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Optimizing horizontal alignment of roads in a specified corridor

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ABSTRACT

Finding an optimal alignment connecting two end-points in a specified corridor is a complex problem that requires solving three interrelated sub-problems, namely the horizontal alignment, vertical alignment and earthwork optimization problems. In this research, we developed a novel bi-level optimization model combining those three problems. In the outer level of the model, we optimize the horizontal alignment and in the inner level of the model a vertical alignment optimization problem considering earthwork allocation is solved for a fixed horizontal alignment. Derivative-free optimization algorithms are used to solve the outer problem. The result of our model gives an optimal horizontal alignment in the form of a linear-circular curve and an optimal vertical alignment in the form of a quadratic spline. Our model is tested on real-life data. The numerical results show that our approach improves the road alignment designed by civil engineers by 27% on average, resulting in potentially millions of dollars of savings.

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1. Introduction

Road design optimization is the problem of finding a curve that minimizes the construction cost while satisfying all of the desired design specifications. The problem is usually divided into three interrelated sub-problems [1]: horizontal alignment optimization, vertical alignment optimization, and earthwork optimization. In typical road design, first a horizontal alignment is proposed and then an associated vertical alignment is optimized considering the earthwork allocations and vertical alignment design constraints.

For a fixed horizontal alignment, the optimization of vertical alignment is a well studied problem [15,16,9,10,6]. Many of the past approaches have modeled the optimization of vertical alignment by way of mixed integer linear programming. This creates a complicated, but deterministic optimization problem that is generally solvable using modern MILP solvers (assuming reasonable road lengths and time allowances) [15]. This implies that given a proposed horizontal alignment, it is possible to evaluate the quality of that alignment in terms of the optimal cost vertical alignment. Which further suggests that it should be possible to have a computer to evaluate and seek an optimal horizontal alignment (in terms of the minimal vertical alignment construction cost). In this paper, we demonstrate the practicality of this idea, and further demonstrate the value of this approach in terms of cost savings for the final road design.

To do this, we formulate the horizontal alignment optimization problem as a bi-level optimization problem. In the inner level, for a fixed horizontal, a vertical alignment optimization problem is solved using the mixed integer linear programming (MILP) from [14] (see Appendix A), which builds on [13–16] and provides a global optimum. The outer level of the problem is solved using a derivative-free optimization algorithm, which gives a local optimum, with the starting alignment being the best one produced by a civil engineer.

The paper is organized as follows: Section 1.1 overviews some of the past research in road design, Section 2 describes basic terminology, Section 3 explains the geometric specifications of a horizontal alignment, Section 4 describes our proposed horizontal alignment optimization models in detail, Section 5 describes the derivative-free optimization solvers we used, Section 6 reports the numerical results for the test problems, and Section 7 summarizes the contributions and highlights some future works.

1.1. Past research in road design

As mentioned, road design is commonly divided into three interrelated sub-problems: earthwork optimization, vertical alignment optimization, and horizontal alignment optimization. Each problem relies on the solution to the sub-problem proceeding it (i.e., vertical alignment optimization requires solving earthwork optimization, and horizontal alignment optimization requires solving vertical alignment optimization). As such, there is a clear hierarchy in terms of problem difficulty.

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Earthwork optimization is perhaps the most established of the three sub-problems. Many studies investigated earthwork allocation and vertical alignment optimization in road design. Hare et al. [16] and de Lima et al. [10] developed two mixed integer linear programming models for earthwork operation in road construction. Unlike Burdett and Kozan [6] who developed a model for the earthwork allocation problem considering earthwork as discrete 3D blocks, in the present paper we use a section-based model, noting that section-based models achieve similar precision as 3D block based model when section lengths are less than 30 m [9].

While vertical alignment optimization is more complicated, it also has a rich research literature. In 2009 Moreb [29] developed a linear programming model combining the vertical alignment and earthwork allocation optimization. In 2010, Koch and Lucet [26] advanced Moreb's model by removing unnecessary errors in slope constraints. More recently, Hare et al. [14] incorporated the vertical alignment in the earthwork allocation model, resulting in a mixed integer linear programming model that can be solved efficiently in practice.

