\text{-}1)$$

for all i = 0, 1, 2 … (n-1)

Where n is the total number of station points.

2.2.2 Location Dependent Cost ($C_{Location}$)

This represents the costs of land acquisitions and special requirements for construction at the locations where the alignment passes through.

$$C_{Location} = \sum_{k=1}^{p} l_k x UCellC \quad (2)$$

Where: $C_{Location}$ is the total alignment location cost; l_k is the length of the alignment located in a grid cell (k) with a specific cost value; UCellC is the unit cell cost of that cell; and p is the total number of cells that the alignment passes through. Thus, (($\sum_{k=1}^{k=p} l_k = L$) where L is the length of the alignment.

2.2.3 User Costs (C_{User})

This cost represents the cost incurred by the users to travel along the road. Here it is calculated by multiplying the annual traffic volume (TV) by the design life of the road (T) to give the total traffic using the road. This in turn is multiplied by the unit cost of the vehicle travelling unit length (UTC) multiplied by the length of the alignment (L). Thus:

$$C_{User} = TV \text{ x } T \text{ x } UTC \text{ x } L \quad (3)$$

2.2.4 Earthwork Costs (C_{EW})

This represents the cost of earthwork in terms of cut and fill amount. An approximate method is used to calculate the amount of cut and fill. The difference in elevation between the grade line and natural ground elevation for cut (h_c) and fill (h_f) is calculated and directly multiplied by the length of that section (l_i), width of the road (w), and unit cost of cut and/or fill. Thus:

$$C_{EW} = \sum_{i=0}^{n-1} l_i x \text{ (} h_c \text{ or } h_f \text{) x w x (UFC or UCC)} \quad (4)$$

Where h_c and h_f is the average cut or fill depth between station points (i+1) and (i) while l_i is the length of that section, and UFC or UCC is the unit fill or cut cost.

2.2.5 Grade Violation Costs ($G_{Violation}$)

This is a form of penalizing the solution and is applied only when the grade of a segment between two station points violates the maximum specified grade. The difference in grade between the actual calculated grade and the maximum grade is multiplied by a user defined cost factor.

$$G_{Violation} = \sum_{i=1}^{n-1} |G_{i-actual} - G_{max}| \text{ x UDC} \quad (5)$$

Where G_i is the grade value between the points (i) and (i-1) while UDC is the user defined cost factor.

2.2.6 Horizontal Curvature Violation Cost ($HC_{Violation}$)

Curvature of horizontal alignment is one of the standard design requirements to ensure gradual transition between two different directions safely at the assigned design speed. The cost of violated curvature according to chord definition at each station point is considered as follow:

$if \sum_{i=0}^{n-1} HC_{i\ existing} > HC_{i\ allowable}$ then:

$$HC_{Violation} = \sum_{i=0}^{n-1} (HC_{i\_existing} - HC_{i\_allowable}) \ x \ CVC \quad (6)$$

Where $HC_{i\_existing}$ is the existing curvature value at point i, $HC_{i\_allowable}$ is the allowable curvature at that point, and CVC is the curvature violation cost.

2.3 The Fitness Function

In this paper, the costs above are combined linearly to form the total cost (C_{Total}) and the aim of the process is therefore to minimize;

$$C_{Total} = a1.C_{Traffic} + a2.C_{Location} + a3.C_{Construction} + a4.C_{Earthwork} + a5.\ G_{Violation} + a6.\ HC_{Violation} \quad (7)$$

Where; a1, a2, a3, a4, a5 and a6 are weighting factors of the individual cost components.
Other combinations of fitness function could also be used.

3 EXPERIMENTAL SETUP

3.1 Chromosome Representation

Using the ideas of station points introduced above, the method defines alignment through generating station points along the centre line of the alignment. The x, y, and z coordinates of the station points are considered as the decision variables of the alignment

The chromosome map is as shown in Figure 3. It contains the three dimensional coordinates of each station point. The station points appear in the order in which they occur along the length of the alignment.

Index (i)	0	1	2	…	i	…	…	n
Individual (j)	X_0	X_1	X_2		X_i			X_n
	Y_0	Y_1	Y_2		Y_i			Y_n
	Z_0	Z_1	Z_2		Z_i			Z_n

Figure 3: Chromosome representation.

