IJTE, Vol. 11, No. 3, Winter 2024, pp. 1547-1570
Research Paper

Optimization of Horizontal Road Alignment Based on Parameters Affecting its Cost and Lifespan Using Genetic Algorithm

Saeid Aftabi Hossein[1], Kamran Rahimov[2,*]

Received: 2023/08/12 *Accepted: 2023/10/14*

Abstract

This paper presents an approach for the optimization of horizontal road alignment with a focus on parameters affecting its cost and lifespan. The study area is the Bandar-e Anzali 16Km bypass highway, situated in north Iran, which holds significant economic, cultural, and environmental importance. The goal is to find the efficient and cost-effective alignment that adheres to design standards. The proposed methodology employs a multi-objective optimization technique using genetic algorithms in MATLAB. Various cost parameters, safety indicators, and environmental constraints are considered as decision variables to formulate the target performance. The genetic algorithm efficiently explores the design space, providing optimal solutions that fulfill all requirements and constraints. The output model ensures a balanced and practical approach to road design. The route design data was collected and the important variables affecting the route design were determined. Then, the optimal balance was evaluated using the genetic algorithms method. After analyzing the generated data, we propose the optimal horizontal alignment as the final recommended option, with four horizontal arcs and a length of 14.99km. The results demonstrate the effectiveness of the genetic algorithm-based method in achieving an optimal alignment for the Bandar-e Anzali bypass highway. The proposed solution reduces road construction costs and enhances safety while considering environmental impacts. This study highlights the importance of considering multiple parameters and utilizing advanced optimization techniques to achieve sustainable and cost-effective road designs. The proposed approach provides decision-makers with valuable tools to explore a wide range of design options and select the favorable alignment for construction.

Keywords: Road Geometric Design, Horizontal Alignment Optimization, Safety Considerations, Environmental Impact, Genetic Algorithm

* Corresponding author: E-Mail: k.rahimof@pnu.ac.ir
[1] Ph.D, Department of Civil Engineering, Payame Noor University (PNU), P.O. Box 19395-3697, Tehran, Iran
[2] Assistant Professor, Department of Civil Engineering, Payame Noor University (PNU), P.O. Box 19395-3697, Tehran, Iran

1. Introduction

Route design is a plan that is presented on the natural ground conditions in an area. The purpose of designing the connecting route between two points (origin point at the beginning and destination point at the end) is with the minimum possible cost as well as the maximum efficiency and usefulness. Of course, it is necessary to explain that in order to achieve an ideal plan in the proposed route plan, several limitations must be taken into account. The most important of these limitations can be classified as follows:

1) Design limitations based on standards and guidelines
2) Environmental restrictions in the intended area
3) Social restrictions on citizens and residents of the affected area

Achieving a horizontal alignment often may not lead to the best possible option, because there are countless proposed routes to connect two points of origin and destination, which will be based on the human judgment of design engineers. In this way, among the unlimited possible options between the origin and the destination, based on the judgment and intuition of the designers, a proposal is obtained as an output. In the meantime, many good options may have been overlooked. In order to examine all possible options on the one hand and to reduce the workload of design engineers, the study of automatic routing methods and methods that can achieve the best results with the lowest costs in the shortest time was started. Automatic methods significantly reduce road design problems, possible errors in manual design methods, and similar issues. In addition, automatic methods make it possible to use optimization techniques to search for the best path. Optimization techniques save design time and provide decision makers with powerful tools to search for the lowest cost option from a large number of possible options. Therefore, route optimization will result in significant savings in construction costs compared to methods that do not follow optimal road design. In recent years, many efforts have been made to realize the methods of determining the candidates of desirable roads. Today, new methods have been presented in developed countries based on new techniques. Some of these many methods that have been proposed in the last two decades are: change calculation method, network optimization, dynamic programming, numerical search, genetic algorithm and geographic information system.

In general, in road design, choosing the best option for a set of origin and destination components is very important. The concept of the best design candidate in this thesis is a way that the following parameters can be observed from three basic points of view according to the flowchart presented in Fig. 1. Considering all these parameters as well as the impact of each of the technical and economic parameters, it is a very difficult and time-consuming way. Traditional methods of determining optimal road options require errors due to large amount of data and time. Horizontal routing of a road is actually a view of the route that can be seen from the eyes of a bird in navigation between the origin and the desired destination. This step is made up of successive extensions that prepare the path at the meeting points with the help of circular horizontal arcs and connection curves (Clothoid). The connecting curves provide a more favorable driving experience with the help of its variable curvature along the track and its gradual change. The cost of road construction in the category of horizontal routing (route plan) depends on the cost of land acquisition and factors like that, so the main considerations in the horizontal design of the route is that the following should be avoided:

1) Lands that are purchased with It is limited or expensive.
2) Natural obstacles that involve more risk and engineering complications.
3) Lands that have high environmental importance.

In the optimization of the horizontal route, we intend to build a low-cost route by complying with the route design standards and reducing the subsequent environmental effects. However, what is important is that the path presented as a plan is useful and functional. Sometimes these two important goals may be in conflict with each other. In this study, the main road optimization model has been investigated as one of the most important classifications of communication arteries. In this model, it was tried to use different parameters to determine the appropriate candidate for road optimization. As mentioned in the previous section, these parameters can be divided into three main categories:

The first category: Cost parameters

A) Indirect cost: Road location cost and land cost.

B) Direct costd: structural cost and length-related cost.

The second category: Safety parameters

Legnth of straight paths, number of vertices of arcs (PI), radius of horizontal arcs and overlaps of horizontal arcs.

The third category: Constraint parameters

A) Dsign limitations: Checking the rights of way.

B) Environmental and geographical limitations: ecologically protected areas, air pollution cost and environmental conventions for greenhouse gas emissions.

Finally, using a genetic algorithm for optimization reduces the time and effort required to develop an optimal road design significantly. The genetic algorithm quickly and efficiently explores a large design space and identifies an optimal solution that meets all the design requirements and constraints and saves time and resources for road design professionals compared to traditional methods.

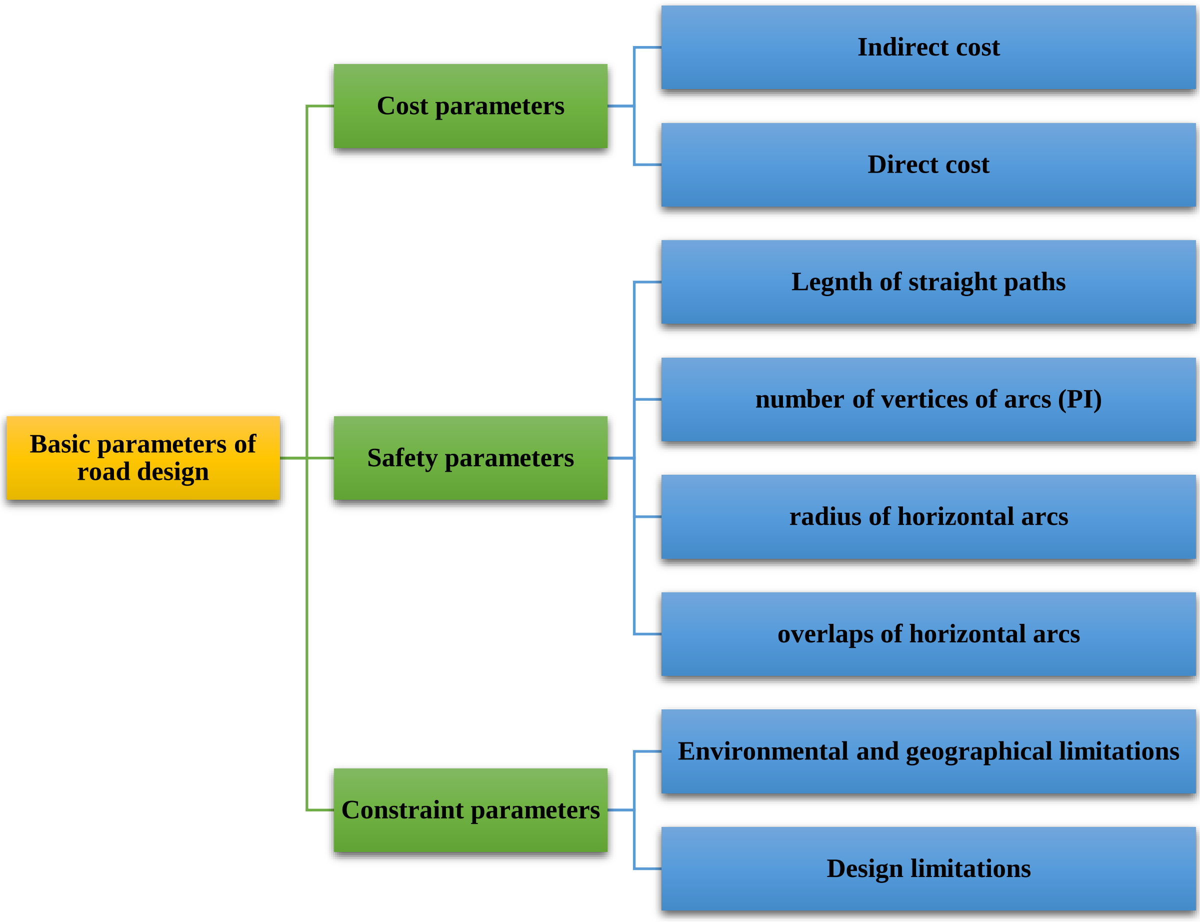

Figure 1. Flowchart of three basic parameters of road design

Although, Numerous inherent limitations exist in any research, often originating from factors beyond the researcher's influence. These constraints can impact the interpretation and generalization of research outcomes and may stem from various sources, such as methodological choices, data availability, or analysis techniques. Given that this study primarily concerns the practical application of a novel routing design approach, it deliberately maintains a delimited scope to enhance the clarity and decisiveness of its findings. The principal limitations encompass:

1) To indicate the horizontal alignment of the road, several intersection points (PI) are checked. The maximum number is set as N PIs according to the case study (Bandr-e Aanzali).

