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Study on Route Alignment Adjustment and Optimization of Existing Road Resource Utilization in Highway Reconstruction and Expansion Projects

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Abstract

This study develops a collaborative optimization framework for highway reconstruction and expansion that integrates "alignment adjustment–existing road utilization–functional improvement." An evaluation indicator system is established to assess the utilization value of existing road resources, covering geometric alignment resources, structural resources, land-use resources, traffic organization, economic benefits, and environmental benefits. The weights of the indicators are determined by combining the analytic hierarchy process and the entropy weight method. On this basis, a multi-objective alignment optimization model is proposed, incorporating engineering cost, traffic safety, existing road utilization, ecological impact, and life-cycle carbon emissions, and the model is solved using the NSGA-II algorithm. A reconstruction and expansion project of a mountainous Class II highway in Tibet is taken as a case study for verification. The results show that the comprehensive coordination scheme achieves the lowest comprehensive evaluation value of 0.28 under the conditions of an existing road utilization rate of 64.2%, a safety risk index of 0.31, and carbon emissions of 118,000 t, outperforming both the existing-road-priority scheme and the alignment-improvement-priority scheme. The findings indicate that embedding the value assessment of existing road resources into the entire process of alignment adjustment can effectively improve the scientific basis of alignment decision-making, enhance resource utilization efficiency, and promote green and low-carbon development in highway reconstruction and expansion projects. This study provides methodological support for optimizing highway reconstruction and expansion schemes under complex constraints.

Keywords

Highway Reconstruction and Expansion; Alignment Adjustment; Existing Road Resource Utilization; Multi-Objective Optimization; Low-Carbon Transportation

1. Introduction

As highway construction in China shifts from incremental expansion toward an equal emphasis on quality improvement of existing infrastructure and functional enhancement, the reconstruction and expansion of existing highways have become an important means of improving road network capacity, safety performance, and service quality [1]. Compared with newly constructed highways, reconstruction and expansion projects are subject to multiple constraints, including existing alignments, subgrades and pavements, bridges and culverts, land use along the corridor, traffic maintenance during construction, and the ecological environment. Consequently, alignment adjustment in such projects is characterized by greater complexity [2]. Domestic studies in this field have mainly focused on route design for reconstruction and expansion projects, treatment of existing roads, and scheme evaluation [3]. In addition, some scholars have adopted methods such as the analytic hierarchy process, fuzzy comprehensive evaluation, and grey relational analysis to incorporate construction cost, land acquisition, construction organization, and ecological impacts into alternative comparison and selection [4]. Internationally, relevant studies have placed greater emphasis on GIS-assisted route selection, multi-objective optimization, and sustainable infrastructure assessment. Methods such as genetic algorithms, ant colony optimization, and particle swarm optimization are commonly employed to comprehensively consider construction cost, environmental impact, traffic safety, and life-cycle benefits [5].

Overall, existing studies have provided a foundation for the design and evaluation of highway reconstruction and expansion projects. Nevertheless, several limitations remain, including the disconnection between alignment adjustment and existing road utilization, the predominantly qualitative nature of existing road resource value assessment, and insufficient multi-objective collaborative optimization. Accordingly, this study develops a collaborative optimization framework integrating "alignment adjustment–existing road utilization–functional improvement." An evaluation indicator system is established for assessing the utilization value of existing road resources, covering geometric alignment resources, structural resources, land-use resources, traffic organization, economic benefits, and environmental benefits. Furthermore, a multi-objective alignment optimization model is proposed that accounts for engineering cost, traffic safety, existing road utilization, ecological impact, and life-cycle carbon emissions. This research is expected to provide theoretical and methodological support for scientific alignment decision-making, efficient utilization of existing road resources, and the development of green and low-carbon transportation in highway reconstruction and expansion projects.

2. Collaborative Mechanism between Alignment Adjustment and Existing Road Resource Utilization in Highway Reconstruction and Expansion Projects

Alignment adjustment in highway reconstruction and expansion projects is not merely the selection of a new alignment, but rather a process of reallocating road space and functions under the combined effects of existing road assets, traffic demand, engineering conditions, and ecological constraints. Therefore, the utilization of existing road resources should be incorporated at the early stage of route alternative development, so as to establish a collaborative decision-making logic of "alignment adjustment–existing road utilization–functional improvement."

