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Research Article

Safety-Based Optimization Model for Highway Horizontal Alignment Design

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The construction cost and crash cost of the highway are contradictory, but there is an optimal balance between them. This study focused on the best balance point by microadjusting the highway alignment design using the optimization theory. A multiobjective optimization method was proposed to optimize the highway horizontal alignment design considering the economy and safety. The optimization model includes three main objective functions which are the economic objective function, safety objective function, and position constraint objective function. Constraints were established for the optimization model following the corresponding specifications, such as constraints for the three elements in the design unit, continuous constraints for adjacent alignments, constraints for the location of horizontal alignment, and constraints for speed coordination. Two scenarios were considered to verify the effect of the optimization model. One scenario considered the constraints of the intermediate control points, and the other does not. In addition, two cases were analyzed. One is optimization for a horizontal alignment design unit. Another one is for a highway segment including four design units. The parallel genetic algorithm was used to solve the optimization model. Case study results indicate that the optimization model could help to improve the safety and economics of highways. In addition, the proposed optimization model could reduce much more redundant debugging work for the designer and reduce the influence of the designer's subjectivity.

1. Introduction

The existing optimization methods for highway geometry design focus on optimizing highway route selection assisted by computer. The core part is to establish an automatic mathematical model. Thus, existing optimization methods mainly focus on highway route optimization. Liu et al. established an optimization method for transportation schemes by using the comprehensive weight and Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) model [1]. Zhao et al. proposed an approach to managing highway alignment in the context of a larger landscape by integrating building information modeling (BIM) and geographic information system (GIS) capabilities [2]. Maji and Jha proposed a multiobjective evolutionary algorithm framework for highway route planning to simultaneously optimize the environmental, economic, and social impacts along with the route cost [3]. Zhang et al. introduced the spatial data analysis technology of geographic information system (GIS) and intelligent evolutionary algorithm into highway route selection process to fully consider the complex geographical environment in the permafrost region of Qinghai-Tibet Plateau [4]. Kang et al. proposed a new bilevel highway route optimization model to best improve the existing roadway system while optimizing the alternatives' alignments on the basis of geometric, cost, and operational considerations [5]. The related researches are usually suitable for the preplanning, prefeasibility, and feasibility stage of a highway construction project. However, they are normally not suitable for the preliminary design and construction drawing design stage.

There is also much research on highway alignment optimization. For example, Jha and Schonfeld have also presented a model for highway alignment optimization integrating a GIS with genetic algorithms. The model examined the effects of various costs on alignment selection and explored the optimization in constrained spaces [6]. Yang et al. proposed a hybrid multiobjective genetic algorithm to examine the tradeoffs among various objectives that represent possibly conflicting interests of different stakeholders. Their model utilized designers' knowledge about the preference of decision-makers and aimed to search for a set of Pareto optimal solutions with an acceptable level of diversity [7]. Kim et al. developed a method using a genetic algorithm for optimizing intersections within highway alignment optimization processes [8]. Kang and Schonfeld developed a prescreening and repairing method for efficiently searching highway alignments [9]. Li et al. formulated highway alignment optimization as a network problem and proposed a bidirectional searching strategy in dynamic programming [10]. Lee et al. presented an optimization heuristic to solve the horizontal alignment of a highway segment. The iterative heuristic works have two stages and both stages used a mixed-integer program (MIP) to ensure that the piecewise linear line crosses the control areas and avoids the restricted ones [11]. Jong et al. proposed an approach integrating geographic information systems (GIS) with genetic algorithms (GAs) for optimizing horizontal highway alignments between two given endpoints [12]. Zhang et al. established a multiobjective optimization model to solve the alignment design problem considering both economic and environmental objectives. They used the particle swarm optimization algorithm to seek nondominated solutions [13]. Kang et al. presented an intelligent optimization tool that assists planners and designers in finding preferable highway alignments. It integrates genetic algorithms with a geographic information system (GIS) for optimizing highway alignments [14]. The commonly used optimization methods for highway alignment optimization mainly are the network optimization method [1, 6], dynamic programming method [10, 15, 16], mixed-integer programming method [17, 18], genetic algorithm [6–8, 12], multiobjective optimization method [3, 7, 13], and optimization based on GIS [2, 6, 12, 14]. From the basic literature review above, most of the research work for highway alignment optimization mainly prefers multiobjective optimization method for optimizing highway alignment and prefers genetic algorithm for searching for the optimal solution. However, most of them are still mainly focused on highway alignment optimization in the macrorange. In other words, it is basically like the optimization for highway route selection. The optimization design focusing on much more details of highway horizontal design elements is more important and helpful for the highway designers. It is worth noting that Casal et al. have tried to conduct the research work for more detailed highway alignment optimization. They presented a general formulation for optimization of horizontal road alignment considering more details about the tangential segments, circular curves, and transition curves. The optimization model mainly considered the cost of the road as an objective function [19]. In this case, this study tries to propose an optimization method to micro-adjust the horizontal alignment design of the highway.

Safety performance has been paid much more attention in highway alignment design [9, 20–22]. Easa and Mehmood presented a new substantive-safety approach for the design of horizontal alignments considering the minimum design requirements and actual collision experience [20]. Li et al. described a method for considering both traffic safety risks and the associated cost burden related to the appropriate planning and design of a mountainous highway [21]. Yue and Wang conducted a simulation research work and established an optimization design method for a combination of a steep slope and sharp curve sections based on the analysis of vehicle driving stability [22]. The research work [23] conducted a simulation test and collected a total of 12800 traffic accident records to identify significant risk factors and explore the influence of different combinations of significant risk factors on roadside accidents. Based on this, they applied the path analysis to investigate the importance of the significant risk factors and established a probability prediction model of roadside accidents using the Bayesian network analysis.

In addition, as mentioned above, the cost of the road is a very important factor for horizontal alignment design. The construction costs and crash costs of the road constitute the total costs of the road. The crash costs are commonly used to quantify and compare the safety of various design alternatives. Sometimes, the crash costs can be called comprehensive crash costs because they include both economic costs (e.g., medical bills, lost wages, and so on) and quality-adjusted life years which are commonly thought of as the cost of pain and suffering [24]. The crash cost is typically broken down by the crash severity. As we know, the improvement of the road design is beneficial to improving the safety of the road and decreasing crash costs of road. It however will greatly increase the construction costs of roads. Therefore, the construction costs and crash costs of a road are contradictory, but there is normally an optimal balance between them. This study aims to find the best balance point between them.

A multiobjective optimization method was proposed to optimize the highway horizontal alignment design considering the economy and safety in this study. Specifically, the established multiobjective optimization model includes three main objective functions which are the economic objective function, safety objective function, and position constraint objective function. In addition, some constraints were established for the multiobjective optimization model following the corresponding specifications, such as constraints for the three elements in the design unit, continuous constraints for adjacent alignments, constraints for the location of horizontal alignment, and constraints for speed coordination. To verify the effect of the established optimization model, two scenarios were considered here. One scenario considered the constraints of the intermediate control points; the other does not. In addition, two cases were analyzed here. One is optimization for a horizontal alignment design unit. Another one is for a real highway alignment including four design units. A genetic algorithm is used to find the Pareto optimal solution. Specifically, the parallel selection method for the genetic algorithm was used to solve the optimization model. Hopefully, the proposed optimization method could reduce much more redundant debugging work for the designer and reduce the influence of the designer's subjectivity.

