Technical-Economic Analysis of Local Technologies for the Rehabilitation of Rural Roads: A Comparative Study of Stabilized Materials

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Abstract

Maintaining rural roads is a crucial challenge in developing regions, where poor infrastructure conditions limit access to basic services and restrict sustainable economic development. This study carries out a technical-economic evaluation of two road maintenance alternatives using the HDM (Highway Development and Management) model: a stabilized base with asphalt crude oil and traditional maintenance with paving material. The research includes a detailed technical characterization of the materials used, as well as an analysis of operating costs, travel times, fuel consumption and associated economic benefits.

The results show that stabilization with Rubiales crude oil offers a 15% reduction in vehicle operating costs and a 12% reduction in travel costs, due to the 25% increase in average transit speed due to better rolling conditions. In addition, a 5% decrease in fuel consumption was observed, even under conservative assumptions about the maintenance of the affirmation. The stabilized alternative demonstrated high economic profitability with an internal rate of return (IRR) of 275% and a benefit/cost ratio of 6.7, far outperforming conventional maintenance. The research also identifies opportunities to optimize the initial investment through adjustments in the thickness of the stabilized layer, which would allow a greater number of projects to be executed with limited resources without compromising economic efficiency.

This study supports the use of sustainable local technologies, such as stabilizations with bituminous products, to improve rural road infrastructure. In addition, the technical and economic approach employed provides a framework that can be replicated in other global contexts with similar characteristics, contributing to the advancement of sustainable road development.

Keywords: Road stabilization, crude asphalt, economic evaluation, HDM model, profitability, sustainability.

Rural and secondary road maintenance represents a critical challenge for many regions of the world, especially in developing areas, where poor road infrastructure limits access to markets, education and health services. According to the World Bank (2019), 40% of rural roads in developing countries are in poor condition, which significantly increases transport costs and reduces economic competitiveness. In this context, local asphalt materials, such as heavy and extra-heavy crude oil, have been explored as a sustainable and economical solution for road rehabilitation and maintenance.

Research conducted in countries such as India, South Africa, and Brazil has shown that stabilizing bases with natural asphalt products improves the load-bearing capacity and durability of roads compared to the use of conventional affirmation materials (Choudhary et al., 2020; Kannemeyer et al., 2017). In Brazil, for example, the use of stabilized heavy crude oil on rural roads reduced maintenance costs by 25% over a five-year period (Silva et al., 2018). These studies highlight the importance of a technical and economic assessment to determine the feasibility of these technologies in specific contexts.

The objective of this article is to economically evaluate two road maintenance alternatives using the HDM (Highway Development and Management) model, widely used in international studies to project maintenance and rehabilitation costs. Alternatives include the use of a stabilized base with asphalt crude and maintenance with affirming material. The aim is to determine which is more efficient in terms of investment costs, durability and sustainability, considering the physical and chemical characteristics of the materials used.

The technical and economic analysis presented here not only aims to contribute to the improvement of road infrastructure in rural areas, but also to offer a scientific basis that can be applied in global contexts with similar conditions. This research is aligned with the recommendations of international organizations such as PIARC (2021), which promote the use of local and sustainable technologies to improve the rural road network efficiently and economically.

GENERAL OBJECTIVE

The objective of this article is to economically evaluate two maintenance alternatives for a road section in San Agustín, Huila, using the HDM model. The use of stabilized base with Rubiales crude and affirmation material is compared in terms of cost, investment and durability. The aim is to determine which option is more efficient in terms of its economic impact and long-term functionality. The evaluation considers the technical and financial aspects of each alternative.

