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Research Article

Balancing Environmental and Economic Considerations in Horizontal Alignment Optimization of a Ring Road near Anzali International Wetland

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Abstract
Roads are the primary transportation infrastructure of every country and play a crucial role in achieving sustainable economic development. Neglecting environmental considerations in civil engineering projects, especially in the design and construction of roads, can cause extensive damage to human societies and ecosystems. One of the most critical issues in road design is selecting an optimal alignment that minimizes changes to land use, preserves wetlands, forests, and agricultural land, and provides a platform for sustainable development. This decision has a significant impact on the execution, operation, and maintenance costs of the route, as well as its surrounding geography. This research examines the optimal horizontal alignment between two desired starting and ending points, taking into account environmental factors, construction cost parameters, and safety indices in the Anzali ringroad highway area. 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 algorithm 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 14.991 kilometers. This alignment is compatible with the environment and has significantly lower greenhouse gas emissions, resulting in a cost savings of 3.7 million dollars compared to the initial alignment. It is a desirable and shorter horizontal alignment between two points in one of the important areas of the Ramsar International Convention (Anzali).
Keywords: Anzali International Wetland, Environmental impact assessment, Genetic algorithm, Horizontal alignment optimization, Road design

Introduction

The development of the transport road network plays an important role in the economic development of a country (Aldagheiri, 2009). Transportation networks play a significant role in the social and economic development of a region. The various modes of travel from one point to another and the provision of services from door to door make roads much more flexible compared to other modes of transportation such as air and sea traffic. In road design, there are two important aspects: (a) the design of the route and the geometric design of the road, and (b) the design of the road pavement structure. Both aspects are important and play a crucial role in the economic valuation of large projects. The route design is the first step in the road design

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process. Then, based on the selected route's geographic specifications, environmental conditions, soil type, and expected traffic, the road pavement is designed.

On the other hand, disregarding environmental considerations in civil engineering projects, especially in road design and construction, will have extensive impacts on human communities and plant and animal species. The development of transportation, especially the development of communication roads, has had a destructive impact on the environment, particularly in the construction of roads in sensitive ecosystems, protected areas, and especially in the study area of this research, which is the international Anzali wetland. One of the most significant impacts of improper road design and construction is the reduction and fragmentation of habitats, noise pollution caused by passing vehicles, pollution of groundwater and surface water resources, and particularly rivers and wetlands located within the path and similar areas.

Optimal road alignment design can reduce the destructive impacts and save project costs. We must remember that road construction projects are different from other economic and civil projects because they are mainly of considerable length, and environmental sensitivity may change during the route. Therefore, the impacts of road construction can be extensive. This important issue can be divided into several parts: physical and chemical effects, including air pollution, noise pollution, water pollution, and adverse effects on soil. These projects are executed on the natural soil structure of the region and may cause soil erosion, destruction, and soil structure change. Also, the presence of pollution and destruction endangers plants and animals along the path, and their lives are increasingly at risk. If the region where the road is constructed is near a protected environmental area, such as the Anzali wetland, it can have irreparable effects on the surrounding area and reduce its environmental value.

In road construction projects, there are environmental impacts both during the construction and operation phases. This is because they provide a route for the passage of vehicles, which are the main cause of air pollution. However, if this route is designed with thorough environmental studies and routing, it can lead to reduced fuel consumption and air pollution. Soil erosion and drainage ditch destruction, soil pollution, environmental disruption, destruction of vegetation cover, topographic destruction of the area, and damage to the animal ecosystem are other environmental effects of improper road project implementation.

In terms of highway engineering, arc sections, tangent sections, and the connections between them (length of connection or clothoid) are the main components of the horizontal alignment. Route design is usually carried out separately from horizontal and vertical profiles. The design method in this article is based on a two-dimensional optimization approach. Road design is not just the geometric path design, but also aspects such as earthwork operational costs, road maintenance costs, road construction costs, vehicle transportation costs, accident costs, and travel time costs. From a financial perspective, the best route is the one with the minimum cost. In addition to these costs, other factors such as environmental, historical, induced demand, social, economic, and political dimensions also affect effective route design. It may not be possible to accurately compare all of these variables from an economic standpoint. Therefore, designing a low-cost route may not be possible for some cases.

Achieving the design of an alignment may often not lead to the best possible option, as there are countless proposed alignments for connecting two desired points that will be based on the engineers' judgment. However, automatic methods reduce design problems, potential errors in manual design methods, and issues such as this significantly, allowing for the use of optimization techniques to search for the best route. In the early 1970s, Turner and Miles proposed the idea of network optimization for modeling the pathfinding problem. (Turner, 1970) So, mathematical modeling and optimization techniques are powerful tools seeking optimal alignment. (Casal et al, 2017) Some of these various methods proposed in some studies over the past few decades include differential calculus, network optimization, dynamic programming, numerical search, genetic algorithm (GA), and geographical information systems (GIS).

In this research, taking into account environmental considerations, the cost parameters of soil construction and safety indicators, the optimal horizontal alignment between two initial and final points was investigated. The study area is the sixteen-kilometer Bandar-e Anzali ring road highway under construction. First, alignment design data was collected from consulting engineers. Then, with consideration of these data and other influential routing indicators, important variables affecting alignment design were determined, and the optimization of the horizontal alignment was evaluated using the genetic algorithm model pattern. Finally, after studying and analyzing the generated information, the optimal alignment was presented as the final proposed option. This alignment is the shortest and most suitable optimal economic route between two points in the study area near the Anzali wetlands in a way that this optimization has fewer biological consequences and risks for the region."

Literature Reviwe

The optimization of road design has been a topic of interest for several decades. With the advent of modern computers and GIS technology, solving mathematical models to minimize the cost of road construction has become more accurate and efficient. However, despite the numerous optimization models proposed, there are still practical limitations that hinder their application. In recent years that marks the start of a new “Decade of Action for Road Safety” (World Health Organization, 2021), sustainability factors have been increasingly considered in road design optimization to achieve more sustainable road infrastructure.

The horizontal alignment of a road, which is crucial for maintaining vehicle stability, can be optimized using mathematical search models based on minimizing the total objective function cost while adhering to existing geometric design constraints. The literature review on sustainability assessment and environmental impact assessment of road construction projects highlights the importance of incorporating sustainability factors in road design optimization to balance environmental, economic, and social factors (Padash, 2017). In addition, the Sustainable Development Goals (SDGs), commonly referred to as the Global Goals, were formally adopted by the United Nations in 2015. The SDGs represent a comprehensive and universal call to action intended to safeguard the planet and foster sustainable development worldwide. (United Nations, 2015)

Umer et al. (2016) conducted a review of sustainable best practices for transportation infrastructure development and management, identifying a need for an improved sustainability assessment tool. They developed a roadway sustainability assessment framework based on fuzzy synthetic evaluation (FSE) technique, which was implemented in an Excel-based tool called Green Proforma. The tool enabled expert-based sustainability assessment through the decision-making phases of a roadway project, incorporating imprecise benchmarks and inputs, and different prioritization of indicators and sustainability objectives depending on stakeholder experience and project constraints. The tool provided a "Roadway Project Sustainometer" to illustrate sustainability indices across objectives and the overall sustainability index of the project. Scenario analysis was performed to evaluate the impact of expert opinion on the model's outputs. The Green Proforma tool was capable of handling uncertainties associated with imprecise benchmarks and inputs, with customizability in benchmarking and prioritizing sustainability criteria. However, the tool had limitations, such as the capability to model the relationship of criteria to multiple objectives and a lack of indicators demonstrating long-term sustainability.

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.

Inti and Kumar (2021) develop a sustainable road network in Northeast India, which is challenging due to various factors such as rough terrain, inclement weather, budgetary constraints, and lack of skilled workforce. The study proposes a hybrid multi-objective optimization model integrating the multi-objective particle swarm optimization with the crowd distance technique and the K-means clustering strategy for sustainable road design. The proposed approach was demonstrated by designing a road suitable for Northeast India, and the results indicated that the model generated sustainable designs by optimizing the budgetary and environmental limits and workforce competence. The study highlights the importance of balancing multiple goals and limitations in the sustainable development of roads and how multiple optimization techniques can be incorporated in the design of sustainable highways. The proposed approach can assist highway engineers in evaluating multiple options and making informed decisions, and can be adapted to a wide range of construction applications.

