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Multiobjective Railway Alignment Optimization Using Ballastless Track and Reduced Cross-Section in Tunnel

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Abstract: The increasing need for railway planning and design to connect growing cities in inland mountainous areas has pushed engineering efforts toward the research of railway tracks that must comply with more restrictive constraints. In this study, a multiobjective alignment optimization (HAO), commonly used for highway projects, was carried out to identify a better solution for constructing a high-speed railway track considering technical and economic feasibilities. Then, two different and innovative scenarios were investigated: an unconventional ballastless superstructure, which is more environment-friendly than a gravel superstructure, and a reduced cross-section in a tunnel, which enables a slower design speed and then, less restrictive geometric constraints and earthmoving. The results showed that the first solution obtained a better performance with a slight increase in cost. Moreover, both scenarios improved the preliminary alignment optimization, reducing the overall cost by 11% for the first scenario and 20% for the second one.

Keywords: railway alignment optimization; decision process; cost-benefit analysis; facilities planning and design

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1. Introduction

Railways are one of the most important means of transport in the world for both people and goods [1,2]. Railway line planning, however, is very complicated as it has a high number of variables related to environmental and social aspects. In addition, the designed railway should satisfy additional requirements such as limited construction time and available financial resources.

Engineers, who are therefore faced with a multiobjective problem in identifying the best route, encounter further obstacles when the morphology of the terrain is characterized by extreme elevation changes. The identification of the optimal railway route depends on geometry and environmental standards, such as land use limitation.

In order to compare the different design route solutions and then identify the best one, several optimization algorithms have been developed in recent decades.

The optimization algorithms represent a valid tool in the infinite field of possible solutions for the connection of two generic points, in compliance with constraints imposed under current standards.

Several researchers have investigated the best optimization methods, which can be grouped into horizontal alignment optimization, vertical alignment optimization, and 3D alignment optimization.

Regarding horizontal alignment optimization, De Luca et al. [3] performed a multicriteria analysis in a GIS environment, applied to a real case in order to evaluate its economic feasibility and social and environmental impact considering three possible corridors (conservative, compromise, and innovative) for the construction of high-speed rail lines in the south of Italy.

Easa et al. [4] proposed a safety approach for design of horizontal alignments based not only on minimum design guidelines but also on actual collision experience, considering also any specified physical obstructions when selecting the optimal alignment.

Jong et al. [5] presented a method that integrates geographic information systems (GIS) with genetic algorithms (GAs) for optimizing horizontal highway alignments between two given end points.

Mondal et al. [6] used a derivative-free optimization algorithm returning an optimal horizontal alignment in the form of a linear-circular curve and an optimal vertical alignment in the form of a quadratic spline.

Casal et al. [7] presented an arc length parametrization of a horizontal road alignment where the objective function was given by a line integral along the layout.

Regarding vertical alignment optimization, Bababeik and Monajjem [8] and Beiranvand et al. [9] presented an optimization to find the best vertical alignment for a track with a given horizontal layout considering construction and operating costs as variables.

Monnet et al. [10] proposed a Mixed Integer Linear Program (MILP) modeling the vertical alignment problem that did not involve integer variables.

Hare et al. [11] showed that the approximation of the sideslopes can generate solutions within an acceptable error margin specified by the user without increasing the time complexity significantly.

Xin et al. [12] investigated the relationship between energy consumption and the parameters of vertical alignment at the station, showing a reduction in the total energy consumption and journey time of 5.6% and 0.53%, respectively.

Regarding 3D alignment optimization, Chiou and Yen [13], using the chord method, calculated the horizontal versines of the left and right rails and derived the vertical versine functions.

De Smith [14] provided an analysis of gradient and curvature constraints.

Kang et al. [15] developed a prescreening and repairing (P&R) method for an efficient search of highway alignments, showing a higher possibility of quickly finding a good solution and at the same time the possibility of evaluating about 70% more solutions that could be evaluated using traditional methods.

Pushak et al. [16] considered multiple near-optimal spatially dissimilar paths as alternatives in the decision-making process for finding optimal corridors.

Maji and Jha [17] used a genetic algorithm for the optimization process and a geographical information system to estimate environmental, economic, and social impacts for highway route planning.

Um et al. [18] developed, using the object function of ride comfort, a solution algorithm to determine the horizontal curves for optimal ride comfort when horizontal and vertical (convex) curves are superimposed under feasible boundary conditions.

The use of electronic tools in the planning and design phase of a linear infrastructure helped to solve several problems [19,20] also related to the identification of the best alignment solution in a reasonably short time [21].

Recently, 3D optimization based on horizontal-vertical alignment has emerged, with the help of different algorithm families such as distance transformed DT [22,23], particle swarm optimization [24], and genetic algorithms [25].

In the past decade, genetic algorithms have been a particular focus to better address the issue of finding the best route. The initiator of this breakthrough in studies is Jong [25], applying genetic algorithms (GA) in a civil infrastructural context, and then, in various transport and design problems such as structural optimization [26,27], shape optimization of freeform steel space-frame roof structures [28], optimal sets identification of construction methods for activities [29], retrofit design optimization [30], the zoning-based vertical transportation logistics of lift cars for workers at peak time in a skyscraper construction [31], and optimal passenger service plan identification [32].

A further key step in the application of genetic algorithms was made by introducing the spatial points of the axis polygon, called PIs, derived by intersections of horizontal planes providing horizontal PI (HPI) coordinates and vertical planes providing vertical PI (VPI) coordinates. These orthogonal cuts of the space between a start and finish point are derived from the application of the algorithm, in particular its random number generation module. The coordinates of the PI become the gene, and the set of PIs that forms the path becomes the "chromosome" which is then reworked by the other GA operators [33].

The step forward in the characterization of the genetic algorithm in the case of path optimization, includes improvements in the selection [34–36], mutation [37–39], and crossover modules [40,41].

Therefore, for the application of the algorithm, the identification of PI points becomes crucial, and research in the field of this process has been active to find other methods to generate the polygonal points. An alternative to the random number generator is the application of the particle swarm optimization (PSO) for the identification of the cutting planes in order to find the HPI and VPI.