2. Materials and Methods

Tangent, circular curve, and transition curve are called three elements of the horizontal alignment of modern roads. Therefore, road horizontal alignment design is to choose and combine the three elements and form a horizontal alignment. The main task of the horizontal alignment design is to determine the tangent intersection points, the circular curve, and the transition curve. Once the parameters of these elements are determined, the centerline of the road is completely determined. In this study, the combination of a tangent and a curve was recognized as a design unit for calculation. That is, each design unit starts from the tangent-to-curve (TC) to the TC of the next curve. Based on the calculation of each design unit, the coordinate of the point of intersection (PI), radius, and parameters of the transition curve for each curve can be obtained, and the centerline of a road can be finally designed. Therefore, the design variables of the optimization model can be expressed as $V = (V_1, V_2, \cdots, V_N)$, $V_i = (PI(i)(x_i, y_i), R_i, SL_{Ai}, SL_{Bi}, e_i)$. V_i represents the i_{th} design unit; $PI(i)(x_i, y_i)$ represents the i_{th} tangent intersection point with the coordinate of (x_i, y_i); R_i represents the curve radius of the i_{th} design unit; SL_{Ai} and SL_{Bi} represent transition length ahead and back for the i_{th} design unit, respectively. α_i represents tangent deflection angle for the i_{th} design unit.

2.1. Objective Function

2.1.1. Economic Objective Function. The road construction costs can be reduced by determining the construction standards reasonably, optimizing design, and decreasing materials consumption. The minimization of construction costs is important for each engineering construction. Road cost is usually composed of the costs related to the road and users. The cost related to the road usually includes construction cost, maintenance cost, and operation cost. The cost related to road users usually include fuel costs and travel time costs. This study mainly focused on the optimization of horizontal alignment design based on safety performance. Hence, only the construction cost was considered here. In addition, the land demolition cost, earthwork cost, and other engineering costs have been already considered to determine the control points and road alignment. The optimization of road horizontal alignment design in this study focused on micro-adjustment. In short, this study mainly focused on the optimization of one design unit mentioned above. Therefore, this study supposes that the construction cost is mainly related to the length of each design unit. That is, the longer the road design unit, the higher the construction cost of the design unit. Thus, the objective function of economic cost for one design unit is simplified as follows:

$$\min f_1(V) = L \times C_C, \tag{1}$$

where L is the length of the design unit; C_C is the unit cost of construction (in RMB).

Suppose that the designed road includes N design units and the length of a curve in the i_{th} design unit can be calculated according to

$$L_i = R_i \times \alpha_i + \frac{SL_{Bi}}{2} + \frac{SL_{Ai}}{2}, \tag{2}$$

where L_i represents the length of the i_{th} design unit; R_i represents the curve radius of the i_{th} design unit; SL_{Ai} and SL_{Bi} represent transition length ahead and transition length back for the i_{th} design unit, respectively. α_i represents tangent deflection angle for the i_{th} design unit. Figure 1 shows a schematic diagram of a horizontal alignment design unit.

The objective function of the economic cost of the whole design road can be expressed as follows:

$$\min f_1(V) = \sum_{i=1}^{N} \left(L_i + L_{Ti,i+1}\right) \times C_C, \tag{3}$$

where L_i is the length of the i_{th} design unit, $L_{Ti,i+1}$ is the distance between $PI\ (i)$ and $PI\ (i+1)$, and

$$L_{Ti,i+1} = T_{i,i+1} + T_{Bi} + T_{A(i+1)} = \sqrt{\left(x_{i+1} - x_i\right)^2 + \left(y_{i+1} - y_i\right)^2}, \tag{4}$$

where $T_{A(i+1)}$ is tangent length ahead of the $(i+1)_{\mathrm{th}}$ design unit; T_{Bi} is tangent length back of the i_{th} design unit; $T_{i,i+1}$ is the tangent length between the i_{th} design unit and the $(i+1)_{\mathrm{th}}$ design unit. (x_i, y_i) and (x_{i+1}, y_{i+1}) represent coordinate of the $PI\ (i)$ and $PI\ (i+1)$, respectively. Figure 2 is a schematic diagram of a horizontal alignment design.

2.1.2. Safety Objective Function. Road designers generally believe that the designed roads are safe for driving when the design meets the specifications. However, although each design unit meets the requirements of the specification, the combination of all design units may still be hazardous to drive. Traffic accident statistics show that the radius and length of a horizontal alignment are the main factors of road safety. The road designer normally designs the road alignment by considering the design code, terrain constraints, and engineering cost. However, it can only ensure that the designed alignment meets the requirements of the specification, but the safety level of the road cannot be predicted. This study also considered safety as one of the objective functions and investigated how to design the safest horizontal alignment. The objective function considering safety is expressed by equation (5), where $S(V)$ is road safety function indicating the safety level of the road.

$$\min f_2(V) = S(V). \tag{5}$$

There are commonly two ways to evaluate road safety; one is based on the direct evaluation index, such as accident number or accident rate; another one is based on the indirect

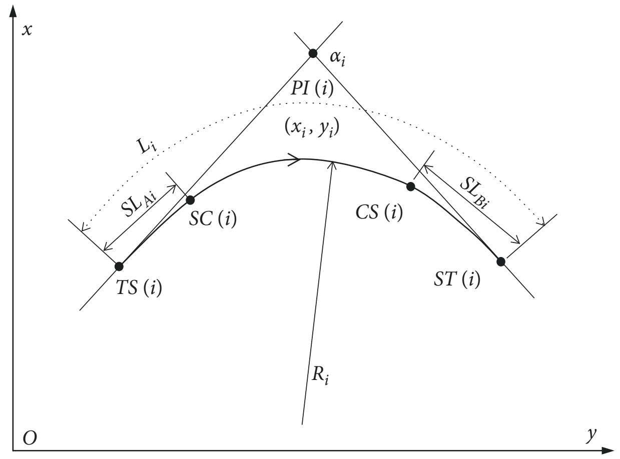

Figure 1: Schematic diagram of a horizontal alignment design unit.

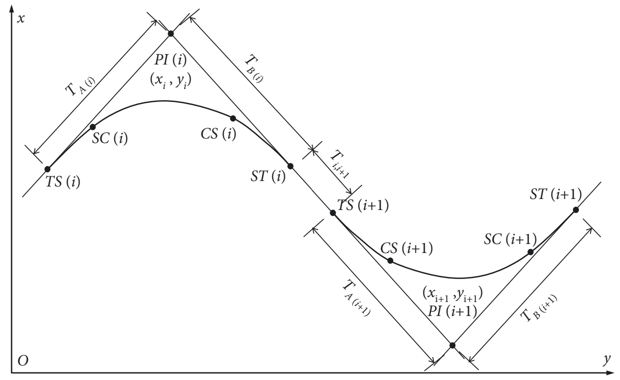

Figure 2: Schematic diagram with two horizontal alignment design units.

evaluation index, such as risk or speed coordination. The accident rate is commonly used for evaluating safety. Thus, the optimization function could be the lowest annual average accident rate which can be predicted using an accident predictive model for the newly designed road. In this way, the safety of a road could be described as the sum of the safety of each design unit. Therefore, the safety function (equation (5)) could be expressed as

$$\min f_2(V) = \sum_{i=1}^{N} AC_i, \tag{6}$$

where AC_i represents the annual average number of accidents that occurred in the i_{th} design unit.

