

Bi-objective Road Route Design : End-to-end Optimization Based on BIM

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Abstract. In recent years, the application of BIM (Building Information Modeling) technology has made significant progress in improving design accuracy and work efficiency. However, road alignment design based on BIM faces the challenge of multiple factors. To address this issue, this study proposes a new optimization design framework aimed at simultaneously improving driving safety and reducing road construction costs. The framework adopts an efficient parametric method for road alignment, enabling rapid adjustments and optimizations of the road layout to ensure the reliability and efficiency of the design results.

Keywords: building information model; modeling route design; genetic algorithm; automatic driving simulation; bi-objective optimization parameterization.

1. Introduction

Existing studies [1] have shown that the quality of road alignment design plays a critical role in traffic safety, and there is a clear positive correlation between road design defects and traffic accident rates [2]. However, in the two-dimensional (2D) design model, it is often challenging to thoroughly review the road alignment and adequately consider all potential accident risks [3]. However, the introduction of Building Information Modeling (BIM) technology provides a new solution for 3D road design, offering advantages over traditional 2D methods in various aspects [4].

This study proposes an innovative BIM-based road alignment optimization framework, aiming to optimize the entire road design process by simultaneously considering construction costs and traffic safety. The framework includes a reliable road alignment parameterization method. In addition, the framework incorporates a dual-objective automatic optimization method based on NSGA-II. This method quantitatively evaluates road safety and comfort through vehicle dynamics simulations. By automatically calculating earthwork volumes within the BIM environment, the method can rapidly estimate construction costs. Furthermore, it enables automated data interaction between the BIM environment and external driving simulation software, ultimately facilitating the determination of the optimal road alignment design.

2. Method

This paper proposes a BIM-based route design optimization framework. The core concept of this framework is to utilize BIM technology to construct a parametric model of the road alignment. Through the data interoperability between BIM and external simulation platforms, an end-to-end dual-objective optimization of the road alignment is achieved.

The external simulation platform consists of two main modules: the vehicle driving simulation module and the optimization module. Through data exchange between BIM and external simulation platforms, the optimal dual-objective road alignment plan is calculated, and the optimization results are dynamically updated to the BIM model, completing the forward design of the road route.

2.1 Parametric modeling method of road alignment based on BIM

This end-to-end parametric modeling method proposed in this study directly stores the 3D parametric route as a set of points, achieving a mapping from road features to discrete points.

2.1.1 Level alignment

In horizontal combined curves where the transition curve is a spiral, all the curve elements can be determined by the radius R of the circular curve and the transition segment length L_{Tra} according to the relevant formulas[1]. As a result, a mapping relationship can be established: $f: A = \{R, L_{Tra}\} \rightarrow B = \{P_i, i = 1, 2, \dots, n\}$, where n represents the number of sampling points along the road's horizontal alignment, and n determines the closeness between the simulated model and the actual route. An appropriate value of n ensures that the distance between adjacent points in the set B is approximately 1 meter.

2.1.2 Vertical alignment

Once the horizontal route is determined, the next step is to parametrize the vertical route. In the case of vertical curve combinations, the parameters of all vertical curves and the positions of characteristic points can be determined from the radius R_L of the circular curve and the intersection point coordinates (x_{L1}, y_{L1}) according to the formulas in [5]. As a result, a mapping relationship can be established: $f_L: A_L = \{x_{L1}, z_{L1}, R_L\} \rightarrow B_L = \{P_{L-i}, i = 1, 2, \dots, n_L\}$, where n_L represents the number of sampling points for the road's vertical curve.

Finally, the parameterization results of the horizontal and vertical routes should be coupled to achieve the direct parameterization of the three-dimensional road route.

2.2 Road route estimation

By the proposed parametric method, a set of road elements can generate a complete route. Therefore, it is necessary to construct a quantifiable evaluation model for the alignment, which will serve as the selection criterion and objective function for alignment optimization.