However, the above-mentioned algorithm has defects. In fact, if the points of the polygon are generated by the launching of particles, it means that they have their own distribution, which implies that the solution path depends on the initialization status. Consequently, finding the type of distribution that enables finding the right cutting planes is not easy, especially in mountainous areas where the terrain profile rapidly changes. Another way to find the points of the axis polygon is to apply distance transform (DT) in which the space between two points is cut out with equal rectangular shapes, such as pixels, associated with a distance. It is generally a technique used to solve minimal route problems.

Li et al. [22] applied the above-mentioned algorithm for finding optimized railway routes, achieving good results especially in the aspect of satisfying geometric constraints. However, the railway track, in the phase following the application of DT belonged to a "band" born from the joining of pixels and consequently was characterized by many linear features. In addition, the subsequent horizontal-vertical alignment optimization was far from the optimum solution.

Railway routes optimization with the application of algorithms has been successful in many cases, even in areas with variable terrain profile, where geometric constraints become stricter.

Li et al. [23] showed a weakness in the solution refinement stages due to geometric constraints, which created a deviation of the final solution from the better global route. Therefore, a combination of algorithms was used. Firstly, the DT algorithm was applied, and then the GA was employed to reduce the set of possible solutions.

A problem faced by researchers is the ability of the analytical process to consider several relevant aspects in mountain areas. An attempt has been made to consider not only the search for a route optimized from the perspective of costs but also of environmental risks [42], such as the loss of vegetation and soil erosion, by using PSO combined with the multicriteria tournament decision (MTD) solving method.

Searching for the optimal solution that reduced the geological risks in a mountainous area was addressed by Song et al. [43], with particular interest in debris flows, landslides, and rockfalls. A multicriteria analysis with the MTD was applied; in the first phase, the DT was applied to identify a "band" of paths respecting the geometric constraints; in the second phase, a combination of PSO (for axis polygon points identification) and GA (for horizontal-vertical alignment definition) was applied, with the aim of reducing the risk of geological hazards, defined as the product of a susceptibility to the event and a vulnerability of a certain structure.

2. Aim of the Study

The aim of the study, using highway alignment optimization (HAO), is to propose alternative solutions to a high-speed railway track identified with a preliminary technical and economic feasibility study (preliminary track) that can solve critical issues in mountain areas, such as environmental impact and cost. HAO is commonly used for highway optimization. For this reason, the current study represents an original contribution to current railway knowledge.

The methodology overview is shown in Figure 1.

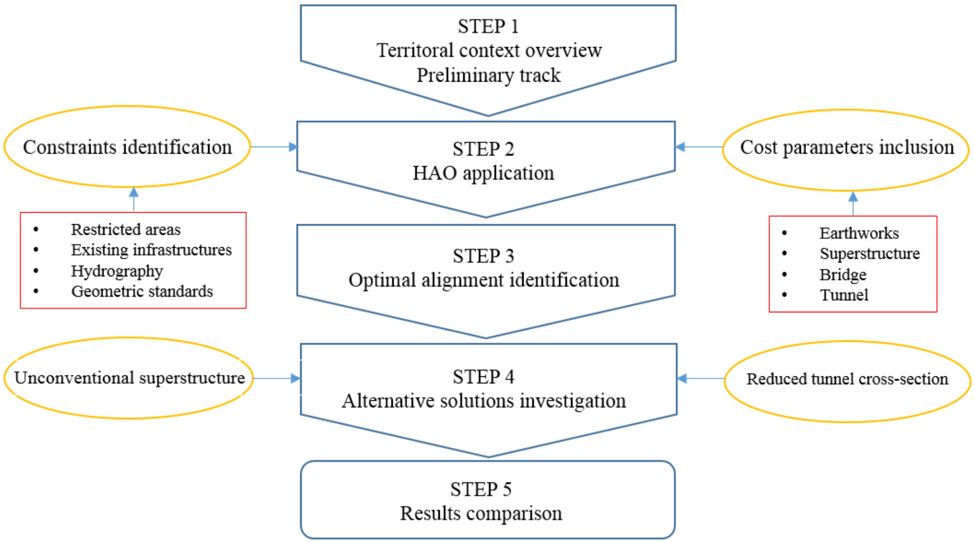


Figure 1. Methodology overview.

In the first step, an assessment of the territorial context is presented with a deepening of the railway preliminary alignment. Then, the HAO was applied by setting geometric constraint values and cost parameters based on local regulations and material price lists to identify the optimized alignment that ensures the use of fewer financial resources. Finally, an original set of solutions, never investigated in previous studies, was investigated, and compared with the previous one, by considering two different parameters that can mitigate issues in crossing a mountain area, such as an unconventional superstructure without ballast and a reduced cross-section at a tunnel.

3. Case Study

In this section, the case study territorial context overview and its HAO application for optimal alignment detection is presented.

3.1. Territorial Context Overview

The preliminary railway alignment under investigation was part of the Trans-European Transport Network (TEN-T) for the Scandinavian-Mediterranean corridor. In this specific case, the high-speed railway line would connect Torre Orsaria to Villamare located in the Apennines Mountains area of Southern Salerno, as shown in Figure 2.

The preliminary railway alignment, conceived with a design speed of 300 km/h, was 9 km long, of which 8.5 km were in tunnels, and was composed of a double-track line with a gravel superstructure, with a double tube of 90 m^2 each built with traditional excavation. The alignment started with a tangent segment of almost 5 km, followed by a circular curve with a radius of 2650 m for almost 2 km, and ended with a tangent element of almost 2 km.

Figure 2. Case study area. [Map data ©2021 Google].

3.2. Functioning HAO Application

HAO is a three-dimensional path optimization model based on a genetic algorithm which is a sequential process of finding a solution derived from the study of the evolution of a species, in which the gene with the best chromosomes is preserved.

In recent years, HAO has been refined to find alignments that best meet all the constraints reported in the beginning steps of the construction process. One of the improvements is the interaction with Geographic Information System (GIS) files, mainly used to digitally represent the environmental, topographic, and geomorphological characteristics of the investigated area. GA and GIS files interact by exchanging input information and obtaining optimized alignments as output.

The HAO process is summarized in Figure 3.

