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A Multiobjective Analysis of Impacted Area of Environmentally Preserved Land and Alignment Cost for Sustainable Highway Infrastructure Design

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Abstract

Sustainable highway infrastructure design requires a good balance between environment and cost. The available computer-based automated highway alignment optimization algorithms minimize the total highway alignment cost towards obtaining the optimized alignment. These are primarily single-objective optimization approaches with limited capability in considering various cost components and factors that may be dissimilar or conflicting in nature. In these approaches, the impacted area of environmentally preserved land is transformed to monetary value and included in the total highway alignment cost. Also, they have limited capability in yielding a set of alternatives with different levels of trade-off between the total highway alignment cost and impacted area of environmentally preserved land. This leads to the need for developing a model to estimate the impacted area of environmentally preserved land in terms of non-monetary values and use concurrently with total highway alignment cost providing a perspective comparison of highway alignment alternatives. A multiobjective analysis is presented in this paper to consider the impacted area of environmentally preserved land information expressed in non-monetary unit and total highway alignment cost expressed in monetary unit. In this analysis, a genetic algorithm (GA) based multiobjective optimization technique is adopted. The paper describes a special algorithm developed to estimate the impacted area of environmentally preserved land from a Geographic Information System (GIS) based study area map and simultaneous minimization of impacted area of environmentally preserved land and highway alignment cost. A Pareto-optimal front is used to graphically represent the trade-off values of highway alignment cost and impacted area of environmentally preserved land. Finally, the developed methodology is applied to a study area and results are compared with the available single objective highway alignment optimization model output.

Selection and/or peer-review under responsibility of the Organizing Committee.

Keywords: multiobjective analysis, environmental sustainabiity, highway alignment optimization, genetic algorithms, geographic information system (GIS).

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1. Introduction

Highway alignment optimization methods strive to minimize total highway alignment cost and impacted area of environmentally preserved land. This paper endeavors to develop a simultaneous minimization methodology for impacted area of environmentally preserved land and highway alignment cost yielding the optimal highway alignment. The methodology is applied to a real-world study area and the results are analyzed in comparison to single objective optimization methods. In this paper, highway alignment cost is expressed in monetary unit and impacted area of environmentally preserved land in non-monetary unit, square feet. The highway alignment cost includes (but not limited to) earthwork cost, right-of-way cost, pavement construction cost, vehicle operating cost, accident cost, travel time cost, and overpass and underpass construction cost. From a financial perspective, the best highway alignment is the one which yield the minimum highway alignment cost. Likewise, the highway alignment with the minimum impacted area of environmentally preserved land is also highly desirable from an ecological perspective. Based on the study area the highway alignment cost and impacted area of environmentally preserved land could be converse; whereby a highway alignment with minimum cost might not yield minimum impacted area of environmentally preserved land and vice versa. Moreover, it is inconvenient and inefficient to estimate the impacted area of environmentally preserved land in monetary value. Therefore, the impacted area of environmentally preserved land and highway alignment cost cannot be combined to form a single objective during optimization.

One approach to solve this type of problem is by considering objectives with different units as separate entities (i.e., treating impacted area of environmentally preserved land and highway alignment cost as separate objectives) and optimize them simultaneously. Unlike single objective optimization, simultaneous optimization yields a set of trade-off solutions. Consequently, simultaneous minimization of highway alignment cost and impacted area of environmentally preserved land will provide the highway planner the flexibility of choosing an alignment from a set of trade-off solutions. These sets would be generated from the simultaneous minimization of impacted area of environmentally preserved land and highway alignment cost. The choices would be based on the significance and importance of impacted area of environmentally preserved land within the study area and the total highway alignment cost. A geographic information system (GIS) based map database is used in this study to estimate the highway alignment cost and impacted area of environmentally preserved land. A special algorithm is developed to estimate the total impacted area of environmentally preserved land from the GIS map database and generate alternatives by simultaneous minimization of highway alignment cost and impacted area of environmentally preserved land.