Karimipour et al. (2021) aimed to evaluate the impact of route optimization of heavy vehicles on fuel consumption and greenhouse gas (GHG) emissions. The study utilized Network Analyst in ArcGIS to simulate optimized distances for two piloted trucks, a waste collector and a tree maintenance truck, in Blacktown City, Australia. The study compared the regular routes of the trucks to the optimized distances, using Fuel Consumption Rate (FCR) and GHG emissions to quantify the amount of fuel usage and GHG emitted from heavy vehicles in the optimized routes versus their regular paths. The results showed that using the optimized route instead of the regular one reduced the distance driven by the tree maintenance truck by 60%, fuel consumption by 62%, and GHG emissions by 62% per month. In addition, the optimized route showed a 10% reduction in distance travelled, 11% in fuel consumption, and 10% in GHG emissions per month. The study suggests that implementing an efficient vehicle routing system can have significant impacts on reducing fuel consumption and GHG emissions from heavy vehicles, and future studies can explore the results of route optimization on fleets of heavy vehicles.

Kazancoglu et al. (2021) evaluate greenhouse gas (GHG) emissions from different types of road transport vehicles in four European countries, as transportation is one of the main reasons for increasing GHG emissions. The study used grey prediction to estimate the amount of GHG emissions for each road transport vehicle in each country, and the numerical results were used to suggest implications for reducing GHG emissions and meeting sustainable development conditions. The study highlights the importance of GHG emission estimation as the initial step to evaluate the current status of countries and presents a base for future studies on GHG emissions in road transportation. The study emphasizes the need for new policies to reduce and prevent GHG emissions to promote sustainable development and mitigate negative environmental impacts caused by human activities.

You et al. (2022) propose a multi-objective optimization model for highway horizontal alignment design that considers both safety and economy. The model was found to reduce the annual average number of accidents and horizontal alignment length, improving road safety and economics. The optimization model could be developed as a road alignment optimization program or embedded in current computer-aided design software, reducing debugging work and the influence of designer subjectivity. However, the model had limitations, including oversimplified safety and economic objective functions and suitability for the design stage only. Future research should focus on establishing more comprehensive safety and economic evaluation indicators and using machine learning or big data analysis to establish more accurate traffic accident prediction models. These insights highlight the need for further research to improve the comprehensiveness and accuracy of safety and economic indicators in highway horizontal alignment design optimization.

Abbasi et al. (2022) in the study of environmental impact assessment (EIA) to evaluate the impacts of a road network in the Kheyrud forest, Iran used the Geocybernetic Assessment Matrix (GAM) criteria to assess the environmental, social, and economic impacts of road construction by obtaining scores from experts who have observed the problems associated with road construction in the three stages. The results showed that road construction had negative impacts on the environment, especially during the construction phase, but social and economic services, especially after road construction, left the total geocybernetic score in a range of 0 to 121, indicating very weak unsustainability. The study highlights the importance of using EIA tools such as GAM to assess the environmental, social, and economic impacts of road construction and ensure the sustainability of projects.

Jiang et al. (2022) focuesd on sustainable road alignment planning in the built environment, where the planning process needs to consider multiple factors such as engineering, traffic, economic, social, and environmental factors. The study proposes a method based on the MCDM-GIS method and the least-cost wide path algorithm to consider building demolition and land use, traffic congestion, noise impact, air pollution impact, and construction costs. Road width, new road construction, and existing road widening are considered simultaneously, and forbidden areas and road buffer areas for road widening are defined. The method is implemented in road planning in Dartford, Kent County, UK. The study highlights the importance of considering various sustainable factors in road alignment planning in the built environment and how road widths can significantly influence road alignments. The proposed method provided a comprehensive approach for sustainable road alignment planning in the built environment, taking into account various constraints and factors.

Cantisani et al. (2022) aimed to improve the capacity and level of service, reduce delays, and decrease emissions caused by queues for redesign of a congested three-level intersection in Italy. Four scenarios were investigated and designed using the Civil 3D tool, and VISSIM 11 was used to simulate their operational performances, while SimaPro was used to assess carbon footprints and estimate construction, maintenance, and usage costs. The proposed 7D BIM methodology consists of geometrical, environmental, and microsimulation approaches to implement a benefit-cost analysis useful for decision-makers. The results showed that the best scenario involved the construction of new overpasses and underpasses to eliminate crossing conflict points, reduce merging and diverging ones, and link directly the busiest arms. This study demonstrates the potential of using BIM-based optimization methods to improve the efficiency and sustainability of road intersections while reducing costs.

Song, et al., (2023) investigated on a literature review of alignment optimization (AO) research for roads, railways, and rail transit lines, highlighting the significant role of alignment determination in the life-cycle performances of these transportation infrastructures. They noted that manual work is time-consuming and laborious, prompting the development of intelligent AO. The authors presented the first-known literature review paper in this field from the past 25 years, starting with a bibliometric visualization to show overall characteristics of AO research. They reviewed existing mathematical models that formulate AO problems, including GIS-based applications, and discussed intelligent solution methodologies for solving AO models. Two specific research topics were provided, including concurrent optimization of railroad alignments and station locations, as well as existing alignment recreation and redesign. Finally, the authors proposed 12 possible research extensions and directions in this realm.

Jiang et al. (2023) conducted updated research based on the development of a systematic framework for sustainable urban road alignment planning that considers functional, economical, people-friendly, and eco-friendly schemes to meet traffic-related demands and promote social development. The study employed a systematic literature review, two rounds of questionnaire surveys using the Delphi method, three focus groups, and questionnaire surveys for multi-criteria decision making (MCDM) to determine the factors that should be considered, digitalisation and parsing methods, factor evaluation, and road alignment generation. The considered factors include traffic, development, cost, social, environmental, and engineering factors, and several digitalisation and parsing methods for the factors are proposed. The MCDM-GIS method using the least-cost wide path analysis is suggested for road alignment generation, and the importance of the factors is evaluated by experts using MCDM. The proposed framework provided a comprehensive approach for sustainable urban road alignment planning, taking into account various factors and providing a systematic process for generating road alignments.

Han et al. (2023) addressed the trade-off between driving safety and construction economy, and the proposed framework was applied to a real-world design project of the Phnom Penh-Sihanoukville highway. The framework utilized a fast and reliable parameterization method for road alignment, BIM technology for modeling and earthworks statistics, and automated driving simulation using MATLAB to quantify driving safety. The results showed that the proposed optimization method achieved a combined improvement of 6.6% compared to expert design results. This study highlights the potential of BIM-based optimization frameworks in achieving cost savings and improving driving safety in road alignment design.

The literature review on sustainability assessment and environmental impact assessment of road construction projects has emphasized the importance of incorporating sustainability factors in road construction projects. The reviewed studies have provided various approaches and tools to assess the sustainability performance of road infrastructure, identify key environmental impact categories, and suggest mitigation measures to reduce the negative environmental impact of road construction projects. However, there is a need for more standardization and consistency in sustainability assessment and environmental impact assessment practices. Incorporating sustainability factors in the road design process can help decision-makers balance the trade-offs among environmental, economic, and social factors and contribute to the broader goals of sustainable development.

One area that has received less attention in previous studies is the optimization of road alignment from both the perspective of modifying the geometric design of the route and the effects of incorrect route design on the environment. In this context, a new study has presented an optimal horizontal alignment that considers both sustainable road infrastructure and lower greenhouse gas emissions using a genetic algorithm. This approach highlights the need for a holistic approach that considers both environmental and economic factors in road design optimization and supports the broader goals of sustainability.

Methodology

Design variables

In road design, the goal is to draw a path between two starting points (a) and ending (b). The horizontal alignment that is designed should be a combination of straight sections (tangents), horizontal arcs and connecting arcs (clothoid). If the proposed variant consists of $N+1$ tangent lines, N arc vertices $v_i = (x_i . y_i)\ i = 1. \dots . N$, N simple circular arcs $R_i \geq 0. i = 1. \dots . N$ and We will have N central angles of the arc $\Delta_i \geq 0. i = 1. \dots . N$. Therefore, for each $N \in N$ we have (Figure 1):

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

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 (Figure 2).