METHODOLOGY

3.1 Collection of Information

For the development of this technical-economic analysis of local technologies for the rehabilitation of rural roads, a comprehensive research was carried out on the characterization, design, behavior and construction with heavy crudes and natural asphalts. This process included consulting various sources that provided a solid base of technical and practical knowledge, among which the following stand out:

- Library of the University of Cauca: Specialized academic resources in materials engineering and technologies applied to road stabilization were accessed.
- Research articles: Scientific and technical publications on the use of heavy crude oils and natural asphalt mixtures were reviewed, focusing on studies that evaluated their performance in conditions similar to those analyzed.
- Online sources: Scientific databases and online platforms were consulted that provided up-to-date information on innovations and success stories in the stabilization of rural roads.
- Interviews with experts: Interviews were conducted with professionals and entities that have experience in the implementation of local technologies for the stabilization of materials, which allowed practical perspectives

and real results to be incorporated into the analysis.

• This information collection methodology was essential to develop a detailed comparative assessment between heavy crude stabilized materials and traditional affirmed solutions, ensuring that the conclusions reflect both scientific evidence and practical experience in the context of rural roads.

RESULTS

4.1 Information Collection

To carry out the economic evaluation of road maintenance, information was collected from works developed with natural asphalt materials, for which an experimental section built using Rubiales crude oil was analyzed. This study compared two improvement alternatives using the HDM (Highway Development and Management) model: one based on stabilization with crude oil and the other through traditional maintenance with affirmation material. The experimental section is located in the municipality of San Agustín, in the department of Huila, providing a representative context of road conditions in rural regions of Colombia.

Traditional alternative: This option consists of a section of pavement subject to periodic maintenance by means of occasional refills with topdressing material to repair potholes. The frequency of maintenance is determined based on the depth of the footprint formed on the surface; In this case, a 5 cm footprint was considered as the threshold for intervention. The structure of the pavement is made up of a layer of affirmation placed directly on the subgrade.

Alternative with natural asphalt: This alternative involves the physical-chemical stabilization of 30 cm of the subgrade, treated with quicklime in a dosage of 1.5% by weight. A 10 cm thick gravel base was placed on top of this stabilised layer, ending with a tread layer composed of a cold mixture. The wearing course uses stone aggregate with a BEE-2 type gradation and is modified with Rubiales crude oil in an optimal content of 5.8%. The final structure is made up of the stabilized layer on the subgrade, followed by the gravel and the wearing layer, designed to offer greater durability and better structural behavior.

The purpose of this comparative analysis is to evaluate the technical and economic performance of each alternative, considering aspects such as initial costs, maintenance, and their impact on the useful life of the road section. Table 4.1 shows the execution costs of each of the layers that constitute the alternative to be evaluated and Table 6.2 shows the different input data to the HDM model.

Table 4.1. Total construction costs of the San Agustín road section (Huila)

TOTAL COSTS ($) / m3	
San Agustín section	
Affirmed Placement	105.000
t Granular Layer (Subbase)	156.000
Asphalt Layer Installation (dense cold mix)	390.000 (Crude, aggregate)

Table 4.2. Input data for HDM model

HDM INPUT DATA	
PARAMETER	**ROAD SECTION SAN AGUSTÍN**
CHARACTERISTICS OF THE ROAD	
Route references	
Geometry	
Longitude	220m.
Road width	6m.
Berm width (avg. pond. Both sides)	No berm
Number of lanes	2
Ascents plus descents (m/Km)	30m/220m.
Number of Uploads Plus Downloads	1
Mean horizontal curvature(°/Km)	Unavailable
Maximum speed found in the section (Km/h)	30 Km./h
Altitud (msnm)	1300
Average cant	It does not have
Environmental Conditions	
Average annual temperature	18°C
Average annual rainfall	2000mm

Moisture Rating (Wet, Dry, Semi-Wet)	Wet
Length of the dry season (how many months of the year it does rain)	
Functional Conditions	
IRI	Affirmed
Percentage of pothole area in the section	20%
Percentage of crack area in the section	Affirmed
Structural Conditions	
Structural Number	4
Benkelman deflection	2,049mm
TRANSIT	
Characteristics of the vehicle fleet	
Vehicle costs	
Repair costs	
Damage Factor	INVIAS
Daily traffic intensity	
Average Daily Traffic (TPD)	592
Percentage distribution of vehicles	
Percentage composition of vehicle types (%A %B %C)	90% / 1% / 9%
Historical traffic series	It does not exist