2) Among the cost components, only those that seem important to the optimal design approach are selected. Therefore, they have been formulated by approximation and simplification.

3) Route geometric design optimization in this research is limited to the horizontal alignment.

4) There are many variables beyond the researcher's control that can affect path optimization.

5) Statistical and design issues naturally exist in correlational studies.

6) There are limitations in data collection and statistical methods in all researches, including this research.

7) The genetic algorithm optimization model in this research is limited to selected cases.

8) The engineering data has been limited to the route and there are restrictions regarding vehicles and pedestrians.

2. Research Background

Optimization of road design using computers began in the 1960s and 1970s. Due to limited computational power, solving optimization problems accurately was difficult. The emergence of modern computers and GIS technology has given us the ability to solve the problem more accurately. The cost of road construction can be significantly minimized by solving mathematical models using modern computer programs. Many optimization models have been proposed to address this issue, each providing a solution from different perspectives. Although existing models work well in some aspects, they still have flaws that practically prevent their application.

The horizontal alignment of a road is composed of tangent sections connected to curved sections to smoothly change directions. Generally, circular curves are considered in the plan view to maintain centrifugal force and prevent lateral slip of the vehicle. This important feature can be achieved by creating appropriate curvature and cross slope based on design speed and lateral friction. The goal of optimizing the horizontal alignment of a road is to develop a mathematical search model to find the global or near-global optimal solution based on minimizing the total objective function cost within existing geometric design constraints.

The optimization problem of horizontal alignment of roads is more complex than the vertical alignment problem. [Jha et al, 2006] The main reasons are that horizontal alignment requires more data and its cost is dependent on vertical alignment, political, socio-economic, and environmental issues. In research, mainly three fundamental approaches have been studied: calculus of variations, network optimization, and dynamic programming.

The calculus of variations approach tries to find the curve connecting two endpoints in space that minimizes an integral function [Wan, 1995]. The nature of the road alignment optimization problem allows us to use the concept of calculus of variations to find the optimal alignment. In another study, the idea of calculus of variations was used to develop the principle of optimal curvature (OCP), which determines the optimal vertical and horizontal curvatures at each point [Howard, 1968]. To apply OCP, two numerical integration methods, namely the circular arc algorithm and the intrinsic equation method, were proposed [Shaw & Howard, 1981]. OCP was applied to determine the optimal alignment of a highway in South Florida [Shaw & Howard, 1982]. The two main requirements for using this method are that the cost function must be continuous and the cost function must be twice continuously differentiable. In practice, the cost function may not be continuous [Jha et al, 2006]. Although OCP ensures global optimization, it requires some assumptions that make it impractical.

In another research [Safarzadeh et al., 2006] they presented a model to find a corridor for the optimal alignment, which has access to all the main points and has the lowest total cost. The most important feature of this model is to consider areas that the route should not pass through for any reason. In this research, the evaluation of common routing methods has been done and finally, two mathematical models for routing in plain areas have been presented. In the first method, the impassable areas are not modeled, in the second method, the forbidden areas are modeled in the shape of a triangle, and the route is prevented from passing through these areas. One of the important issues of the route corridor plan is not to pass through the protected environmental or military areas. In the plains and Tepe rolling areas, passing through valleys, lakes, mountains or other such areas imposes a lot of cost on the project, so these areas, like the protected areas, are difficult areas for the corridor. The most important feature of the second method is to consider these areas in the optimal routing of the corridor. A very important point in the corridor plan is to determine the general model of the route, or in other words, the order of access to the points and the method of this access. Routing should be done with a comprehensive view and a long-term plan, so that the most cost-effective road network can be created. Therefore, one of the most important applications of the presented mathematical model is to use it to prepare a comprehensive plan for freeway and rail corridors in the country's plains and rolling hills. It can also be used for navigation on larger scale maps in plain areas. In this research, mathematical nonlinear programming model was used for modeling.

[Lee et al. 2009] proposed an exploratory method for optimizing the horizontal alignment, which works in two stages. In the first stage, it attempts to approximate a piecewise linear path, and in the second stage, it provides a solution to align the previously created piecewise linear path with an actual road alignment.

Kang and colleagues [Kang, 2012] provided an intelligent optimization tool that integrated genetic algorithms with a Geographic Information System (GIS) to optimize highway alignments. Two real highway projects in Maryland were analyzed using the model. The results show that the model can effectively optimize highway alignments in a complex area of various natural and cultural land use patterns. The model was able to significantly reduce the time required for planning and designing highways and produce cost-effective solutions.

Anouthet study proposed a bi-level optimization model that combined horizontal alignment, vertical alignment, and earthwork optimization to find an optimal alignment connecting two end-points in a specified corridor [Mondal et al., 2015]. The model used derivative-free optimization algorithms to solve the outer problem and gave an optimal horizontal alignment in the form of a linear-circular curve and an optimal vertical alignment in the form of a quadratic spline. The approach was tested on real-life data and improved the road alignment designed by civil engineers by 27% on average, resulting in potentially millions of dollars of savings.

The Path Planner Method (PPM), introduced by [Sushma and Maji, 2017], draws its foundation from the Rapidly-exploring-Random Tree (RRT) algorithm, a prominent tool in path planning. PPM is meticulously designed to efficiently explore complex high-dimensional spaces, with the primary aim of achieving an optimal horizontal highway alignment. The methodology revolves around generating random Points of Intersection (PIs) to comprehensively cover the entire study area. These PIs serve as the building blocks for a tree-like path that iteratively extends from the starting to the ending points. These paths adhere to prescribed geometric guidelines for highways while minimizing construction costs. The PPM operates through an interactive two-stage process. To evaluate its efficiency and applicability, a case study employs geographical mapping data from a location in Odisha, India. The results of this case study offer valuable insights into the PPM's effectiveness in optimizing horizontal highway alignment.

[Casal et al., 2017] present a comprehensive approach for optimizing horizontal road alignment, encompassing tangential segments, circular curves, and transition curves known as clothoids. Their model addresses a wide range of scenarios by capturing cost factors in a flexible line integral-based objective function. Practical applications are demonstrated through designing new road layouts and improving existing roads to meet current regulations, exemplified by the reconstruction of regional road NA-601 in northern Spain. This work provides a foundational reference for enhancing road alignment efficiency and compliance in road design and reconstruction.

In anouther research [Babapour et al., 2018], the focus was on the optimization of vertical alignment in road planning and construction, taking into account design constraints and costs. Various linear, nonlinear, and heuristic techniques were explored to minimize road construction costs by manipulating different variables. The utilization of genetic algorithms (GA) and Particle Swarm Optimization (PSO) was considered for efficient vertical alignment allocation. The study aimed to find a near-optimal forest road profile connecting specific endpoints, while considering design restrictions and cost evaluation. Parameters such as population size, crossing over, and mutation rate in GA, as well as best group and particle positions in PSO, were tested to achieve a global optimal solution. Comparative analysis of the optimization results using GA and PSO with the manual road profile drawing method revealed that both GA and PSO could effectively reduce earthwork volume costs and deliver smoother and better-aligned designs. Among the applied methods, GA demonstrated superiority in achieving optimal solutions with reduced computed costs, making it the most suitable approach for this problem. For larger numbers of control points, optimizing the fixed length of road profiles using GA yielded better results, while smoother outcomes were obtained for lower numbers of control points.

Anouther study, [Zhang et al. 2020] proposed a multi-objective optimization model for railway alignment design considering both economic and environmental objectives. The study aimed to find an economical and eco-friendly railway alignment that reduces negative impacts on mountain environments. The proposed method included two new quantitative indexes for measuring environmental impacts and a multi-objective optimization method based on the particle swarm optimization algorithm. The results showed that the proposed method effectively traded off economic and environmental objectives and provided a set of non-dominated alignment alternatives. This study provides a promising approach to the design of railway alignments in environmentally-sensitive regions.

Sushma and Maji (2020) introduced an innovative approach for optimizing the development of horizontal highway alignments in their next study. Horizontal alignment, a crucial aspect of road development, involves the interplay of three essential factors: the number of horizontal points of intersection (HPIs), their precise locations, and the corresponding horizontal curve radii. Determining these three factors simultaneously represents a significant challenge, particularly when undertaken manually. Most computer-aided methods currently available prioritize one or more of these factors within automated alignment development processes. However, these methods are not without limitations, including the approximation of HPI locations and the pre-selection of HPI numbers and curve radii. This study presents a novel motion-planning based algorithm designed to address these limitations and optimize the development of new horizontal alignments while considering both cost and environmental impacts. The algorithm simultaneously employs a low-discrepancy sampling technique to generate increasingly dense potential HPIs, enabling the rapid exploration of random trees to identify an appropriate number of intermediate HPIs at optimal locations. Furthermore, a sequential quadratic algorithm is employed to select curve radii that are optimally suited for the alignment. To enhance the practical applicability of this algorithm, it is integrated with a Geographic Information System (GIS) database. This integration facilitates the assessment of location-dependent costs and environmental impacts, ensuring that the alignment development process aligns with real-world conditions. The study utilized two real-world case study areas to compare results with those reported in existing literature and to evaluate the algorithm's backtracking capability. The results underscore the proficiency of the proposed algorithm in generating new alignments effectively.