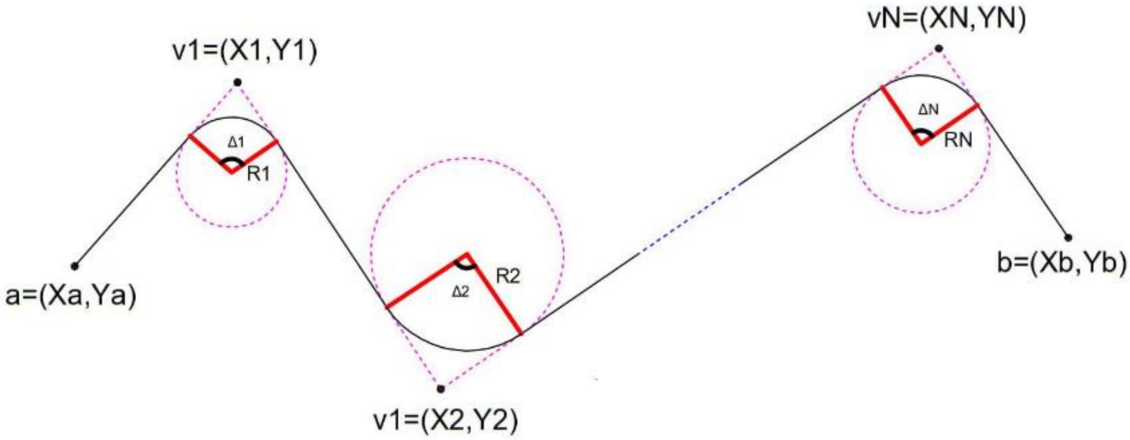


Figure 1. The horizontal alignment of communication between the starting point (a) and the end point (b), including the components of the x^N vectors and the execution path C_{x^N}

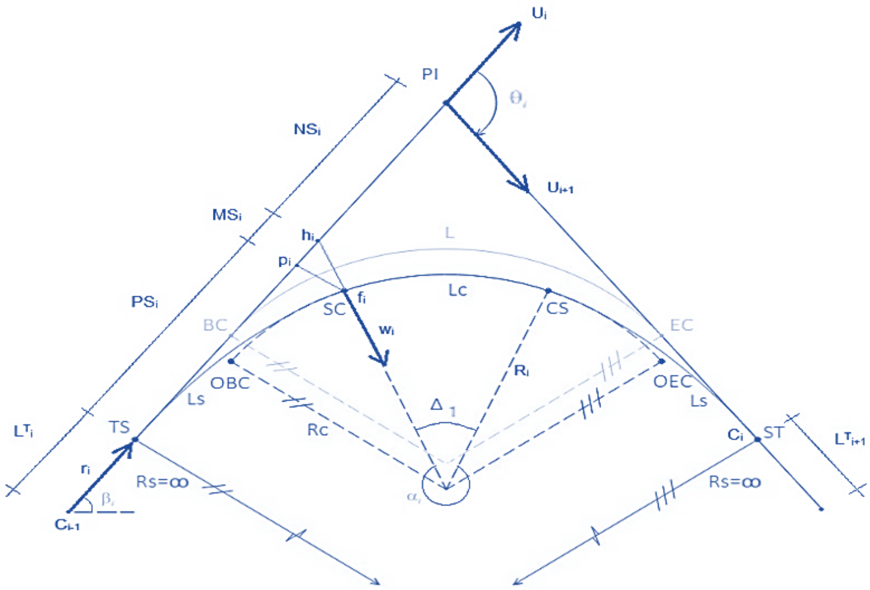


Figure 2. Contractual variables in the design of the horizontal alignment of the road

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:

- The unit vector that gives the tangent direction of *j*

$$u_j(x^N) = \frac{(x_j - x_{j-1}.y_j - y_{j-1})}{\sqrt{(x_j - x_{j-1})^2 + (y_j - y_{j-1})^2}} \quad (2)$$

- Tangent azimuth j

$$\emptyset_j(x^N) = \begin{cases} acos(y_j - y_{j-1}) & if\ x_j - x_{j-1} \geq 0 \\ 2\pi - acos(y_j - y_{j-1}) & if\ x_j - x_{j-1} < 0 \end{cases} \quad (3)$$

- Azimuth difference between tangents i and i+1

$$\theta_i(x^N) = |\emptyset_{i+1}(x^N) - \emptyset_i(x^N)| \quad (4)$$

- The length of the circular arc i

$$L_i^C(x^N) = R_i(\theta_i(x^N) - \Delta_i) \quad (5)$$

- Length of each circulating clothoid i

$$L_i^S(x^N) = R_i\Delta_i \quad (6)$$

- The distance between the straight segment *i* and the start of rotation *i* **(**the start of the a rc's clothoid**)**

$$t_i(x^N) = v_i - (\overline{tp_i}(x^N) + \overline{ph_i}(x^N) + \overline{hv_i}(x^N))u_i(x^N) \quad (7)$$

$$PS_i = \int_0^{L_i^C} cos\left(\frac{\tau^2}{2R_iL_i^S}\right)d\tau \quad (8)$$

$$\overline{pf_i} = \int_0^{L_i^C} sin\left(\frac{\tau^2}{2R_iL_i^S}\right)d\tau \quad (9)$$

$$MS_i = \overline{pf_i}\ tan\left(\frac{\theta_i - \Delta_i}{2}\right) \quad (10)$$

$$NS_i = \left(R_i + \frac{\overline{pf_i}}{cos\left(\frac{\theta_i - \Delta_i}{2}\right)}\right)\frac{sin\left(\frac{\Delta_i}{2}\right)}{sin\left(\frac{\pi - \Delta_i}{2}\right)} \quad (11)$$

- The distance between the end of rotation *i* (the end of the end of the arc) and the start of the straight segment *i+1*

$$C_i(x^N) = v_i - (PS_i(x^N) + MS_i(x^N) + NS_i(x^N))u_i(x^N) \quad (12)$$

- The length of straight segment *j* (orientation distance from the end of turn *j-1* to the start of *j*) where r_j is the vector that starts at point C_{j-1} and ends at point t_j

$$L_i^T(x^N) = r_j(x^N) \cdot u_i(x^N) \quad (13)$$

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).

$$R_i \geq 0;\ \Delta_i \geq 0; i = 0.1. \dots . N \quad (14)$$

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

$$\theta_i(x^N) - \Delta_i \geq 0;\ i = 0.1. \dots . N \quad (15)$$

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

$$L_j^T(x^N) \geq 0;\ i = 0.1. \dots . N + 1 \quad (16)$$

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

$$L_j(x^N) = L_1^T(x^N) + \sum_{k=1}^{j-1} 2L_k^S(x^N) + L_k^C(x^N) + L_{k+1}^T(x^N) \quad (17)$$

Even if all the aforementioned conditions are met, it cannot be conceded that any route is acceptable. For example, the laws of each country usually have legal restrictions on design elements. Constraints such as limits on culvert lengths or restrictions on straight sections, limits on distances between two consecutive curves, and the like. Other common constraints exist due to the presence of certain areas that the horizontal alignment should not pass through or in some others where passage through them is recommended. In general, all these limits can be collected in a series C_{ad} where: $C \subset R^2$. The C_{ad} 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:

$$X_{ad}^N = \{X^N \in R^{4N}\ .\ Conditions\colon 3-5\ .\ C_{x^N} \in C_{ad}\} \tag{18}$$

On the other hand, the goal of designing an alignment is to optimize certain technical aspects such as minimizing length, earthmoving operations, land acquisition and clearance costs, environmental impacts, and so on. Defining and calculating the objective function in each practical application is very important. In order to search for a simple and general formula for the problem, we introduce the cost function as follows:

$$F\colon C_{ad} \to R$$

$$J^N\colon R^{4N} \to R \tag{19}$$

$$J^N(x^N) = F(C_{x^N})$$

The problem of optimal design of the horizontal alignment connecting the initial point *a* and the final point *b* includes solving this problem, in such a way that C_{x^N} it has the lowest value:

$$\min_{x^N \in X_{ad}^N} J^N(x^N) \tag{20}$$

The mathematical function F, like the series X_{ad}^N, is known for any particular problem. To obtain a good expression of the function F (taking into account all available costs) can be a difficult task in many practical applications. As an example, the cost of earthworks is considered according to the vertical alignment design. In this article, each point of the domain has a cost in the form of a function *p(X,Y)*. Therefore, by adding the price of all the places that the route passes through, we have the total cost of the project as follows:

$$F(C) = \int_C p(x.y)\, d\sigma \tag{21}$$

The parametric expression C_{x^N} in the execution path including arcs, the objective function J^N is defined as follows:

$$J^N(x^N) = \int_0^{L(x^N)} p(\sigma_{x^N}(s))\, ds \tag{22}$$

The concept of price, represented by the function p, should be considered as a general function that models a wide range of possibilities; such as economic issues (price of land release, cost of asphalt, earthworks, etc.), environmental issues, ecological issues, or political issues. This cost can also be considered as a penalty for passing certain points, which allows to simplify the C_{ad} set by including points where the design should not enter the objective function. Finally, p(X,Y) can also be a combination (weighted sum) of different types of prices.