4.2 Results

The analysis of the road section located in the municipality of San Agustín, Huila, using the HDM model, allowed the evaluation of the improvement alternatives designed for roads with low vehicular traffic. These options include the use of a stabilized base with natural bituminous products and traditional breeding using affirming material. The study, developed under a 15-year analysis horizon, reveals significant differences in terms of economic efficiency and structural performance between both alternatives.

4.2.1. General Economic Comparison of the Alternatives

Table 4.3 presents the results of the economic evaluation, highlighting the key indicators that support decision-making in road infrastructure projects. This analysis compares the associated costs, technical performance and benefits obtained for each alternative.

Table 4.3. Economic comparison between stabilization with bituminous products and improvement with affirmation

ECONOMIC COMPARISON PROD STABILIZATION. BITUMINOUS VS IMPROVEMENT WITH FIRM		
VOC Savings	Savings in TM travel time costs	Net Economic Benefits (NPV)
$ 570,000,000	$ 240,000,000	$ 990,000,000

Internal Economic Rate of Return (IRR) = 275.3%

The analysis carried out shows that stabilization with natural bituminous products offers substantial economic benefits compared to the traditional method based on affirmation material. Among the main advantages are the significant reduction in operating costs, greater durability of the road structure and a higher benefit/cost ratio, which reinforces the viability of this technology to optimize road infrastructure in rural areas. These findings underscore the potential of innovative technologies as a key tool to maximize the efficiency of public investments in the road sector.

The alternative based on stabilization with natural bituminous products showed significant savings in aspects such as vehicle operating costs, travel times and generation of exogenous benefits. This is reflected in a high internal rate of return (IRR) of 257.3%, which demonstrates the economic profitability of this technique compared to traditional maintenance with affirming material. These results not only support the implementation of bituminous stabilizations as a cost-effective and sustainable solution, but also highlight their ability to extend road life and reduce costs associated with transportation in regions with specific budget constraints and traffic conditions.

4.2.2 Vehicle operation costs. The analysis of the vehicle operating costs in the evaluated road section shows that the alternative based on stabilization with natural bituminous products offers a significant reduction compared to conventional maintenance using affirming material. In particular, a 15% decrease in the costs associated with the vehicular operation was achieved, which is attributed to the improved condition of the tread provided by the asphalt mixture used in the tread layer (see Figure 4.2).

This improvement in the quality of the running surface not only reduces wear and tear on vehicles, but also optimizes fuel consumption and decreases the need for frequent vehicle maintenance. These results support the positive impact that bituminous stabilization technologies can have on the operational efficiency of transportation, especially in rural regions where road conditions are often challenging.

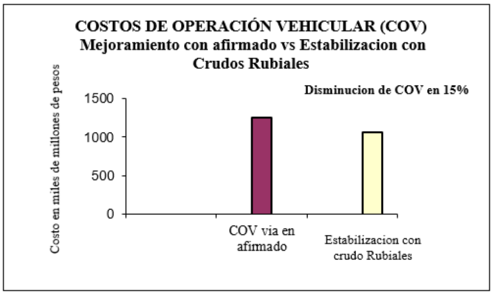

Figure 4.2 Comparison of the vehicular operating costs of the alternatives of the San Agustín road section

4.2.3 Travel time costs. The comparative analysis between road improvement alternatives reveals that the costs associated with travel time decrease by 12% when traveling on a road improved with heavy crude oil, compared to a road maintained with paving material. This significant savings is attributed to the increase in average travel speeds, which results from the improved rolling conditions provided by stabilization with bituminous products.