3.2 Initial Population Generation

An initial population of random individuals is generated such that:

- All station points are within the study area.
  $X_{min} \le X_i \le X_{max}$, $Y_{min} \le Y_i \le Y_{max}$,
  and $Z_{min} \le Z_i \le Z_{max}$ where i = 1, 2, … , n-1.
- The 3D components of each gene are encoded using floating point numbers with single precision.
- The first and last points (0 and n) are fixed as the required terminal points.
- The station points are sorted in the order of their X values ($Xi \le Xi+1$). This process is specific to the initial population generation only.

3.3 Reproduction

3.3.1 Selection

In this study parents are selected according to their fitness (based on ranking). The selected parents undergo crossover and mutation to produce offspring. The created offspring are then evaluated by the fitness function. The fittest individuals are merged into the population to breed in the next generation while the bad solutions die off (Davis, 1991).

3.3.2 Crossover

In this paper a multiple random point crossover is used to swap a segment or segments of genes between two individuals to form two offspring. The entire gene code (X, Y, and Z coordinates) within the segments are swapped during this process.

3.3.3 Mutation

First, simple uniform mutation, as a standard GA operator, is used to help the solution in evolving over the successive generations. Different parameters (e.g. number of individuals, number of station points, mutation probability, number of generations up to 100,000, and so on) have been investigated. Moreover, different strategies have been applied during the process. The strategies are considered to be different mutation rates to select different station points for mutation and dynamic consideration of the study area. These strategies are considered to test the level of effectiveness of the applied method. None of these parameters and strategies has produced a good solution.

Later, as an attempt to improve the effectiveness of the mutation operator, the simple uniform mutation is modified. This modified uniform mutation (MUM) is based on that described by Michalewicz (1999). It is adapted to associate a number of station points with a single mutated one. The trend of this mutation is to enhance the search, reduce the messiness of the alignment configuration, and to produce a smoother alignment. This operator, as with simple uniform mutation, selects a gene position (p) randomly and assigns a new random value for its X, Y, and Z coordinates. Then the operator generates two more locations (l_1 and l_2) provided that $l_1 < p < l_2$. Then, all the genes (station points) that locate between l_1 and p, and l_2 and p on the other side are reallocated and put on a straight line connecting the newly generated gene at (p) with the selected genes at l_1 and l_2.

4 EXPERIMENTAL RESULTS

4.1 Standard GA Tests

Figure 4 shows a typical result with simple uniform mutation for a 2D highway alignment. A legend list (Figure 5) is also provided to illustrate the land feature configurations of the study region.

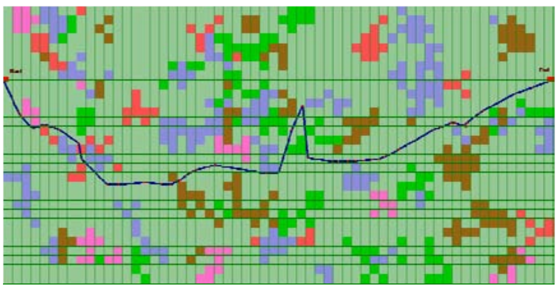

Figure 4: An alignment result for a horizontal highway alignment using standard GA operators. (Land use grid map).

The result which obtained by this method was not satisfactory even after 50,000 generations. The fitness value of the final solution was 38,339,321 unit cost.

Low cost	Moderate cost	Normal cost
High cost	Very high cost	Most high cost

Figure 5: Cost colour legends of the land use grid maps.

4.2 Modified GA Tests

The modified GA formulation, which specified by MUM as mentioned above, was also tested on a 2D highway alignment as shown in Figure 6. The result holds a fitness value 24,583,831 unit cost at generation 1000. The resulting alignment is as straight as possible, relatively smooth, and passes through the low cost fields. The practicality of this mutation was then tested on a 3D alignment as well. The 3D result holds a fitness value 53,624,912 unit cost at generation 2000. It worth to mention that this operator, as for the 2D horizontal alignment, has the following merits on the vertical profile:

a. It produces as low as possible earthwork costs.

b. It yields a relatively smooth alignment.

c. It tries to locate the alignment as close as possible to the natural ground surface.

d. It tries to wind around the high and low elevation locations to minimize cut and fill costs.

Typical results are shown in Figures 7 to 10.

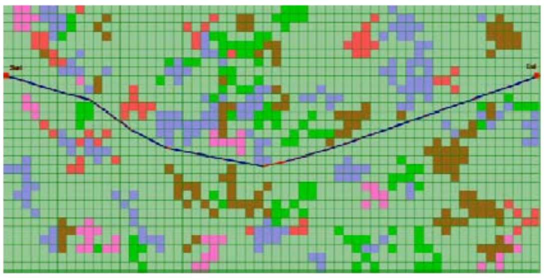

Figure 6: Test result of a modified uniform mutation (MUM) for a 2D alignment. (Land use grid map).