Alignment adjustment in highway reconstruction and expansion projects mainly includes in-situ widening, unilateral or bilateral widening, local realignment, separated new construction, curve cutting and straightening, and vertical profile optimization. Existing road resources include the horizontal and vertical alignments, subgrade and pavement, bridges and culverts, acquired land, drainage and protection facilities, and traffic organization conditions. There exists a distinct bidirectional coupling relationship between alignment adjustment and existing road resource utilization. On the one hand, the geometric indicators, structural technical conditions, and land-use boundaries of the existing road determine the feasible space for alignment adjustment. On the other hand, different alignment adjustment strategies affect the extent to which existing road resources are retained, reconstructed, or functionally transformed. Existing road resources should not be regarded as passive objects to be treated after route design is completed; instead, they serve as important bases for determining alignment corridor selection, transverse widening patterns, and the magnitude of vertical profile adjustment. The different collaborative pathways and their effects are shown in Table 1.

Table 1. Collaborative pathways between alignment adjustment and existing road resource utilization

Collaborative dimension	Utilization mode of existing road resources	Collaborative effect
Alignment collaboration	Utilizing the existing corridor and locally cutting curves and straightening the alignment	Improving driving safety and reducing large-scale realignment
Structural collaboration	Utilizing the existing subgrade, base course, bridges, and culverts	Reducing construction quantities and material consumption
Land-use collaboration	Utilizing existing right-of-way and corridor resources	Reducing additional land acquisition and demolition
Traffic collaboration	Using the existing road to maintain traffic during construction	Reducing traffic disturbance during construction
Environmental collaboration	Reducing newly opened corridors and abandoned works	Reducing ecological disturbance and carbon emissions

To quantitatively describe the degree of collaboration between the two, a comprehensive synergy degree can be defined as follows:

$$S = \left(A^{\alpha} R^{\beta} F^{\gamma} \right) C_e C_t \tag{1}$$

where S denotes the synergy degree; A denotes the adaptability of alignment adjustment, reflecting the adaptability of the route alternative to technical standards, topographic and geological conditions, and control points; R denotes the utilization degree of existing road resources; F denotes the degree of functional improvement;

α, β, and γ are weights satisfying $\alpha+\beta+\gamma=1$; and C_e and C_t are the ecological environment constraint coefficient and construction traffic organization constraint coefficient, respectively, with values in the range of $0< C_e, C_t \leq 1$.

Equation (1) indicates that route optimization for highway reconstruction and expansion should not one-sidedly pursue either geometric improvement or the retention of existing roads. Excessive realignment may improve technical indicators, but it can also lead to the waste of existing road resources and additional environmental disturbance. Conversely, excessive reliance on the existing road may preserve unfavorable geometric conditions and potential structural deficiencies, thereby restricting the improvement of road functions. Therefore, a reasonable alternative should achieve a balance among safety, economy, resource utilization, and environmental protection.

Based on the above mechanism, alignment adjustment in highway reconstruction and expansion projects should follow the procedure of "resource investigation–value evaluation–alternative generation–collaborative comparison and selection–feedback optimization." For road sections with high resource value, priority should be given to in-situ widening, widening with reinforcement, or local geometric correction. For sections with low resource value and prominent functional constraints, local realignment or separated new construction may be adopted, while the existing road can be transformed into an auxiliary road, a slow-traffic system, or a local road. In this way, hierarchical utilization of existing road resources and coordinated improvement of road functions can be achieved, thereby providing a theoretical basis for the subsequent construction of an evaluation indicator system for the utilization value of existing road resources.

3. Evaluation Indicator System for the Utilization Value of Existing Road Resources

The evaluation of the utilization value of existing road resources should be incorporated as a prerequisite step in the generation and comparison of route alternatives for highway reconstruction and expansion projects. In this study, the utilization value of existing road resources is defined as the comprehensive utility generated by the retention, reconstruction, recycling, or functional transformation of existing road resources during reconstruction and expansion, under the premise of satisfying technical standards, traffic safety requirements, and functional improvement objectives. The evaluation indicator system is established according to the "objective layer–criterion layer–indicator layer" structure shown in Fig. 1. The meanings and attributes of the corresponding indicators are presented in Table 2.

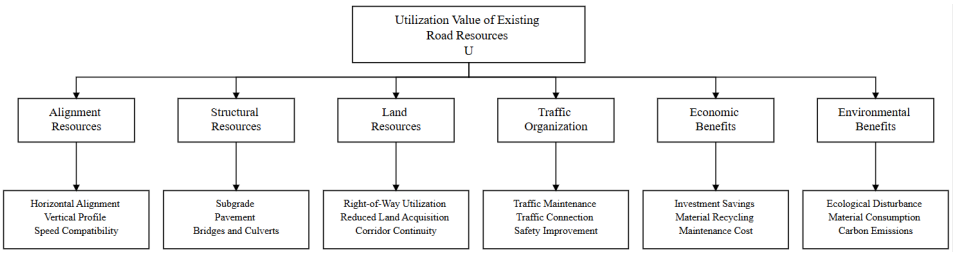


Fig 1. Evaluation system for the utilization value of existing road resources

Table 2. Evaluation indicators for the utilization value of existing road resources