2.1.3. Accident Prediction Regression Model. According to the existing accident prediction models, such as Persaud and Dzbik Model [25], Park and Fitzpatrick Model [26], Safety Performance Function in Highway Safety Manual [27], and other previous research work [28, 29], eight variables were chosen normally to establish average accident-number regression model (see equation (7)). They are length(L), annual average daily traffic volume ($AADT$), speed limit (V_{lim}), the radius of the curve (R), superelevation (E), longitudinal slope (G), lane width (W_l), and right shoulder width (W_s)

$$AC = f\left(L, AADT, V_{\mathrm{lim}}, R, E, G, W_l, W_s\right). \tag{7}$$

The stepwise autoregressive method was used to perform significant interpretation on the eight variables mentioned above. The stepwise process analysis in SAS software was used to calculate the statistic and the corresponding p-value of each explanatory variable. And the significance test level of the variable was set to 0.10. Take the two-lane highway in the hilly area as an example, and four variables, i.e., L, $AADT$, V_{lim}, and R, were selected as the significant variables to establish the traffic accident prediction model for the curved sections. The accident prediction model based on the negative binomial regression model was established as follows:

$$\begin{aligned}\ln(AC) = b_0 + b_1 \times R + b_2 \times V_{\mathrm{lim}} + b_3 \times \ln(L) + b_4 \\ \times \ln(AADT),\end{aligned} \tag{8}$$

where $b_0, b_1, b_2, b_3,$ and b_4 are coefficients. Considering the driving failure probability which includes failure probability of sideslip, rollover, and stopping sight distance, the accident prediction model indicated by equation (8) can be transformed to a new model as

$$\begin{aligned}\ln(AC) = b_0 + b_1 \times R + b_2 \times V_{\mathrm{lim}} + b_3 \times \ln(L) + b_4 \\ \times \ln(AADT) + b_5 \times P_{nc},\end{aligned} \tag{9}$$

where b_5 is coefficient and P_{nc} is driving failure probability. GENMOD (generalized linear model) process in SAS was used here to fit the negative binomial regression model, and the Akaike Information Criterion (AIC) was used to evaluate the complexity and fitting goodness of the estimated model. A total of 409 accident records from the Dayun highway in Shanxi Province in China and two years (2006–2008) of traffic accident records of Washington State, collected from the HSIS database, were obtained and used to fit the regression model. Based on the obtained data, the estimation results of the regression coefficients and the overall fitting effect of the model for a two-lane highway are shown in Table 1. It is worth noting that the driving failure probability in this study mainly refers to the probability of the vehicle slipping or rolling over.

Based on the estimation results, the accidents predictive model could be expressed as

$$\begin{aligned}AC = e^{-9.7771} \times L^{0.6306} \times AADT^{0.7630} \\ \times e^{\left(-0.0021\times R + 0.0268\times V_{\mathrm{lim}} + 1.5164\times P_{nc}\right)}.\end{aligned} \tag{10}$$

Thus, the objective function should be

$$\begin{aligned}\min f_2(V) = \sum_{i=1}^{N} AC_i = \sum_{i=1}^{AC_i} e^{-9.7771} \times L_i^{0.6306} \times AADT_i^{0.7630} \\ \times e^{\left(-0.0021\times R_i + 0.0268\times V_{\mathrm{lim}}(i) + 1.5164\times P_{nc}(i)\right)}.\end{aligned} \tag{11}$$

AC_i denotes the annual average number of accidents that occurred in the i_{th} design unit. L_i is the length of the i_{th}

Table 1: Estimation results of the prediction model considering driving failure probability.

Coefficients	Estimated value	Standard error	p-value	Regression coefficients
Intercept	−9.7771	2.1960	<.0001	Deviance = 88.8588
R	−0.0021	0.0008	0.0115	Deviance/DF = 1.1848
Lim	0.0268	0.0146	0.0664	Scaled deviance = 81.0000
L	0.6306	0.2148	0.0033	Scaled deviance /DF = 1.0800
AADT	0.7630	0.1726	<.0001	Pearson chi-Square = 88.8588
P_{nc}	1.5164	0.6827	0.0264	Pearson chi-Square/DF = 1.18
L	0.6579	0.1937	0.0007	Log Likelihood = −118.6843
AADT	0.5615	0.1645	0.0006	**AIC = 247.3686**
P_{nc}	2.0149	0.6036	0.0008	

AIC in Table 1 denotes the Akaike Information Criterion.

design unit, m, $AADT_i$ is the annual average daily traffic volume in the i_{th} design unit, and it can be obtained based on predicted traffic volume for the new road; R_i is the radius of the circular curve in the i_{th} design unit; $V_{\text{lim}}(i)$ is speed limit in the i_{th} design unit and the design speed can be used instead; and $P_{nc}(i)$ is the failure probability of driving in the i_{th} design unit.

2.1.4. Position Constraint Objective Function. It is usually desirable to design the geometry alignment as close as possible to the control points. To keep the designed alignment as close as possible to the control points, P_i, the objective function can be expressed as follows according to [30].

$$\min f_3(V) = \sum_{i=1}^{M} |W_i|, \tag{12}$$

where W_i is the offset from a control point P_i to the designed horizontal curve (see Figure 3). Following the direction of the curve, making a line crossing the point P_i and intersecting at the point Q_i, then $W_i = \overline{Q_i P_i}$; when point P_i locates at the right of the horizontal curve, $W_i \geq 0$, $i = 1, 2, \cdots, M$, and M is the total number of control points.

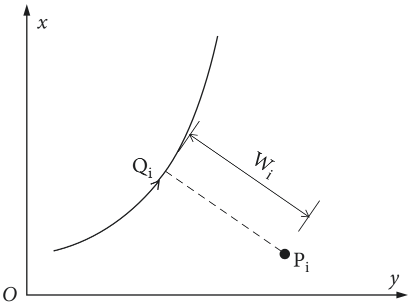

Figure 3: Definition of offset from control point to designed horizontal curve.

2.2. Constraints. The constraints mainly considered the requirements of the design specifications, the requirements of the control points, and other constraints, such as linear coordination and speed coordination.

2.2.1. Constraints for Elements in the Design Unit
(1) Constraint for the *Radius of Circular Curve*

$$R_{\min} \leq R_i \leq R_{\max}. \tag{13}$$

The radius of the circular curve should be adapted to the design speed. The China technical standard of highway engineering (JTG B01-2014) [31] gives the minimum and maximum for the radius of the circular curve in highway geometry design.

(2) Constrain for Parameters of Transition Curve. It is empirically shown that when the parameters of the transition curve meet the following conditions, the designed horizontal curve will be visually coordinated and smooth.

$$\begin{aligned} \frac{R_i}{3} &\leq S_{Ai} \leq R_i, \\ \frac{R_i}{3} &\leq S_{Bi} \leq R_i, \end{aligned} \tag{14}$$

where S_{Ai} and S_{Bi} represent the parameter of the ahead transition curve and back transition curve in the i_{th} designed unit. Also, according to the China technical standard of highway engineering (JTG B01-2014) [31], the minimum transition curve should meet the requirements as equations (15) and (16), where $L_{\min}^{s}$ represents the minimum length of the transition curve allowed by the design specification.

$$SL_{Ai} \geq L_{\min}^{s}, \tag{15}$$

$$SL_{Bi} \geq L_{\min}^{s}. \tag{16}$$

(3) Constrain for the Length of the Horizontal Curve. The minimum length of the horizontal curve should meet the requirement as follows and $L_{\min}$ represents the minimum length of each horizontal curve allowed by China JTG B01-2014 [31].

$$L_i \geq L_{\min}. \tag{17}$$

2.2.2. Continuous Constraints for Adjacent Alignments. In Figure 4, (x_i, y_i) and (x_{i+1}, y_{i+1}) represent coordinate of $PI\ (i)$ and $PI\ (i+1)$, respectively. $(x_{TS}(i), y_{TS}(i))$ and $(x_{ST}(i+1), y_{ST}(i+1))$ represent the coordinates of the

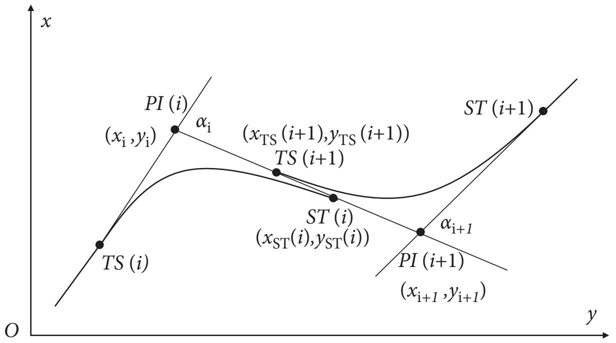

Figure 4: Schematic diagram of discontinuities between two adjacent alignments.