[Biancardo et al. 2021] presented a result of study on the optimization of railway track alignment to connect growing inland mountainous areas. The study applied a multiobjective alignment optimization commonly used in highway projects to identify a better solution for constructing a high-speed railway track while considering technical and economic feasibilities. The study investigated two different and innovative scenarios: an unconventional ballastless superstructure and a reduced cross-section in a tunnel. The results showed that the ballastless superstructure had a better performance with a slight increase in cost. Both scenarios improved the preliminary alignment optimization, reducing the overall cost by 11% and 20%, respectively. This study demonstrates the potential of multiobjective alignment optimization in railway design, and the importance of considering innovative solutions that are more environment-friendly and cost-effective.

In the study by [Khalil et al. 2021], a method for optimizing the horizontal corridor of a highway in mountainous areas using GIS and critical failure state charts (CFSC) was proposed. The authors highlighted the importance of considering essential criteria related to construction, maintenance, and structural subjects during the preliminary design phase. To address the issue of road slope stability, soil properties were predicted using the California Bearing Ratio (CBR) test and CFSCs were proposed to evaluate the safe height of the slope and the need for supporting systems such as concrete retaining walls. The optimal location of the retaining walls was determined using GIS and Least-Cost Path Analysis (LCPA) method. A mathematical model was implemented to find the optimum corridor between two points, and the cost of the retaining wall was classified as low according to the adopted cost classification.

[Rouhi Mashhadsari and Behzadi, 2021] conducted a research study with the aim of reducing the number of accidents by investigating variables influencing the severity of injuries in accidents. This investigation involved the modification of the geometric design of road horizontal alignments. In this study, the researchers utilized three powerful machine learning techniques, including the Bayesian classifier, random forest, and support vector machine techniques. To begin, three prediction models for imbalanced data were created, revealing an inability to distinguish fatal data from injury data. To address this issue, three clustering techniques, including random clustering, k-means, and metaheuristic algorithms, were employed to balance the data. These metrics aided in the evaluation of the developed models, leading to the identification of the best-performing model. Ultimately, a sensitivity analysis was conducted on the best model, revealing that highways, horizontal curves, and oncoming variables play a significant role in accidents resulting in fatalities. Therefore, the modification and optimization of horizontal geometric design can significantly enhance route safety.

[Yu et al., 2022] introduced a multi-objective optimization framework targeting the design of horizontal highway alignment with considerations for safety and cost-efficiency. Their model exhibited notable achievements in terms of a reduced annual average accident rate and overall horizontal alignment length, concurrently ameliorating road safety and economic parameters. This model's potential applications extend to the development of dedicated road alignment optimization software or its integration into contemporary computer-aided design tools, which could subsequently mitigate debugging complexities and reduce the impact of subjective design decisions. Nevertheless, certain limitations became evident within this model, characterized by its somewhat oversimplified formulations of safety and economic objectives, rendering it particularly suitable for deployment during the design phase exclusively.

In a recent study by [Pu et al. 2023], a bi-objective model was proposed for railway alignment optimization that considered carbon emissions throughout the life cycle of a railway project. The model integrated carbon emissions generated during construction, operation, and maintenance stages, as well as the loss of carbon sink during a railway's life, into a single objective function. The model was solved using a particle swarm algorithm and successfully applied to a real-world railway case, demonstrating its effectiveness in minimizing both costs and carbon emissions. The study highlighted the importance of low-carbon design in railway alignment optimization, especially in the context of climate change.

Song et al. (2023) conducted an extensive literature review focusing on the optimization of alignment (AO) within the domains of roads, railways, and rail transit lines. Their investigation underscored the pivotal role of alignment determination in shaping the life-cycle performance of these transportation infrastructures. It was observed that manual alignment work is not only time-consuming but also labor-intensive. Consequently, the demand for intelligent AO methodologies has risen. Song and colleagues contributed the initial literature review within this sector spanning a quarter-century. Their study commenced with a comprehensive bibliometric visualization, unveiling the overarching characteristics of AO research. This review encompassed a scrutiny of prevailing mathematical models employed for formulating AO problems, incorporating applications grounded in Geographic Information Systems (GIS). Additionally, it delved into an extensive discussion concerning intelligent methodologies aimed at addressing the AO challenges. Two specific research areas were elucidated, embracing the concurrent optimization of railroad alignments and station locations, alongside the pertinent matter of existing alignment reconfiguration and redesign. In conclusion, the authors proffered a spectrum of twelve prospective research extensions and directions within this distinctive domain.

Zhang et al. (2023) presented an innovative approach in their next paper that introduces a Sequential Exploration Algorithm (SEA) designed to optimize horizontal road alignment in a distinct manner. Unlike conventional optimization methods, SEA systematically explores the entire optimization space in a sequential fashion, allowing for the independent adjustment of parameters for each node. This characteristic eliminates the need for rigid dependencies among performance indicators

(PIs), which is a common constraint in traditional optimization algorithms. SEA's versatility is further highlighted by its capacity to operate without preconceptions regarding the number or positioning of PIs. It excels in designing nearly optimal road alignments that adhere to geometric restrictions while also accounting for transition curves. A notable aspect of this algorithm is its direct optimization of geometric element parameters based on the actual milepost, eliminating the necessity for secondary optimization nesting during the process. The study conducted comparative analyses of the optimization outcomes using SEA, which included a problem of obstacle avoidance, a new road design scenario, and an existing road reconstruction problem. Results showed that the SEA outperforms two leading-edge optimization algorithms by yielding optimization improvements ranging from approximately 3% to 10%. This remarkable enhancement underscores the SEA's potential to significantly enhance optimization outcomes in horizontal road alignment design. Overall, this work offers a novel approach to road alignment optimization by effectively integrating discrete and continuous optimization components. The discrete element optimizes precision, while the continuous component addresses real optimization needs, providing a promising avenue for improving road design and reconstruction processes.

Previous studies have proposed various optimization models to address the issue of road alignment design from different perspectives, including calculus of variations, network optimization, and dynamic programming. However, in previous studies, the issue of optimizing the alignment in a simultaneous approach from both the perspective of modifying the geometric design of the route and the effects of incorrect route design on the environment has been less considered. In addition, most studies have mainly focused on the optimization of the geometric design, while the other variables such as environmetal and safety indicaors has been less considered. Moreover, the proposed models have not fully addressed the complexity of the problem, where environmental and socio-economic factors significantly influence the design. Therefore, there is a research gap in developing a comprehensive optimization model that considers horizontal alignment and takes into account environmental and socio-economic issues. The proposed models need to be more practical, adaptable, and capable of considering innovative solutions that are more environment-friendly and cost-effective.

3. Methodology

In this research, an optimization method for road design is presented, aiming to provide a set of horizontal alignment design options from a single stage of the design process. The study begins by identifying limitations and cost parameters, including technical, safety, and environmental factors affecting route design. It emphasizes the selection of crucial variables influencing the geometric design of horizontal roads. The research explores various optimization models to enhance optimization quality and formulates the final model considering cost, safety and limitation perspectives. The genetic algorithm method is employed to design the final optimization model. A key innovative aspect of this research lies in the consideration of safety aspects, including correcting horizontal arches and distances between arches, a crucial factor often overlooked in previous studies. Additionally, the study introduces the concept of optimizing the number of Points of Intersection (PIs) in road curves, directly related to design speed and road safety. The smaller the radius of curvature, the more PIs are needed for safety, highlighting the intricate relationship between curvature, safety, and design efficiency. Furthermore, the research pioneers the inclusion of pollution costs during the road's lifecycle, providing a holistic environmental perspective in road design. The study evaluates modifications to existing roads and incorporates environmental fees, a factor often disregarded in previous research, contributing significantly to the optimization process. The innovative model is applied to the Bandar Anzali Beltway, a critical area between the Caspian Sea and the Anzali Lagoon, demonstrating its potential in addressing complex real-world challenges.

The optimization model developed in this research serves as a groundbreaking tool for road design experts and engineers. It not only provides an automatic and scientifically sound method for optimizing road designs but also addresses critical safety aspects, environmental concerns, and user indirectional costs, which are often overlooked in traditional design methods. By employing genetic algorithms, the model efficiently explores vast design spaces, ensuring cost-effectiveness, safety, and efficiency in road networks. This approach stands as a pivotal step toward cost-effective, safe, and efficient road networks, aligning with the global efforts to enhance transportation infrastructure and minimize environmental impact.

This study aims to develop a comprehensive horizontal alignment optimization method that considers various parameters affecting the cost and lifespan of the road. this study proposes a multi-objective optimization approach that simultaneously minimizes the land acquisition cost, road construction cost, travel time cost and costs related to safety and the environment. The proposed method utilizes genetic algorithms to solve the multi-objective optimization problem, where performance indicators (PIs) are considered as decision variables for formulating the target performance. However, the cost function cannot be formulated as a function of PIs like in conventional multi-objective optimization problems, thus requiring a special multi-objective GA process. The PI coordinates are encoded in chromosomes, where the alleles of each chromosome represent continuous real numbers defined in the search space of the problem. The construction and user cost are evaluated for each path created by the coordinate information stored in the allele of the chromosomes. Based on the fitness function values, non-dominant and dominant solutions are classified, and separate selection pressures from non-dominant and dominant solutions are found based on total cost ranking. The next generation of chromosome sets is produced by crossover and mutation of the original solution set, leading to the reproduction of children and the achievement of optimal solutions. Overall, this proposed method provides a more practical, adaptable, and comprehensive approach to horizontal alignment optimization, considering various parameters and utilizing advanced optimization techniques.