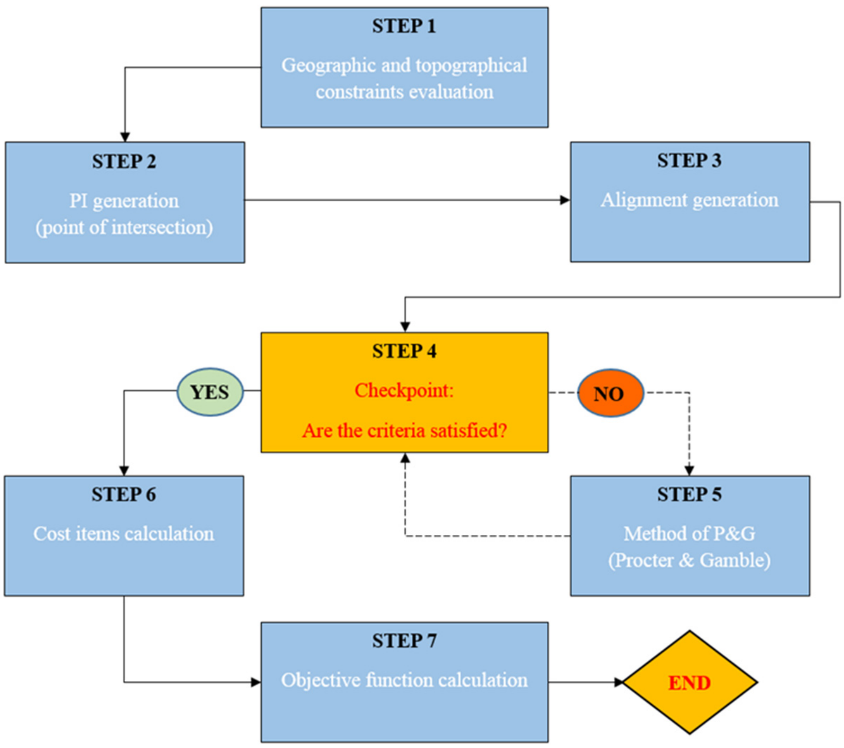


Figure 3. HAO Workflow.

In step 1, geographical and topographical constraints (restricted areas, existing infrastructures, hydrography, and geometric standards) were evaluated.

In step 2, the intersection points of the axis polygon were simultaneously produced with a series of points intersection (PIs) generated by the genetic operators.

The PIs belong to orthogonal plans. The number of plans, greater or equal to the number of PIs, is selected before running the model, and represents the way to divide the actual space between the starting and ending points (see Figure 4).

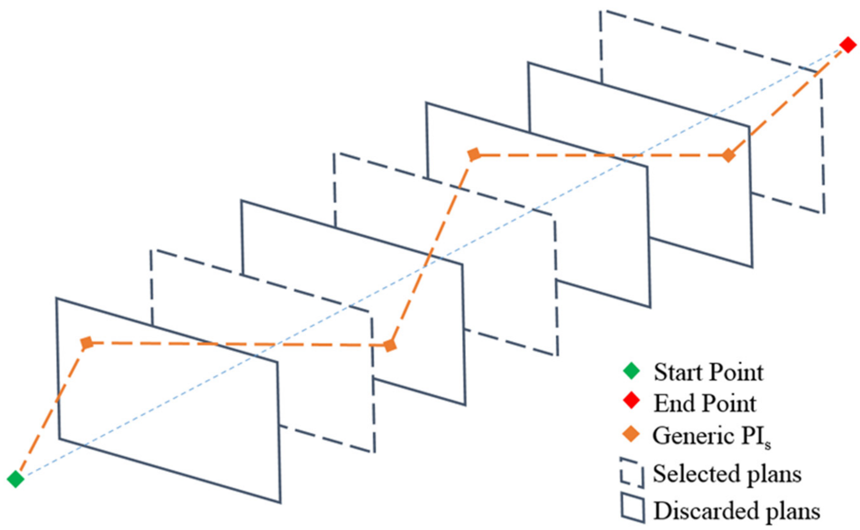


Figure 4. Axis polygon creation.

Part of step 2 was the application of the feasibilities gates (FG) procedure, which reduces computational time.

After creating the PIs, in step 3, the algorithm created, with an iterative approach, the paths with a simultaneous evaluation of the horizontal-vertical aspects, generating the three-dimensional alignments.

The control points in step 4 were used to discard the alignments that significantly violate compliance with the identified constraints. Among these, there are solutions that have geometric elements that preserve a certain degree of advantage in their use, i.e., they have "genes" that combined in different ways lead to alignments with good fit.

With the aim of verifying and preserving these alignments, step 5 was characterized by a pre-screening and repairing procedure, which consisted of the manipulation and re-management of the axis intersection points.

Step 6 consisted in the calculation of the individual items' cost, which depend on the overall length, such as the construction cost for bridges/tunnels/superstructures, earthworks cost, and expropriation cost.

Finally, in step 7, the objective function was calculated by identifying the optimized solution.

3.3. Geometric Constraints Identification

Geometric constraints generally depend on the quality of service to be offered for a given railway route, which results in the definition of the design speed. The dependence of geometric constraints can be summarized as shown in Equation (1):

$$G = [(X,Y,R(S),K,H)] \tag{1}$$

where G is the set of numerical values of the geometric constraints; X and Y are the horizontal coordinates; R is the radius of the circular curves, which depends on the speed S; K is the denotation of the VPI point; and H is the vector joining the K points.

By fixing geometric constraints, depending on the reference geometric design standard, PI points can be plotted, and consequently the railway alignment.

The numerical values of the geometric constraints were assessed according to Italian Geometric Design Standard for Railways [44] as shown in Table 1, where R is the horizontal circular curve radius, R_v is the vertical curve radius, L_T is the tangent length, L_i is the gradient length, L_R is the radius lengths, and S is the design speed.

Table 1. Geometric constraints according to Italian Design Geometric Standard [42].

Geometric Constraint			300 km/h
R	$\frac{11.8}{D^{(a)}+I^{(b)}} \times S^2_{max}$	(2)	5460 m
L_T and L_R	$S/1.5^{(c)}$	(3)	200 m
R_V	$0.175 \times S^{2\ (d)}$	(4)	15,750 m
L_i [e]	$S/1.8$	(5)	167 m

NOTE: [a] superelevation; [b] insufficient superelevation; [c] in exceptional cases, $S_{MAX}/1.8$; [d] +10% tolerance for crest and + 30% for sag; [e] 30 m as minimum value corresponding to 2 as travel time.