2. Highway Alignment Design

A highway alignment is a combination of horizontal and vertical profiles. Circular, parabolic, tangent, and transition sections are the basic components of horizontal and vertical profiles. Alignment design is generally considered as separate projections of horizontal and vertical profiles. This design procedure is basically a 2-dimensional (2-D) approach. Computer based automated highway alignment design models were developed and have evolved over the last four decades. The models use a single-objective optimization approach to minimize total highway alignment cost. These models use different methodologies such as calculus of variation (Wan, 1995; Howard, et al., 1968; Thomson & Sykes, 1988), network optimization (Turner & Miles, 1971; Turner, 1978; Athanassoulis & Calogero, 1973), dynamic programming (Trietsch, 1987; Hogan, 1973; Nicholson, et al., 1976), numerical search (Chew, et al., 1989) and genetic algorithm (Jong, 1998; Jha, et al., 2006; Jha & Schonfeld, 2004). In all of these methodologies the highway alignment factors or objectives are tied together to form a single-objective (Jong, 1998; Jha, 2000). Later, GIS map and database were integrated into the genetic algorithm (GA) based highway alignment design model (Jha, 2000) and improved the highway alignment cost estimation functions.

The GA based highway alignment design model uses a GIS map database as a search space where the start and end points of constructed alignment are pre-specified. The decision variables used are described as the set of points along the orthogonal cutting planes drawn at user-specified intervals along the Euclidian line connecting the start and end points. Those points are known as Point of Intersections (PI) and they are similar to the PI in traditional roadway design. Appropriate curves are fitted along the PIs to obtain a highway alignment. If a PI falls along the straight line joining the other PI on either side, a tangent section is obtained; otherwise a curved section is obtained.

Appropriate curves are fitted using American Association of State Highway and Transportation Officials (AASHTO, 2001) design criteria. Thus, an alignment can be sufficiently described by the random location of cutting (orthogonal) planes and the random location of PIs along the planes. Different highway alignment cost components are estimated from the generated alignment. Some of the major highway alignment costs, such as travel-time cost, pavement and construction cost, vehicle operation cost, length dependent cost etc are estimated using empirical equations whereas other costs, such as location dependent cost, earthwork cost, impacted environmentally preserved lad area etc are derived from the GIS map database (see Jha, 2000 for details). These cost components are added to obtain the total highway alignment cost. The total highway alignment cost information is used to generate a new set of PIs using GA operators and the process is continued until the total highway alignment cost is minimized. Extensive research by Jong et al. (Jong, et al., 2000) and Jong and Schonfeld (2003) indicate that a reasonably good solution is obtained by this method within 100 generations of the search. However, this research work is limited to optimization of total highway alignment cost expressed in monetary values and objectives with non-monetary values cannot be considered directly in the optimized design process. One technique adopted to resolve this and to include the non-monetary objective is to express it in monetary value. However, the technique neither guarantees simultaneous optimization of both objectives nor is the transformation to monetary value unbiased. The method also lacks the ability to deliver solutions with a trade-off.

3. Highway Alignment Cost

The highway alignment cost consists of alignment sensitive costs, such as right-of-way cost, construction cost, earthwork cost, vehicle operation cost, user cost etc. The user cost comprises travel-time cost, vehicle operating cost, and accident cost whereas the right-of-way cost is derived from the land area needed and the property damage incurred. These are estimated from the GIS map database and transmitted to the GA based highway alignment optimization process. Minimizing these costs facilitates obtaining an optimal highway alignment. The locations of PIs (x_p, y_p, z_p) control the designed highway alignment and thus influence different alignment dependent costs. Therefore, minimizing the highway alignment cost helps to obtain the optimum highway alignment within the search space. The detailed formulations of alignment sensitive costs that can be considered are available in previously published works (Jong, 1998; Jha, et al., 2006; Jha & Schonfeld, 2004; Jha, 2000) and have been skipped here for brevity.

$$HAC = TC_L + TC_N + C_F + C_T + C_A + C_E \tag{1}$$

where,

TC_L	=	Total location dependent cost
TC_N	=	Total length dependent cost
C_F	=	Total fuel cost for the base year
C_T	=	Travel time cost for the base year
C_A	=	Accident cost for the base year
C_E	=	Earthwork cost