The improvement in the quality of the road surface allows for more efficient driving, reducing both travel times and costs related to travel time. This positive impact is particularly relevant on rural roads with low traffic volumes, where rolling conditions are often a critical factor for mobility.

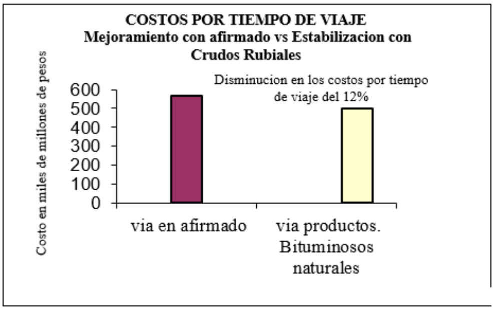

Figure 4.3 Comparison of costs by travel time of the San Agustín road

Figures 4.4 and 4.5 show a summary of the annual variation during the period of analysis of vehicle operating costs and travel time costs.

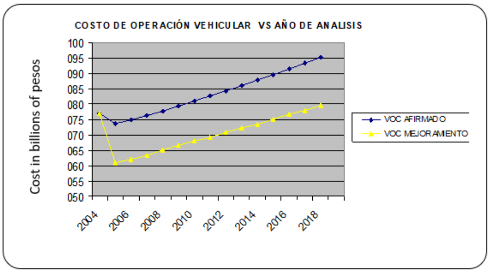

Figure 4.4 Variation in vehicle operating costs

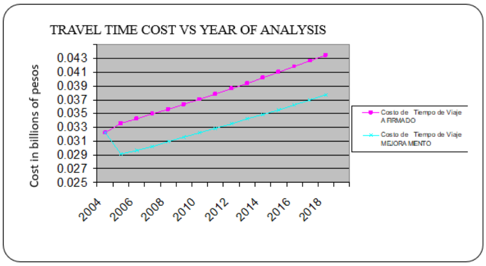

Figure 4.5 Variation in travel time costs

4.2.4 Fuel consumption costs. The analysis of fuel consumption costs shows a 5% reduction when traveling on a road stabilized with Rubiales crude oil compared to a road whose surface is maintained by pavement, as shown in Figure 4.6. These savings are due to the improved rolling conditions offered by bituminous stabilization, which reduces rolling resistance and, therefore, optimizes the efficiency of the fuel used by vehicles.

It is important to note that this percentage could increase in real scenarios, since the HDM model assumes continuous maintenance of the affirmation layer in good condition during the analysis period. In practice, roads with pavements often show significant deterioration before being intervened, which increases rolling resistance and, consequently, fuel consumption. These findings underline the advantage of stabilization technologies with bituminous products in terms of economic and environmental sustainability.

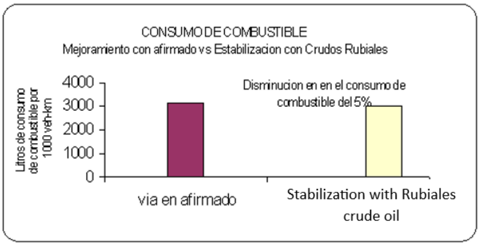

Figure 4.6 Comparison of fuel consumption costs for the San Agustín road section

4.2.5. Average traffic speeds. The analysis of average traffic speeds reveals an increase of 25% when driving on a road stabilized with crude oil, compared to a road maintained by pavement, during the period of analysis. This significant increase in speed is attributed to the improved rolling conditions provided by crude stabilization, which reduces surface roughness and facilitates more efficient vehicle movement.

Improvements in the stabilized surface not only positively impact travel times, but also contribute to the reduction of vehicle wear and tear and increased traffic safety. These advantages make crude stabilization technologies a viable and superior alternative to traditional affirmation methods.