3.4. Cost Parameters Inclusion

The operation of identifying and inserting the cost parameters allows the objective function to calculate the value of the total cost of each railway alignment solution.

The objective function is shown in Equation (6):

$$\min\,[F_{cost}\,(X,Y,R,K,H)] = C_L + C_R + C_E + C_S + C_{EN} + C_P \tag{6}$$

where C_L indicates the cost per linear meter, which means all costs that are repeated along the route such as the railway equipment's costs and all the superstructure material costs; C_R is the cost for expropriation; C_E is the cost for earthworks; and C_S is the cost for civil works. The sum of these first four addends represents the "Total Agency Cost", i.e., the costs related to railway geometric design. C_{EN} and C_P are, respectively, the environmental costs (cost penalties that are activated when passing through a certain area within the project context) and the penalty costs (fixed costs that are activated regardless of the alignment). These cost items can have a constant form or a linear form depending on the alignment length.

In Table 2, the cost parameters used for the calculation of the objective function are listed according to the Public Works price list [45]. As no specific information was provided for the environmental costs, they were associated with the civil works construction costs and its impact related to land use.

The penalty cost is activated when certain constraints, which are not strictly geometric, are exceeded, such as the community of interest area. This penalty cost varies linearly with the length of alignment incoming in avoided areas as shown in Equation (7).

$$C_P = C_{P\_FIXED} + L_{avoid} \times \beta_{penalty\_cost} \tag{7}$$

where C_{P_FIXED} is the intercept of the linear cost; L_{avoid} is the length incoming in avoided areas; and β is the coefficient cost of the penalty area.

The C_{P_FIXED} value used in this study was set with a default high value in order to automatically discard the solutions that violated the imposed conditions.

Table 2. Parameter cost [45].

	C_L—Linear Cost		
Superstructure	Ballast	75	€/m
	Rail	500	€/m
	Sub Ballast	174	€/m
	Super-Compacted Layer	25	€/m
Signaling system	SCC Type	40	€/m
Electrification lines	Primary Overhead Lines	130	€/m
	Feeder Contact Lines	26	€/m
Tunnel Safety	Safety System	3000	€/m
	C_R—Right of Way		
Expropriation Costs	-	1300	€/m^2
	C_E—Earthwork Cost		
Cost for Earthworks	Dump	12	€/m^3
	Borrow	15	€/m^3
	Fill	6.9	€/m^3
	C_s—Structure Cost		
Bridge	Civil Works	1750	€/m
Tunnel	Portal Cost	3333	€/m^2
	Civil Works	12,000	€/m
	C_{EN}—Environmental Cost		
Cost of Environmental Impact	N/A	N/A	N/A
	C_P—Penalty Cost		
Restricted Area	Community Interest Site Fixed	1,000,000,000	€
	Community Interest Site Linear	1,000,000,000	€/m

3.5. Optimal Alignment Detection

The HAO algorithm workflow was carried out, exploring the infinite field of solutions connecting the starting and ending points.

For computational reasons, only the best five solutions are shown in Figure 5.

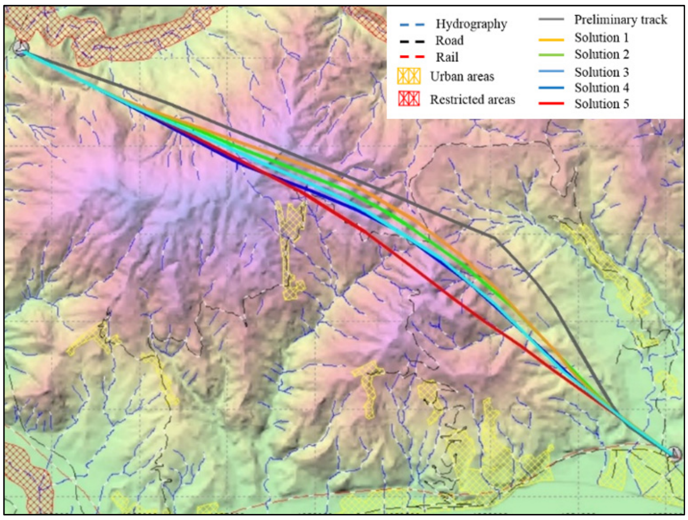
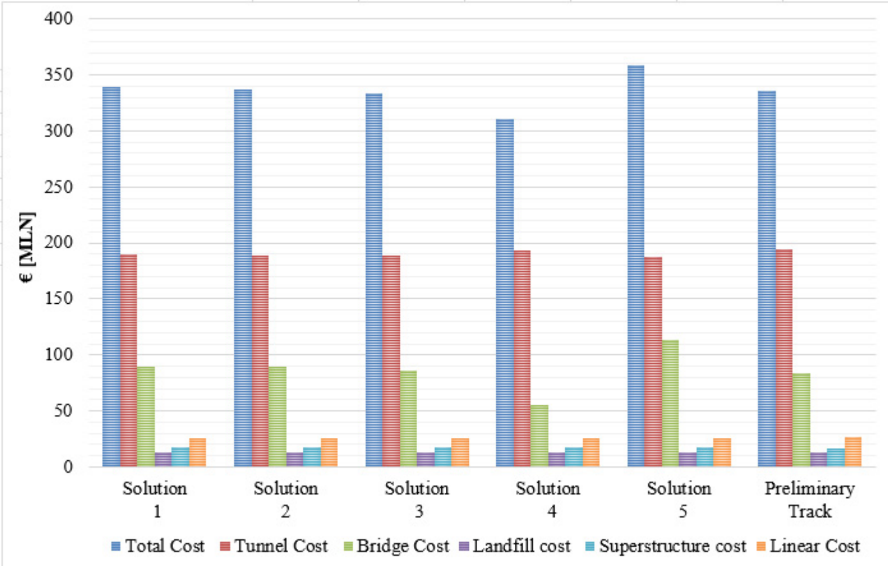


Figure 5. Alternative railway alignments.

Figure 6 shows the construction costs comparison between the first attempt track and the other five optimized solutions.