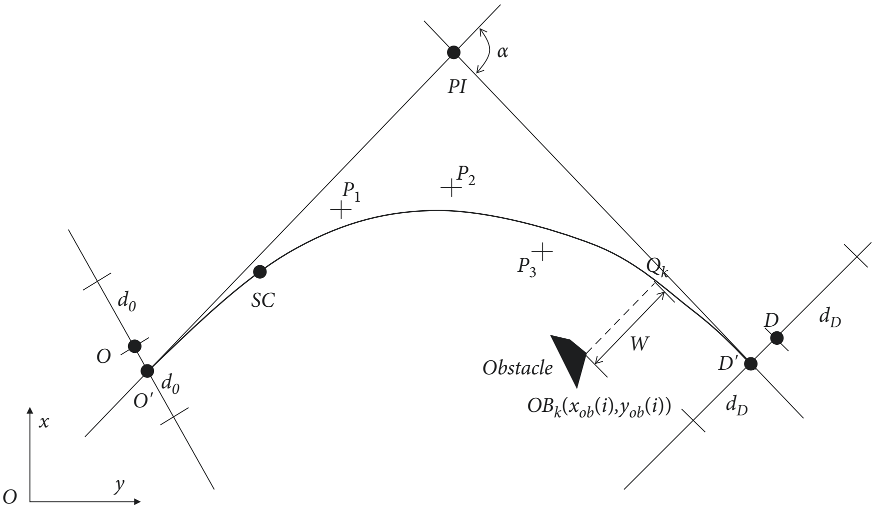

Figure 5: Schematic diagram for location constraint of horizontal alignment.

tangent to the curve (TS) in the i_{th} design unit and the curve to tangent (ST) in the $(i+1)_{\text{th}}$ design unit, respectively.

To avoid the discontinuities of two adjacent alignments, the designed horizontal curve should meet the requirement as follows.

$$\begin{aligned}&\text{IF } x_{i+1} > x_i \text{ THEN } x_{TS}(i+1) < x_{ST}(i)\\&\text{ELSEIF } x_{i+1} < x_i \text{THEN } x_{TS}(i+1) > x_{ST}(i).\end{aligned} \tag{18}$$

2.2.3. Constraints for the Location of Horizontal Alignment. In Figure 5, $O'(x_{O'}, y_{O'})$ and $D'(x_{D'}, y_{D'})$ are the start point and endpoint in one design unit, respectively. $O(x_O, y_O)$ and $D(x_D, y_D)$ represent the control points corresponding to the start point and endpoint of a design unit. Suppose the start point should be within the distance of d_O from the control point O. Similarly, the endpoint should be within the distance of d_D from the control point D; thus,

$$\begin{aligned}\text{DIS}(O', O) &< d_O,\\ \text{DIS}(D', D) &< d_D.\end{aligned} \tag{19}$$

DIS is a function to find the distance between two points. Suppose one obstacle locates nearby the designed horizontal alignment (see Figure 4) and the distance between the obstacle and the designed horizontal alignment should not be less than the offset from the obstacle to the curve, i.e.,

$$\text{DIS}(OB_k, Q_k) \geq W, \quad k = 1, 2, \cdots, K. \tag{20}$$

2.2.4. Speed Coordination Constraint. The speed coordination constraint normally considers two aspects. One is the consistency between the driving speed and the design speed; it could be indicated by the difference between the design speed and the driving speed of the same road section. Another one is the coordination between adjacent road sections. The constraint for good speed coordination can be expressed as equations (21) and (22).

$$\left|v_{85}^{i-1} - v_{85}^{i}\right| < CR, \tag{21}$$

$$\left|v_{85}^{i} - v_d\right| < CR, \tag{22}$$

where *CR* is the judging criteria that can be obtained from [31]. v_{85}^{i} is driving speed which can be obtained from the speed predictive model used in [31].

2.3. Solution Based on Genetic Algorithm

2.3.1. Genetic Algorithm. A genetic algorithm (GA) is a search-based optimization technique following the concepts of natural selection and genetics. It is frequently used to find optimal or near-optimal solutions to difficult problems [32, 33]. In GA methodology, the solution of an optimization problem involves a stochastic search of the solution space using chromosomes that represent the parameters being optimized. Gene is an integer within chromosomes and has a decimal value between 0 and 9. The advantage of the decimal representation is that it allows a wider range of possible values in smaller chromosomes and is particularly suitable for both model and design optimization [32]. For the optimization procedure, an initial population of chromosomes is firstly generated at random and then decoded to obtain the corresponding parameters. Secondly, a simulation is run to obtain results for each set of parameters based on a cost function. Thirdly, find the cost values and sort them into ascending order along with the corresponding chromosomes. The smallest cost values are chosen as the best and are then subjected to operations involving reproduction, crossover, and mutation. The reproduction process is a rank-based selection process and allows only the elite chromosomes to proceed to the next iteration. The crossover process produces two new chromosomes, and the procedure is repeated until there is sufficient offspring to replace most of the present population that has the worst cost values. The mutation process provides a random element within the GA search process so that more of the search space is considered [32].

GA has various advantages which have made them immensely popular. For example, it does not require any derivative information and is faster and more efficient as compared to the traditional methods. GA can optimize both continuous and discrete functions and also multiobjective problems. In addition, it has very good parallel capabilities and is useful when the search space is very large and there are many parameters involved. Therefore, GA is widely applied for random searching and optimization and is one of the most promising computing methods. To find the Pareto optimal solution for solving multiobjective problems, there are several common methods based on genetic algorithms, such as weight coefficient transformation method, parallel selection method, shared function method, mixed-method, etc. [33, 34].

2.3.2. Parallel Selection Method. The parallel selection method for a genetic algorithm is also called a parallel genetic algorithm. It uses multiple genetic algorithms to solve a single task [29]. All the used algorithms try to solve the same task. After finishing their job, the best individual of every algorithm is selected. Then the best of them is selected and this is the solution to a problem. It is worth noting that this is one of the most popular approaches to parallel genetic algorithms. In this method, those genetic algorithms do not depend on each other, and they run in parallel [35, 36]. Thus, it can take advantage of a multicore CPU. In addition, each algorithm has its own set of individuals who may differ from individuals of another algorithm, because they may have different mutations and crossover histories. It is worth noting that the parallel genetic algorithm could also use two independent algorithms to improve its performance. In fact, it is the same as the parallel genetic algorithm using dependent algorithms mentioned above. The difference is the way individuals are selected for mutation and crossover. This study used the parallel genetic algorithm using the dependent algorithms mainly because the latter parallel genetic algorithm needs much higher computer performance.

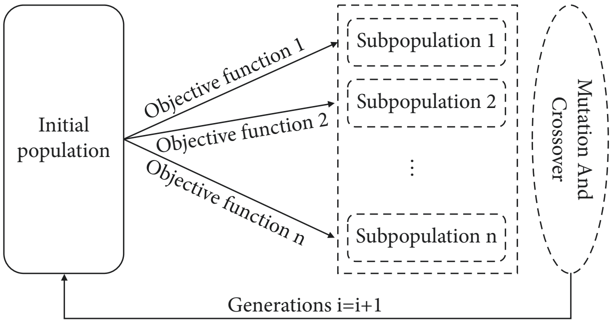

Figure 6: Genetic algorithm for parallel selection.