Obtaining a P-function, as it happens with an F-function, can be difficult if we want to consider all available costs. However, in some simple applications, the function P can be easily defined, as in this article we will follow an example of optimizing an alignment.

Research Process Flowchart

This article aims to develop an optimization method for horizontal alignment design that can provide a set of design options from a stage in the design process. Horizontal alignment optimization minimizes land acquisition costs, earthmoving costs, road construction costs, travel time costs, vehicle operating costs, safety-related costs, and environmental costs as objectives.

To achieve this goal, the following steps will be taken to provide the best road optimization model, as shown in the Figure 3.

The multi-objective optimization problem discussed in this thesis is solved using a genetic algorithm. The decision variables for the objective function are formulated as Performance Indicators (PIs). Variants are determined by PIs and they, in turn, affect the performance. However, the objective function, which is the cost function in this case, cannot be formulated as a function of PIs. In common multi-objective optimization problems, the objective functions are functions of decision variables. Therefore, a special multi-objective GA process is used to solve this particular problem.

PI coordinates are encoded in chromosomes. Therefore, the alleles of each chromosome (the control genes of a trait) are continuous real numbers defined in the search space of the defined problem.

The cost of construction and operation for each route created by the coordinate information stored in the alleles of chromosomes is evaluated. Based on the fitness values, non-dominated and dominant solutions are classified.

Separate selection pressures are applied to non-dominated and dominated solutions based on the overall ranking of costs. The next generation of chromosome sets is produced by crossing over and mutation of the main solution set. Thus, this process is used to generate offspring solutions to achieve an optimal solution.

Findings

Introducing the case study

This study aims to identify the optimal candidate for routing between two origin and destination points. The proposed model is implemented through a case study in Iran, specifically in Bandar-e Anzali, a city located in Gilan province in northern Iran, with approximate geographical coordinates of 36.4°N and 41.48°E (in zone 39S).

Bandar-e Anzali, as the second most populous city in Guilan, is one of the most densely populated cities in Iran with a humid and moderate climate. It is also the rainiest city in Iran. Due to its location adjacent to the international Anzali wetland in the southern part of the city, along with its large port and long history, and commercial relationships with other parts of the world, especially Europe, it has become renowned as the gateway to Europe.

Anzali, with its unique and ancient history, is one of the active regions among the coastal countries of the Caspian Sea and the largest northern port of the country. It is distinguished from other ports in the region by having multi-purpose warehouses, various terminals, and the most modern unloading and loading equipment, making it the first equipped traffic area of this port.

After the collapse of the Soviet Union, the coastal countries of the Caspian Sea and the Caucasus region became important in regional and global equations. This coincided with the post-war reconstruction period in Iran and the beginning of the country's development era, during which Iran sought to enter the global economy and acquire capital, new knowledge, and technology by creating free zones in the country. In this regard, the Anzali Free Trade Industrial Zone was established in 2003.

Given the unique position of Bandar-e Anzali from an economic, tourist, political, military, and cultural perspective, the transportation infrastructure in this geographical area plays a critical role (Figure 4).

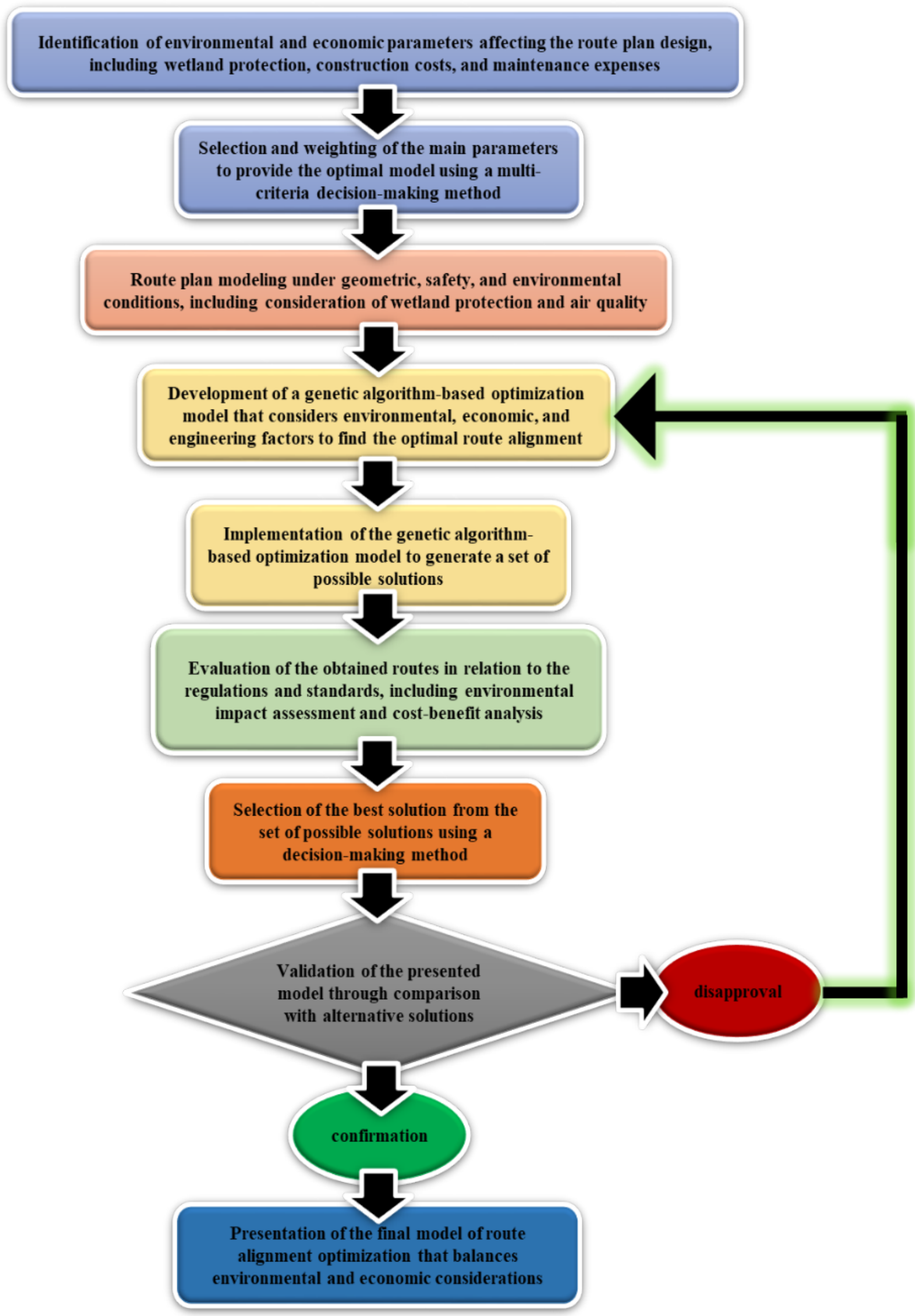


Figure 3. Research process flowchart

The Anzali International Wetland is a biosphere reserve and one of the most valuable blue and coastal ecosystems in Iran. It is registered in the "Montreux" list of the Ramsar Convention as one of the wetlands with severe ecological changes and is located in the aforementioned study area. This wetland has the potential to attract tourists, and its marsh plants act as a natural purifier and a source of freshwater resources for irrigation and agriculture. It is also a habitat for some migratory birds, a spawning ground for various fish species, and a factor in attracting floods and preventing urban flooding in the area (UNESCO, 1971).