While horizontal alignment optimization is the most complicated problem, it has nonetheless seen a number of approaches. Jong et al. [20,21] developed a horizontal alignment optimization model which was solved by a genetic algorithm. However, the resulting horizontal alignment does not offer any guarantee of (local) optimality. In 2008, Easa and Mehmood [11] developed an optimization model incorporating safety constraints, which were quantified as the expected collisions for an alignment. Although this model guarantees global optimality, the associated vertical alignment cost is not incorporated in the optimization process. In 2009, Lee et al. [28] presented a heuristic based method to optimize the horizontal alignment that works in two stages. In the first stage, the heuristic tries to approximate a piecewise linear alignment and then in the second stage, it refines the solution to make the previously generated piecewise linear alignment compatible with a real road alignment. The solution alignment of the model yields a practical alignment but since a heuristic algorithm was used to solve the model, optimality is not guaranteed [28].

In the literature, a few studies also investigated the problem as a three dimensional alignment optimization problem in which the vertical and horizontal alignments are optimized simultaneously.

Tat and Tao [33] proposed a three-dimensional alignment optimization model, which they solved using a genetic algorithm. Their model considers all of the major constraints in road design. Akay [2] developed a model for three dimensional alignment optimization for forest roads and solved it using a simulated annealing algorithm. Aruga [3] used a tabu search method to optimize three dimensional alignments of forest roads.

A criteria-based decision support system for three dimensional alignment optimization was developed by Jha [17] considering the environmental costs. Jong and Schonfeld [22] presented an evolutionary model for optimizing the vertical and horizontal alignment simultaneously. The previous two models [17,22] were improved in [18] by considering accessibility, proximity, and land-use changes, and further improved in [25] to consider incorporating bridge and tunnel costs.

Cheng and Lee [8] also proposed a heuristic-based model for three dimensional alignment optimization. The heuristic solves the models in three steps: first, it generates a good general horizontal alignment by adding, deleting, or moving the intersection points one by one, then it determines an improved horizontal alignment by adjusting the intersection points based on the previously generated horizontal alignment, and finally, it finds a better three dimensional alignment by tuning the vertical alignment corresponding to the previously obtained horizontal alignment.

Most similar to this work, Kang et al. [24] developed a bi-level optimization model for road alignment design. In the upper level a set of alternative good alignments is generated and in the lower level an alignment is selected from the alternative alignments obtained in the upper level. The model [24] was solved using a genetic algorithm. Recently, Kang et al. [23] also proposed a three dimensional alignment optimization model based on genetic algorithm and geographic information system (GIS).

All of the above mentioned three-dimensional alignment optimization models use heuristic-based algorithms which do not guarantee optimality (or even local optimality), and have no or very weak convergence guarantees.

2. Terminology

Horizontal alignment optimization consists of finding an optimal curve connecting two given end-points within a designated corridor. The ground profile data in a corridor is given at some discrete points, named *data points*, within the specified corridor.

There are two types of data points, namely, *base data points* and *offset data points*. Typically, the base data points are the points along the engineer's original horizontal alignment (however, this is not strictly necessary). The offset data points represent the horizontal displacement from the base data points. The base data points are selected a few units apart between the two end-points along the baseline. Each of the base data points has some associated offset data points in both the left and the right directions, see Fig. 1. A base data point together with the associated offset data points is defined as a *station*. The baseline of a corridor is a curve connecting the base data points (i.e., the dotted curve in Fig. 1). In practice, a baseline is a primarily defined alignment by engineers.

Base data points, offset data points, stations, and baselines are all fixed input data for a given horizontal alignment problem. Ultimately, the horizontal alignment problem is to determine the optimal curve (in terms of vertical alignment and earthwork cost) through those stations, subject to road design constraints.

Each data point within the corridor, either a base data point or an offset data point, has some associated ground profile data. Therefore, for the vertical road profile, we can move vertically up and down for each horizontal data point. The horizontal and the vertical displacements from the baseline make a discrete grid for each station, see Fig. 2. Our goal is to find, for each station, a horizontal offset that generates a horizontal alignment and a vertical alignment which is (locally) optimal.

3. Geometric representation

A horizontal alignment consists of a sequence of circular curves and tangential lines, which are defined by some intersection points and the radius of curvature associated with each intersection point. In Fig. 3, S and E are the start and end points of the alignment, respectively. The intersection points of the alignment are P_1, P_2, and P_3. Each intersection point has a radius of curvature that defines the

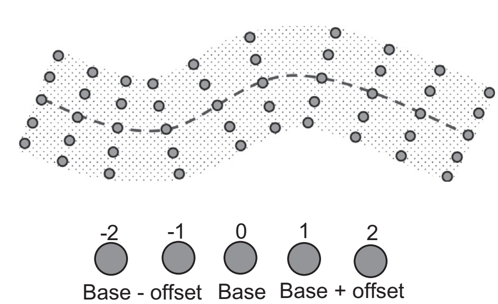

Fig. 1. Corridor of a horizontal alignment.

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