Table 2: Assumed parameters for the genetic algorithm.

Variables	Values
Chromosome length (L_C)	18
Initial population (P_I)	100
Crossover probability (P_C)	0.7
Mutation probability (P_M)	0.04
Terminal evolutionary generations (T)	100

The parallel selection method includes the following four steps: first, dividing all the individuals in the initial population into subpopulations according to the subobjective functions (see Figure 6); second, assigning each subpopulation to the corresponding objective function; third, calculating each subpopulation independently and selecting individuals with high adaptability to form a new population; fourth, combining these new populations into an integrated population and conducting crossover and mutation. And then generate a complete next-generation population. Based on the iterative process, the Pareto optimal solution can finally be obtained.

The parameters for the genetic algorithm based on the parallel selection method are assumed in Table 2.

Based on the genetic toolbox embedded in MATLAB, programming was conducted to solve a multiobjective optimization model based on the genetic algorithm. Figure 7 shows the flow diagram of the genetic algorithm using the parallel selection method.

3. Results and Discussion

3.1. Optimization Design of Single Horizontal Alignment Design Unit. As mentioned above, a complex road alignment could be formed by several horizontal alignment design units through different combinations. Therefore, the optimization model could be simplified to an optimization

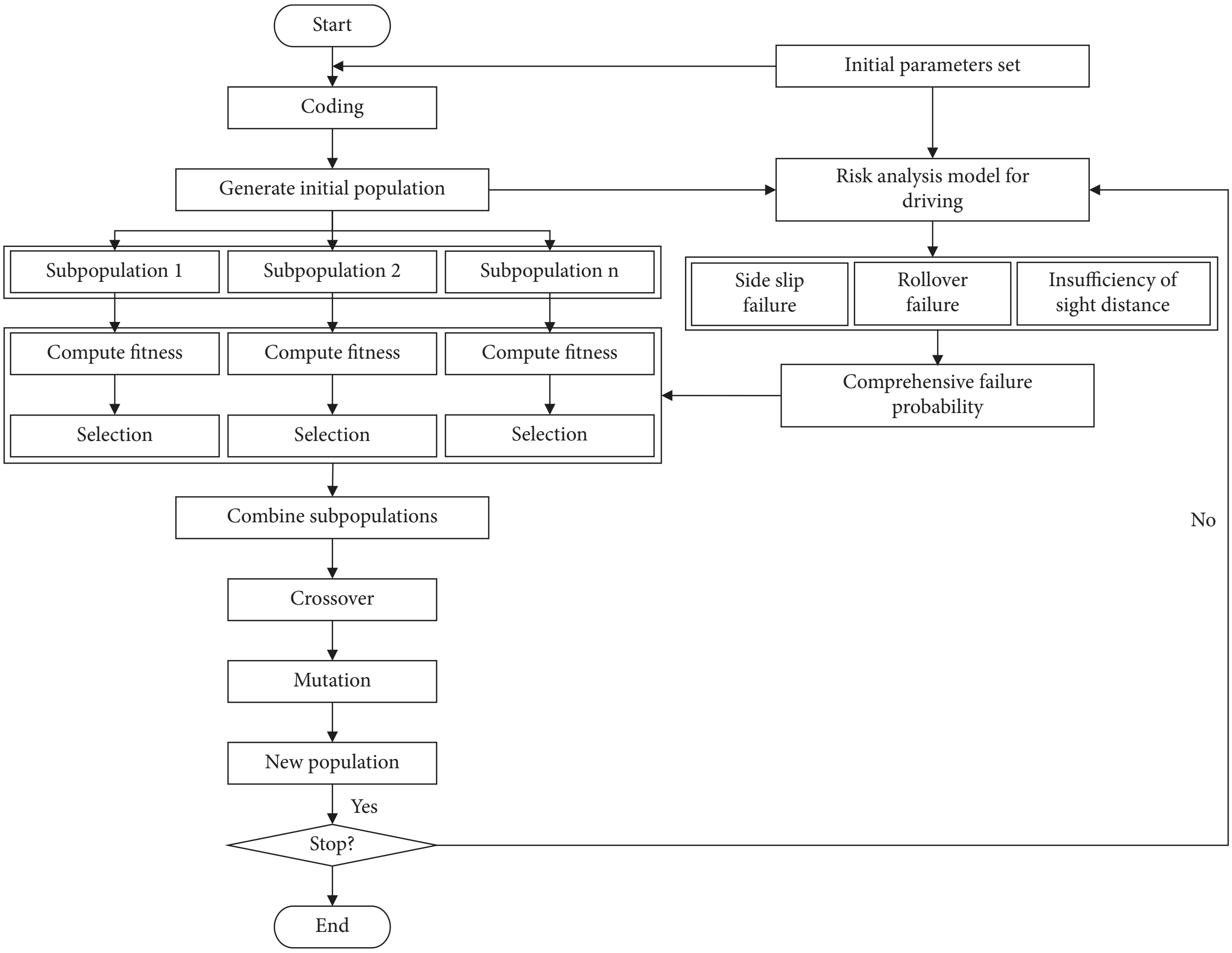

Figure 7: Flowchart for parallel selection method.

model for a single horizontal alignment design unit when the unit number equals 1. Thus, the optimization problem becomes a specific problem which is how to determine the optimal values, such as the radius of the curve, parameters of the transition curve, and superelevation for a designed speed. In this case, the designed horizontal curve not only meets all the requirements of the specifications but is also more economic and safer for driving.

This study took a design for a two-lane road as an example and made some assumptions about the variables used in the established model above. The details for the assumption could be found in Table 3.

Table 3: Assumed parameters for the genetic algorithm.

Variables	Values
Design speed (v_d)	60 km/h
Annual average daily traffic volume (AADT)	2000 pcu
Lane width (W_L)	3.5 m
Shoulder width (W_S)	3 m
Roadside guardrail width (W_G)	1 m
Unit road construction cost (C_U)	1

In this case, the economic optimal problem could be simplified to find the shortest length of the design unit. The safety objective function used the accident prediction model considering the driving failure probability mentioned above. The vehicle type is set to a truck and the road pavement condition is set to wet. The driving speed is obtained based on the speed predictive model (see equation (23)).

$$v_{85} = \frac{94.398 - 3188.656}{R}. \tag{23}$$

Assume that the coordinate of the start point and endpoint in the single horizontal alignment design unit is $O'\,(x_{O'}, y_{O'})$ and $D'\,(x_{D'}, y_{D'})$, respectively, and the range for the start point is $0 \leq x_{O'} = y_{O'} \leq 10$. Two situations were considered here. One is the optimization design without considering the constraint of intermediate control points. The other one is optimization design with the consideration of the constraint of intermediate control points.

3.1.1. *Optimization Design without considering Constraint of Intermediate Control Points*

(1) Optimization Model with Constraints. The established optimization model can be expressed by equation (24) and basic constraints are shown in equation (25).

$$\left.\begin{aligned} \min f_1(x) &= SL_A + L_C + SL_B \\ \min f_2(x) &= e^{-9.7771} \times L^{0.6306} \times AADT^{0.7630} \\ &\quad \times e^{\left(-0.0021\times R + 0.0268\times V_{\text{lim}} + 1.5164\times P_{nc}\right)}. \end{aligned}\right\} \tag{24}$$

s.t.