Criterion layer	Main indicators	Evaluation implication
Alignment resources	Horizontal alignment, vertical profile, speed consistency	Evaluating the adaptability of the existing alignment to reconstruction and expansion standards
Structural resources	Subgrade, pavement, bridges and culverts	Evaluating the potential of existing structures for continued use or reinforced utilization
Land-use resources	Right-of-way utilization, reduction in land acquisition, corridor continuity	Measuring the saving effect of existing corridors and land-use resources
Traffic organization	Traffic maintenance capacity, traffic connection, safety improvement	Reflecting traffic service capacity during both construction and operation periods
Economic benefits	Investment saving, material recycling, maintenance cost	Measuring the economic benefits generated by existing road utilization
Environmental benefits	Ecological disturbance, material consumption, carbon emissions	Measuring the effects of resource conservation and low-carbon emission reduction

Since the indicators have different dimensions and units, standardization is required before evaluation. The comprehensive weights can be determined by combining the analytic hierarchy process (AHP) and the entropy weight method:

$$w_j = \lambda w_j^{AHP} + (1-\lambda) w_j^{E} \tag{2}$$

where w_j is the comprehensive weight of the j-th indicator; w_j^{AHP} is the subjective weight obtained using the analytic hierarchy process; w_j^{E} is the objective weight obtained using the entropy weight method; and λ is the adjustment coefficient between subjective and objective weights, with a value range of $0 \le \lambda \le 1$. When a project is in the preliminary alternative selection stage and available data are relatively insufficient, λ may be appropriately increased. When sufficient testing and investigation data are available, λ may be reduced to enhance the objectivity of the evaluation. On this basis, the utilization value of existing road resources for the i-th road section can be expressed as:

$$U_i = \sum_{j=1}^{n} w_j x'_{ij} \tag{3}$$

where U_i denotes the utilization value of existing road resources for the i-th evaluation section; x_{ij}' is the standardized value of the j-th indicator for the i-th section; and n is the total number of evaluation indicators. A larger U_i indicates a higher comprehensive value for retaining, reconstructing, and reusing existing road

resources in that section. According to the comprehensive score, the utilization value of existing road resources can be classified into three levels, as shown in Table 3.

Table 3. Evaluation grades and recommendations for alignment adjustment

Range of U_i	Grade	Recommended strategy
$0.75< U_i \leqslant 1.00$	High value	Give priority to in-situ widening and widening by utilizing existing resources, with local alignment optimization
$0.50< U_i \leqslant 0.75$	Medium value	Adopt widening with reinforcement, curve cutting and straightening, and bridge and culvert strengthening
$0< U_i \leqslant 0.50$	Low value	Adopt local realignment or separated new construction, and transform the existing road into an auxiliary road or local road

Table 3, the purpose of evaluating existing road resources is not simply to determine whether they should be utilized, but rather to formulate hierarchical utilization strategies based on differences in resource value. For high-value sections, priority should be given to retaining existing corridors and structural resources. For medium-value sections, reuse should be achieved through reinforcement and reconstruction. For low-value sections, excessive reliance on the existing road should be avoided, as it may constrain safety enhancement and functional improvement. The evaluation results can serve as an important basis for defining the objective function and constraints related to existing road utilization in the subsequent multi-objective alignment optimization model.

4. Multi-Objective Alignment Optimization Model for Highway Reconstruction and Expansion Projects

The utilization value of existing road resources can provide hierarchical strategies for alignment adjustment; however, specific alternatives still need to be comprehensively optimized under constraints related to engineering cost, safety, traffic organization, and the environment. Therefore, based on the evaluation results of existing road resource value, this study constructs a multi-objective alignment optimization model for highway reconstruction and expansion projects, as shown in Fig. 2. Taking road sections as the basic units, the model embeds "existing road resource utilization" into the entire process of route alternative generation, objective calculation, and scheme screening, thereby realizing a transition from a single engineering-economy-oriented approach to comprehensive collaborative optimization.