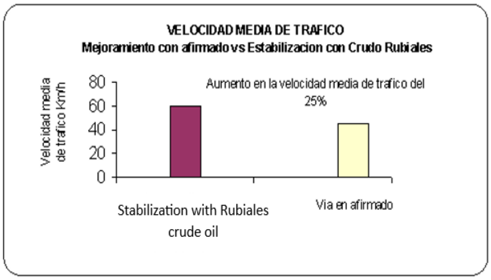

Figure 4.7 Average Traffic Speeds

4.2.6 Benefit/cost ratio and internal rate of return for the different projects. The economic evaluation of road improvement alternatives shows that the implementation of non-conventional dense mixtures, stabilized with bituminous products, presents a benefit/cost ratio (B/C) significantly higher than 1, which supports their viability and justifies their investment compared to traditional maintenance based on the replacement of affirming material. These results confirm that stabilization technology is not only sustainable, but also cost-effective in the context of low vehicular traffic roads, as shown in Table 4.5.

Likewise, the analysis reveals a remarkably high internal rate of return (IRR) for the 15-year period considered, which underlines the economic efficiency of the stabilized alternative. However, this high IRR also suggests the possibility of optimizing the initial investment by reducing the thickness of the stabilized layer. A lower initial investment would allow the available resources to be extended, facilitating the execution of a greater number of similar projects without compromising the quality or benefits derived from the intervention.

This approach allows technological solutions to be adapted to local budgetary and traffic conditions, striking a balance between profitability and sustainability

Table 4.5 Benefit/cost ratio and IRR

PROJECT	INTERNAL RATE OF RETURN	BENEFIT/ COST
I am a student	275	6,7

CONCLUSIONS

In relation to the economic efficiency of bituminous technologies, stabilization with natural bituminous products proved to be significantly more profitable than traditional maintenance with affirming material, as it presents a higher benefit/cost ratio and a high internal rate of return (IRR), which validates its viability for roads with low vehicular traffic.

Regarding the reduction of operating costs, it was determined that the roads stabilized with Rubiales crude oil reduced vehicle operating costs by 15% compared to the affirmation alternatives, due to the improvement in rolling conditions.

In terms of the optimization of travel time, a 12% decrease in the costs associated with travel time is obtained, attributable to the 25% increase in the average traffic speed on stabilized roads, significantly improving mobility and access in rural areas.

In terms of fuel consumption savings, the stabilized alternative allowed a 5% saving in fuel consumption, highlighting its ability to optimize energy use in vehicular transport. These savings could be even greater in real scenarios where the affirmation is not kept in optimal condition.

Associated with structural durability, non-conventional dense mixtures stabilized with bituminous products have greater durability against traffic and adverse weather conditions, reducing the need for frequent maintenance and prolonging the useful life of the track.

Analysing the sustainability of the initial investment, the high IRR obtained suggests that design optimisation, such as reducing the thickness of the stabilised layer, can generate additional savings, allowing more projects to be executed within the same budget.

In terms of the impact on rural road infrastructure, the adoption of stabilization technologies with heavy crude oil is a sustainable and efficient solution to improve rural road infrastructure, increasing connectivity and facilitating socioeconomic development in hard-to-reach regions.

These alternatives show great technical and economic resilience, providing resilient solutions to fluctuations in traffic conditions and resources, ensuring consistent benefits over the 15-year analysis period.

The technical results showed that the cold mixture, composed of Rubiales crude oil and stone aggregate with BEE-2 gradation, meets the performance standards to support vehicular traffic on rural roads, presenting high technical feasibility of stabilization

The environmental perspectives of these technologies show a reduction in fuel consumption and the reduction of frequent maintenance contribute to minimizing the environmental footprint of vehicular transport, positioning this technology as a more ecological alternative.

The methodological approach based on the HDM model is presented as a replicable tool to evaluate road improvement alternatives in similar contexts, facilitating data-based decision-making.

This study supports the development of public policies aimed at the adoption of local and sustainable technologies in road infrastructure projects, promoting smarter investments aligned with the sustainable development goals.

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