4. Environmentally Preserved Land Parcels

Different types of environmentally preserved land parcels impacted by the highway alignment alternatives are estimated in the impacted area of environmentally preserved land. For example, forest, wetland, certain water bodies, etc. are considered as important resources to maintain balance in the ecosystem. Thus they are considered as environmentally sensitive. Total impacted area for environmentally sensitive regions should be as minimal as possible and if there are any impacts, special care should be taken to mitigate and restore them. If due to unavoidable circumstances, certain portion of a forest area is needed to build a highway, then equivalent land should be reserved to restore the forest impacted. Similar type of mitigation would be required for other environmentally preserved land. Though the impact on environmentally preserved land, transformed to monetary value with suitable factor, is included in the total highway alignment cost and used in the GA based highway alignment optimization process (Jong, 1998; Jha, 2000) discussed above, it is difficult to precisely estimate its actual monetary value during planning. The monetary value will significantly vary with project, location and type of impacted land parcel. Hence, during planning it is desirable to represent affected environmentally preserved land as the impacted area. This provides a better control over the parameter while simultaneously minimizing the highway alignment cost and the impacted area of environmentally preserved land. It enhances comparison of impacted area values of environmentally preserved land with other generated highway alignment alternatives. This becomes useful in the presentation of highway alignment alternatives to environmental agencies to secure permits and federal grants.

The environmentally preserved land within the study area of the highway alignment to be designed are identified and suitably represented in the GIS map database. A highway alignment generated by joining the PIs is overlaid on the GIS map of the study area and the affected environmentally preserved land is identified. The fraction of the affected land needed to build the alignment is estimated and summed up to obtain the total impacted area of environmentally preserved land. Considering nlp as the total number of land parcels in the study area and af as the fraction of land area (could be in square feet or square meters) needed for highway alignment, the total impacted area of environmentally preserved land can be estimated as follows:

$$C_{env} = \sum_{j=1}^{nlp} af_j \times E_j \tag{2}$$

where,

$$E_j = \begin{cases} 1, & if\ j^{th}\ land\ parcel\ is\ environmentally\ preserved\ \ property \\ 0, & otherwise \end{cases}$$

C_{env} = Total impacted area of environmentally preserved land parcel

E = Factor to identify environmentally preserved land

The total impacted area of environmentally preserved land depends on the value of E, af and the PIs of the highway alignment. Therefore, the mathematical function for impacted area of environmentally preserved land can be represented as follows:

$$C_{env} = f_{Env}\left(PI_i, af_j, E_j\right) \tag{3}$$

where,

$f_{Env}()$ = Function identifying impacted area of environmentally preserved land

i = 1, 2, 3, …., poi

j = 1, 2, 3, …., nlp

poi = Number of point of intersections

5. Application of the Model

The GIS based GA optimization procedure is used to simultaneously minimize total highway alignment cost and impacted area of environmentally preserved land. A Harford County GIS map database in the State of Maryland is used in this study. The highway alignment cost is expressed in monetary value and the impacted area of environmentally preserved land parcels in the unit of area, i.e., in dollars and square feet respectively. As usual, the PIs are the primary decision variables for the GA optimization procedure and therefore, the PI coordinate information are encoded in the chromosomes. The initial search domain is selected within the study area and the two end-points of the highway alignment are specified. In this case, the 3-dimensional coordinate (467181.78, 195764.21, 133.01) is used as the start point, $S(x_s, y_s, z_s)$ and (460405.75, 208371.55, 141.11) is used as the end point, $E(x_e, y_e, z_e)$ of the designed highway alignment. The alignment is designed for a typical 2-lane highway with 40 ft. average right-of-way width and 50 mph design speed. Also, a set of 10 controlling PIs are considered to define the highway alignment.

The GA population is initialized by randomly generated PIs in the chromosome. A set of 100 such chromosomes are used as the initial population size. PIs in each set of chromosomes are joined to form the highway alignment and overlaid on the GIS map. These highway alignments are evaluated for the total highway alignment cost and impacted area of environmentally preserved land using the empirical highway alignment cost formulation discussed elsewhere (Jong, 1998; Jha, et al., 2006; Jha & Schonfeld, 2004; Jha, 2000) and the GIS map database along with equation 3 respectively. The methodology discussed in the previous section is used for the evaluation. This problem is evaluated for 50 generations or until the non-dominated solution set reaches its storage limit. Considering the complexity of the study area, a storage limit of 200 non-dominated solutions is established for this problem. The offspring obtained are re-evaluated for the total highway alignment cost and impacted area of environmentally preserved land and suitably stored in the existing non-dominated and dominated solution pool. The non-dominated solution set is also updated in each generation. This process is continued until the termination criteria are satisfied. Finally, the summary of the final set of non-dominated solution is displayed.

