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Multi-objective highway alignment optimization incorporating preference information

Ning Yang [a,1], Min-Wook Kang [b,2], Paul Schonfeld [c,3], Manoj K. Jha [d,*]

[a] ITS and Traffic Engineer, Parsons Corporation, 100 Broadway, 18th Floor, New York, NY 10005, United States
[b] Department of Civil Engineering, University of South Alabama, Mobile, AL 36688, United States
[c] Department of Civil Engineering, University of Maryland, College Park, College Park, MD 20742, United States
[d] Department of Civil Engineering, Morgan State University, Baltimore, MD 21251, United States

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ABSTRACT

This paper presents a GIS-based multi-objective optimization model, particularly designed to aid highway engineers and planners in proposing competitive highway alignment alternatives when building a new highway or expanding an existing highway. The proposed model can effectively examine tradeoffs among various objectives that represent possibly conflicting interests of different stakeholders. A Hybrid Multi-Objective Genetic Algorithm, which utilizes designers' knowledge about the preference of decision makers, is developed to search for a set of Pareto-optimal solutions with an acceptable level of diversity. Two case studies demonstrate the capability of the proposed approach in providing multiple trade-off solutions. The results indicate that the incorporation of preference information, even if preliminary in nature, has great potential to save computation time and improve the quality of the obtained Pareto-optimal set.

1. Introduction

Building new highways or expanding existing highways requires massive public spending and has dramatic effects on the natural and human environments through which they pass. This important public investment naturally generates strong and conflicting interests among different stakeholder groups, making the design of highway alignments a great challenge. To aid engineers in searching and evaluating competitive alternative alignments with limited time and effort, researchers have conducted extensive studies on the Highway Alignment Optimization (HAO) problem over past decade (Fwa et al., 2002; Jong and Schonfeld, 2003; Jha, 2003; Cheng and Lee, 2006; Easa and Mehmood, 2008; Lee et al., 2009; Kang et al., 2012; Kang et al., 2013). In most previous studies candidate alignment plans are evaluated with one single-objective function, which aggregates a variety of judgment criteria using the weighted sum method. Consequently, an optimal or near-optimal solution is returned as the final result.

In typical practice, however, a set of competitive alternatives have to be presented to the agency during the preliminary design phase. The one winning the maximum support and satisfying diverse concerned groups is chosen as the final plan, which then proceeds to the detailed design phase. To better support the decision-making process in complex real-world domains, a multi-objective HAO model is developed here by adapting the single-objective HAO model developed by Jong, Jha,

* Corresponding author. Tel.: +1 443 885 1446; fax: +1 443 885 8125.
E-mail addresses: vivian.ning.yang@gmail.com (N. Yang), mwkang@southalabama.edu (M.-W. Kang), pschon@umd.edu (P. Schonfeld), manoj.jha@morgan.edu (M.K. Jha).
[1] Tel.: +1 212 266 8403; fax: +1 212 266 8536.
[2] Tel.: +1 251 460 6174; fax: +1 251 461 1400.
[3] Tel.: +1 301 405 1954; fax: +1 301 405 2585.

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Kang, and Schonfeld (Jong and Schonfeld, 2003; Jha and Schonfeld, 2000a, 2004; Kang et al., 2009, 2012) into a multi-objective optimization framework. The enhanced model incorporates in the optimization process the highway designers' knowledge about the decision makers' preferences so that a set of competitive non-dominated solutions can be searched with an acceptable level of diversity. The model provides the flexibility of generating trade-off alternatives for further negotiation and conflict resolution among stakeholders.

The rest of this paper is organized as follows: Section 2 formulates the optimization objectives and constraints of the greatest concerns in highway design. Section 3 introduces the concept and the main steps of the Hybrid Multi-Objective Genetic Algorithm (HMOGA) developed to solve the problem. The proposed methodology is tested in Section 4 through a *hypothetical case* study. Section 5 summarizes the research findings and discusses the usefulness and limitations of the proposed multi-objective HAO model.

