Life cycle costs and mid-term performance of a geogrid-stabilized pavement section, an economical and sustainable approach, case study, RN-39 Honduras

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Abstract. When we talk about mechanical stabilization of granular layers with geogrids in roadway applications, we often mention that these pavements have a better performance along the time and a reduced cost along the whole life cycle. In the last years we have been measuring the International Roughness Index (IRI) of a segment of multi-axial with triangular aperture geogrid-stabilized road of 45.6 km of length and comparing it with a non-stabilized segment of 30.7 km of length, which was constructed in the same period and was commissioned the same year, for the same traffic. In terms of deterioration based on the International Roughness Index (IRI) for each segment, the mechanically stabilized road has shown a better performance than the non-stabilized segment, this publication seeks to show the tendency of the IRI curve for both sections, and the differences in their behavior. In addition, an analysis with the software; Highway Development and Management, version 2.0 (HDM-4) will be conducted to estimate the impact in the road user's costs which are part of the life cycle cost and compare both sections, as well as an attempt to emulate and calibrate the IRI curve for the stabilized road section. This publication will help pavement engineers, designers, asset managers, highway engineers, departments of transportation and any people involved on roads, to better understand the economic advantages and performance benefits of mechanically stabilized granular layers with multi-axial geogrids on pavements and how they can help building resilient, durable, and sustainable road infrastructures.

1 Introduction

Life cycle cost analysis is a technique that builds on the well-founded principles of economic analysis to evaluate the over-all-long-term economic efficiency between competing alternative investment options. [1].

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All the relevant costs that occur throughout the life of an alternative, not simply the original expenditures, are included. Also, the effects of the agency`s construction and maintenance activities on users, as well as the direct costs to the agency, are accounted for. [2] from this perspective, we can construct expenditure diagrams flow including agency costs for initial construction, costs of activities of maintenance and rehabilitation during a time analysis period and its impact, as well as the effects of the pavement condition on the user costs.

In Honduras, both user costs and proper management of pavements in their life cycle have generally been underestimated, traditionally there has been no promotion or investment in road research, therefore, the idea and development of this research initiative represent the personal endeavor and self-motivation of the author with the support and funding of the co-author, representing the commitment and effort investing in generating knowledge and contribution to science and engineering. During the last decades most of the road network has suffered an accelerated deterioration due to the lack of maintenance, improvement, and rehabilitation activities, representing a high cost for the agency and for the users. Focusing on user costs they are an aggregation of three separate cost components: vehicle operating costs (VOC), user delay costs and crash costs [1]. The three user costs in normal operation of the road will be influenced by the pavement condition, whilst the pavement deterioration increase, the vehicle operation cost increase, the running speed is reduced and therefore the user delay costs also increase, on the other hand, a deteriorated pavement may contribute to increase the accidents and crash costs. Hence, the lack of adequate management not only conduct to a premature failure of a pavement condition but also significantly impacts user costs.

There are a variety of methods for monitoring the pavement condition, nonetheless most of the departments of transportation collect the International Roughness Index (IRI) collecting annually data on roads comprising the National Highway System, NHS, and a 2-year cycle for routes non-NHS [3]. The International Study of Highway Development and Management (ISOHDM), managed by the World Road Association under the support and actions of the World Bank since 1998, stablish the pavement strength and the road roughness as the most important factors in pavement performance, condition which is used in the calculation of road user cost, particularly VOC. [4] This paper describes the performance in the mid-term of two road sections in the Highway known as Route-39 (RN-39) which connect the departments of Olancho and Colon while serving as touristic and agricultural corridor, since 2016 several IRI surveys have been carried out in order to compare the performance of the two sections, the segment 2 correspond to the non-stabilized segment of the Highway San Francisco de la Paz - Gualaco Olancho, and the segment 5 is the stabilized section El Carbon Olancho - Bonito Oriental Colón, the average IRI and its evolution through the years have been calculated and plotted for real conditions, then the segments have been modelling in HDM-4 using the calibration factors for adjust the roughness progress to the real conditions and related to its cost respectively, for estimating the impact on user costs, performance, resilience and benefits of the stabilized segment 5 compared to the non-stabilized segment 2.