An overview of the proposed method is shown in Fig. 2. In this flowchart, the following steps will be taken to provide the road optimization modeling process, with the goal of achieving horizontal alignment optimization.

4. Horizontal Path Variables and Objective Function

4.1. Design Variables

4.1.1. Geometric Variables

Horizontal alignment optimization plays a crucial role in road design to ensure efficient and safe vehicle operation within the available space while considering various constraints. This paper focuses on the significance of horizontal path constraint variables in genetic algorithm-based horizontal alignment optimization. These variables define the feasible design space and guide the search process towards high-quality solutions. Compulsory points, including start, end, and vertices, establish the path's endpoints and milestones, connecting the desired origin(O) and destination(D) points. The length of tangent lines and the angle of the apex of the arc affect the overall path length and curvature, influencing smoothness and vehicle stability. The center of the horizontal arc determines the curve's position relative to the road, affecting visibility and maneuverability. The intersection of the arc and tangent ensures a smooth transition between straight and curved sections. The arc's radius impacts lateral acceleration and ride comfort. Additionally, the total path length affects travel time, construction cost, and maintenance expenses. To optimize horizontal alignment, appropriate objective functions balancing design criteria and constraint variables are essential to generate practical, geometrically feasible solutions and achieve optimization goals effectively.

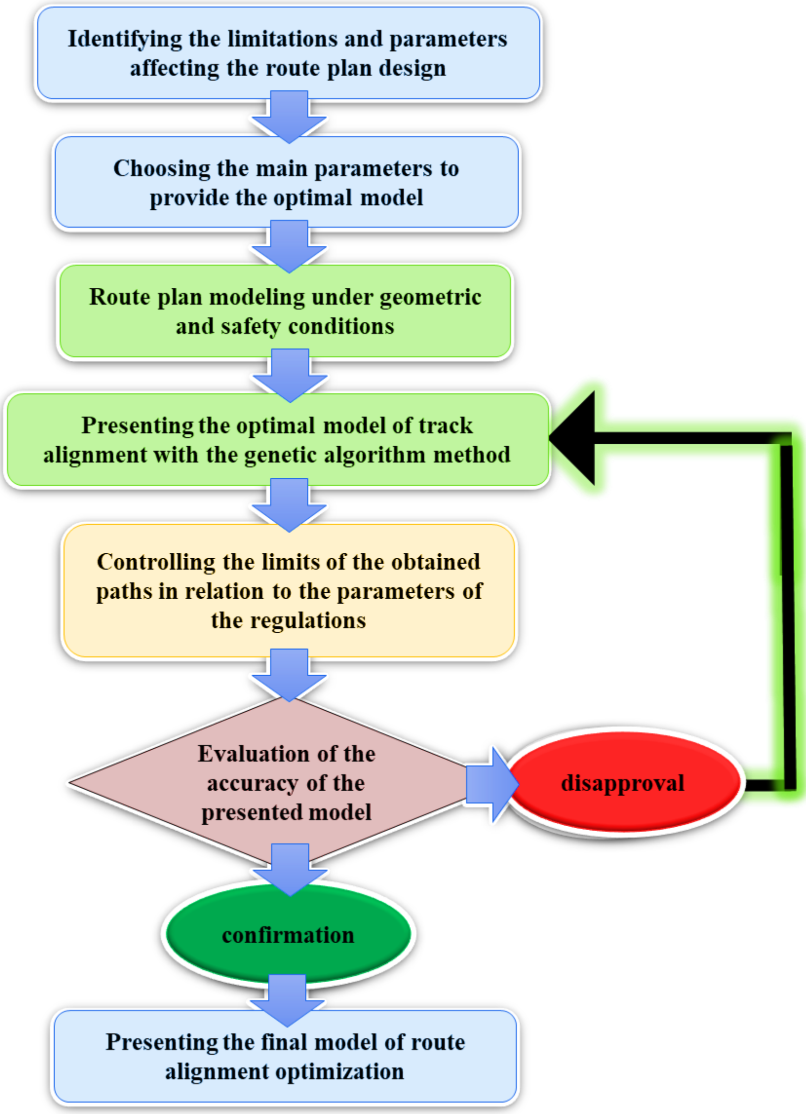

Figure 2. Flowchart of Research

n path design, the goal is to draw a path between two starting points O and ending D. The horizontal path that is planned should be a combination of straight sections (tangents), horizontal arcs and connecting arcs (Clothoid). (Fig. 3) If the proposed variant consists of N+1 tangent lines, we will have N vertices of the arc $v_i = (x_i . y_i)\ i = 1. \dots . N$, N simple circular arcs $R_i \geq 0 . i = 1, \dots, N$ and N central angles of the arc $\Delta_i \geq 0 . i = 1. \dots . N$ So for every N ∈ We will have N:

$$x^N = (x_1 . y_1 . R_1 . \Delta_1 . \dots . x_N . y_N . R_N . \Delta_N) \in R^{4N} \quad (1)$$

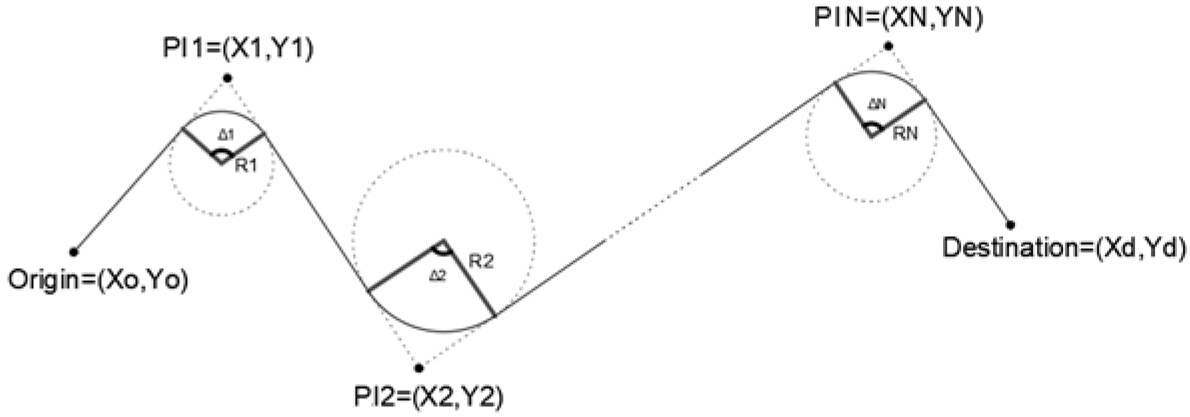

Figure 3. Horizontal path of communication between the starting point O and the end point D including the components of x^Nvectors and the execution path C_{x^N}

Therefore, in road design, the vector of decision-making variables to solve the alignment optimization problem is x^N. In addition, the execution alignment of the road, which will also include arcs, is in the form of $C_{x^N} \subset R^2$, which is specified by x^N. (Fig. 4)

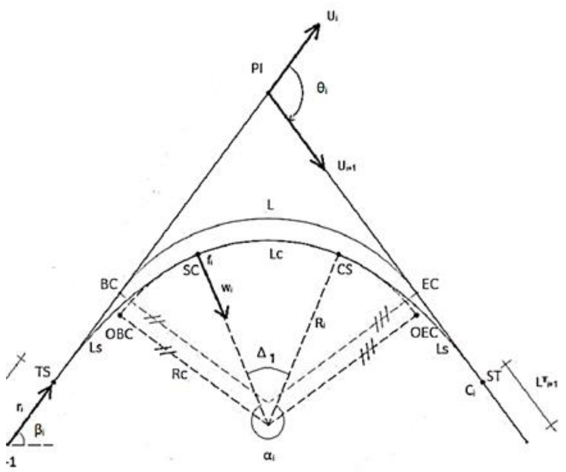

Figure 4. Contractual variables and vectors in the design of the horizontal alignment of the road

4.1.2. Safety Variables

Safety variables are of utmost importance in optimizing horizontal alignment as they directly impact the safety of road users. Factors like design speed, extreme height, and curvature radius significantly influence road safety. This paper explores the role of safety variables in genetic algorithm-based horizontal alignment optimization and their incorporation into objective functions and constraints to ensure safe and efficient solutions. Design speed, determined by safety levels, traffic volume, and roadside environment, can be maximized while meeting other objectives. The distance between consecutive horizontal arcs affects smoothness and continuity, and optimizing it considers driver visibility and stopping distance. Safety can be addressed using surrogate safety measures or direct integration of accident risk in the genetic algorithm through cost functions or constraints. Accident prediction models can estimate expected crash frequencies based on road geometry, allowing hybrid objective functions to combine safety considerations with construction cost and travel time. However, it is crucial to validate models and consider additional safety factors like traffic volume and driver behavior. A case study on Greater Tehran highways demonstrated the relationship between accidents and variables such as cross-section length and arc curvature. As a result, an accident occurrence variable with penalty imposition was incorporated into the path optimization objective function to enhance road safety.