2. Highway alignment optimization

The mathematical formulation of the proposed multi-objective HAO model is presented in this section. Instead of returning a unique global optimum in single-objective optimization, the model searches for a set of Pareto-optimal solutions which are not dominated by any other feasible solutions and are likely to receive the support of diverse concerned groups.

2.1. Decision variables

The decision variables in the HAO model are the 3 Dimensional (3-D) coordinates of a series of points of intersections (PI's) used to specify both the horizontal and vertical alignment of a highway, as shown in Fig. 1. After the PIs are determined, the horizontal alignment can be generated by fitting the appropriate circular curves and spiral transition sections to these PI's. Simultaneously, the corresponding vertical alignment is determined by fitting parabolic curves to grade-tangents at every PI. Important design parameters, such as the radius of circular curves, length of spirals, transition curve parameters, and the length of vertical curve, are determined based on the design speed, maximum supper elevation, and side friction specified by the model users as well as the approach/departure grades of PI's generated from the model. Note that minimum values of the design parameters based on the design speed are used to minimize earthwork and right-of-way costs.

It is important to note that a PI can generate: (1) both horizontal and vertical curves, (2) either one of them, or (3) neither of them. In other words, a subset of the PI's used for generating horizontal curves can differ from that used for generating the vertical curves. In the model, a horizontal PI (HPI) is determined by x and y coordinates of a PI whose deflection angle is nonzero. (Note that no horizontal curve is needed for zero deflection angle at a PI.) As with the horizontal curve, there is no vertical curve at the middle PI among three consecutive PI's if they have the same elevation (i.e., z value) or they are aligned in a sloping straight line (Kang et al., 2012). The process of converting the PI coordinates to horizontal and vertical alignments is controlled by a pre-screening and repair operator to yield smooth and realistic alignment that satisfies the geometric design standards (e.g., AASHTO, 2011). Due to space limits, we refer readers to our previous papers for more details (Kang et al., 2009, 2012). The set of PIs is defined as follows:

$$
\begin{aligned}
&PI_i = (x_i, y_i, z_i) \quad \text{for all } i = 1, 2, \ldots, n_{PI} \\
&\qquad x_{LB} \leqslant x_i \leqslant x_{UB} \\
&\text{Subject to } y_{LB} \leqslant y_i \leqslant y_{UB} \\
&\qquad z_{LB} \leqslant z_i \leqslant z_{UB}
\end{aligned} \tag{1}
$$

where PI_i = the ith point of intersection (PI); n_{PI} = total number of PIs that outline a new highway alignment; x_i, y_i, z_i = x, y, z coordinates, respectively, of the ith PI; x_{LB}, y_{LB}, z_{LB} = lower bounds of x, y, z coordinates, respectively, in the 3D search space and x_{UB}, y_{UB}, z_{UB} = upper bounds of x, y, z coordinates, respectively, in the 3D search space.

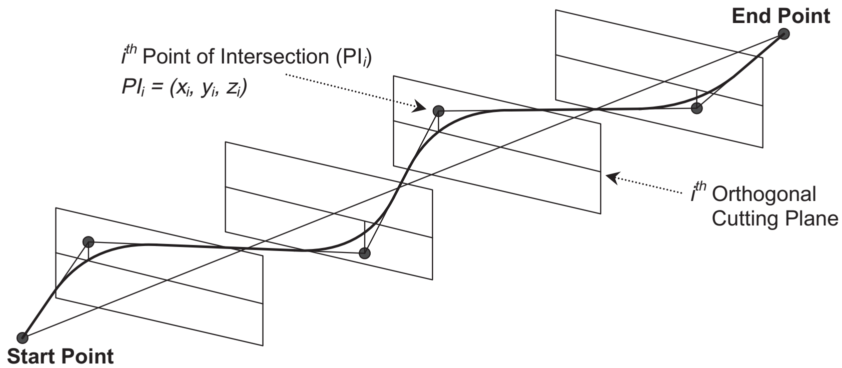

Fig. 1. An alignment generated with PI's placed along orthogonal cutting planes.