2 Background

The benefits of geosynthetics in pavement systems application have been published in several papers and scientist articles, in 2013 a new standard practice with reference on the GMA`s White Paper I and White Paper II and the Participant Notebook of the National Highway Institute (NHI) was published by AASHTO under the designation R 50-09, this standard provides guidance to pavement designers interesting in incorporating geosynthetics on flexible pavements structures for reinforcement the aggregate base layer. The standard practice is of empirical nature and restricted to applications already demonstrated to be useful, the design procedures uses experimentally derived input parameters for specific geosynthetic, thus computed engineering designs and economic benefits are not easily translated to other geosynthetics, the users of this document are encouraged to affirm their designs with field verifications of the performance, both in engineering design and economic benefits. [5]. As time goes by, the concept of the behavior of geogrids in conjunction with the soil has changed from reinforcement to mechanical stabilization of the aggregate layer, the term *reinforcement* implies "add-ing force" whilst "to stabilize" means "to keep unchanged". Indeed, lateral restraint is a mechanism aimed at keeping the road base as close as possible to its initial stage for as long as possible, which is consistent with low strains, hence small road deformation and limited rutting [6], proving different results and performance of the compost geogrid-soil for different types of geogrids. Since small-scale laboratory testing conducted to evaluate the load transfer in geogrids for base stabilization using transparent soil [7] to the interaction soil-geosynthetic test program which was conducted on 15 identified geosynthetic evaluated along with the field performance of over 80 test sections located at 10 sites at Texas [8] as well as full scale evaluation of geogrid, multi-axial geogrids of triangular aperture has demonstrated not only the best performance but also have proved its performance with optimized / reduced thickness of aggregate base layer and asphalt layers [9], just to mention some examples of the performance and interaction soil-geosynthetic.

3 Project Background

3.1 Location

The two study sections belong to the Agricultural Corridor Route 39 (RN39), the segment 2 begin in San Francisco de la Paz, Olancho, and finish in Gualaco, Olancho, the segment 5 begin in El Carbón, Olancho and finish in Bonito Oriental, Colón. GPS coordinates are 14.8854, -86.1683 to 15.0248, -86.0767 and 15.4516, -85.5927 to 15.7403, -85.7369 respectively.

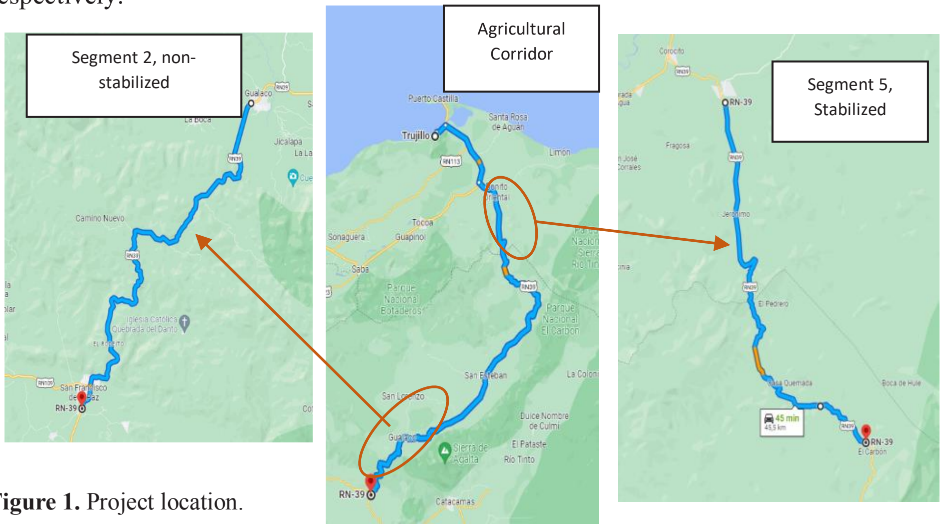

Figure 1. Project location.