	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5	Preliminary Track
Total Cost [MLN €]	339	337	334	**311**	359	335.4
Tunnel Cost [MLN €]	190	189	189	193	**188**	194.5
Bridge Cost [MLN €]	89.5	89.3	85.8	**55.2**	113	83.8
Landfill cost [MLN €]	**12.6**	12.8	13	13	12.8	13.4
Superstructure cost [MLN €]	17.9	17.8	17.8	18.2	17.3	**16.8**
Linear Cost [MLN €]	25.5	25.4	25.4	25.7	**25.2**	26.8
One-Way Length [m]	8916	8883	**8844**	8846	8798	9070
One-Way Tunnel Length [m]	7900	7860	7860	7960	**7800**	8350
Bridge Length [m]	513	513	492	**316**	647	450

Figure 6. Cost comparison: preliminary versus optimized alignment.

HAO found in four out of five cases a better horizontal-vertical alignment than the preliminary solution; in contrast, solution number 5 was the most disadvantageous. Solutions 1 to 4 belonged to the same main corridor, and therefore had approximately the same individual cost items values. The key item cost affecting the total construction cost was the bridge cost, since the length value was 30% less than the the preliminary solution.

Solution 4, which allowed a 6% saving cost compared with the preliminary alignment, was, then, the best solution for HAO, which is from now on defined as Optimal Alignment.

4. Solution Set Creation

Given the complexity of design and the consequent burden of resources and costs correlated to the high terrain elevation variability in mountain areas, alternative alignment solutions, not considered in the technical and economic feasibility study, were investigated, and compared with the preliminary one, by varying design parameters. In particular, an unconventional superstructure without ballast and a lower value of design speed were considered.

4.1. Unconventional Superstructure

The gravel superstructure for high-speed lines can claim a consolidated knowledge and application over the years. However, the demand in exploiting the railway network at higher speeds has pushed researchers into investigating alternative materials to use in the superstructure construction.

On the other side, when design speed increases, dangerous conditions for safety and travel comfort are accentuated, such as the corrosion process, vibration [46] and noise [47] increment, crushing of the ballast inert material (as well-known as "flying ballast"), sleepers' usage, and superstructure deterioration.

A way to mitigate the mentioned criticalities is the adoption of a ballast-free superstructure, which guarantees better performances especially in mountain areas with long tunnels. The possibility of using concrete slabs, such as a slab of ballast, significantly reduces the use of raw materials, and thus reduces the general environmental impact, as there is no availability of raw materials for making ballast with the appropriate physical and mechanical characteristics.

For long-term durability, in addition to the concrete slab, it is necessary to use appropriate rails and plan their periodic maintenance, estimated to be approximately equal to the cost of replacing sleepers and ballast in a conventional superstructure [48,49].

When maintenance works are needed, the presence of a slab in the tunnel allows the rapid action of rubber-tired vehicles reducing the downtime, which is an aspect that becomes even more important in the presence of a single tube. Downtime can be further reduced with the application of maintenance management optimization algorithms [50].

The main disadvantage in using the unconventional superstructure is the higher overall linear cost caused by the type and quality of materials used. This difference is attributable to the higher cost coefficient of the concrete reinforcement layer, the actual value of which depends on the construction technology used.

The linear cost is therefore a summation of many individual products of a cost coefficient for a length.

The gravel superstructure for a high-speed railway consists of the superstructure layer, which includes ballast and sleepers, the subballast layer, and the supercompacted layer. Its cost was assessed using Equation (8).

$$C_S = [(C_{RC} + C_b \times S_b) + C_{Sb} \times S_{sb} + C_{sc} \times S_{sc}] \times L \quad (8)$$

where CS is the cost of the superstructure, C_{RC} is the cost of the crossbars, C_b is the cost of the ballast, S_b is the thickness of the ballast, C_{sb} is the cost of the subballast, S_{sb} is the thickness of the subballast, C_{sc} is the cost of the supercompacted, S_{sc} is the thickness of the supercompacted, and L is the length of the track.

Changing the type of superstructure also changes the armor support layers. The unconventional superstructure is composed, from the top down, of a concrete slab that acts as a reinforcement, a bedding layer that serves to correctly position the upper slab, and a foundation layer made of concrete that takes care of supporting the vehicle loads. Its cost was assessed using Equation (9).

$$C_{SI} = [C_{rie} \times S_{rte} + C_{bl} \times S_{bl} + C_{fl} \times S_{fl}] \times L \quad (9)$$

where C_{SI} is the cost of the superstructure innovation, C_{rie} is the cost of the railway innovation equipment, S_{rte} is the thickness of railway traditional equipment, C_{bl} is the cost of bedding layer, S_{bl} is the thickness of the bedding layer, C_{fl} is the cost of the foundation layer, S_{fl} is the thickness of the foundation layer, and L is the length of the track.

The proposed ballastless superstructure, dimensioned according with the Italian Standards, is composed, from the top down, of a 17.50 cm precast concrete slab with upward facing rolling stock attachments suitable for high speed, a 0.30 cm mortar and resin bedding layer, and a 30 cm concrete foundation layer (see Figure 7).

The tunnel foundation level must be thick enough to fill the reverse arch formed by the tunnel and to bring the rolling surface to the correct design level. The layer is made of in situ concrete with a cubic resistance ($f_{ck,cube}$) of at least 37 N/mm^2. To realize the layer of the new track different technologies, such as a continuous concrete casting or the use of precast cap elements, has been considered. The decision of using a precast element derives from the certainty associated with industrial production of the elements, which makes it possible to have controlled products, certified in compliance with performance requirements and cheaper. The final resistance concrete slab is commensurate with the axial load it must withstand, in particular for the passage of high-speed trains, the $f_{ck,cube}$ must fall in the range of 55–60 N/mm^2.