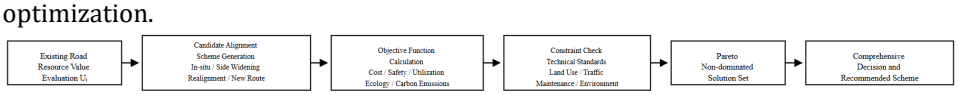


Fig 2. Framework of the multi-objective alignment optimization model for highway reconstruction and expansion projects

Assume that the reconstruction and expansion alignment is discretized into N control sections. The decision vector is denoted as $X=\{x_1,x_2,\ldots,x_N\}$, where x_i represents the alignment adjustment mode and the corresponding parameter combination for the i-th section. The multi-objective optimization problem can then

be expressed as:

$$\min F(X) = \left[f_1(X), f_2(X), -f_3(X), f_4(X), f_5(X) \right] \tag{4}$$

where $f_1(X)$ denotes the total engineering cost; $f_2(X)$ denotes traffic safety risk; $f_3(X)$ denotes the benefit of existing road resource utilization; $f_4(X)$ denotes ecological impact; and $f_5(X)$ denotes life-cycle carbon emissions. The objective functions can be expressed as follows:

$$f_1(X) = \sum_{i=1}^{N} \left(C_i^n L_i^n + C_i^r L_i^r + C_i^a L_i^a \right) \tag{5}$$

$$f_3(X) = \sum_{i=1}^{N} U_i \cdot \eta_i \tag{6}$$

$$f_4(X) = \sum_{i=1}^{N} \left(E_i^{land} + E_i^{eco} \right) \tag{7}$$

$$f_5(X) = \sum_{i=1}^{N} \left(\mu_i^{mat} M_i + \mu_i^{trans} T_i + \mu_i^{con} P_i \right) \tag{8}$$

where L_i^n, L_i^r, and L_i^a denote the quantities of new construction, reconstruction, and ancillary works, respectively; η_i denotes the utilization coefficient under the corresponding alternative; E_i^{land} and E_i^{eco} denote land-use disturbance and ecological disturbance, respectively; and M_i, T_i, and P_i represent material consumption, transportation emissions, and construction emissions, respectively.

The model constraints mainly include technical standards, traffic organization, land-use boundaries, and environmental control requirements, as listed in Table 4. For sections with high existing road resource utilization value, the model gives priority to improving $f_3(X)$ through measures such as in-situ widening and widening with reinforcement. For sections with low utilization value, local realignment or separated new construction is allowed so as to avoid potential safety hazards and functional deficiencies caused by "retention for the sake of retention."

Table 4. Main constraints of the multi-objective alignment optimization model

Constraint category	Mathematical expression	Implication
Technical standard constraint	$R_i(X) \geq R_{\min}, i_i(X) \leq i_{\max}$	Satisfying the requirements for minimum horizontal curve radius and maximum longitudinal gradient
Sight distance constraint	$SD_i(X) \geq SD_{\min}$	Ensuring safe stopping sight distance and meeting sight distance
Traffic maintenance constraint	$Q_i(X) \geq Q_0$	Satisfying traffic organization requirements during both construction and operation periods
Land-use constraint	$A_i(X) \leq A_0$	Controlling the scale of additional land acquisition and demolition
Environmental constraint	$E_i(X) \leq E_0$	Limiting the disturbance scope of ecologically sensitive areas
Existing road	$X_i \in \Omega_i(U_i)$	Giving priority to retaining or reusing high-value

utilization constraint		sections

In terms of solution methodology, the non-dominated sorting genetic algorithm II (NSGA-II) is adopted to obtain the Pareto-optimal solution set, after which a compromise alternative is selected using a comprehensive evaluation function. To enhance the comparability among different objectives, a standardized comprehensive objective function can be further established as follows:

$$Z(X)=\sum_{k=1}^{5}\omega_k\frac{f_k(X)-f_k^{\min}}{f_k^{\max}-f_k^{\min}} \tag{9}$$

where ω_k denotes the weight of the k-th objective, satisfying $\sum\omega_k=1$. When greater emphasis is placed on resource conservation and low-carbon construction, the weights of the existing road utilization objective and the carbon emission objective may be appropriately increased. When the project is located in a safety-sensitive control area, the weight of the safety risk objective should be increased. Accordingly, the proposed model can not only reflect the engineering feasibility of alignment adjustment, but also quantitatively reveal the collaborative relationships among existing road resource utilization, functional improvement, and environmental constraints.

5. Case Study

To verify the applicability of the proposed multi-objective alignment optimization model, a reconstruction and expansion project of a mountainous Class II highway in Tibet was selected as a case study. The studied section has a total length of 18.6 km. The existing subgrade width is 8.5 m, and the highway is planned to be reconstructed and expanded to a width of 24.5 m in accordance with Class I highway standards. Along the route, there are several problems, including small-radius curves, steep gradients, partial village crossings, and insufficient bearing capacity of bridges and culverts. In addition, the project is subject to strong ecological and land-use constraints, making it a representative case. Based on the evaluation system proposed in Section 3, the route was divided into six sections, and the utilization value of existing road resources was calculated. The results are shown in Table 5.