3.2 Pavement structure details and design parameters

The segment 2, was constructed with a double surface bituminous treatment over a nominal 200-mm-thick of base granular layer, 350-mm-thick of imported aggregate subbase and the natural subgrade, the total width of the road is 9.5m with a length of 30.7 km. [10]. The segment 5 was constructed with a double surface bituminous treatment over a nominal 200-mm-thick multi-axial with triangular aperture geogrid-reinforced aggregate base, 200-mm-thick existing subbase, and the natural subgrade [11]. The total width of the road is 10.2m with a length of 45.6km.

An *In Situ* validation of the mechanically stabilized granular base in segment 5 was conducted at the end of the project with an Automated Plate Load Test (APLT) repetitive/cycling testing in conformance with the test methods, ASTM D1196 and AASHTO T-221 [12]. Segment 5, was designed for 1.8 million of standard axles (msa), for the segment 5 the average resilient modulus of the subgrade was estimated in 180 MPa, for the subgrade of the segment 2 in this comparison is assumed the same resilient modulus. Solving the AASHTO 1993's equation for flexible pavements for these conditions, with a 80% of reliability and 0.44 of standard deviation for an actual present service of 1.7, the structural number (SN) required over the subgrade was 2.19 (figure 2b), for the designed stabilized pavement segment 5 a SN=2.49 was estimated at design stage due to the benefits of the multi-axial geogrid in the stabilized base layer (figure 2c) [13], nonetheless after the validation with the APLT, the structural number *In Situ* obtained was SN=2.64. [13] (figure 2d).

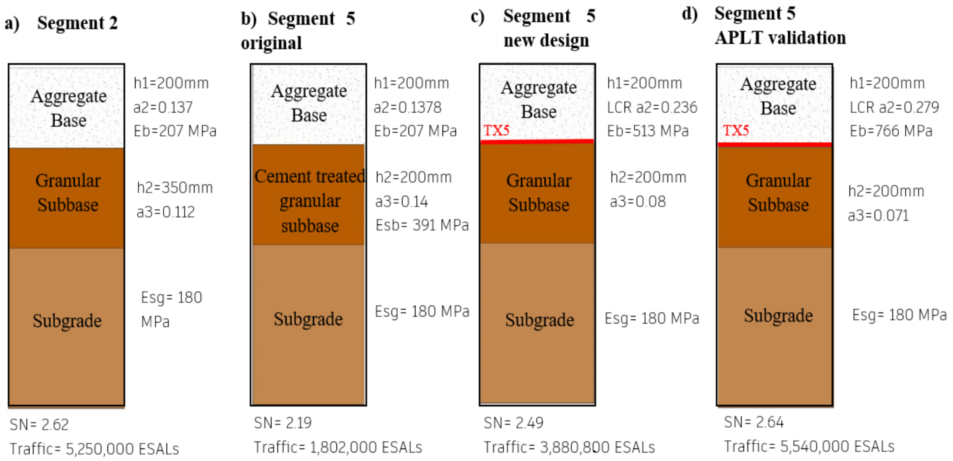

Figure 2. Pavement structures for segment 2 and segment 5

Whilst for the segment 2, the estimated structural number was, SN=2.622 (figure 2a) the segment 5 changed its original design shown in figure 2b [13], due to the that the real conditions was different regarding to the conditions considered in the design, concluding that it was not technically feasible to implement the original pavement structure that considered a cement stabilization in the subgrade [14] and was changed to the stabilized section with a multi-axial geogrid and validated with APLT, shown in figures 2c and 2d above, Segment 5 is structurally similar to the segment 2 (figure 2a). Excluding the geogrid, the notable difference between segment 2 and segment 5 was that the segment 2 needed 145,000 m3 [15] of natural subbase, extracted from a natural source and imported the project, otherwise, for the segment 5, the subbase considered in the design was the same existing material only scarifying, moistening and compacting the subgrade (subgrade mechanization) which represented an important reduction in aggregates consume in the segment 5, therefore reducing time of construction, pollution, traffic disruption and with a demonstrated better performance than the non-stabilized segment 2, even when it is assumed that the segment 2 has the same average subgrade modulus, the reduction in aggregates thickness will continue to be important in comparison with the segment 5, because the ESAL`s (traffic capacity) are greater than 1.8 million.