4.1.3. Cost Variables

Environmental damage, air pollution, and the cost of land release are key cost variables that impact the optimization process using genetic algorithms. Firstly, environmental damage must be carefully considered during transportation infrastructure design, as road construction and operation can significantly affect wildlife habitats, water resources, and air quality. Genetic algorithms can be utilized to find design parameters that minimize the environmental impact of an alignment while meeting other objectives and constraints. Secondly, the optimization process should account for air pollution resulting from vehicle emissions, which can have adverse effects on public health and the environment. Genetic algorithms can identify design parameters that reduce vehicle emissions, optimize travel time, alleviate congestion, and enhance overall transport system efficiency. Lastly, the cost of land release is a crucial factor affecting route feasibility and cost-effectiveness. Genetic algorithms can identify design parameters that minimize land acquisition costs by optimizing the alignment to require less land or exploring alternative routes with reduced land acquisition needs. Overall, cost variables significantly influence horizontal path optimization using genetic algorithms and must be thoughtfully integrated into objective functions and constraints to ensure cost-effectiveness and environmental sustainability of the obtained solution.

4.2. Parametric Calculations of the Path Length

In the context of road alignment optimization, one critical aspect is the calculation of the path length. The path length refers to the distance traveled by a vehicle along the road, and it is influenced by several factors such as horizontal curvature, grade, and superelevation. Accurate parametric calculations of the path length are essential to determine the cost and lifespan of a road section accurately. In this study, we employ a genetic algorithm-based approach to optimize the horizontal road alignment based on parameters affecting its cost and lifespan, including the path length. By considering the path length as a critical parameter, we aim to develop an optimized road alignment that minimizes the overall construction and maintenance costs while ensuring a long lifespan for the road.

Considering that $C_{x^N} \subset R^2$ must be a combination of straight segments and circular curves connected by clothoids, the road alignment can be easily parametrized in terms of the arc length parameter. We assume that the alignment will start with a straight section $v_0 = c_0 = a$ and end $v_{N+1} = c_{N+1} = b$ in the same way. For i=0, 1, …, N and j=0, 1, ..., N+1 we will have:

- Run (the change in x from one to the other)

$$\Delta_x = x_j - x_{j-1} \quad (2)$$

- Rise (the change in y from one to the other)

$$\Delta_y = y_j - y_{j-1} \quad (3)$$

- The unit vector that gives the tangent direction of j

$$u_j(x^N) = \frac{1}{\|u_j\|} u_j \qquad u_j = (\Delta_x . \Delta_y) \quad (4)$$

$$\|u_j\| = \sqrt{(\Delta_x)^2 + (\Delta_y)^2} \quad (5)$$

- Tangent azimuth j

$$\Delta_{x_j} = x_j - x_{j-1} \quad (6)$$

$$\emptyset_j(x^N) = \begin{cases} acos(\Delta_y) & if \Delta_{x_j} \geq 0 \\ 2\pi - acos(\Delta_y) & if \Delta_{x_j} < 0 \end{cases} \quad (7)$$

- Azimuth difference between tangents i and i+1

$$\theta_i(x^N) = |\emptyset_{i+1}(x^N) - \emptyset_i(x^N)| \quad (8)$$

- The length of the circular arc i

$$L_i^c(x^N) = R_i(\theta_i(x^N) - \Delta_i) \quad (9)$$

- Length of each circulating clothoid i

$$L_i^S(x^N) = R_i \Delta_i \quad (10)$$

- The distance between the straight segment i and the start of rotation i (the start of the arc's clothoid) and thedistance between the end of rotation i (the end of the end of the arc) and the start of the straight segment i+1

$$C_i(x^N) = v_i - \left(\int_0^{L_i^C} cos\left(\frac{\tau^2}{2R_iL_i^S}\right)d\tau(x^N) + \left[\int_0^{L_i^C} sin\left(\frac{\tau^2}{2R_iL_i^S}\right)d\tau\right] tan\left(\frac{\theta_i - \Delta_i}{2}\right)(x^N) + \left[\frac{\int_0^{L_i^C} sin\left(\frac{\tau^2}{2R_iL_i^S}\right)d\tau}{cos\left(\frac{\theta_i-\Delta_i}{2}\right)}\right. + R_i\left|\left(\frac{sin\left(\frac{\Delta_i}{2}\right)}{sin\left(\frac{\pi-\Delta_i}{2}\right)}\right)(x^N)\, u_i(x^N)\right. \tag{11}$$

- The length of the straight section j (the distance of the direction from the end of the p.c j-1 to the start of j) where r j is a vector that starts at point C j-1 and ends at point t j

$$L_i^T(x^N) = r_j(x^N) \cdot u_i(x^N) \tag{12}$$

Considering $C_{x^N} \subset R^2$the following conditions must always be met:

1- The radii and central angles of simple circular arcs must be positive (non-negative).

$$R_i \geq 0;\ \Delta_i \geq 0;\ i = 0.1.\dots.N \tag{13}$$

2- The angles of simple circular arcs must be smaller than the difference in azimuths between the tangents on the sides of each turn.

$$\theta_i(x^N) - \Delta_i \geq 0;\ i = 0.1.\dots.N \tag{14}$$

Turn i+1 must start after the end of turn i.

$$L_j^T(x^N) \geq 0;\ i = 0.1.\dots.N+1 \tag{15}$$

With these explanations, the total length of the road is:

$$L_j(x^N) = L_1^T(x^N) + \sum_{k=1}^{j-1} 2L_k^S(x^N) + L_k^C(x^N) + L_{k+1}^T(x^N) \tag{16}$$

Despite meeting numerous above conditions, not all routes can be deemed acceptable for road design. Legal restrictions imposed by the laws of each country can significantly influence design elements. Constraints, such as limits on culvert lengths, restrictions on straight sections, prescribed distances between consecutive curves, and others, play a crucial role in determining the feasibility of a road alignment. Additionally, certain areas may be designated as unsuitable for the passage of the horizontal alignment, while others may be recommended for inclusion. Therefore, it is essential to address these constraints during the optimization process to ensure a well-designed and compliant road alignment.

4.3. Route Optimization Formulation

Generaly, all these limits that we mentioned above can be collected in a series Cad where: $C \subset R^2$. The Cad series depends on the specific problem we are dealing with. C is also an acceptable cutoff for the new way. Therefore, we define the series as follows:

$$X_{ad}^N = \left\{\begin{matrix} X^N \in R^{4N} \\ Conditions: 13 - 15\ \&\ C_{x^N} \in C_{ad} \end{matrix}\right\} \tag{17}$$

On the contrary, the primary objective of designing a road alignment is to optimize specific technical aspects, which include minimizing various factors such as road length, earthmoving operations, land acquisition and clearance costs, and environmental impacts, among others. The definition and calculation of the objective function for each practical application hold significant importance. To facilitate the search for a straightforward and universally applicable formula for this problem, we introduce the cost function as follows:

$$\begin{gathered} F: C_{ad} \to R\ \ \&\ \ CF^N: R^{4N} \to R \\ CF^N(x^N) = F(C_{x^N}) \end{gathered} \tag{18}$$

The problem of achieving the optimal design for the horizontal alignment that connects the initial point "O" and the final point "D" involves finding a solution where the cost function C_{x^N} attains its minimum value. The objective is to determine the most efficient alignment configuration that minimizes the overall cost associated with the road construction while ensuring a safe and reliable connection between the specified points.

$$\min_{x^N \in X_{ad}^N} CF^N(x^N) \tag{19}$$

The mathematical function F, represented by the series X_{ad}^N, is well-defined for any specific problem. However, obtaining an effective expression of the function F that comprehensively accounts for all associated costs can be challenging in numerous practical applications. For instance, considering the cost of earthworks based on the vertical alignment design can pose difficulties. In this article, the cost associated with each point in the domain is denoted by a function P(X,Y). Consequently, by summing the costs of all locations along the route, we arrive at the total cost of the project, expressed as below. In addition, the parametric expression C_{x^N} in the execution path including arcs, the objective function J^N is defined as follows:

$$F(C) = \int_C p(x.y)\, d\sigma \tag{20}$$

$$CF^N(x^N) = \int_0^{L(x^N)} p(\sigma_{x^N}(s))\, ds \tag{21}$$

The concept of price, denoted by the function P serves as a versatile model encompassing a wide array of possibilities, including economic factors (such as land release costs, asphalt expenses, and earthworks), environmental and ecological considerations, as well as political aspects. This cost function can also be utilized as a penalty mechanism for certain points, thereby simplifying the Cad set by incorporating regions where the design should not be included in the objective function. Additionally, P(X,Y) can be formulated as a weighted sum, representing a combination of various price components.

Obtaining a P-function, akin to an F-function, can be a complex task when attempting to encompass all potential costs. However, in certain straightforward applications, defining the P-function may prove relatively straightforward. In this article, we provide an illustrative example of optimizing an alignment, where the P-function is easily defined, showcasing its practical applicability.

The consideration of the price function P as a versatile model that encompasses a wide range of possibilities, including economic, environmental, ecological, and political factors, plays a crucial role in the optimization of horizontal road alignment. By incorporating the cost function, the design process can effectively address various constraints and penalties associated with specific points, ultimately leading to a more efficient and feasible road alignment.

While obtaining a comprehensive P-function may pose challenges in applications involving numerous costs, simpler cases, like the one presented in this article, demonstrate the ease with which the P-function can be defined and utilized for alignment optimization.

Overall, the integration of the cost function P and its role in the optimization process highlight the significance of considering multiple parameters to achieve an optimal road design that balances economic efficiency, environmental sustainability, and safety. This approach ensures the successful implementation of road projects that meet both engineering standards and regulatory requirements, paving the way for more effective and sustainable transportation infrastructure.