Constraints based on the design specification:

$$\left.\begin{aligned} & R_{\min} \le R \le R_{\max}, \\ & \frac{R}{3} \le S_A \le R, \\ & \frac{R}{3} \le S_B \le R, \\ & SL_A \ge L^s_{\min}, \\ & SL_B \ge L^s_{\min}, \\ & L \ge L_{\min}, \\ & 0 \le E \le 8\%. \end{aligned}\right\} \tag{25}$$

Constraints for the start point and endpoint:

$$\begin{gathered} 0 \le x_{O'} = y_{O'} \le 10, \\ \sqrt{\left(x_D - x_{D'}\right)^2 + \left(y_D - y_{D'}\right)^2} \le d. \end{gathered} \tag{26}$$

Constraint for speed consistency:

$$\left|v_{85} - v_d\right| = \left|94.398 - \frac{3188.656}{R} - 60\right| \le 20, \tag{27}$$

where all variables have the same meaning as above. In addition, $R \cdot SL_A = S_A^2$, and $R \cdot SL_B = S_B^2$. According to [37], set $R_{\min} = 125\,\text{m}$, $L^s_{\min} = 100\,\text{m}$, and $L_{\min} = 50\,\text{m}$. And assume the endpoint locates within 10 m from the endpoint $D(170, 83)$ which is given before design.

(2) Parallel Selection Method Solution. According to the parallel selection method mentioned above, the optimization results were obtained and shown in Table 4. In addition, based on the optimized calculations, the iterative optimization processes have also been visualized and shown in Figures 8 and 9. Figure 8 describes the iterative optimization process for the annual average number of accidents in the design unit without considering the constraint of the intermediate control points. Figure 9 describes the iterative optimization process for the length of the design unit without considering the constraint of the intermediate control points.

From Figure 8, the annual average number of accidents decreases dramatically after twice iterative optimization and increases after 7 times iterative optimization and decreases again dramatically after 20 times iterative optimization. It is worth noting that the iterative curve fluctuates greatly before 20 times iterative optimization and keeps decreasing after 20 times iterative optimization till around 100 times iterative optimization. This indicates that the optimization efficiency is relatively low. In addition, the annual average number of accidents stays at around 1.91 after 100 times iterative optimization. In other words, the optimized horizontal

TABLE 4: Optimization results of the objective function.

Items	Variables	Optimization results
Design variables after optimization	Transition length ahead (SL_A)	57.96
	Circular curve length (L_C)	62.13
	Transition length back (SL_B)	57.96
	Tangent deflection angle (θ)	0.8367
	Radius of curve (R)	218.1
	Coordinate of start point (O' ($x_{O'}$, $y_{O'}$))	(4.6334, 4.6334)
	Superelevation (E)	0.032
Objective function after optimization	Economic ($f_1(x)$)	178.05
	Safety ($f_2(x)$)	1.91

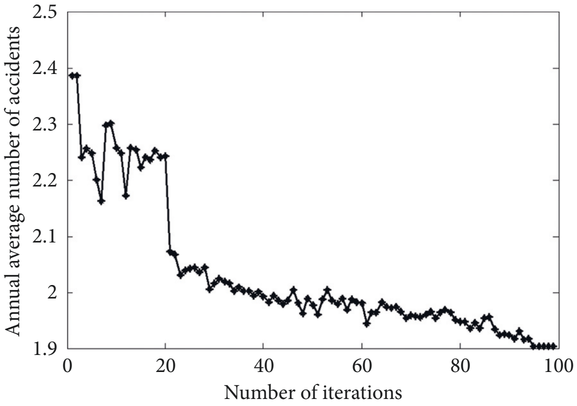

FIGURE 8: Iterative optimization for the safety of the horizontal alignment design unit.

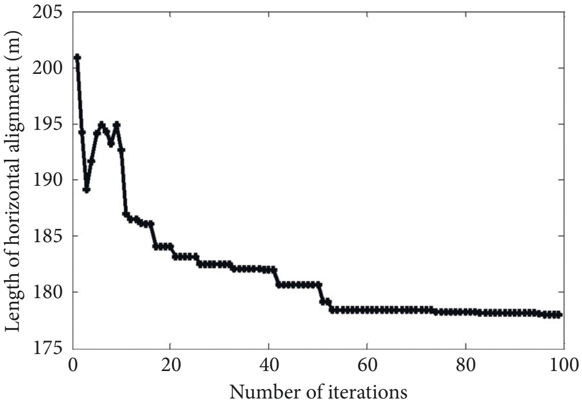

FIGURE 9: Iterative optimization for the length of the horizontal alignment design unit.

alignment may have the risk of about two traffic accidents each year.

From Figure 9, the length of the design horizontal alignment unit decreases dramatically at the beginning of the iterative optimization process and increases after 3 times iterative optimization and again decreases dramatically after 9 times iterative optimization. After 50 times iterative optimization, it tends to be stable and stays at 178.05 m. Thus, under current constraints, the length of 178.05 m represents the most economical design for the design horizontal alignment unit.

3.1.2. Optimization Design considering Constraint of Intermediate Control Points.

Assuming two intermediate control points, P_1 (80, 60) and P_2(100, 70) (see Figure 8), need to be considered during design. In this case, the constraints of the two control points need to be added to the optimization model expressed by equation (24). Thus a new multiobjective optimization model is formed and expressed as follows:

$$\left.\begin{aligned} &\min f_1(x) = SL_A + L_C + SL_B,\\ &\min f_2(x) = e^{-9.7771} \times L^{0.6306} \times AADT^{0.7630}\\ &\times e^{\left(-0.0021\times R+0.0268\times V_{\mathrm{lim}}+1.5164\times P_{nc}\right)},\\ &\min f_3(x) = \sum_{i=1}^{4} \left|W_i\right|. \end{aligned}\right\} \tag{28}$$

Meanwhile, this study also considered the effect of the obstacle on the horizontal alignment. Assume the coordinate of the obstacle is $OB_k\,(120, 60)$ as shown in Figure 10. And assume the distance between the obstacle and the designed horizontal alignment should not be less than 10 m. That is, the shortest distance between the obstacle and the horizontal alignment should be larger or equal to 10 m. As Figure 9 described, the shortest distance between the obstacle and the horizontal alignment is the distance between the point OB_k and the point Q_k. Thus, the constraint can be expressed as follows:

$$\mathrm{DIS}\left(OB_k, Q_k\right) \geq 10, \quad k = 1. \tag{29}$$

Assume that the initial population is 90 and contains 3 subpopulations. The other parameters have the same values as above. Solve the problem using the parallel selection method and the results are shown in Table 5. In addition, based on the optimized calculations, the iterative optimization processes have also been visualized and shown in Figures 11 to 13. Figure 11 describes the iterative optimization process for the annual average number of accidents of the design unit considering the constraint of the intermediate control points. Figure 11 describes the iterative optimization process for the length of the design unit considering the constraint of the intermediate control points. Figure 12 describes the iterative optimization process for the distance of the design unit from the intermediate control points.

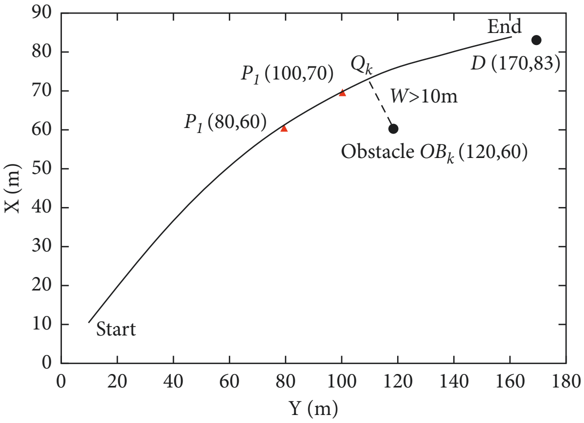

Figure 10: Layout of horizontal alignment.

Table 5: Optimization results for design variables and objective function after optimization.