4 Data Collection of Pavement Condition and IRI Curves

4.1 IRI Survey and Previous Data

The International Roughness Index is used by highway professionals throughout the world as a standard to quantify road surface roughness. A continuous profile along the road is measured and analyzed to summarize qualities of pavement surface deviations that impact vehicle suspension movement [16]. The current options available for collecting objective pavement condition data are costly and require specialized equipment [17].

Smartphone based technology for surveying the IRI have been used from the beginning in the monitoring of this project, using the system developed by TotalPave Inc. which is a calibrated system against the standard profiler using different types of smartphones and vehicles, the data collection process is fully automated, using a smartphone with a TotalPave IRI calculator app mounted on the vehicles' windshield [18]. The initial average IRI value of 1.5 m/km for the segments 2 and 5 have been assumed, the data for the stabilized section of 2019 for the north and south bound measured on May 14th and 15th respectively were taken from the paper "Pavement Performance Evaluation of Geogrid Stabilized Roadways, GeoAmericas 2020" [18]. For the 2022 and 2023 new IRI surveys were conducted in May and September respectively for both segments. The summary of the historical IRI measurements for segment 2 and segment 5, is listed in the table 1 below.

Table 1. Summary of the historical IRI per segment.

Segment	Description	2016	2019	2022	2023
2	**RN-39 San Francisco de La Paz - Gualaco**	**1.5***	**2.23**	**2.60**	**2.51****
	Average	---	---	2.60	2.51
	minimum	---	---	2.05	2.16
	maximum	---	---	3.13	2.86
	Std. Dev.	---	---	0.31	0.20
	CV	---	---	0.12	0.08
5	**RN-39 El Carbón - Bonito Oriental**	**1.5***	**1.69**	**2.09**	**2.32**
	Average	---	1.69	2.09	2.32
	minimum	---	1.42	1.71	1.67
	maximum	---	2.07	2.86	3.15
	Std. Dev.	---	0.20	0.37	0.54
	CV	---	0.12	0.18	0.23

*Assumed initial IRI.

** A reduction in IRI is shown, regarding to 2022 due to works in maintenance and patching at the segment.

From the data of the Table 1, a regression technique with a spreadsheet has been used to determine the IRI curves resulting in the Equation 1 for the segment 2 (non-stabilized) and the Equation 2 for the segment 5 (stabilized), with a very confident coefficient of determination (R^2) of 0.97 and 0.95 respectively as shown in figures 3 and 4.

$$Y = 370Ln(x) - 2813.7 \quad (1)$$
$$Y = 231.45Ln(x) - 1759.6 \quad (2)$$

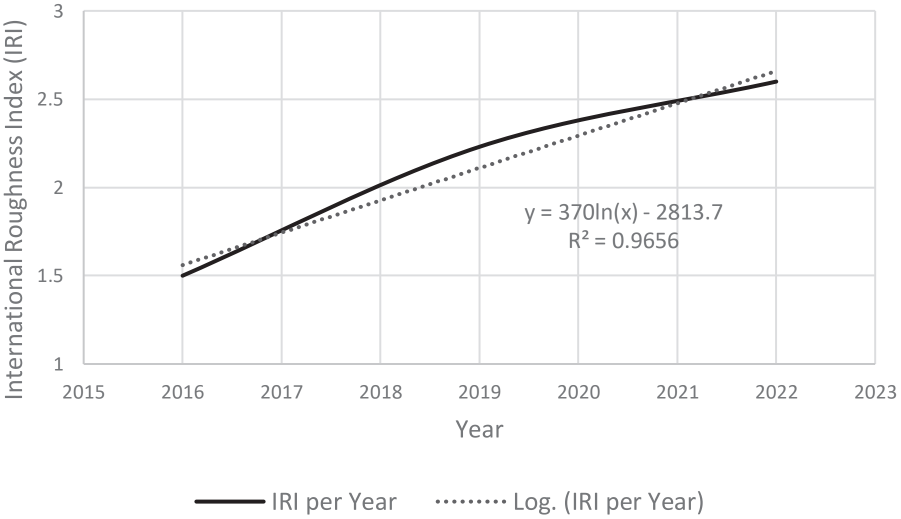

Figure 3. IRI per year and regression for the segment 2 (non-stabilized).