4.4. Objective Function

Route optimization aims to achieve a dual objective, encompassing the reduction of both construction costs and overall route expenses during lifespan. From the perspective of road users, the ideal route design should entail minimal costs in terms of travel-time expenditure, vehicle operation, and accident-related expenses. Conversely, the governmental authorities seek to establish a path with the lowest toll charges, construction costs (including paving), and maintenance expenditures. However, it is often challenging to find a proposed route that can fully optimize both of these objectives simultaneously. In such instances, the designer aims to provide a set of optimized routes, each representing different trade-offs between the aforementioned objectives. As a result, both construction costs and route expenses need to be minimized concurrently, giving rise to the following mathematical formulation:

$$\min f(PI_1, PI_2, \ldots, PI_n) \quad (22)$$

The PI variables are integral components of the problem's objective function, as they play a crucial role in determining the optimal path. Consequently, these PI variables directly impact the various costs associated with the route. Hence, the costs are considered as indirect functions of the path PIs. This distinctive relationship between the PI variables and costs renders the challenge of multiple path optimization a unique and intriguing problem within the domain of multiple optimization.

The genetic algorithm possesses a remarkable capability to handle multi-dimensional and multi-objective optimization problems. In the context of multi-dimensional optimization, this algorithm effectively conducts a simultaneous search across multiple variables' solution space. Similarly, in multi-objective optimization scenarios, the genetic algorithm adeptly identifies multiple optimal solutions within the solution space. In light of these advantages, this paper utilizes the genetic algorithm to address the problem at hand. The approach involves creating an initial variant between the specified starting and ending points, and subsequently designing the corresponding arcs, while adhering to defined arc vertex points and constraints. The optimization process then focuses on reducing project costs while taking into account paramount factors such as safety and environmental considerations.

This research utilized MATLAB to implement a genetic algorithm aimed at optimizing design parameters while adhering to specific design constraints. The genetic algorithm employed a population of candidate solutions, which underwent evaluation based on their fitness, i.e., how well they satisfied the design requirements. By employing selection, crossover, and mutation operators, the genetic algorithm generated a new population of candidate solutions, iteratively refining them over successive generations. Each candidate solution is represented using a coding scheme based on coordinates derived from Important Points (PIs), which encompass both the start and end points, as well as other relevant points along the path. The genes present in the chromosomal structure encode the decision variables, forming the basis for the optimization process.

Moreover, a multiple random point crossover technique is utilized to exchange a segment or segments of genes between two individuals, resulting in the formation of two offspring. During this process, the entire gene code, consisting of X and Y coordinates, within the identified segments is swapped between the parent individuals.

In this paper, the costs mentioned above are combined linearly to formulate the total cost (C_{Total}), and the objective of the process is to minimize C_{Total}:

$$\min(C_{Total} = \sum_{i=1}^{n} C_i) \quad (23)$$

Where C_i represent each individual cost component such as geometric, safety and other costs that mentioned above. Different combinations of the fitness function could also be considered for the optimization process.

5. Study Area

The objective of this study is to determine the optimal horizontal alignment between two origin and destination points, taking into account environmental considerations, cost parameters, and safety indicators. The study area is the Bandar-e Anzali bypass highway, a 16-kilometer-long highway located on the southern side of the city and between the Caspian Sea and the Anzali International Wetland in Guilan province, Iran. This region is of high importance due to its economic, tourism, political, military, and cultural significance. (Fig. 5)

The Bandar-e Anzali bypass highway is part of the 700-kilometer-long Astara-Gorgan highway, which is considered an important transportation axis in Iran. Despite the fact that the construction of this highway started in 1998, it is still only 50% physically advanced.

Therefore, the study and review of the existing 16-kilometer route of the highway will be effective in evaluating the current situation and improving the remaining parts.

A portion of the 16-kilometer route of the highway passes through the connection point of the Anzali International Wetland to the Caspian Sea. Failure to follow environmental considerations along the way can have destructive effects on this delta, including increasing erosion of the wetland's watershed, changing the use of its marginal lands, heavy vehicle traffic, noise pollution, and air pollution caused by passing traffic. Anzali International Wetland is a biosphere reserve and one of the most valuable aquatic and coastal ecosystems in Iran, which is registered in the list of wetlands with severe ecological changes in the "Montreux" list of the Ramsar International Convention. This wetland has the ability to attract tourists, wetland plants as a natural refinery, and fresh water storage resources for irrigation and agriculture. Additionally, it is the habitat of some migratory birds, the spawning place of all kinds of aquatic animals, and the factor of attracting floods and preventing flooding of the urban area.

To determine the optimal horizontal alignment of the highway, road design data was collected from consulting engineers (Table 1). Then, important variables affecting the route design were determined, and the optimality of the route was evaluated using the genetic algorithm model. After studying and checking the generated information, the optimal route was presented as the final proposed option. This optimized route is considered the shortest and most economically suitable path between the two points in the study area on the edge of Anzali Lagoon, with the least consequences and biological hazards for the region.

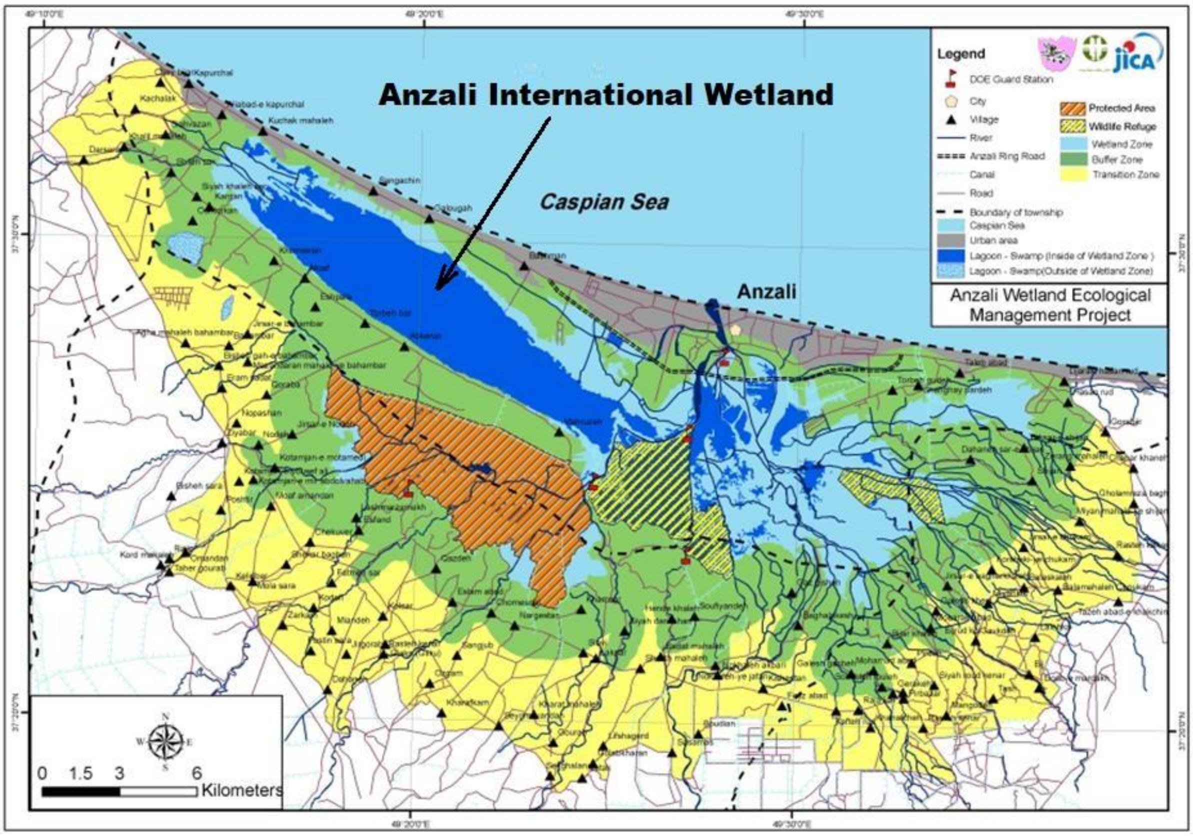

Figure 5. Study area zone: Bandar Anzali international wetland environment

Table 1. Data collected from the study area

Number of PIs	$PI_i = (x_i . y_i)$	R_i	Δ_i	Curve Lenght	Tangent Lenght	Other Properties
Start Point	000.00,3801.73	-	-	-	-	Design Speed
					429.74	110 Kmph
PI 1	397.79,3359.20	1500	12.58	329.26		Total Curvatre
					4814.49	25%
PI 2	4651.96,327.99	700	38.41	469.28		Total Tangent
					311.12	75%
PI 3	5558.61,374.55	3000	13.42	702.54		Road Boundary
					1466.92	38 m
PI 4	7583.90,000.00	2000	13.68	477.39		Highwy Class
					1110.90	Median Divided
PI 5	9105.70,085.04	2000	9.02	346.16		Environment
					224.61	Int. Wetland
PI 6	9701.11,024.39	1000	22.67	395.64		Lane NO.
					1060.27	2 / Line
PI 7	11058.77,435.63	1000	17.94	313.15		Physical Situaion
					1655.77	51%
PI 8	13236.97,394.17	700	55.07	672.82		Longitudinal Sploe
					380.74	±1%
End Point	13675.48,997.30	-	-	-		Topography
					-	Flat

6. Discussions and Results

In this section, we present the methodology for optimizing the horizontal alignment of an existing road using the genetic algorithm. The objective is to upgrade the old road, which has been under construction for a long time, and align it with current design rules, such as the use of connecting arches, maximum radius restrictions in arcs, and length of straight segments. Our goal is to design a new horizontal alignment connecting points O and D while making use of the old design and adhering to legal restrictions. For this purpose, we assume that the old plot of the graph of a function is known:

$$y_{old}: [x_{in}, x_{end}] \subset R \to R. \quad O = (x_{in}, y_{old}(x_{in})) \quad D = (x_{end}, y_{old}(x_{end})) \tag{24}$$

The first step is to compile the Cad series with all the constraints that the new design must meet and determine X_{ad}^N. This step is problem-specific and will be further elaborated on in the case study of the Bandar-e Anzali bypass presented in the next section.