6. Results

The simultaneous minimization of total highway alignment cost and impacted area of environmentally preserved land within the Harford County study area generated 39 highway alignment alternatives at the end of the 50th generation. The highway alignment cost for the obtained alternatives varies from 6.745 to 7.247 million dollars whereas the impacted area of environmentally preserved land varies from 359,518 to 628,470 square feet. The lengths of these highway alignments range from 8.3 to 8.7 miles. It took 42,233 seconds for the GIS database linked C computer program to obtain this information. The non-dominated total highway alignment cost and impacted environmentally preserved land area values of these highway alignment alternatives are shown in Table 1. The extreme alternatives, i.e. highway alignment with the highest cost but the least impacted area of environmentally preserved land and highway alignment with the least cost but the highest impacted area of environmentally preserved land, are plotted on the Harford County GIS map. These two representative highway alignments are shown in Figure 1.

Table 1: Total highway alignment cost and impacted area of environmentally preserved land for the alternatives

Sl. #	Total Highway Alignment Cost (million $)	Impacted Area of Environmentally Preserved Land (sq. ft.)	Sl. #	Total Highway Alignment Cost (million $)	Impacted Area of Environmentally Preserved Land (sq. ft.)
1	6.745	628470	21	7.126	382451
2	6.756	609340	22	7.128	382246
3	6.772	590880	23	7.129	381275
4	6.791	569696	24	7.136	379718
5	6.822	561985	25	7.143	378205
6	6.825	561203	26	7.146	377596
7	6.854	526027	27	7.151	377109
8	6.874	475220	28	7.157	375633
9	6.875	464299	29	7.160	372552
10	6.891	449973	30	7.172	372225
11	6.893	439413	31	7.174	370558
12	6.903	438390	32	7.179	369265
13	6.933	437961	33	7.179	368689
14	6.936	437935	34	7.190	368376
15	6.973	401734	35	7.194	368348
16	6.984	401615	36	7.196	365860
17	7.027	398706	37	7.212	362937
18	7.111	392581	38	7.245	360378
19	7.119	392053	39	7.247	359518
20	7.120	385635			

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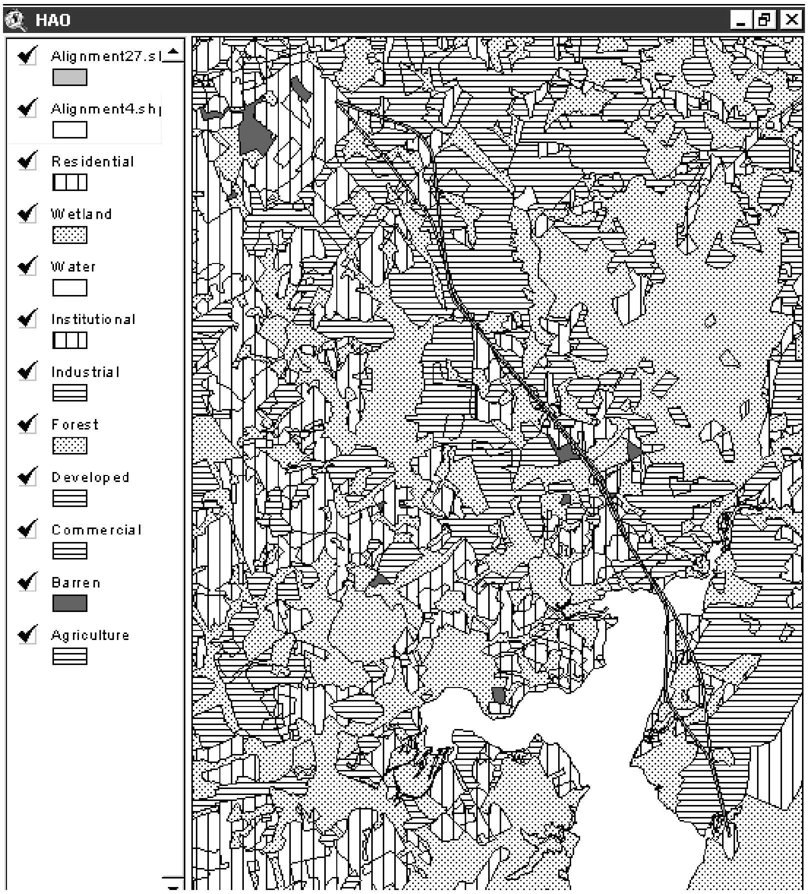

Figure 1: The best highway alignments obtained by simultaneous optimization of total highway alignment cost and impacted area of environmentally preserved land

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