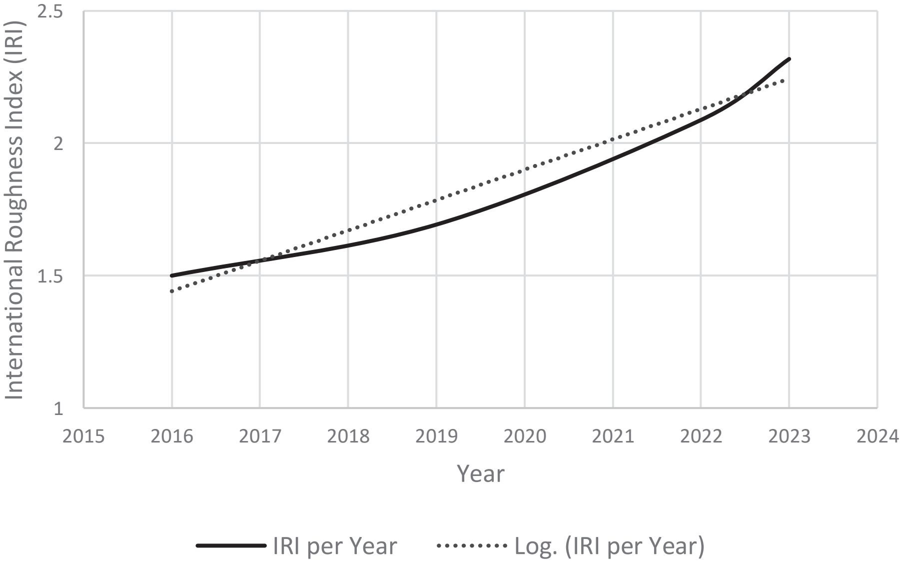

Figure 4. IRI per year and regression for the segment 5 (stabilized).

Note that the segment 2 received maintenance and patching in 2023 and show a reduction in the IRI of 2023 regarding to 2022, to compare this segment with the segment 5, the IRI of

2023 of the segment 2 was not considered to determine the curve of tendency, due to the segment 5 has not received any maintenance since its construction.

4.2 Analysis with HDM-4 and Calibration of the Deterioration Model.

The models of deterioration in HDM-4 need to be calibrated to local conditions "the reliability of the results is dependent upon how well the data provided to the model represent the reality of current conditions and influencing factors, in terms understood by the model; and, how well the predictions of the model fit the real behavior and interactions between various factors for the variety of conditions to which it is applied" [19].

At the moment there is not a HDM-4 model of deterioration calibrated for Honduras and the specific site, nonetheless the field data collected and the equations generated with the empirical regression model (figures 3 and 4), have been incorporated in HDM-4 modifying its calibration factors for the deterioration model to adjust or "calibrate" the behavior of the IRI curve obtained to the curve for real conditions of this project, in both analysis sections, by this way we could try to forecast the deterioration based on the real deterioration during the first seven years and predicting the future behavior of the pavement, the summary of calibration factors applied to HDM-4 model to emulate the real condition measured until 2023, are illustrated below in Table 2.

Table 2. Calibration factors applied in hdm-4 for the pavement structures in study.

Calibration Set	Segment 2 (non-stabilized)	Segment 5 (stabilized)
Starting of structural cracking (Kcia)	1	0.65
Progress of structural cracking (Kcpa)	1.1	0.65
Starting of Wide Structural Cracking (Kciw)	1	0.65
Progress of Wide Structural Cracking (Kcpw)	1	0.65
Starting of ravelling (Kvi)	1.1	0.65
Progress of ravelling (Kvp)	1.1	0.65
Starting of potholes due to cracking (Kpic)	1.1	0.5
Starting of potholes due to ravelling (Kpir)	1.1	0.5
Progress of potholes (Kpp)	1.1	0.5
Edge break in (Keb)	1	0.5
Texture depth (Ktd)	1.1	0.5
Rutting due initial densification (Krid)	1.1	0.5
Rutting due to structural deformation (Krst)	1.1	0.5
Adjusted structural number due to cracking (Ksnpk)	1	0.8
Roughness/ Contribution of cracking (Kgc)	1.1	0.4
Roughness/ Contribution of rutting (Kgr)	1.1	0.4
Roughness/ Contribution of potholes (Kgp)	1.1	0.4