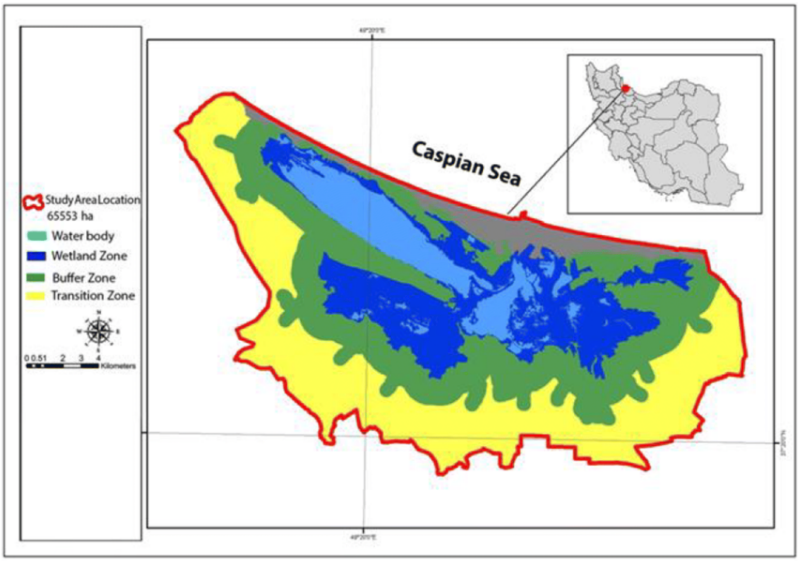


Figure 4. The location of Bandar-e Anzali ring road in Guilan province (Badamfirooz and Mousazadeh, 2019)

The existing road used in this case study is the Bandar-e Anzali beltway, which is a highway approximately 16 kilometers long located on the southern side of the city and between the Caspian Sea and the Anzali International Wetland.

It should be noted that this 16-kilometer road is part of the 700-kilometer-long North-South corridor known as the Astara-Gorgan highway, which is considered one of the important transportation axes in Iran. Currently, most of its sections have been constructed, and by completing the remaining parts, suitable connectivity will be created on the shores of the Caspian Sea. Despite the fact that the construction of this beltway began in 1998 and is still 50% physically incomplete, studying and evaluating its current situation and improving its remaining parts will be effective.

Part of the highway route is under construction passing through the point where the wetland is connected to the sea. If environmental considerations are not taken into account in the route, it will have destructive effects on this delta.

Increased erosion in the Anzali watershed, land-use changes in its margins, heavy traffic, noise pollution in the area, and air pollution caused by passing traffic are some of the effects that need to be controlled and managed (Figure 5).


Figure 5. Dangerous environmental conditions in the bed of Anzali lagoon

Mathematical Modeling

In this section, we use the general formula proposed in section 3-1 to improve an existing road. We assume that the road is an old construction that has been extended for many years and needs upgrading, and the design must comply with current laws (for example, the feasibility of using connecting arcs, maximum radius limitations in arcs, length of straight sections, etc.).

The goal here is to design a new horizontal alignment that connects points A and B as much as possible by utilizing the old design and complying with legal constraints. To achieve this, we assume that the old design is represented by a known function:

$$y_{old}\colon\ [x_{in}.x_{end}] \ \subset R \rightarrow R. \qquad (23)$$
$$a = (x_{in}.y_{old}(x_{in}) \quad . \quad b = (x_{end}.y_{old}(x_{end})$$

Obviously, the first step involves compiling the C_{ad} series with all the constraints that the new design must meet. Then we determine X_{ad}^{N}. This work should be done for each specific problem, and in the next part of this series, we will specify the specific case study of the Bandar-e Anzali ring road.

In the second step, we define an objective function that provides the quality of each alignment. If our goal is to use as much of the existing road as possible, this can be done by setting a price for each point using the distance y from the old road: a price of zero (0) for all points that are on the old road (points In the new design that intersects the plan of the old road), the price of one (1) for all points whose distance y exceeds a certain maximum range d_{max} (beyond this value, the old road is no longer usable and is harmful to the environment In order to acquire more lands and surrounding nature, more damage will be done) and for other places, the price is a monotonous increasing function of the distance y. In addition, in order to use a derivative-based optimization method to solve problem 20, we suggest:

$$p(x.y) = p_{y_{old(x)}}(y) \qquad y_0 \in R \qquad (24)$$

$$p_{y0}(y) = \begin{cases} \frac{2}{d_{max}^2}(y-y_0)^2 - \frac{1}{d_{max}^4}(y-y_0)^4 & if\ y_0 - d_{max} \le y < y_0 + d_{max} \\ 1 & Other\ cases \end{cases} \qquad (25)$$

The cost function P (X,Y) is like a valley along an old road. If the new design abandons the old route (if the distance **y** is greater than d_{max}), a new highway must be built, and we charge an equal cost for each new section built (we ignore other costs and are just careful to minimize the design length of the horizontal alignment).

Now we apply this method to the optimization problem of Bandar-e Anzali ring road alignment. To test the proposed method, we chose a part of Bandar-e Anzali ring road highway. This road was previously designed in the 1970s and before the Islamic Revolution of Iran as a two-way road with a crossing lane on each side. Later, it was revised in the mid-1990s and started working in 1999. Later, while the executive operations of its construction were still in progress, due to the increase in the traffic needs of the region, by the order of the project employer (Ministry of Roads and Urban Development-Deputy of Road Construction and Development), the two-way majour rural road under construction was converted into a median devided highway in 2007. At the same time, despite the passage of more than 23 years since the start of executive operations, half of the physical building of this project still remains. Therefore, we decided to put its optimization on the agenda for decades to pass from its initial design. By mentioning the important point that according to Fig. 6., the changes should not end at the expense of the environment around the track.

Bandar-e Anzali ring road boundary is equal to 38 meters on both sides of the axis, and on the southern side, 100 meters more is considered as construction boundary. On the other hand, in the northern part of the route, the national railway boundary is considered at a distance of approximately 100 km from the vicinity of the road boundary, which will be considered as the limit of the northern development. We assume that there is a corridor that we consider from the north and south equal to 138 meters from each side (the total width of the corridor is equal to $2d_{max}$) (See Figure 7 and Figure 8).

Figure 6. Environmental constraints around the route to change and optimize the road variant

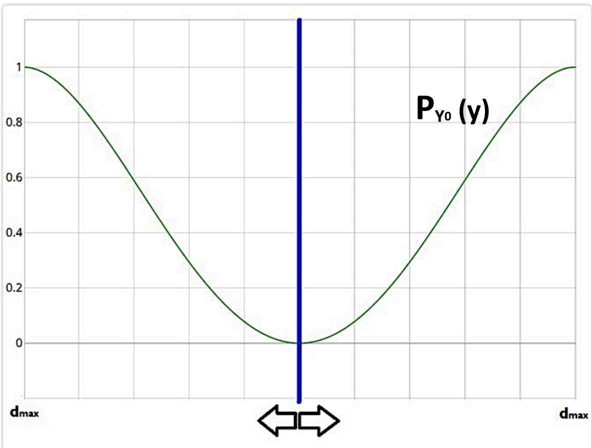


Figure 7. Function of operational and environmental costs according to equation

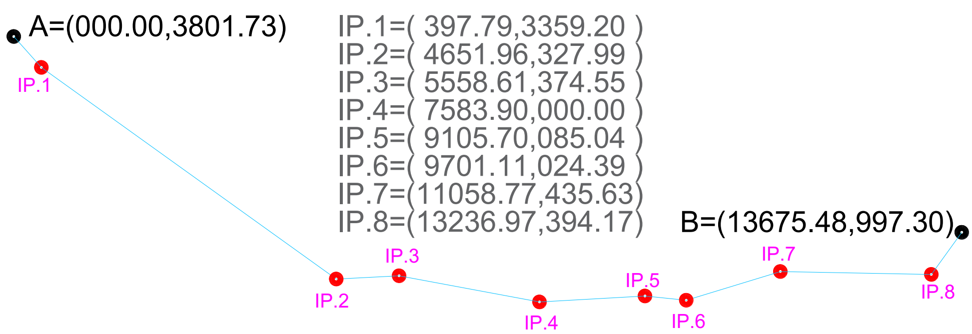


Figure 8. The plan of the old ring road of Bandar-e Anzali based on the contractual coordinates of this article

