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A bi-objective optimization framework for three-dimensional road alignment design

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ABSTRACT

Optimization of three-dimensional road alignments is a nonlinear non-convex optimization problem. The development of models that fully optimize a three-dimensional road alignment problem is challenging due to numerous factors involved and complexities in the geometric specification of the alignment. In this study, we developed a novel bi-objective optimization approach to solve a three dimensional road alignment problem where the horizontal and vertical alignments are optimized simultaneously. Two conflicting cost objective functions, *earthwork* cost and the *utility* cost, are cast in a bi-objective optimization problem. We numerically compare several multi-objective optimization solvers, and find that it is possible to determine the Pareto front in a reasonable time.

1. Introduction

Road design consists of finding a three-dimensional route alignment on the ground surface. It aims to connect two terminals (the start and the end of a road) at minimum possible cost and maximal utility, subject to design, environmental, and social constraints (Jha and Maji, 2007). Since the number of alternative routes connecting two end points is unlimited, a traditional route location analysis, which has relied heavily on human judgement and intuition, may overlook many good alternatives (Chew et al., 1989; Li et al., 2013). In order to consider all such route alternatives, and to reduce the workload for engineers, several automated procedures that determine good road alignments and approximate construction costs have been developed (Jong and Schonfeld, 2003). The automation of the road design problem reduces the tedious and error-prone manual tasks, most notably drafting (Kim et al., 2004). In addition, this procedure allows the use of optimization techniques in search of a good alignment (OECD, 1973). Optimization techniques save design time and provide the decision maker with powerful tools that search for an alignment with minimum cost from a large number of alternative alignments. In fact, optimization of road alignment can yield considerable savings in construction costs when compared with unoptimized design procedures (OECD, 1973).

The road design problem can be broken down into three interconnected stages: the horizontal alignment, the vertical alignment, and the earthwork (Hare et al., 2011). The horizontal alignment is a bird's eye view of a road trajectory. A typical horizontal alignment is composed of a sequence of tangents, circular curves, and transition curves. Transition curves have the property that the radius of curvature changes progressively along them. The main considerations in horizontal alignment design are that

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it should avoid lands which are restricted or expensive to purchase, obstacles which present engineering difficulties, and ground which may involve large amount of earthwork. The cost of road construction for the horizontal alignment problem depends on the cost of acquiring land and on the output of the vertical alignment stage (Hare et al., 2011). Optimization of the horizontal alignment seeks a low cost route while adhering to the design standards and reducing environmental impacts (Ahmad Al-Hadad, 2011). However, optimization of horizontal alignment should also seek a highly utile route. These two goals may often be in conflict with each other. In the literature, the following models have been developed for optimizing horizontal alignments: calculus of variation (Nicholson, 1973), network optimization (Trietsch, 1987), dynamic programming (OECD, 1973), and genetic algorithms (Jong et al., 2000). Detailed discussion on the advantages and disadvantage of these methods can be found in (Jha et al., 2006).

The vertical alignment is the view of the centreline of the road when seen along the longitudinal cross-section of the road. A typical vertical alignment is composed of straight sections known as vertical tangents and parabolic curves, namely crest and sag curves. The design of vertical alignment is a crucial step in the road design problem since it has implications on road construction costs, traffic operations, vehicle fuel consumption, and safety (Fwa et al., 2002). In vertical alignment optimization, one fits a road profile to the ground profile while respecting various grade constraints and other road specifications. The objective is to minimize the cost of construction and the negative impacts on the environment (Fwa et al., 2002). Vertical alignment optimization models include linear programming (Easa, 1988; Mayer and Stark, 1981), numerical search (Hayman, 1970), state parametrization (Goh et al., 1988), dynamic programming (Goh et al., 1988; Göktepe et al., 2009), genetic algorithm (Ahmad Al-Hadad, 2011; Fwa et al., 2002), and mixed integer linear programming (Hare et al., 2014, 2011). (See also (Goh et al., 1988; Göktepe et al., 2009; Jha et al., 2006) for more references).

A three-dimensional road alignment is the superimposition of two-dimensional horizontal and vertical alignments. In essence, road alignment design is a three-dimensional problem represented in X, Y, and Z coordinates. The development of models that fully optimize a three-dimensional road design problem is not yet successful, because there are many factors involved and complexities in the geometric specifications (Aruga et al., 2005; Göktepe et al., 2009; Jha et al., 2006). Three-dimensional road alignment optimization is presented as a constrained, nonlinear, and non-differentiable optimization problem (Aruga et al., 2005). There are two basic approaches found in the literature: models that simultaneously optimize the horizontal and vertical alignments (Aruga et al., 2005; Chew et al., 1989; Jong and Schonfeld, 2003), and models that employ two or more stages of optimization (Nicholson, 1973; Parker, 1977). Existing approaches for three-dimensional alignment optimization include genetic algorithms (Jong and Schonfeld, 2003; Kang et al., 2012; Kim et al., 2007), swarm artificial intelligence (Bosurgi et al., 2013), dynamic programming (Li et al., 2013), neighbourhood search (Cheng and Lee, 2006), and distance transform (DeSmith, 2006). Dynamic programming and numerical search methods suffer from the high computational effort and large memory requirements (Jha et al., 2006; Maji and Jha, 2012; Jong and Schonfeld, 2003). So far, all of these method focus only on minimizing the overall design cost, and omit the conflicting cost of road utility.

This paper presents a novel bi-objective framework for optimizing a three-dimensional road alignment problem. In our model, a bi-objective cost function is formulated that consists of the ‘earthwork cost’ and the ‘utility cost’. The cost associated with earthwork is the cost of ground cut, ground fill, waste material, and borrow material, all of which depend on the volume of the material. The utility cost is computed based on the length of the road. Model constraints restrict maximum grade and radius of curvature for horizontal turns.

This paper advances research in horizontal alignment in several manners. First, this paper considers the three-dimensional alignment as a bi-objective problem. Research in this direction has been limited, but shown great promise in application (Jha and Maji, 2007; Maji and Jha, 2009, 2011). Indeed, aside from (Jha and Maji, 2007; Maji and Jha, 2009, 2011) (which all present different aspects of the same model), research in this direction appears absent. The principal difference in our model, as compared to (Jha and Maji, 2007; Maji and Jha, 2009, 2011), is expanded details on exactly how the road alignment is designed and costs are computed. As a result, our model also provides a detailed new surrogate model that can produce both an earthwork cost and a utility costs for a potential alignment. This is a very significant contribution to the field, as it makes future research in this area more accessible. We show that the model is computationally tractable, but retains many of the key aspects required to model earthwork and utility costs. Finally, a case study is provided that demonstrates the Pareto front of the bi-objective problem can be computed in reasonable time. This case study compares three different multiobjective optimization algorithms namely, the multiobjective genetic algorithm (GAMOO) (Deb, 2001), the direct multisearch for multiobjective optimization (DMS) (Custdio et al., 2011), and the weighted sum method (WS) (Grodzevich and Romanko, 2006; Marler and Arora, 2010).

The remainder of this paper is organized as follows. In Section 2, the models for both horizontal and vertical alignments are presented. The cost functions are formulated in Section 3. The bi-objective optimization model is provided in Section 4. The numerical experiments performed and their results are reported in Section 5. Finally, Section 6 presents some concluding remarks.

2. Model variables

2.1. The geometric design for horizontal alignment

In our model, a horizontal alignment is composed of tangential segments and circular curves. The horizontal alignment geometry is required to satisfy two criteria: (1) the alignment should satisfy the orientation specified as