From Table 2 we can see an important reduction in factors related to cracking, ravelling, potholes, rutting and roughness for the mechanically stabilized section (segment 5) compared with the non-stabilized pavement section (segment 2) these factors were applied in HDM-4 to emulate the real performance observed for both sections since 2016, as show in figures 5 and 6 below.

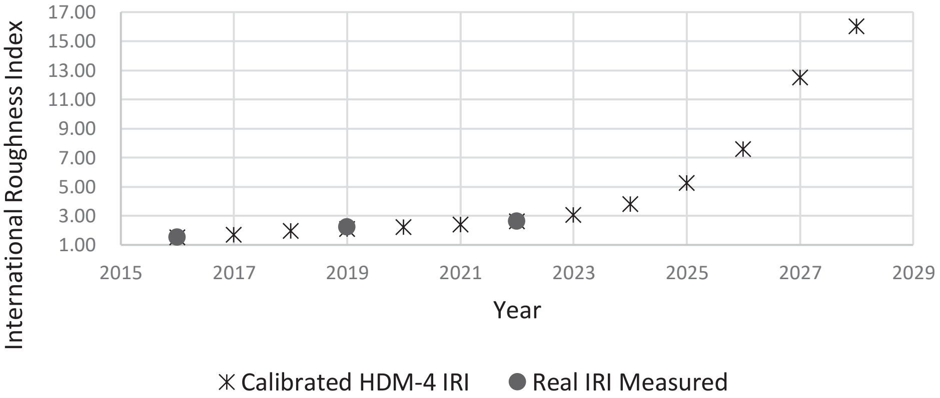

Figure 5. Real IRI and HDM-4 adjusted IRI for segment 2 (non-stabilized).

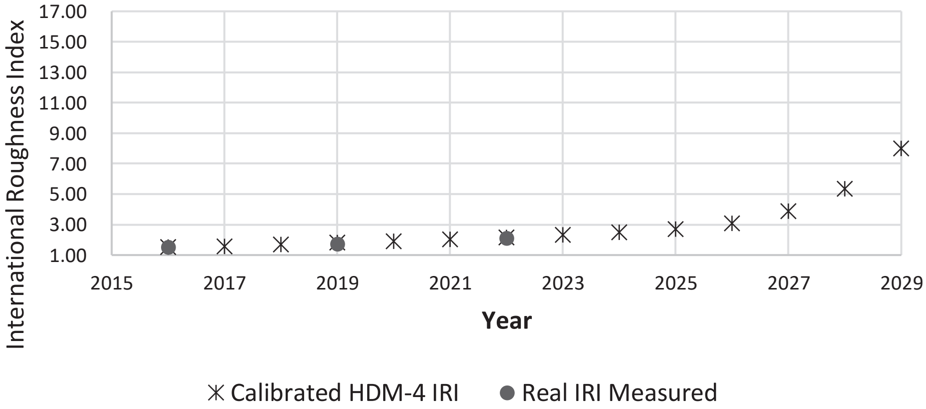

Figure 6. Real IRI and HDM-4 adjusted IRI for segment 5 (stabilized).

In the figures 5 and 6 above, we can observe a better performance of the stabilized section against the non-stabilized section in terms of IRI, even when the segment 2 was constructed with an imported subbase of selected natural aggregate whilst the segment 5 was constructed only with the natural subgrade as a poor subbase. Is important to highlight, that only the non-stabilized segment 2 had it first maintenance in 2022 but, the figure 5 shows the tendency of the section without maintenance with the objective of compare with the stabilized segment 5 without maintenance.