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.

$$X_{ad}^{N}=\left\{X^{N}\in R^{4N}\quad /\begin{array}{c}0.700\leq R_i\leq 6000\\ \theta_i(X^N)-\Delta_i\geq 0.1\\ 0.200\leq L_i^S(X^N)\leq 2000\\ 0.150\leq L_i^C(X^N)\\ 0.600\leq L_j^T(X^N)\leq 2.500\end{array}\ .\ \begin{array}{c}i=1.\cdots.N\\ j=1.\cdots.N+1\end{array}\right\} \tag{26}$$

According to regulation number 415 of the Planning and Budget Organization (Road Design Journal), certain constraints must be considered. For a design speed of 110 kilometers per hour, a value between 415 and 635 meters is considered as the minimum radius for horizontal curves (depending on the gradient and friction coefficient) in the mentioned regulation. Since the radius of the current curves in the Bandar-e Anzali beltway is larger than 700 meters, we consider the minimum radius to be 700 meters, which is slightly higher than 635 meters in the regulation. Regarding the length of the spiral, the radius constraint ranges from 150 to 1000 meters for two-lane roads, and there is no limit for four-lane roads. Also, curves with radii greater than 6000 meters can be designed as a compound curve. Therefore, we aim to keep the radius of circular curves up to 6000 meters. The minimum radius of a clothoid curve, which is necessary for safety and driving comfort, is considered to be 1000 meters and 1700 meters for design speeds of 80 and 100 kilometers per hour, respectively. Therefore, by interpolation, this radius for a design speed of 110 kilometers per hour will be equivalent to 2050 meters, which we consider as 2000 meters for ease of design. The minimum length of the clothoid curve is also considered to be 200 meters for a design speed of 40 kilometers per hour.

TRB1195 recommends a minimum and maximum tangent length between two curves, where the minimum is proportional to the operational traffic speed, and the maximum is related to driver fatigue, ranging from about 6 to 20 times the design speed. However, AASHTO has not suggested a specific value for this issue. For a design speed of 110 kilometers per hour, the minimum length of the tangent between two consecutive curves in the same direction should be 600 meters. This value will be equivalent to 660 to 2200 meters for a design speed of 110 kilometers per hour. However, a maximum of 3000 meters is also suggested to prevent driver fatigue. Therefore, to simplify the design process, the minimum and maximum lengths can be considered between 600 and 2500 meters. Thus, the outputs will be evaluated based on these constraints. However, there are no constraints for other initial and final sections outside of these limits.

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

Step 1: 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 as shown in Figure 9.

Step 2: We consider the value of *dmax=0.1* km from the old yold route made in step 2. Based on formula 26, we present the cost function *p(X,Y)* and based on formula 22, *JN*.

Step 3: Based on the acceptable series X_{ad}^{N} in step 1 and the JN function in step 3, for each *N=0,1,...*, solve problem 20 by using programming in the MATLAB environment and using the genetic optimization algorithm.

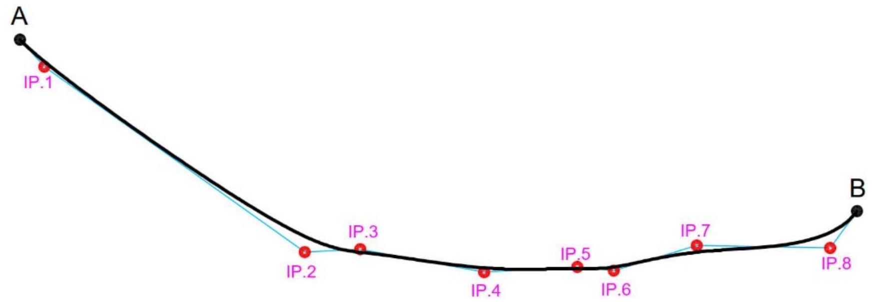


Figure 9. The spline of the Bandar-e Anzali ring road is based on the interpolation of the coordinate points of the existing route

After this stage, environmental pollution indices resulting from road construction are added. So far, there is no specific framework for improving the quality of road design based on environmental preservation in design guidelines. While road design guidelines such as the American Association of State Highway and Transportation Officials (AASHTO) and the Highway Capacity Manual (HCM) exist, they have not adequately addressed the environmental impacts of roads. For example, the HCM is a widely used reference for highway design in the United States, but it does not explicitly consider environmental factors such as air quality and noise pollution in the design process. Instead, the HCM focuses on maximizing the capacity and efficiency of highways, with an emphasis on minimizing travel time and delay for vehicles (American Association of State Highway and Transportation Officials, 1994; Wang et al, 2016). Although the HCM acknowledges the importance of considering environmental factors in the design process, it does not provide specific guidance on how to do so. Similarly, the AASHTO Green Book, another important resource for road design, lacks emphasis on environmental considerations (American Association of State Highway and Transportation Officials, 2011; Tumlin, 2012).

In other words, current road design guidelines do not fully address the environmental effects related to geometric highway design. However, there is growing recognition of the importance of considering environmental factors in the design process, and efforts are underway to develop more sustainable and environmentally compatible road design guidelines (et al., 2023, Nodoushan et al., 2022; BagherzadehKouhbanani et al., 2022). Therefore, credible research studies are necessary in order to achieve this goal.

In this section, we intend to examine the impact of horizontal geometric design and vehicle performance on fuel consumption and the emission of pollutants produced by passenger cars after optimizing the road alignment. The results of studies show that travel distance, rate of change of path curvature, and average speed have a significant impact on the average fuel consumption and air pollutant emissions. Finally, different regression models based on these variables are used to estimate fuel consumption [l/100 km] and pollutant emissions [gr/km]. These results can serve as a basis for incorporating principles of environmental sustainability into road design guidelines, as the current guidelines do not consider the environmental impact of geometric highway design.

In this study, the final goal is based on the analysis of how the optimization of the geometric design of the highway affects fuel consumption and the emission of important pollutants. As a result, from the nonlinear regression models presented in previous similar studies to estimate fuel consumption and greenhouse gas emissions including CO_2 (Leroutier & Quirion, 2022; Jin et al, 2016), NO_x (Selleri et al, 2016), $PM_{2.5}$ (Meng et al., 2022; Tunno et al, 2016) and CO (Moussa, 2022) are calibrated and used in Bandar-e Anzali ring road. The basic hypotheses of this research are:

- Road design affects fuel consumption and emissions, as it strongly affects driver performance.

- Fuel consumption and greenhouse gas emissions increase on winding roads.
- As the speed of drivers increases, fuel consumption and emissions increase.

With these explanations, non-linear regression models show the relationship between geometric design, vehicle speed and air pollution using four formulas that emit carbon dioxide (CO_2), nitrogen oxides (NO_x), particulate matter ($PM_{2.5}$) and carbon monoxide. (CO) we present. In these models, v is the speed of the vehicle in kilometers per hour (km/h) and L is the length of the road in kilometers (km). In addition, the effect R of the road radius in kilometers (km) was ignored due to its very small effect on the emission production.

- Carbon dioxide (CO2) emissions

$$CO_2\left(\frac{\mathrm{gr}}{\mathrm{km}}\right) = \mathrm{L} \times (0.059V^2 + 0.246\mathrm{V} + 0.101) \tag{27}$$

This formula estimates CO2 emissions from light vehicles on roads with different grades, curves and radii. The coefficients of 0.059, 0.246, and 0.101 depend on the road grade, horizontal curvature, and vehicle speed, respectively, and L is the length of the road segment in kilometers.