Items	Variables	Optimization results
Design variables after optimization	Transition length ahead (SL_A)	57.23
	Circular curve length (L_C)	58.10
	Transition length back (SL_B)	57.23
	Tangent deflection angle (θ)	0.834
	Radius of curve (R)	204.54
	Coordinate of start point ($O'\,(x_{O'}, y_{O'})$)	(9.765, 9.765)
	Superelevation (e)	0.03
Objective function after optimization	Economic ($f_1(x)$)	172.56
	Safety ($f_2(x)$)	1.93
	Distance from the intermediate control points ($f_3(x)$)	1.22

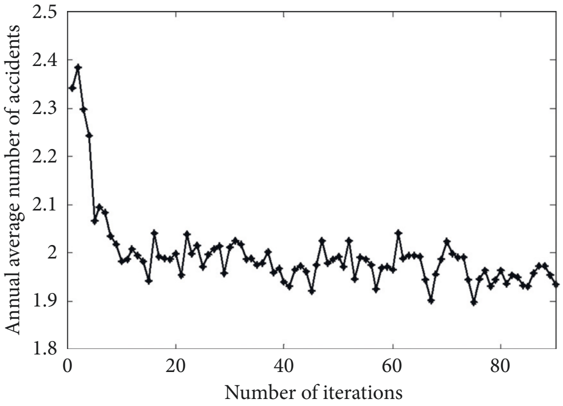

Figure 11: Iterative optimization for safety considering intermediate control points.

From Figure 12, the annual average number of accidents decreases dramatically after 10 times iterative optimization and tends to be stable after 15 times iterative optimization. And finally, the annual average number of accidents is stable at around 1.93 after 75 times iterative optimization. In other words, the optimized horizontal alignment may also have

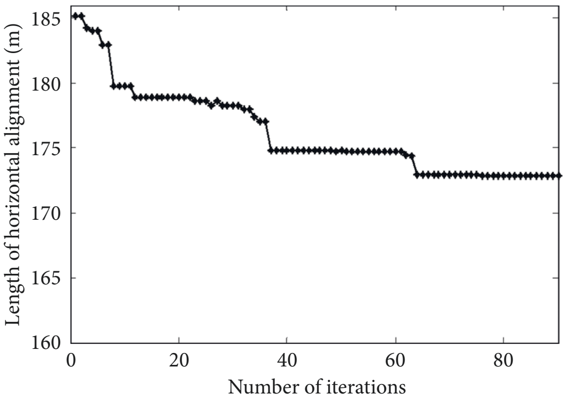

Figure 12: Iterative optimization for the length of horizontal alignment considering intermediate control points.

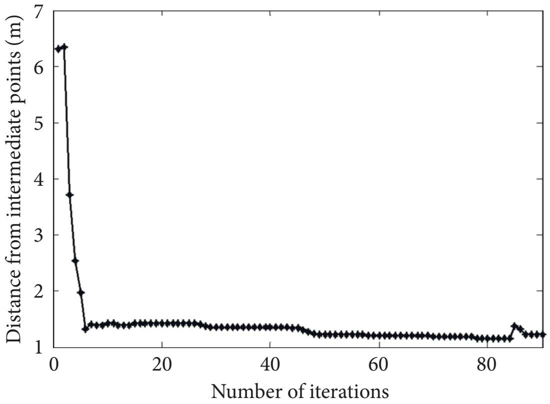

Figure 13: Iterative optimization for distance from intermediate control points.

the risk of about two traffic accidents each year. It almost has the same safety level as the optimized results without considering the intermediate control points. However, it has more optimization efficiency compared to the optimization model established above.

From Figure 13, the length of the horizontal alignment unit also decreases obviously after 10 times iterative optimization and reaches about 178 m. After that, it has three stable stages which are 178 m, 175 m, and 172.56 m, respectively. The first stage decreases to 175 m at 38 times iterative optimization and decreases to 172.56 m at 60 times iterative optimization. The decrease is gradually getting smaller. It can be concluded that the length of the horizontal alignment unit will finally tend to be stable with the increase of iterative optimization. This study stops iterating at 90 times and obtains an optimal design unit length with a value of 172.56 m. Compared to the optimized results without consideration of the intermediate control points, this optimized horizontal alignment has a shorter length. In this case, the length of 172.56 m represents the most economical design for the design horizontal alignment unit under current constraints.

Table 6: Coordinates of points of intersection.

Tangent intersection points	Coordinates of tangent intersection points	
	X (N)	Y (E)
Start	4077410.485	567745.344
PI_1	4077173.065	567642.142
PI_2	4077420.012	567071.624
PI_3	4077454.655	566677.167
PI_4	4077828.540	565456.558
End	4077826.745	565076.690

From Figure 13, the distance of the design unit from the intermediate control points decreases dramatically after two times iterative optimization and tends to be stable. This indicates that the optimization model has good optimization efficiency. The smaller the distance between the design unit and the intermediate control point, the more optimal the designed horizontal alignment. From Figure 12, the distance stabilizes at 1.22 m which means that the most optimal distance of the design unit from the control point is 1.22 m. In other words, the safety and economics could be the best for the design unit when the distance is close to 1.22 m.

3.2. Optimization Design of a Highway Segment. This study took one segment (stake from K25 + 642.826 to K28 + 190.907) of a highway in Shanxi Province in China as an example. Assume that the design speed is 60 km/h and Table 6 gives the coordinates of the intersection points denoted by *PI*. The horizontal alignment optimization model with the consideration of economics and safety was established to optimize the horizontal alignment between the start and endpoint. Assume that the coordinates of the start and endpoints are determined. Thus, the variables of the optimization model could be simplified to $V_i = (R_i, SL_{Ai}, SL_{Bi}, e_i)$, $i = 1, 2, \cdots, N$. Also, assume that the construction cost per unit length of highway is 1. Thus, the economic optimal problem becomes to find the shortest design length of the horizontal alignment of the highway. Other assumptions are the same as above.

The established multiobjective optimization function and corresponding constraints can be expressed as equations (30) and (31). It is worth noting that this case did not consider the intermediate control points. All the symbols have the same meaning as above. The continuous constraints were considered here to ensure the continuation of all design units and could be expressed as equation (18). The speed coordination constraint follows equation (32).

$$\left.\begin{aligned} &\min f_1(V) = \sum_{i=1}^{N}\left(L_i + L_{Ti,i+1}\right),\\ &\min f_2(V) = \sum_{i=1}^{N} e^{-9.7771} \times L_i^{0.6306} \times AADT_i^{0.7630}\\ &\times e^{\left(-0.0021\times R_i + 0.0268\times V_{\text{lim}}(i) + 1.5164\times P_{nc}(i)\right)}. \end{aligned}\right\} \tag{30}$$

Table 7: Optimization results of the designed horizontal alignment of the selected highway segment.