Overlapping the figures 5 and 6, we can observe a benefit in delaying of the maintenance activities in the segment 5 related to the incorporation of the multi-axial geogrid with triangular aperture in the granular base layer, if we take the value of 2.6 of IRI as reference when the segment 2 received its first maintenance, hypothetically the segment 5 will need it first maintenance when reach the same IRI of 2.6 approximately in 2025, this may represent a delay of 50% of time for the first intervention in the segment 5, as we can see in the figure 7 below:

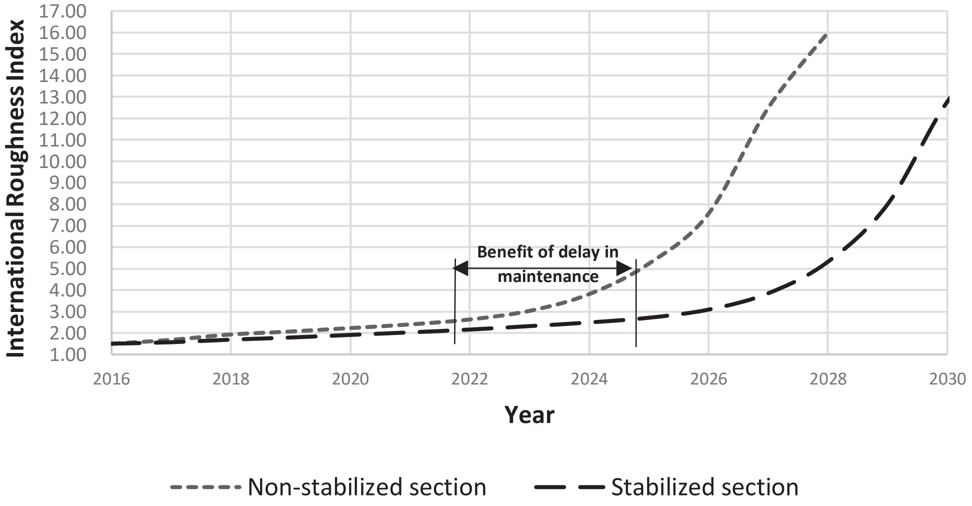

Figure 7. Benefit in performance and delaying of maintenance of segment 5 Vs. Segment 2.

In addition, as we can see in figure 7, although both pavement structures are structurally similar, the base stabilized section with multi-axial geogrid over a poor subbase have demonstrated a better performance than the segment 2 which have a selected natural material of 350mm thickness as subbase.

5 Users Cost Analysis

Some authors and publications state that the velocity in a road have influence only for IRI greater than 5m/km [20] nonetheless, the IRI have an important impact on the vehicle operation cost (VOC) even for small changes in the IRI, for this publication only the users cost have been considered with the objective of stablish a relation between the total road user cost (RUC) and the roughness of the roads in study. An analysis with HDM-4 was used to determine the total RUC based on the deterioration curves of figure 7. Even when the maintenance activities of 2022 represent agency costs and additional road user cost due to the work zone for the segment 2, they are not considered in this analysis, alternatively only the tendency of the deterioration curve without maintenance and user costs, forecasted until 2029 are considered. A comparing of total road user cost is plotted in figure 8.

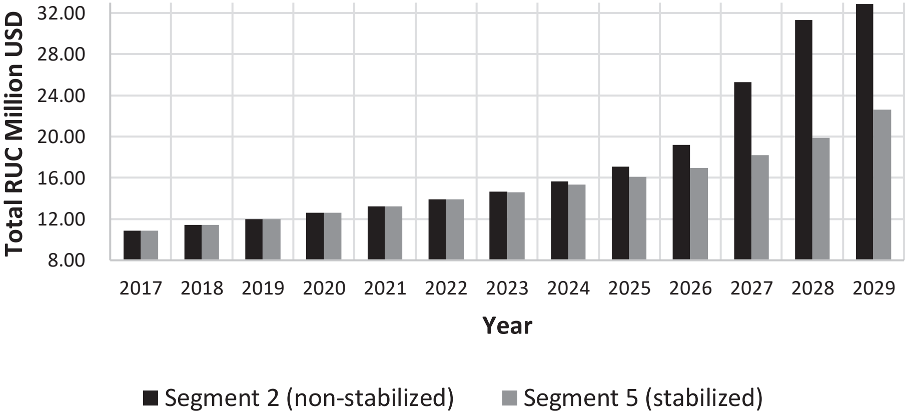

Figure 8. Forecasted RUC of Segment 2 (non-stabilized) – Vs – Segment 5 (stabilized)

For a period analysis of 13 years, starting from 2017 to 2029 the total RUC for the segment 2 is 300.68 million dollars whilst for the segment 5 is 263.48 million dollars, this appears to represent savings of 14% in the stabilized section compared with the non-stabilized section.