- Emission of nitrogen oxides (NOx)

$$NO_x\left(\frac{gr}{km}\right) = L \times (0.115V^2 + 0.083V + 1.265) \tag{28}$$

This formula estimates NOx emissions from heavy-duty diesel trucks on roads with different grades, curves, and radii. The coefficients of 0.115, 0.083, and 1.265 depend on the road grade, horizontal curvature, and vehicle speed, respectively, and L is the length of the road segment in kilometers.

- Release of suspended particles (PM2.5)

$$PM_{2.5}\left(\frac{gr}{km}\right) = (1 + 0.013V) \times (0.302L + 0.355) \tag{29}$$

This formula estimates PM2.5 emissions from light vehicles on roads with different grades, curves and radii. The coefficients of 0.302 and 0.355 depend on the grade of the road, and the coefficient of 0.013 indicates the effect of vehicle speed on emissions.

- Carbon monoxide (CO) emissions

$$CO\left(\frac{gr}{km}\right) = L \times (0.0002V^2 + 0.03V + 0.23) \tag{30}$$

This formula estimates CO emissions from light vehicles on urban roads with different grades and road radii. The coefficients of 0.0002, 0.03 and 0.23 depend on road grade, vehicle speed and acceleration, respectively, and L is the length of the road section in kilometers.

To develop a cost model based on the presented emission formulas, we need to consider the cost of greenhouse gas emissions in terms of their impact on the environment and public health. One approach is to use the "social cost of carbon" (SCC), which is a measure of the economic damage associated with each ton of pollutant emissions. SCC is usually expressed in dollars per ton of pollutant emissions. According to the United States Environmental Protection Agency, the SCC in 2020 is estimated to be equal to the following values. Using these values, we can create a cost model for each of the emission formulas as follows:

- 51$ per metric ton of CO_2 emission
- 2,410$ per metric ton of NO_x emissions
- 1,400$ per metric ton of $PM_{2.5}$ emissions
- 13,000$ per metric ton of CO emissions

Using these SCC values, we can modify the unit cost model I presented earlier to include the costs of all four pollutants (TCP):

$$TCP\ \left(\frac{USD}{Km}\right) = 51 \times CO_2\left(\frac{gr}{km}\right) + 2410 \times NO_x\left(\frac{gr}{km}\right) + 1400 \times PM_{2.5}\left(\frac{gr}{km}\right) + 13000 \times CO\left(\frac{gr}{km}\right) \tag{31}$$

Using this modified unit cost model, we can estimate the total economic damage associated with vehicle emissions for a trip on the Bandar-e Anzali ring road route or other similar routes by considering the costs of all four pollutants. This model can be used to compare the costs of greenhouse gas emissions from different road sections and identify opportunities to reduce emissions and improve air quality.

Running the model

If we do not adhere to a series of limitations in solving the problem, the problem solving will go astray. Figure 10 shows an example of false profit to solve the problem. A number of important constraints that can shorten the solution of the problem and lead the answer to the optimality are: 1- Definition of the interval of the beginning and end of the proposed routes 2- Definition of the corridor with a maximum width equal to 2dmax 3- Limitation of the number of PIs of the new alternative route for the existing axis (Figure 10).

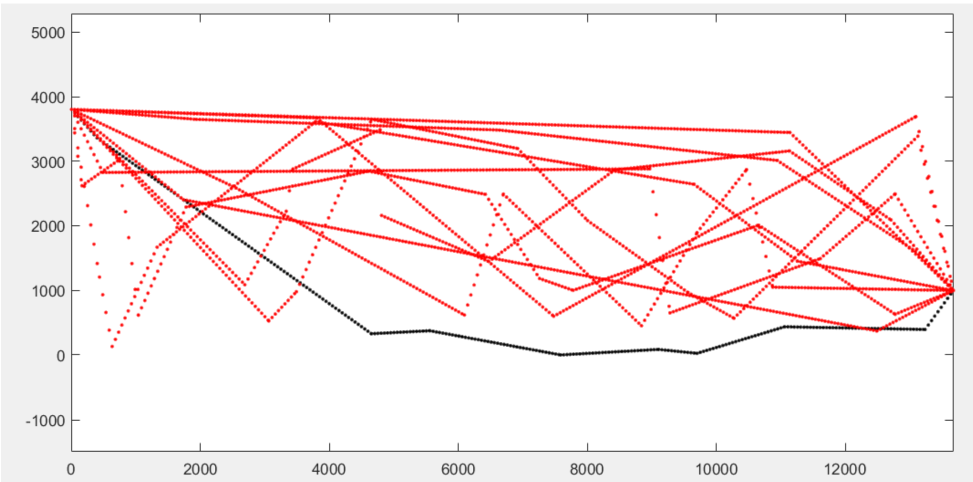
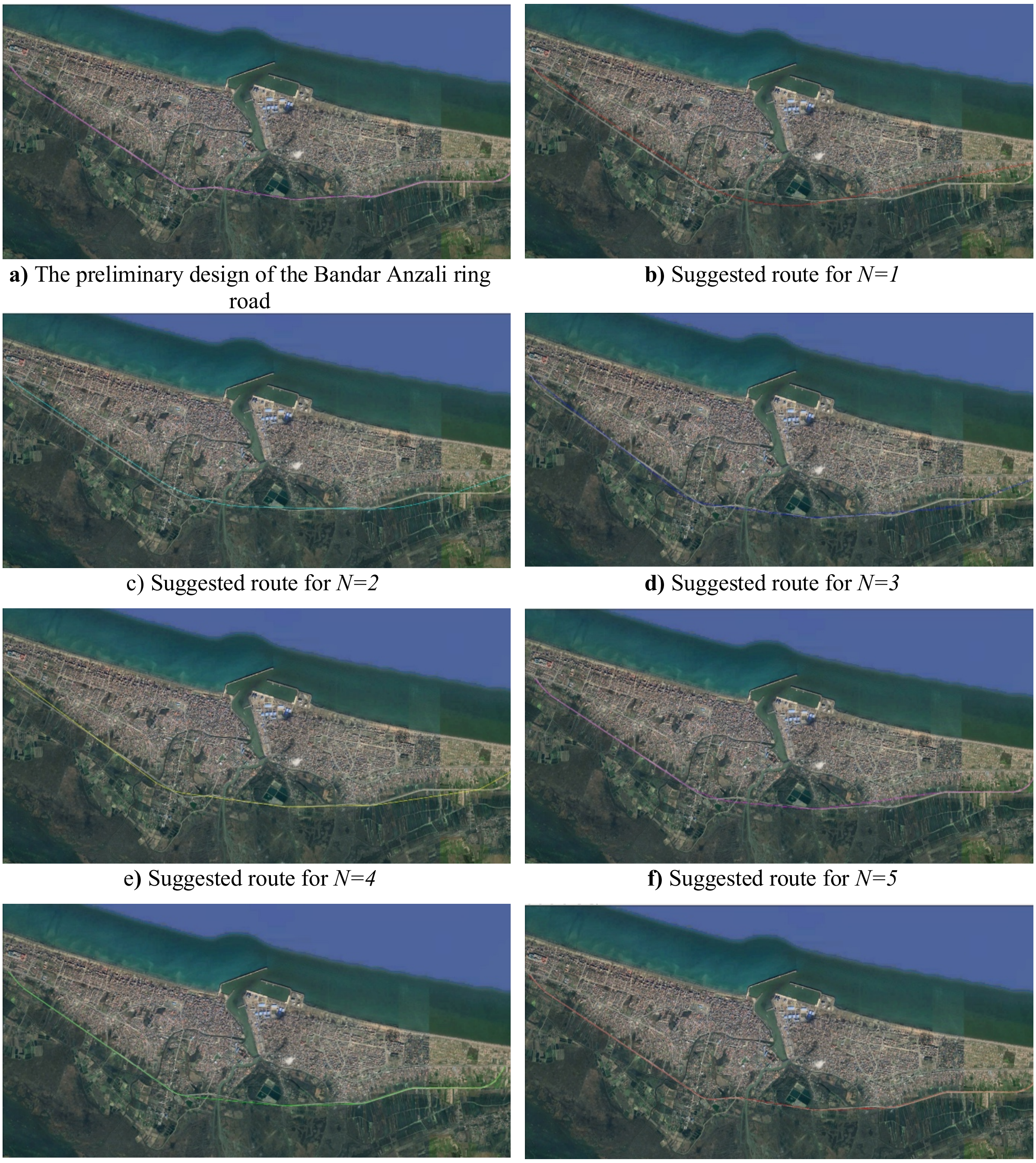


Figure 10. Search in incorrect conditions for the alternative route of Bandar-e Anzali ring road due to the lack of restrictions

As shown in Table 1, the best option for improving the route is an option with four curves (*N=4*). The optimized designs are depicted in Figure 11. Examination of the figure and data indicates that as the number of rotations increases, better adjustment is achieved with the old design. For N = 1, since only one curve is allowed, the optimal solution is to follow the longest straight section of the old route at the intersection. This point should also be added to the first proposed route, where more penetration into the wetland bed (southward) has occurred. Finally, in Fig. 11c, we compare the improvement of the current road with our proposed solution with N = 4. It shows that both are close to each other. This is an important and relevant point that suggests that the proposed method can be a good way to deal with road rehabilitation projects, as introduced in this section.