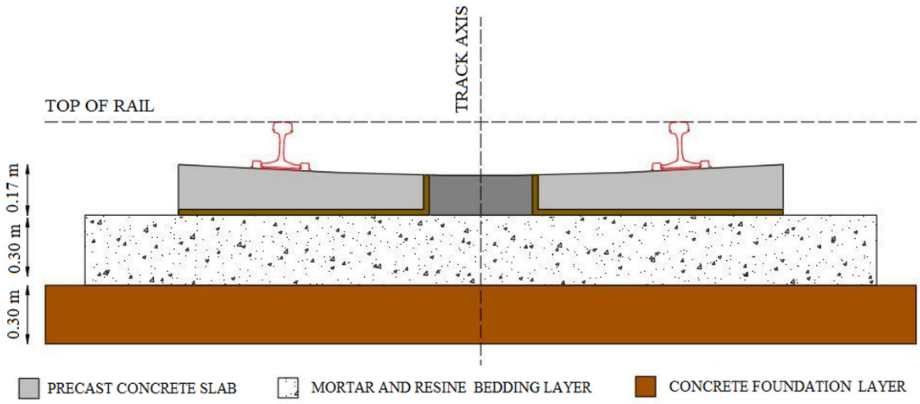


Figure 7. Unconventional type of railway superstructure.

The tunnel must be structurally controlled; in particular, it must not suffer phenomena of humidity, water infiltration, or freezing and thawing phenomena, which is why it must be waterproofed. With reference to the pathogenic action caused by water or other chemical agents linked to the environment of use, the choice of the bedding layer is of particular interest. In fact, the surface bedding layer has many functions, including bringing the rolling stock to the correct design level, providing the right support surface for the track bed, reducing vibrations caused by the passage of vehicles, but above all it has the task of protecting the track bed, which is already more stressed as it is in direct contact with vehicular traffic, infiltration of water, and corrosive chemical agents. For this purpose, it is recommended that the surface layer is made of elastomeric resins, which have greater durability and adherence than mortar.

The concrete superstructures may also require special work to repair the foundation; the underlying layers must be homogenous and have sufficient load-bearing capacity to withstand traffic loads without significant deformation and protect the upper layers from water infiltration.

4.2. Reduced Cross-Section in Tunnel

The presence of mountains, which make the railway route rich in civil works to overcome narrow geometric constraints, implies an increase in costs depending on the extent of these works. To reduce the overall cost, a reduced cross-section in tunnel can be considered, which allows a lower design speed. The related savings are justified by two aspects:

- possibility to obtain an alignment that fits better in the territorial morphology. By reducing the speed, geometric constraints with smaller values can be considered, which allow for example the positioning of curves in the horizontal-vertical plan with a reduced radius value. Therefore, a more “angular” alignment can be obtained compared to the one with a higher design speed;
- possibility to reduce the tunnel tube section size since a smaller dynamic encumbrance of the railway wagon shape in bends is performed. Considering the high presence of mountains, and consequently of tunnels, even a slight reduction in the tunnel tube section size results in substantial cost savings.

The use of open-air sections turns out to have a lower cost of realization compared to the ones in tunnels and on bridges; in fact, for long sections in tunnels special investments are necessary, such as the creation of stations inside the emergency tunnel, or even the realization of safety exit tunnels.

A design speed of 250 km/h was considered, returning the possibility of using minor geometric constraints values, and therefore, in a better adaptation of the railway alignment in the surrounding territory, as shown in Table 3. On the other hand, the expected travel time is expected to increase.

Table 3. Geometric constraints according to Italian Design Geometric Standard.

S	R	L_T and L_R	R_V	L_i
250 km/h	3750 m	166 m	10,937 m	139 m
300 km/h	5460 m	200 m	15,750 m	167 m

A speed of 250 km/h can lead to a reduction in the cross-section in tunnel (15–20%), but a reduced cross-section in tunnel of 82 m^2 has been used in order to preserve the safety characteristics related to high speed. This reduced speed therefore becomes a fair compromise between achieving the aim of reducing construction costs in a mountainous area and maintaining a high comfort level for users.

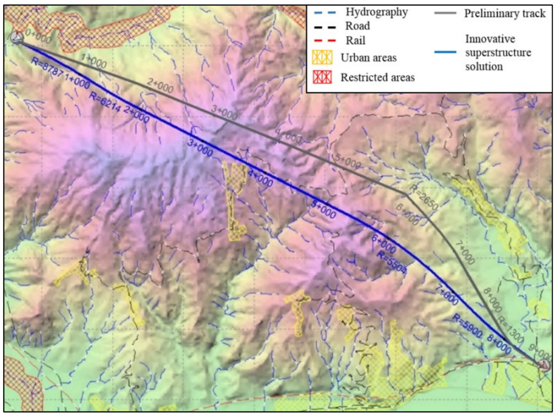
5. Discussion

In this section, the results in adopting HAO for the two proposed scenario, unconventional superstructure solution and reduced cross-section in tunnel, are presented.

5.1. HAO for Unconventional Superstructure Solution

For the proposed ballast-free superstructure, according to the available national price list, 517 € per linear meter for precast concrete slab, 11 € per cubic meter for bedding layer, and 157 € per cubic meter for concrete foundation layer were considered.

Figure 8 shows the HAO graphical results for the horizontal alignment (Figure 8a) and the vertical alignment (Figure 8b).



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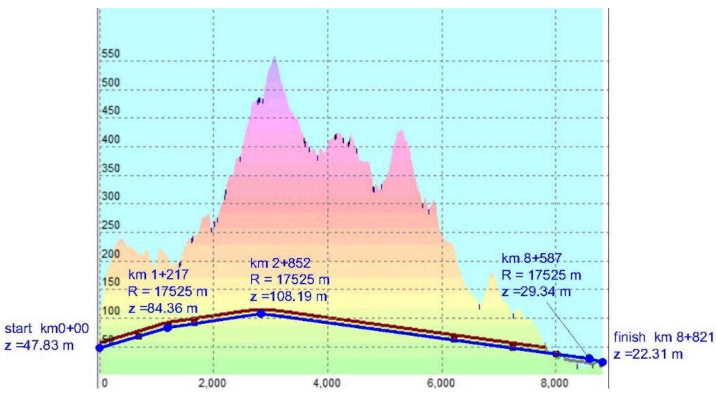
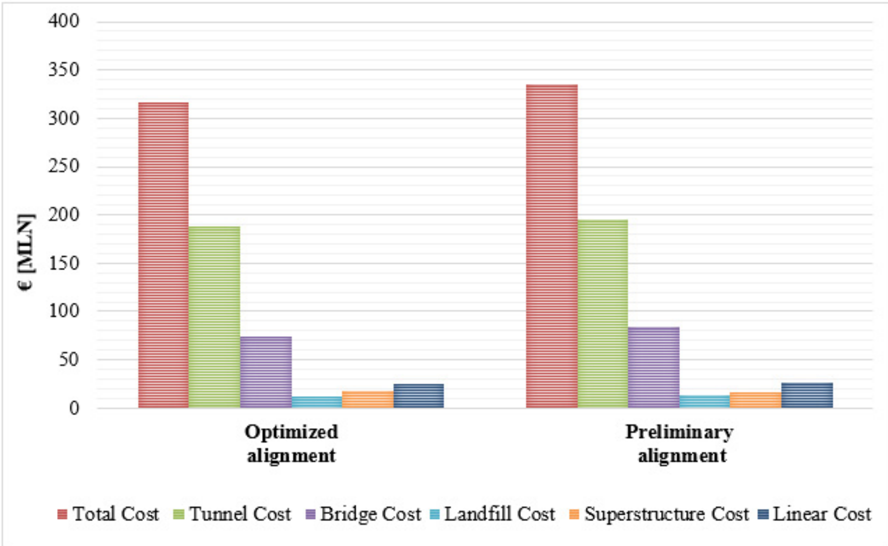