Next, we define an objective function that evaluates the quality of each alignment. If our goal is to make use of the existing road as much as possible, we assign a price to each point based on its distance y from the old road. Points that lie on the old road are assigned a price of zero (0), while points whose distance y exceeds a certain maximum range dmax are assigned a price of one (1). For other points, we use a monotonically increasing function of the distance y as the price. The cost function P(X,Y) is akin to a valley along the old road. If the new design deviates from the old route (y>dmax), we charge an equal cost for each new section built while aiming to minimize the length of the horizontal alignment (Fig. 6).

$$p(x.y) = p_{y_{old(x)}}(y) \quad . \quad y_0 \in R \tag{25}$$

$$\Delta_y = y - y_0 \tag{26}$$

$$a = \left(\frac{\sqrt{2}}{d_{max}}\right)^2, b = \left(\frac{1}{d_{max}}\right)^4 \tag{27}$$

$$p_{y0}(y) = \begin{cases} a\Delta_y^2 - b\Delta_y^4 & if\ y < y_0 \pm d_{max} \\ 1 & if\ y \geq if\ y < y_0 \pm d_{max} \end{cases} \quad (28)$$

We apply this method to optimize a section of the Bandar-e Anzali bypass highway, which was previously designed in the 1970s as a two-way road with a crossing lane on each side. Later, it was revised in the mid-1990s and converted into a median divided highway in 2007 due to increased traffic needs. However, despite the passage of over 23 years since the start of construction, half of the project remains incomplete. Therefore, we aim to optimize the alignment to update it from its initial design while considering the impact on the environment around the track. The plan of the Bandar-e Anzali bypass variant based on the contractual coordinates of this article and its satellite map are shown in Fig. 7.

Figure 6 shows the environmental constraints around the route that need to be considered during optimization. The Bandar-e Anzali bypass road boundary is 38 meters on both sides of the axis, and an additional 100 meters is considered as the construction boundary on the southern side. The national railway boundary is approximately 100 m from the vicinity of the road boundary in the northern part of the route, which is considered the limit of the northern development. We assume a corridor of 138 meters on both sides of the road (2dmax) as the width of the optimization area.

In order to apply our methodology to this particular case, we perform the following steps:

Step 1: We determine the allowed set of X^N according to the restrictions that the new plan must provide. In this paper, we assume that the radius of all circular curves should be at least 300 meters, the length of clotuids should be between 80 and 450 meters, the length of each circular arc should be between 85 and 1300 meters, and the straight segments should be between 100 and 2500 meters.

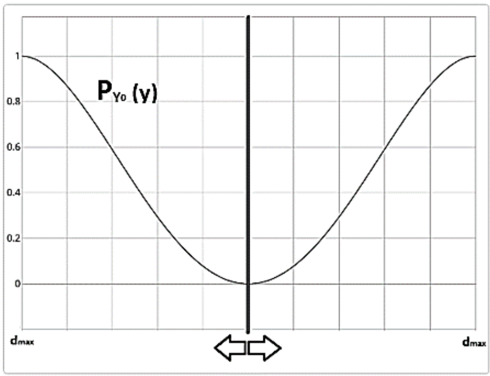

Figure 6. Cost Function

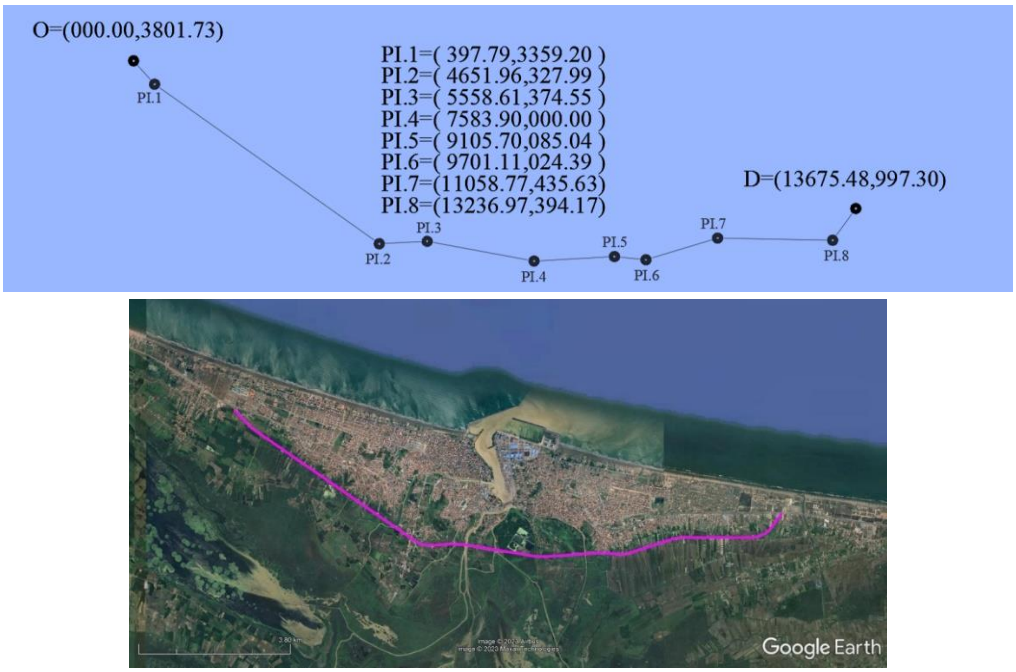

Figure 7. Anzali bypass based on the contractual coordinates of this article and its satellite map

To apply our methodology to this specific case, we undertake the following steps:

Step 1: We establish the permissible set of X^N based on the constraints imposed by the new plan. For this study, we assume that the radius of all circular curves must be no less than 300 meters, the length of clothoids should range from 80 to 450 meters, the length of each circular arc should fall between 85 and 1300 meters, and the straight segments should be within the range of 100 to 2500 meters.

According to Regulation No. 161 of the Plan and Budget Organization (Journal of Geometric Design of Roads), certain restrictions must be taken into account. For a design speed of 110 km/h, the minimum radius of horizontal arcs should range from 415 to 635 meters (depending on the elevation and friction coefficient). However, given that the radius of the existing arches of the Bandar-e Anzali bypass exceeds 700 meters, we set the minimum radius at 700 meters, which is slightly greater than the 635 meters stipulated by the aforementioned regulation.

In terms of the bend length, a radius limit of 150 to 1000 meters has been proposed for two-lane roads, while no limit has been established for four-lane roads. Additionally, arcs with a radius greater than 6000 meters can be designed as a parabola. Hence, we aim to set the radius of circular arcs up to 6000 meters. The minimum radius of the arc that requires a clothoid arc to ensure safety and ease of driving is 1000 meters and 1700 meters at design speeds of 80 km/h and 100 km/h, respectively. Consequently, by interpolation, this radius value for a speed of 110 km/h is equivalent to 2050 meters, which we round down to 2000 meters for ease of design. The minimum length of the clothoid is also taken into account, and we consider it as 200 meters for a speed of 40 km/h.

The TRB1195 regulation recommends the minimum and maximum length of the tangent between two arcs, with the minimum being proportional to the functional speed of traffic flow and the maximum related to driver fatigue, estimated to be roughly between 6 and 20 times the design speed of the route. However, AASHTO does not provide a specific value for this parameter. For a design speed of 110 km/h, the minimum distance between two turns in the same direction should be 600 meters, which corresponds to 660 to 2200 meters for a design speed of 110 km/h. Additionally, a maximum of 3000 meters is suggested to mitigate the risk of driver fatigue. Therefore, for the sake of simplicity and ease of design, we can consider the minimum and maximum values to be between 600 meters and 2500 meters.

Therefore, the outputs will be evaluated with the limits. At the same time, there is no limit for other beginning and ending parts outside of it.

Step 2: From the coordinates of a number of points of the old route and its execution maps, we will have the function of the old route. In some cases, it is possible to use the interpolation of points to obtain a cubic spline.

Step 3: We consider the value of d_{max}=0.1km from the old $\mathbf{y_{old}}$ route made in step 2. Based on formula 25, we present the cost function p(X,Y) and based on formula 21, J^N.

Step 4: Based on the acceptable series X_{ad}^N in step 1 and the CF^N function in step 3, for each N=0, 1,..., solve problem by using programming in the MATLAB environment and using the genetic optimization algorithm we show.

To ensure that the problem is solved correctly, it is crucial to adhere to a set of constraints. Failure to do so can lead to false solutions. Several important constraints can help to expedite the problem-solving process and guide the solution towards optimality. These include: (1) defining the interval for the start and end of the proposed routes, (2) defining the corridor width with a maximum value of 2dmax, and (3) restricting the number of PIs for the new alternative route to the existing axis.