The two tests (2D and 3D) resulted in obtaining two different horizontal alignment configurations (Figures 6 & 7) due to the effect of the third dimension (Z) on the final outcome. These demonstrate that the horizontal and vertical alignments are unlikely to be global optima unless they are considered simultaneously. It should be noted that the initial test was conducted without considering the grade and curvature costs as they need special techniques to handle them and these are discussed in the succeeding sections.

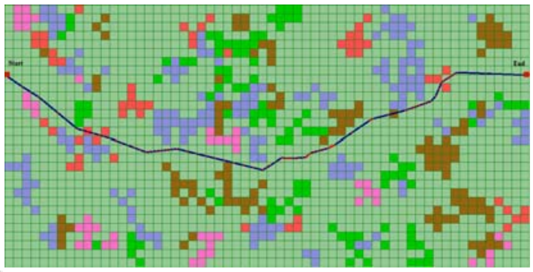

Figure 7: Horizontal alignment test result of MUM for a 3D highway alignment. (Land use grid map).

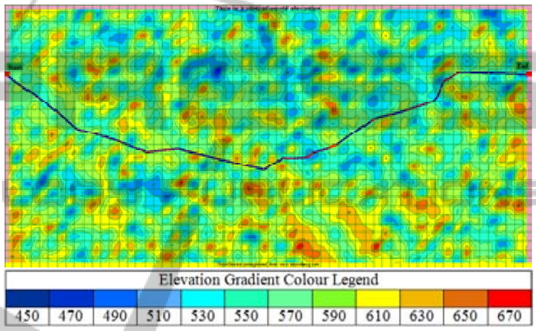

Figure 8: Horizontal alignment result of MUM for a 3D alignment on contour map.

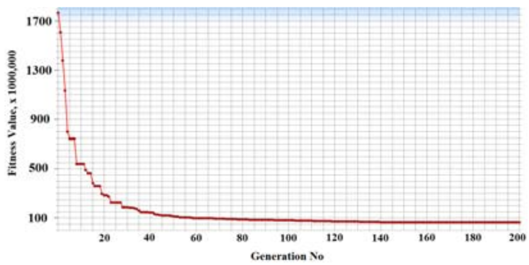

Figure 9: Fitness graph. (Note: only the substantial improvements over 200 generations are shown).

However, as is clear in the results, the modified uniform mutation (MUM) method still keeps some sharp bends (horizontally and vertically) throughout the length of the alignment. These sharp bends are expected from such a mutation method.

Furthermore, the vertical one possesses some grades (upwards and downwards) which are greater than the maximum permitted one. These alignment criteria cannot be improved unless specific algorithm techniques are developed and associated with the search process. This needs to be considered as constraints according to the geometric design and safety requirements of the highway.

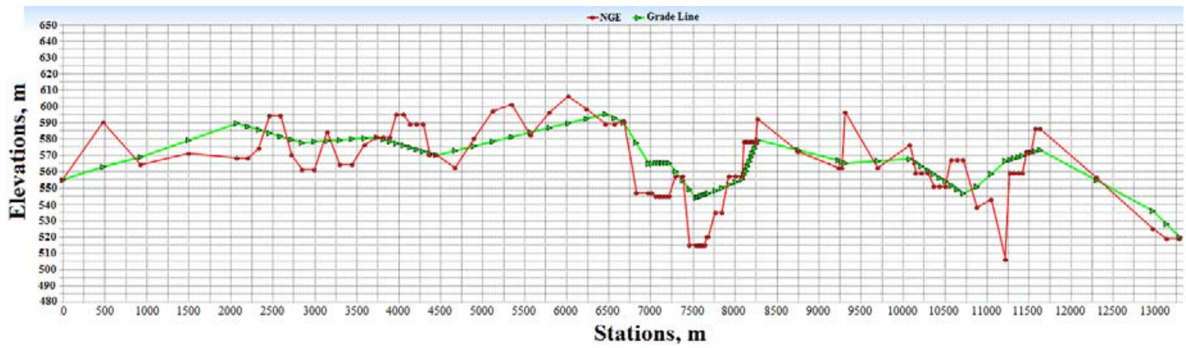

Figure 10: Vertical alignment profile result (grade line elevations) of MUM for a 3D highway alignment.