2.2.1 Optimization objective 1: driving safety and comfort

For optimization objective 1, a vehicle driving simulation module is required to interact with BIM in order to achieve the mapping: $f_{01-1}: B = \{P_i = (x_i, y_i, z_i), i = 1, 2, \dots, n\} \rightarrow C_1 = \{(a_x, a_y, a_z, a_L, a_R, a_L, \omega_y)_i, i = 1, 2, \dots, n\}$. Once the set C_1 is obtained, the quantification of optimization objective 1 is further analyzed by calculating the results of the elements within the set.

for optimization objective 1, we propose four evaluation indicators and establish a mapping: $f_{01-2}: C_1 = (a_x, a_y, a_z, a_L, a_R, a_L, \omega_y)_i, i = 1, 2, \dots, n \rightarrow D_1 = K_S, K_Y, K_L, K_C$. Based on the results of set D_1 appropriate weights are assigned to the four indicators, allowing the calculation of the evaluation value for optimization objective $E_{01} = \gamma_1 K_S + \gamma_2 K_Y + \gamma_3 K_L + \gamma_4 K_C$, The smaller the value, the better the road alignment's performance in terms of safety and comfort.

2.2.2 Optimization goal 2: Road construction cost

In the process of achieving optimization objective 2, we establish a mapping relationship from the road alignment to the earthwork fill and cut volumes using the earthwork statistics tools provided by BIM [6], ensuring both efficient earthwork construction and cost control. The mapping relationship is established to enable this $f_{02-1}: B = \{P_i = (x_i, y_i, z_i), i = 1, 2, \dots, n\} \rightarrow C_2 = \{(EWF_i, EWC_i), i = 1, 2, \dots, n\}$. After obtaining the earthwork fill and cut volumes of the road from BIM, the construction cost for optimization objective 2 can be calculated. The construction cost related to the earthwork fill and cut is denoted as E_{Con} , which consists of three components: fill material cost, excavation cost, and material cost. It can be expressed as: $E_{Con} = E_F + E_C + E_M$.

2.3 Road alignment optimization based on NSGA-II

After obtaining optimization objective 1 and optimization objective 2, multi-objective optimization is carried out to find out the Pareto optimal set, and these two objectives are weighted according to the actual engineering requirements. Finally, the optimization results are obtained.

NSGA-II is a widely used genetic algorithm for multi-objective optimization problems. It is based on the principles of evolutionary algorithms, simulating processes such as natural selection, inheritance, and mutation to find the optimal solution to a problem. For multi-objective optimization problems, NSGA-II introduces two key improvements over traditional genetic algorithms: First, it constructs a Pareto non-dominated set to identify and select locally optimal solutions; second, it uses the concept of crowding distance to rank solutions within the same Pareto set, maintaining solution diversity and avoiding premature convergence. As a result, NSGA-II not only effectively distinguishes between different solutions but also ensures that the final solution set has a good distribution and coverage in the objective space.

3. Case study

This study uses the highway construction project in Hailar City as a case study to validate the proposed BIM-based route optimization design framework. In this case study, Civil 3D is used to build the BIM environment, while for vehicle simulation, MATLAB's Automated Driving Toolbox™ [7] is employed.

First, the control points of the road alignment are exported from Civil 3D into a JSON file. Then, using MATLAB scripts, these control points are automatically read and imported into the driving scene simulation module. In the driving scene simulation module [8], the vehicle type and its driving trajectory required for the simulation are defined.

The highway is divided into five sections, and a calculation unit of approximately 5 kilometers in length is selected for detailed computation to avoid repetitive calculations for the entire highway.

Table 1 Deterministic part of horizontal alignment

	P_{Start1}	$P_{Intersection-1}$	$P_{End1(Start2)}$	$P_{Intersection-2}$	P_{End2}
North (x)	132,465.659	134,423.744	133,853.043	133,282.341	134,566.485
Earth (y)	296,452.295	296,626.845	265,846.291	265,948.215	264,846.152

Table 2 Deterministic part of vertical alignment

	$P_{L-Start}$	$P_{L-Intersection}$	P_{L-End}
Earth (x)	132,465.659	$x_L \in [560,1060]$	134,566.485
elevation (z)	69.818	$z_L \in [65,70]$	65.928

* All units in the table are in meters

Based on the information in Table 3, we implemented the parameterization of the road alignment using the method described in Section 2.1, which is the mapping process. $f_s: A_s = \{R_1, L_{Tra1}, R_2, L_{Tra2}, x_L, z_L, R_L\} \rightarrow B = \{P_i = (x_i, y_i, z_i), i = 1, 2, \dots, n\}$ Given the 7 parameters in the set, the road alignment can be uniquely determined.