Tangent intersection points	Coordinates of tangent intersection points $X(N)$	$Y(E)$	Tangent deflection angle Turn left	Turn right	Radius of circular curve (m)	Transition length (m) Ahead	Back	Superelevation
Start	4077410.485	567745.344						
PI_1	4077173.065	567642.142		89°54′41″	224	65	65	0.06
PI_2	4077420.012	567071.624	18°23′09″		243	52	52	0.03
PI_3	4077454.655	566677.167		12°00′40″	460	52	52	0.03
PI_4	4077828.540	565456.558	10°28′30″		502	56	56	0.04
End	4077826.745	565076.690						

s.t.

$$\left.\begin{aligned}
&R_{\min} \le R_i \le R_{\max},\\
&\frac{R_i}{3} \le S_{Ai} \le R_i,\\
&\frac{R_i}{3} \le S_{Bi} \le R_i,\\
&SL_{Ai} \ge L^{s}_{\min},\\
&SL_{Bi} \ge L^{s}_{\min},\\
&L_i \ge L_{\min},\\
&L_{T\min} \le L_{Ti,i+1} \le L_{T\max},
\end{aligned}\right\} \tag{31}$$

where $L_{T\min}$ and $L_{T\max}$ represent the minimum and maximum length of tangent between two adjacent design units, respectively. According to specifications, $R_{\min} = 100\,\text{m}$, $L_{\min} = 50\,\text{m}$, $L^{s}_{\min} = 100\,\text{m}$, and $L_{T\max} = 20\,V = 1600\,\text{m}$; also, when the two adjacent curves form a reverse curve, $L_{T\min} = 120\,\text{m}$; when they are in one direction, $L_{T\min} = 240\,\text{m}$.

$$\left.\begin{aligned}
&\left|v_{85}^{i-1} - v_{85}^{i}\right| < CR = \frac{20km}{h},\\
&v_{85}^{i} = f\left(R_i\right) = 94.398 - \frac{3188.656}{R_i}.
\end{aligned}\right\} \tag{32}$$

In addition, assume the chromosome length is 10 and thus the mutation probability should be 0.07. Other parameters used in the genetic algorithm are the same as above. Table 7 gives the iterative optimization results including the tangent deflection angle, radius of the circular curve, transition length, and superelevation. Figure 14 describes the iterative optimization process for the annual average number of accidents of the horizontal alignment of the selected highway segment. Figure 15 describes the iterative optimization process for the length of the horizontal alignment of the selected highway segment.

From Figure 14, the annual average number of accidents decreases obviously at the beginning of the iterative optimization processes and tends to be stable after 23 times of iterative optimization. And finally, the annual average number of accidents is stable at around 6.35 after 50 times iterative optimization. This indicates that the optimization efficiency of the established model is good as mentioned above. In addition, the optimized horizontal alignment may have the risk of 6.35 traffic accidents per year.

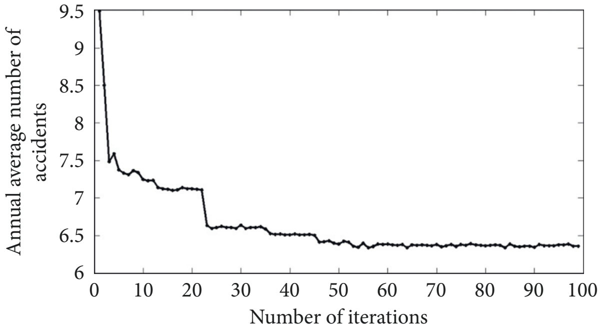

Figure 14: Iterative optimization for safety of the horizontal alignment of the selected highway segment.

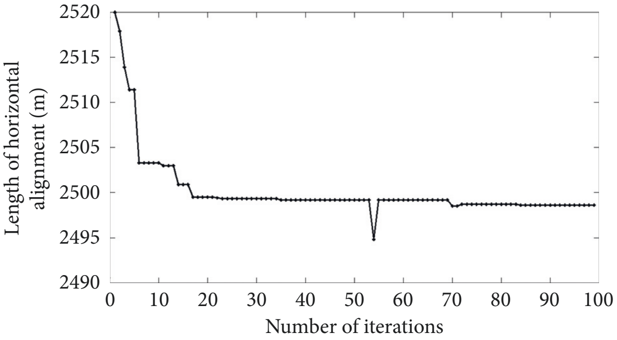

Figure 15: Iterative optimization for length of the horizontal alignment of the selected highway segment.

From Figure 15, the length of horizontal alignment also decreases obviously at the beginning of the iterative optimization processes and tends to be stable after 15 times of iterative optimization. It can be found that the length of the horizontal alignment finally is stable at 2498.6 m. Compared to the design before optimization, the optimized horizontal alignment has a shorter length. In this case, the length of 2498.6 m represents the most economical design for the horizontal alignment of the selected highway segment.

From the optimization results, the total design length of the selected highway segment was reduced to 2498.6 m from the original design length of 2548.1 m after optimization. In other words, the construction cost of the selected highway segment could be reduced by 49.5 units of construction cost by optimizing the horizontal alignment design. In addition, the annual average number of accidents decreased to 6.35 from 9.5 predicted by the accident prediction model according to accident data. It can be found that both horizontal alignment length and safety have an improvement after optimization. However, the improvement is not large, which can be attributed to the short highway segment. As shown in Table 7, the entire highway segment only contains four design units. If the start and end of the selected highway segment are far away, the horizontal alignment will include much more design units and would have a significant improvement after optimization using the established optimization model in this study.

4. Conclusions

The purpose of road safety design is to provide a safe and comfortable driving environment to road users. It is of great research significance to carry out how to optimize the horizontal alignment of the road, because this could effectively improve the safety and economy of the designed horizontal alignment. This study established a multiobjective optimization model for highway horizontal alignment design considering the economy and safety. Two scenarios were considered for constraints of the optimization model. One scenario considered the constraints of the intermediate control points; the other does not. In addition, two cases were analyzed here to introduce the optimization model. One is optimization for a horizontal alignment design unit. Another one is optimization for a real highway alignment including four design units. It can be found that the annual average number of accidents and the horizontal alignment length both decreased after optimization for either a design unit or a highway alignment with more than one design unit. The optimization model could help to improve the safety and economics of roads. In particular, the optimization model could be developed as a road alignment optimization program or embedded in current computer-aided design software for road horizontal alignment. It can not only reduce much more redundant debugging work for the designer but also reduce the influence of the designer's subjectivity. The optimization would be useful to the road designer.

However, some limitations exist for the established optimization model. First, the safety objective function was oversimplified and denoted only by the annual average number of accidents. The annual average number of accidents is not a comprehensive indicator to evaluate the safety of a horizontal alignment design. Also, it has a great relationship with the collected traffic accident data or the accuracy of the accident prediction model. Second, the economics objective function was also oversimplified and denoted only by the length of design horizontal alignment. The economic indicator also can not represent the economics of the designed horizontal alignment comprehensively. Third, this optimization model is mainly suitable for the design stage of the horizontal alignment. In this case, it is hard to verify the safety improvement effect of the road design because there is no traffic accident data yet for the design road. The best way is to use the simulation technology or refer to similar roads. To solve the limitations mentioned above, some research methods or directions would be tried in the future. First, the optimization effect of the safety objective function can be improved by establishing more comprehensive indicators or by establishing more accurate traffic accident prediction models. In particular, it would be a good way to establish an accident prediction model based on machine learning or big data analysis. Second, establish more comprehensive economic evaluation indexes for road construction related to the horizontal alignment design. Third, the traffic conflict could be considered for evaluating the safety of the design, especially for the ramp entrance and exit.

Data Availability

The data that support the findings of this study contain two parts. One part is two years (2005–2007) of traffic accident data from the Dayun Expressway Administration in Shanxi Province in China. The data are available from the Dayun Expressway Administration. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from the authors with the permission of the Dayun Expressway Administration. The other part is two years (2006–2008) of traffic accident data of Washington State in the USA, collected from the HSIS database. The data are available in HSIS (Highway Safety Information System) at https://hsisinfo.org.

Disclosure

The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

Conceptualization was done by Q.Y. and K.Y.; methodology was developed by Q.Y. and K.Y.; software was provided by Y.H.; validation was done by W.H. and Q.Y.; formal analysis was done by Q.Y. and K.Y.; investigation was done by Q.Y.; resources were providedby W.H.; data curation was done by Y.H.; original draft preparation was done by Q.Y.; review and editing were done by Q.Y.; project administration was done by W.H.; and funding acquisition was done by Y.H. All authors have read and agreed to the published version of the manuscript.

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