4.3 Grade and curvature Constraint Handling Technique Tests

Three different algorithms are developed to handle curvature for the horizontal alignment, curvature and gradient for the vertical alignment. Penalty and repair techniques are considered to look after the point locations along the alignment that violate the allowable horizontal curvature limits. Penalty is used for maximum gradient violation while repair technique is applied for vertical curvature violation. The formulations of these techniques are based on standard design requirements for both geometric design and safety. These techniques are individually applied to each single station point or location where the violations exist.

Different experiments have been carried out to test the effect of each technique separately and simultaneously. The test results show that the resulting solutions are improved significantly as shown in Figure 11 to 13. The results show that the solution is good with no or very few gradient and curvature violations.

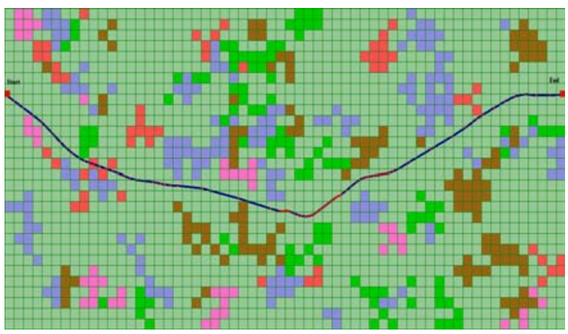

Figure 11: Horizontal alignment result for a 3D alignment evolved with curvature and grading constraint handling. (Land use grid map).

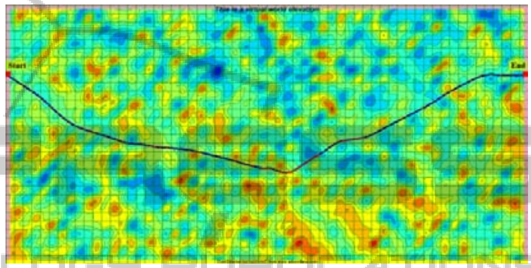

Figure 12: Horizontal alignment result for a 3D alignment evolved with curvature and grading constraint handling. (Contour map).

5 CONCLUSIONS

A three dimensional highway alignment optimization model based on a genetic algorithm has been developed. A new technique has been introduced to define the alignment configuration. Station points along the centre line of the alignment have been used to generate alignments of different configurations. Specific genetic algorithm operators and constraint handling techniques were tested and the results indicate that the method holds promises.

The results also show that the station point technique is promising if it is assisted by constraint handling algorithms to produce better solutions. It is concluded that the constraint handling techniques assisted in the improvement of the alignment curvature characteristics and the reduction or prohibition of the gradient violations.

However, the results show that further developments and further investigations are required to verify generating more realistic alignments. More specific GA operators and further modifier and constraint handling techniques will be investigated. Moreover, the model needs to be tested on different worlds and the model parameters need to be determined and verified for applicability in real world application problems.

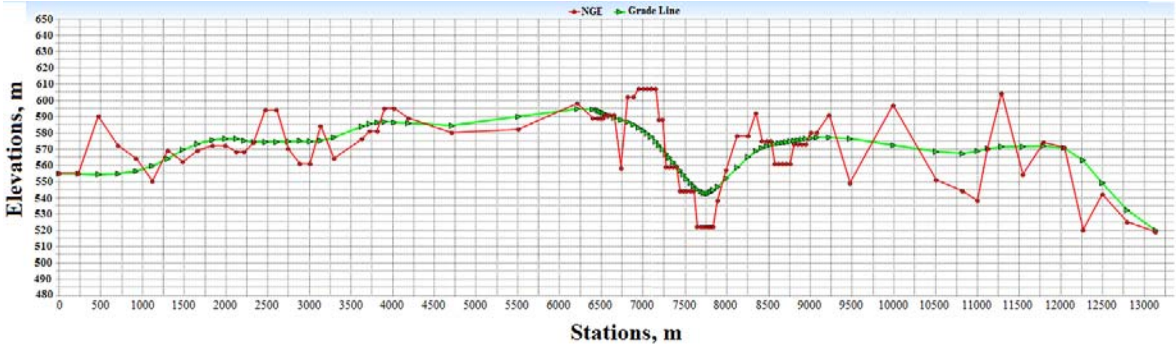

Figure 13: Vertical alignment profile for a 3D highway alignment evolved with curvature and grading constraint handling.

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