(**b**)

Figure 8. HAO graphical result. (**a**) Horizontal Alignment: Preliminary (grey line) and Optimized Alignment with unconventional superstructure (blue line). (**b**) Optimized Vertical Alignment (blue line) and tunnel track (red line).

In Figure 9 the economic comparison results are presented.

As expected, the construction cost for the ballastless superstructure is higher than the construction cost for the gravel superstructure.



	Optimized alignment	Preliminary alignment
Total Cost [€ MLN]	**317**	335.4
Tunnel Cost [€ MLN]	**188**	194.5
Bridge Cost [€ MLN]	**73.6**	83.8
Landfill [€ MLN]	**11.7**	13.4
Superstructure [MLN €]	17.2	**16.8**
Linear cost [MLN €]	**25.3**	26.8
One-way Total length [m]	**8820**	9070
One-way Tunnel Length [m]	**7820**	8350
Bridge Length [m]	464	**450**

Figure 9. Results comparison.

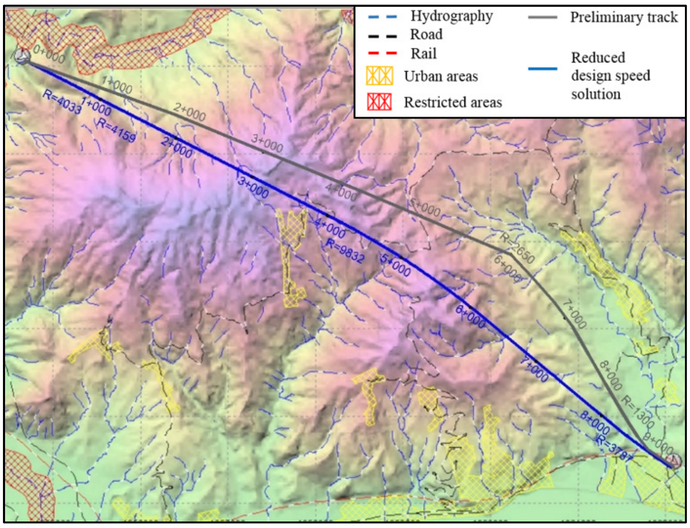
The optimized alignment length is shorter than the preliminary length due to the new horizontal-vertical configuration obtained, with consequent 3% of expected saving travel time. Moreover, the new horizontal alignment allows a tunnel section reduction with minor tunnel construction costs, at the expense of higher superstructure costs.

Nevertheless, we must consider long-term environmental and economic benefits in using the proposed innovative solution and their combination with the ameliorative effects of the optimization process.

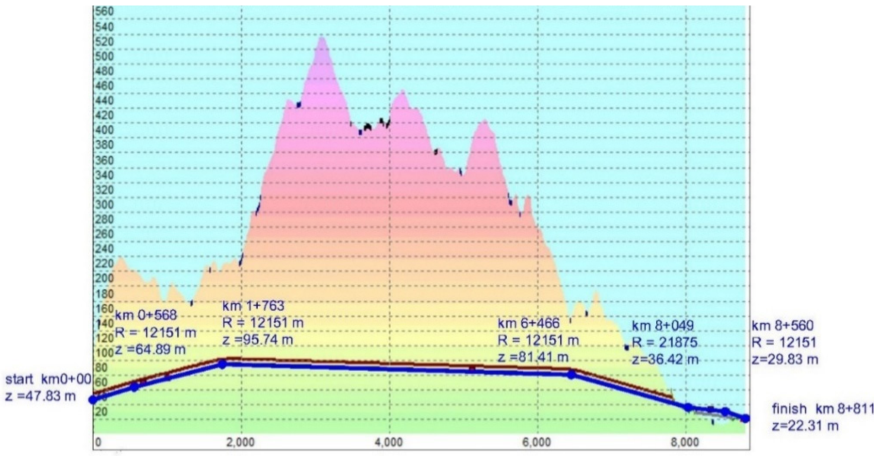
5.2. HAO for Reduced Cross-Section in Tunnel

A reduced cross-section at the tunnel allows the use of a lower design speed value and then, the use of lower geometrical constraints values with consequent reduction in civil works and thus, cost savings and lower environment impact.

Figure 10 shows the HAO graphical results for the horizontal alignment (Figure 10a) and the vertical alignment (Figure 10b).