As indicated in Table 2, the optimal option for improving the alignment is the one with four turns (N = 4). The corresponding optimal designs are illustrated in Fig. 8-a. An examination of the figure and the data reveals that an increase in the number of turns results in a better fit with the old design. When N = 1, and only one turn is permitted, the optimal solution is located at the intersection of the longest straight segment of the old route. Moreover, it should be noted that the first proposed alignment led to greater infiltration in the wetland bed (to the south).

Finally, in Fig. 8-b, we compare the current road improvement with our proposed solution for N = 4. The results show that both designs are in close proximity to each other. This finding is significant and suggests that the proposed method can be an effective approach for addressing road modification in the road reconstruction projects presented in this section.

8-a) All suggested variants

8-b) Suggested alignment by N=4 PIs

Figure 8. Output alignments of Optimization

7. Conclusions

Designing a road is a multifaceted and challenging undertaking. The increasing concern for safety, environmental impact, and irreparable costs resulting from improper road design necessitates a flexible, dynamic, and sustainable framework for improving road and environmental indicators. Traditional design methods and decision-making models based solely on human expertise and intuition are inadequate for maintaining safety, environmental compatibility, and comprehensive optimization. Therefore, there is a need for an algorithm that can provide optimal road alignment based on full parameterization, interpretation of costs, and the ability to address various problems while reducing potential environmental and safety risks.

In this study, we proposed a genetic algorithm-based optimization method to obtain the optimal alignment design for the Bandar-e Anzali bypass highway. The results confirm the effectiveness of the proposed method in achieving the optimal alignment, thereby reducing road costs and increasing safety. The obtained results also support the potential of this method to improve the quality of road improvement in road reconstruction projects, particularly in areas of high environmental importance. Furthermore, the proposed method can be extended to the design of the vertical alignment of roads or both horizontal and vertical alignments.

However, optimizing complex objective functions that include technical road specifications as well as environmental impacts can be challenging. Hence, the genetic algorithm optimization technique can be an effective solution for addressing these problems. In conclusion, this study has demonstrated the potential of genetic algorithm-based optimization for the design of horizontal road alignment, and further research can be conducted to explore the application of three-dimensional techniques for optimizing both horizontal and vertical alignments.

Table 2. Numerical results obtained to solve the problem

	Number of PIs	$v_i = (x_i . y_i)$	R_i	Δ_i	Curvature Percentage	Tangent Percentage	L_{Total}	CF
i = 1	1	5769.45, -393.67	5.02	0.80	27%	73%	14.93	7.12
i = 2	2	5026.62,176.74	4.70	0.59	32%	68%	14.91	4.10
		10518.48, -024.76	5.79	0.35				
i = 3	3	4271.75, 470.96	1.92	0.52	20%	80%	14.96	2.09
		7583.90,000.00	2.86	0.20				
		11357.42, 210.52	5.29	0.27				
i = 4	4	4241.77,508.27	1.87	0.51	14%	86%	14.99	1.03
		7369.23,032.65	2.23	0.15				
		9701.11,024.39	3.56	0.13				
		12608.95,406.13	0.95	0.38				
i = 5	5	397.79, 3359.20	0.83	0.22	26%	74%	15.00	2.53
		4651.96,327.99	3.18	0.51				
		7583.90,000.00	2.96	0.24				
		11058.77,435.63	5.44	0.14				
		13236.97,394.17	0.70	0.96				
i = 6	6	397.79, 3359.20	0.80	0.22	17%	83%	15.15	1.98
		4651.96,327.99	1.25	0.51				
		7583.90,000.00	3.27	0.12				
		9701.11,024.39	0.85	0.28				
		11058.77,435.63	1.13	0.31				
		13236.97,394.17	0.75	0.96				

	Number of PIs	$v_i = (x_i . y_i)$	R_i	Δ_i	Curvature Percentage	Tangent Percentage	L Total	CF
		397.79, 3359.20	0.70	0.22				
		4651.96,327.99	0.70	0.67				
		5558.61,374.55	3.04	0.23				
i = 7	7	7583.90,000.00	3.16	0.19	27%	73%	15.16	1.53
		9701.11,024.39	3.87	0.28				
		11058.77,435.63	1.21	0.31				
		13236.97,394.17	0.70	0.96				

8. References

- Babapour, R., Naghdi, R., Ghajar, I., & Mortazavi, Z. (2018). Forest road profile optimization using meta-heuristic techniques. Applied Soft Computing, 64, 126-137. https://doi.org/10.1016/j.asoc.2017.12.015

- Biancardo, S. A., Avella, F., Di Lisa, E., Chen, X., Abbondati, F., & Dell'Acqua, G. (2021). Multiobjective Railway Alignment Optimization Using Ballastless Track and Reduced Cross-Section in Tunnel. Sustainability, 13(19), 10672. https://doi.org/10.3390/su131910672

- Casal, G., Santamarina, D., & Vázquez-Méndez, M. E. (2017). Optimization of horizontal alignment geometry in road design and reconstruction. Transportation Research Part C: Emerging Technologies, 74, 261-274. https://doi.org/10.1016/j.trc.2016.11.019

- Jha, M.K., Schonfeld, P., Jong, J.-C., & Kim, E. (2006). Intelligent Road Design. In Advances in Transport Series (Book Series 19). Hardback. ISBN 978-1-84564-003-3. Morgan State University, USA; University of Maryland, USA; Sinotech Engineering Consultants Inc., Taiwan, R.O.C.; University of Incheon, South Korea. 448 pages. https://www.witpress.com/books/978-1-84564-003-3

- Kang, M.-W., Jha, M., & Schonfeld, P. (2012). Applicability of Highway Alignment Optimization Models. Transportation Research Part C-Emerging Technologies, 21. https://doi.org/10.1016/j.trc.2011.09.006

- Khalil, N., Mhanna, M., & Assaf, H. (2021). Horizontal corridor optimization of highway using GIS & CFSC method in mountainous areas. The Egyptian Journal of Remote Sensing and Space Science, 24(3), 509-514. https://doi.org/10.1016/j.ejrs.2021.08.008

- Lee, Y., Tsou, Y.-R., & Liu, H.-L. (2009). Optimization Method for Highway Horizontal Alignment Design. Journal of Transportation Engineering-ASCE, 135, 217. https://doi.org/10.1061/(ASCE)0733-947X(2009)135:4(217)

- Mondal, S., Lucet, Y., & Hare, W. (2015). Optimizing horizontal alignment of roads in a specified corridor. Computers & Operations Research, 64, 130-138. https://doi.org/10.1016/j.cor.2015.05.018

- Pu, H., Cai, L., Song, T., Schonfeld, P., & Hu, J. (2023). Minimizing costs and carbon emissions in railway alignment optimization: A bi-objective model. Transportation Research Part D: Transport and Environment, 116, 103615. https://doi.org/10.1016/j.trd.2023.103615

- Rouhi Mashhadsari, A., & Behzadi, G. (2023). New Optimization Approach for Handling Imbalanced Data in Road Crash Severity. International Journal of Transportation Engineering, 10(3), 1089-1102. doi:10.22119/ijte.2021.311028.1593

- Safarzadeh, M., Mehrazzin, H., & Mirzabrojerdian, A. (2006). Optimal corridor

routing model of road and railway route design in plain areas. Journal of Technical Faculty 40(5), 665-651.
https://www.sid.ir/paper/14319/fa

- Shaw, J.F.B., & Howard, B.E. (1981). Geometric Design of Highways. Transportation Research Record, 806, 8-13. ISSN: 0361-1981. http://onlinepubs.trb.org/Onlinepubs/trr/1981/806/806-002.pdf

- Shaw, J.F.B., & Howard, B.E. (1982). Geometric Design of Highways. Journal of Transportation Engineering, 108(TE3), 227-243. ISSN: 0733-947X. American Society of Civil Engineers.
https://ascelibrary.org/journal/jtepbs

- Song, T., Schonfeld, P., & Pu, H. (2023). A Review of Alignment Optimization Research for Roads, Railways and Rail Transit Lines. IEEE Transactions on Intelligent Transportation Systems.
https://doi.org/10.1109/TITS.2023.3235685

- Sushma, M., & Maji, A. (2017). Optimization of horizontal highway alignment using a Path Planner method. WIT Transactions on the Built Environment.

- Sushma, M., & Maji, A. (2020). A modified motion planning algorithm for horizontal highway alignment development. Computer-Aided Civil and Infrastructure Engineering, 35, 818 - 831.
https://doi.org/10.1111/mice.12534

- Wan, F. (1995). Introduction to the Calculus of Variations and Its Applications (2nd Edition). Chapman & Hall. ISBN 9780367449247. 656 pages. Published December 3, 2019.
https://www.routledge.com/Introduction-To-The-Calculus-of-Variations-And-Its-Applications/Wan/p/book/9780367449247

- Yu, K., Yu, Q., Huang, W., & Hu, Y. (2022). Safety-Based Optimization Model for Highway Horizontal Alignment Design. Mathematical Problems in Engineering, 2022.
https://doi.org/10.1155/2022/6214910

- Zhang, H., Pu, H., Schonfeld, P., Song, T., Li, W., Wang, J., Peng, X., & Hu, J. (2020). Multi-objective railway alignment optimization considering costs and environmental impacts. Applied Soft Computing, 89, 106105.
https://doi.org/10.1016/j.asoc.2020.106105

- Zhang, T., Gao, Y., Gao, T., Schonfeld, P.M., Wu, Y., Zhu, Y., Yang, S., Wang, P., & He, Q. (2023). A sequential exploration algorithm for the design optimization of horizontal road alignment. Computer-Aided Civil and Infrastructure Engineering, 38, 2049 - 2071.
https://doi.org/10.1111/mice.12990