In addition to choosing the optimal alignment for the Bandar-e Anzali ring road based on preserving environmental lands and not encroaching on the wetland buffer zone to optimize the current alignment, we can estimate future savings from the pollution perspective. According to the calculations presented in section 4-2, we can estimate the amount of cost savings we have achieved by choosing the optimal horizontal alignment compared to the initial alignment proposed for the Bandar-e Anzali ring road. The CO_2 emission formula shows that the speed of the vehicle has a significant impact on pollution, and higher speeds result in more emissions. The NO_x emission formula shows that emissions increase with vehicle speed and road radius. The $PM_{2.5}$ emission formula shows that road length, road radius, and vehicle speed all play a role in greenhouse gas emissions, and higher values for each parameter lead to more emissions.

Finally, the CO emission formula shows that vehicle speed and road radius are the dominant factors in greenhouse gas emissions. Calculations show that the geometric design of roads can have a significant impact on vehicle emissions. The horizontal alignmnet proposed in this article, regardless of environmental considerations in the design of the optimal horizontal alignment, reduces the pollution level of the path in the proposed option. With a design speed of 110 kilometers per hour, the total length of the proposed option is 14.991 kilometers, compared to 16 kilometers for the original alignment. Therefore, it can be concluded that we will have at least a USD 3.7 million equivalent in TCP in preventing environmental damage. This amount of cost savings is very significant. In other words, with a reduction of about one kilometer in the length of the horizontal alignment, the negative impact of pollutant emissions is reduced.



a) The preliminary design of the Bandar Anzali ring road

b) Suggested route for *N=1*

c) Suggested route for *N=2*

d) Suggested route for *N=3*

e**)** Suggested route for *N=4*

f) Suggested route for *N=5*

g) Suggested route for *N=6*

h**)** Suggested route for *N=7*

Figure 11. Preliminary plan of the Bandar-e Anzali ring road and the 7 proposed options for Ns 1 to 7

Table 1. Numerical results obtained to solve the problem

	$v_i = (x_i \cdot y_i)$	R_i	Δ_i	L_i^C	L_i^T	L_{Total}	J
N = 1	5769.45, -393.67	5.032	0.80	4.040	4.998	14.929	7.635
					5.891		
N = 2	5026.62,176.74	4.730	0.59	2.7818	4.765	14.907	4.390
	10518.48, -024.76	5.789	0.35	2.0248	3.040		
					2.296		
N = 3	4271.75, 470.96	1.915	0.52	0.9977	4.906	14.959	2.150
	7583.90,000.00	2.863	0.20	0.5639	2.552		
	11357.42, 210.52	5.290	0.27	1.4361	2.774		
					1.725		
N = 4	4241.77,508.27	1.870	0.51	0.9524	4.896	14.991	1.030
	7369.23,032.65	2.230	0.15	0.3287	2.500		
	9701.11,024.39	3.562	0.13	0.4776	1.928		
	12608.95,406.13	0.946	0.38	0.3553	2.514		
					1.040		
N = 5	397.79, 3359.20	0.831	0.22	0.1824	0.504	15.097	2.800
	4651.96,327.99	3.180	0.51	1.6144	4.307		
	7583.90,000.00	2.964	0.24	0.6999	1.774		
	11058.77,435.63	5.437	0.14	0.7816	2.759		
	13236.97,394.17	0.700	0.96	0.7170	1.422		
					0.357		
N = 6	397.79, 3359.20	0.795	0.22	0.1745	0.507	15.149	2.057
	4651.96,327.99	1.250	0.51	0.6346	4.812		
	7583.90,000.00	3.273	0.12	0.4023	2.425		
	9701.11,024.39	0.850	0.28	0.2402	1.795		
	11058.77,435.63	1.130	0.31	0.3539	1.119		
	13236.97,394.17	0.746	0.96	0.7170	1.611		
					0.357		
N = 7	397.79, 3359.20	0.700	0.22	0.1537	0.520	15.155	1.735
	4651.96,327.99	0.700	0.67	0.4693	4.927		
	5558.61,374.55	3.035	0.23	0.7107	0.307		
	7583.90,000.00	3.156	0.19	0.6135	1.395		
	9701.11,024.39	3.870	0.28	1.0937	1.259		
	11058.77,435.63	1.210	0.31	0.3789	0.677		
	13236.97,394.17	0.700	0.96	0.6728	1.623		
					0.381		

The values of distances and coordinates in Table 1 are in terms of the length scale of kilometers (Km).

Conclusion

Designing a road with optimal horizontal alignment is crucial for ensuring safety, reducing environmental impact, and minimizing costs. Conventional design methods that rely solely on human knowledge and expertise are insufficient to ensure comprehensive optimization and maintain safety and environmental compatibility. Therefore, there is a need to develop a flexible, dynamic, and sustainable framework to enhance road and environmental indicators. In this study, we proposed a methodology for balancing environmental and economic considerations in horizontal alignment optimization using a genetic algorithm-based optimization model. The proposed methodology consists of several steps, including the identification of environmental and economic parameters affecting the route plan design, the selection of main parameters, route plan modeling under geometric, safety, and environmental conditions, the development of a genetic algorithm-based optimization model, the implementation of the model to generate a set of possible solutions, the evaluation of the obtained routes in relation to regulations and standards, and the selection of the best solution.The findings of the case study on the optimization of the ring road highway of Bandar-e Anzali demonstrate the effectiveness of the proposed methodology in reducing road costs and increasing safety while considering environmental impacts. The optimized horizontal alignment, designed to accommodate a design speed of 110 kilometers per hour, resulted in a significant reduction in length by approximately 1 kilometer and yielded at least $3.7 million in environmental savings for Iran. The methodology can also enhance the quality of alignment improvement in road construction and reconstruction projects, particularly in regions of high environmental significance. Furthermore, the proposed route, generated by the model with four IP's, was compared to the existing road and proved to be relevant and beneficial to the surrounding environment by minimizing environmental damage and disturbance. Moreover, the design of road geometry has a significant impact on the emission of greenhouse gases from vehicles, including CO_2, NO_x, $PM_{2.5}$, and CO. Therefore, taking into account geometric design factors in road planning and design can reduce pollutants and improve air quality. The proposed methodology provides a valuable framework for balancing environmental and economic considerations in horizontal alignment optimization, which can lead to the selection of optimal route alignment that reduces costs, increases safety, and minimizes environmental impact. The methodology can be applied to different road design projects and can be tailored to specific environmental and economic contexts. The presented model can be validated through comparison with alternative solutions, leading to the final model of route alignment optimization that can provide recommendations for policy and planning decisions. However, further research is needed to investigate the complex interactions between geometric design, vehicle speed, and greenhouse gas emissions to develop effective strategies to reduce air pollution caused by vehicle emissions. Optimizing more complete objective functions by considering more technical specifications of roads and their greater environmental impacts will be more challenging. The proposed methodology can be expanded to optimize more complete objective functions, and different techniques can be incorporated to improve the prediction accuracy of environmental and economic parameters affecting the route plan design. It has the potential to contribute significantly to the development of sustainable road systems that benefit society as a whole.

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