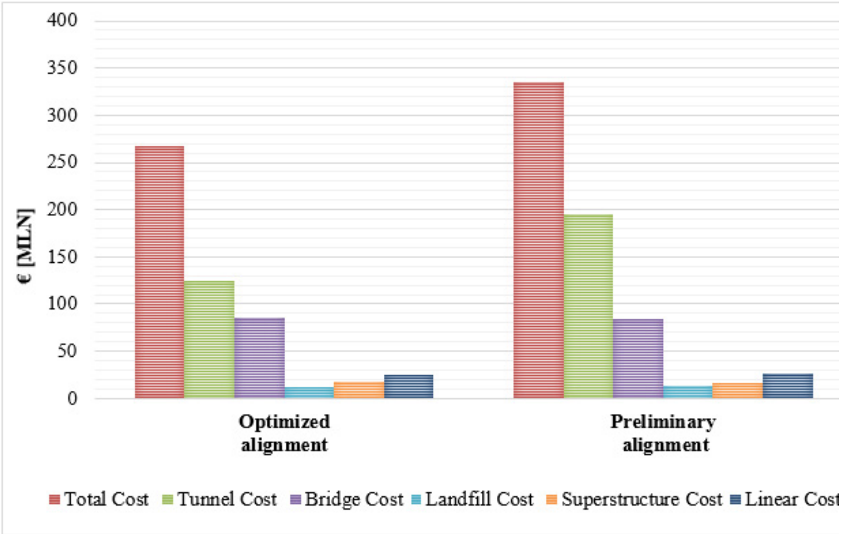
(**a**)



(**b**)

Figure 10. HAO graphical result. (**a**) Horizontal Alignment: Preliminary (grey line) and Optimized Alignment with reduced design speed (blue line). (**b**) Optimized Vertical Alignment (blue line) and tunnel track (red line).

The savings expected for the route built with a speed of 250 km/h, which would be the optimized alignment found with the application of the HAO optimization algorithm, is confirmed by the reduced overall cost compared to the case of the preliminary solution which considered a higher design speed of 300 km/h as shown in Figure 11.



	Optimized alignment	Preliminary alignment
Total Cost [€ MLN]	**268**	335.4
Tunnel Cost [€ MLN]	**125**	194.5
Bridge Cost [€ MLN]	**86.1**	83.8
Landfill [€ MLN]	**11.6**	13.4
Superstructure [MLN €]	17.7	**16.8**
Linear Cost [MLN €]	**25.2**	26.8
One-way Total Length [m]	**8811**	9070
One-way Tunnel Length [m]	**7800**	8350
Bridge Length [m]	494	**450**

Figure 11. Results comparison.

The 20% cost savings are primarily due to the reduced length of the alignment. Specifically, the tunnel construction cost is substantially reduced as less stringent constraints are given with the use of a lower design speed, and secondly, the alignment is better suited to the mountainous terrain. The tunnel costs have therefore significantly decreased due to the reduction in the tunnel bore section, as shown in Figure 12. In fact, by using a reduced design speed of 250 km/h a cross-section in the tunnel of 82 m^2 (blue line) can be considered, which is smaller than the cross-section in the tunnel for the preliminary solution equal to 90 m^2 (grey line).

On the other side, a reduced speed reduction, will negatively impact expected travel time which in this case is balanced by the almost 3% reduced length of the optimized solution compared with preliminary alignment with, consequently, a 14% increment of travel time.

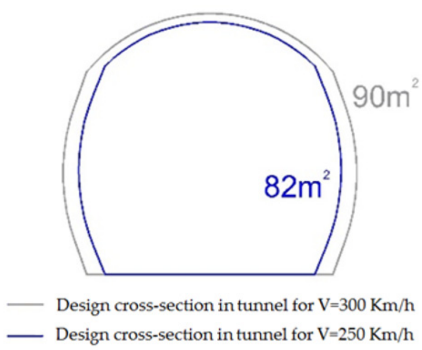


Figure 12. Reducing cross-section in tunnels.

6. Conclusions

The goal of the study was, starting from a high-speed railway track identified after a technical and economic feasibility study, to evaluate, using HAO, the possibility of reducing the costs and the environmental impact of the construction of a railway alignment in a mountainous area, by varying significant design parameters, such as the use of an unconventional ballast-free superstructure and a reduced cross-section in tunnel.

The study demonstrated how HAO can find more cost-effective solutions in a mountainous project area and how it is a useful tool for rapidly and efficiently considering multiple project scenarios, using a real preliminary alignment as a comparison solution.

With the new optimal alignment almost 10% cost savings can be obtained, which are essentially due to the HAO's ability to find a horizontal-vertical profile with reduced linear and bridge item costs.

Therefore, having demonstrated the advantage of using HAO, its capacity of dealing with variations in design parameters was exploited to expand the solution set, by using a ballastless superstructure and a reduced cross-section in tunnel.

The optimized ballastless alignment was almost 10% cheaper than the preliminary solution, with also a 3% reduction in the expected travel time, although the ballastless superstructure costs are higher than the same coefficients of the gravel superstructure.

The optimized alignment with reduced cross-section in the tunnel was 15% cheaper than the preliminary solution due to the reduction in civil works and tunnel bore sections, even if it means an 14% increase in the expected travel time.

However, some unexpected HAO anomalies were observed, since the algorithm did not adapt to the geometrical constraint's variation. Thus, it failed to find a smoother alignment; in particular, in Figure 8a, the optimized alignment did not follow the curves dictated by the terrain profile; in Figure 8b, the optimized alignment elevation, for which less use of the tunnel section was foreseen, was still characterized by a high extension of the tunnel alignment.

In conclusion, it can be confirmed that in mountainous areas:

- The combination of the optimization application and the use of an unconventional superstructure without ballast generates a solution with economic advantages related to the management and maintenance aspects, and not to the direct cost of the solution. However, this solution has relevant environmental advantages.
- Lower design speeds values generate substantial advantages in terms of immediate cost, but the optimization application does not respect the horizontal-vertical alignment expectation. Due to expected travel time increment, the investment per minute of saving time needs also to be considered.

7. Future Developments

The bad response to design speed variation by the HAO is attributable to its method of searching for PI points, which is completed through the random number generation module that launches the first generation. Therefore, a first line of development could made to deepen the PI point search through hybrid algorithms or the use of PSO.

A second line of improvement could be to interpret noncompliance with geometric constraints economically, by implementing the objective function with penalty equations that are triggered when the constraint is not met, so that unsuitable solutions are removed from the optimum. One could also provide a negative element within the cost objective function. In the same way it might be useful to improve terms in the objective function (for example with terms that would lower the fitness value if activated). Another improvement could be to provide a certain advantage to the choice of using eco-friendly manufacturing technologies.

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(Francesco Abbondati), X.C. and G.D.; writing—original draft preparation, F.A. (Francesco Avella) and E.D.L.; writing—review and editing, S.A.B.; visualization, F.A. (Francesco Avella) and E.D.L.; supervision, S.A.B. and G.D.; funding acquisition, G.D. All authors have read and agreed to the published version of the manuscript.

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