Table 5. Evaluation results of existing road resource utilization value

Section	Stake range	Comprehensive score U_i	Utilization grade
I	K0+000–K3+200	0.77	High value
II	K3+200–K6+100	0.57	Medium value
III	K6+100–K9+400	0.44	Low value
IV	K9+400–K12+800	0.71	Medium value
V	K12+800–K15+600	0.80	High value
Ⅵ	K15+600—K18+600	0.56	Medium value

As shown in Table 5, Sections I and V have smooth alignments, favorable structural conditions, and continuous corridor resources, and are therefore suitable for priority utilization. Section III has poor geometric alignment, weak structural conditions, and significant disturbance caused by village crossings; thus, local realignment should be the dominant strategy. Sections II, IV, and VI can be reused through widening with reinforcement and local optimization. Accordingly, three types of alignment alternatives were established: Alternative A is an existing-road-priority scheme, Alternative B is a comprehensive coordination scheme, and Alternative C is an alignment-improvement-priority scheme.

To ensure consistent comparison among different alternatives, standardization was performed. Cost-type objectives were processed according to Eq. (10), while benefit-type objectives were processed according to Eq. (11). The comprehensive evaluation was still calculated using Eq. (9), with weights of 0.25, 0.25, 0.20, 0.15, and 0.15 assigned to engineering cost, safety risk, existing road utilization, ecological impact, and carbon emissions, respectively. After solving the model using NSGA-II, representative comparison results of the alternatives were obtained, as shown in Table 6.

Table 6. Comparison of optimization results for different alignment alternatives

Indicator	Alternative A	Alternative B	Alternative C
Total engineering cost / 10^8 yuan	5.82	6.14	7.05
Safety risk index	0.46	0.31	0.24
Existing road utilization rate / %	78.5	64.2	41.6
Additional land occupation / hm^2	21.4	26.8	39.5
Carbon emissions / 10^4 t	12.6	11.8	14.3
Comprehensive evaluation value	0.42	0.28	0.39

As shown in Table 6, Alternative A has the lowest cost but a relatively high safety risk, while Alternative C provides the best safety performance but requires larger additional land occupation and generates higher carbon emissions. Alternative B achieves a better balance among cost, safety, existing road utilization, and environmental impact, and has the lowest comprehensive evaluation value; therefore, it is recommended as the preferred scheme. This case demonstrates that sections with higher existing road resource value should preferentially adopt in-situ widening or widening based on existing resources, whereas low-value sections should avoid “retention for the sake of retention” and instead achieve functional improvement through local realignment. The results verify the effectiveness of the proposed collaborative optimization framework of “alignment adjustment–existing road utilization–functional improvement.” They also indicate that embedding existing road resource value evaluation into the comparison and selection of alignment alternatives can improve the scientific basis of alignment decision-making and promote green and low-carbon development in highway reconstruction and expansion projects.

6. Conclusions

To address the insufficient utilization of existing road resources and the cost-oriented tendency in alternative comparison during alignment adjustment for highway reconstruction and expansion projects, this study developed a collaborative optimization framework of "alignment adjustment–existing road utilization–functional improvement." An evaluation indicator system for the utilization value of existing road resources was established, and a multi-objective alignment optimization model considering cost, safety, ecology, and carbon emissions was proposed. The effectiveness of the method was verified through a case study. The main conclusions are as follows:

Alignment adjustment and existing road resource utilization in highway reconstruction and expansion projects exhibit a significant coupling relationship. Existing road resources should be incorporated in advance into the entire route alternative decision-making process, rather than being treated as a post-design disposal issue.

The proposed evaluation system enables the utilization of existing roads to shift from qualitative judgment to quantitative assessment. In the case study, the comprehensive scores of the six sections ranged from 0.44 to 0.80. Sections I and V were identified as high-value sections, while Section III was identified as a low-value section, providing a basis for differentiated utilization strategies.

The multi-objective optimization results show that Alternative A has the lowest cost but a relatively high safety risk, whereas Alternative C provides the best safety performance but involves greater additional land occupation and carbon emissions. Alternative B is the optimal comprehensive scheme, with a comprehensive evaluation value of 0.28, reflecting a coordinated balance among cost, safety, existing road utilization, and environmental constraints.

The study demonstrates that embedding existing road resource value into alignment optimization can effectively improve the scientific validity of alignment decision-making, resource utilization efficiency, and the green and low-carbon performance of highway reconstruction and expansion projects.

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