The initial set A_s is set as $\{R_1 = 1300, L_{Tra1} = 110, R_2 = 1300, L_{Tra2} = 100, x_L = 900, z_L = 67, R_L = 20,000\}$, we selected the Sedan model as the simulation vehicle and set the vehicle's speed to a fixed 100 km/h. The simulation time step was set to 0.01 seconds. Finally, we ran the simulation model and obtained the variation of the INS sensor data with respect to the mileage.

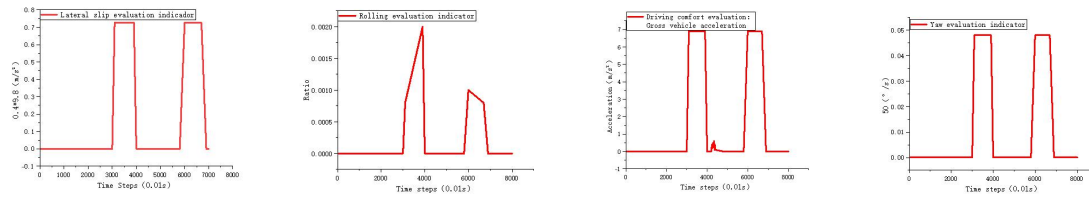


Figure 1: Variation of Driving Safety and Comfort Indicators with Mileage.

Based on the method described in Section 2.2.1, we calculated the final evaluation results for each of the four evaluation elements and computed the optimization objective 1 E_{01} using the same set of weights : $E_{01} = K_S + K_L + K_Y + K_C = 0.3315 + 0.000332 + 0.0164 + 0.9631 = 1.3113$

From the evaluation results of objective function 1, we can observe that the road's safety condition is good and E_{01} is mainly controlled by driving comfort.

Next, Based on the actual project conditions, we discounted labor costs, machinery costs, and other expenses. the reference formula for calculating optimization objective 2 is: $E_{Standard} = E_C + E_F + E_M = 1348.416 + 3163.845 + 0 = 4512.261$ (RMB)

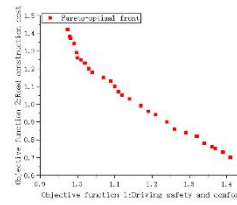
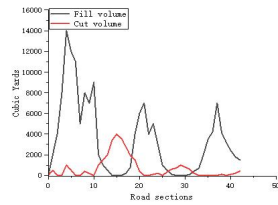


Figure 2: Earthwork Volume of the Initial Route Calculated by Civil 3D.

Figure 3: Pareto Front of the Pareto-Optimal Solutions After 100 Iterations.

Afterward, we used the NSGA-II algorithm to optimize the road alignment, achieving the optimal results for both objective functions. we calculated the final fitness score for each solution in the Pareto-optimal set. The final scores for each solution are displayed. Ultimately, we obtained the optimal solution for the road alignment parameters. $A_{S-Best} = \{R_1 = 1987, L_{Tra1} = 152, R_2 = 1520, L_{Tra2} = 148, x_L = 1300, z_L = 66.592, R_L = 17000\}$, The actual road alignment parameters for the Hailaer Highway segment are as follows : $A_{S-Best} = \{R_1 = 1987, L_{Tra1} = 152, R_2 = 1520, L_{Tra2} = 148, x_L = 1300, z_L = 66.592, R_L = 17000\}$

After completing the calculations for the five units, we compared the actual road alignment with the route optimized using the dual-objective optimization method, Additionally, the overall performance of the framework improved by 6.6%.

4. Conclusion

This study established an end-to-end optimization framework for dual-objective road alignment design based on Building Information Modeling (BIM), By adopting the Non-Dominated Sorting Genetic Algorithm II (NSGA-II), we implemented an automated dual-objective optimization process that considers both the construction cost of the road and the safety and comfort of driving as a joint objective function. Simultaneously, we proposed an efficient and reliable road alignment parameterization method, This new parameterization method greatly facilitates the data flow between BIM and external environments.

Taking the Hailaer Highway as an example, we applied the BIM-based optimization framework for route design in five sections of the project. The results showed that, under the dual objectives of driving safety and construction economy, the route designed using this method improved efficiency

by 6.6% compared to traditional design methods. This case study fully demonstrates the practicality and effectiveness of the proposed BIM-based route optimization framework.

Acknowledgementse

This research was funded by the Key Research and Development Program of Sichuan Provincial Department of Transportation (2023-A-10).

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