In some other way, as we can see in table 1, the segment 2 received maintenance and patching activities between 2022 and 2023, but its IRI only experimented a little reduction from 2.60 to 2.51 and as effect of these activities, both agency cost and user costs were incremented due to the work zone, but these costs have been not considered in figure 8.

Another characteristics to emphasize is that despite the two sections in study are structurally similar based on calculations explained in the chapter 3.2, the stabilized segment 5 have shown a better performance than the non-stabilized segment 2 , even when the segment 2 have 350mm thickness of additional selected granular material and the segment 5 was constructed with a mechanized subgrade as poor subbase using the multi-axial geogrid with triangular aperture for stabilizing the granular base layer, showing therefore, not only a slowly deterioration curve but also lower road user costs than the segment 2.

6 Environmental benefits

Detailed investigation needs to be realized to accurately estimate de tons of carbon dioxide (CO_2) for each segment, notwithstanding the CO_2 is directly related with the consumption of fuel, hence activities like excavating, carrying, laying, and compacting granular materials during the road construction will be factors generating emissions of CO_2. For the road sections in analysis, in the segment 2, 145,000 m3 of natural subbase were extracted and laying along the 30.7km in a thickness of 350mm [15] whilst for the segment 5 was not used a selected natural material for the subbase, instead the existing material (subgrade) was mechanized and considered as a poor subbase with a California bearing ratio (CBR) of 15%.

By this way we could assume that this important reduction in consumption of the natural subbase, avoiding the whole process of extract, carry and lay natural aggregates to construct a new subbase in the segment 5, reduced the CO_2 emissions, this from the viewpoint of natural aggregates use, only for illustrative effects, using a spreadsheets to give an approximate value of CO_2 emissions [21] (with default values) the construction of the new imported natural subbase in the segment 2 could represent about 357 tons of CO_2, on the other hand, only were mechanized the existing subgrade in the segment 5 could represent about 177 tons of CO_2, this reflects a reduction in CO_2 emissions of 50% in the construction stage.

Additionally, based on calculations of the deterioration model, the segment 5 shows a delay of 50% to date, in the maintenance activities, which means a reduction of traffic disruption due to work zones as well as a reduction in VOC for a better performance and lower IRI, that also are directly related with CO_2 emissions. Future calibration in environment effects is needed to represent with accuracy these benefits and consider all the variables implicit in the segment 5 including, but not limited to the CO_2 emissions of producing the geogrids.

7 Summary and Key Findings.

Two segments of the agricultural corridor, RN 39 were constructed in Honduras in 2016, the segment 2, a non-stabilized section with 350mm of natural imported subbase, 200mm of granular base and a double bituminous surface treatment as surface and, the mechanically stabilized segment 5, with 200mm of poor subbase (mechanized existing subgrade, with CBR of 15%) 200mm of multi-axial geogrid with triangular aperture stabilized granular base layer and a double bituminous surface treatment as surface, the IRI of both sections have been measured since its construction and the summary of key findings are as follows:

- Both pavement structures are structurally similar where the segment have a calculated structural (SN) of 2.62 and the segment 5 have a validated in situ SN of 2.64.
- Despite that both study sections are structurally similar regarding to the initial conditions, the stabilized segment 5 shows a better performance than the non-stabilized segment 2, based on the progression of the IRI in the first seven years of service life.
- The segment 2 received its first maintenance and patching between 2022 and 2023, nonetheless the segment 5 still show a better performance even without having any maintenance to date, the 2023 IRIs are 2.51 and 2.32 for the segments 2 and 5 respectively.
- With the IRI measured in the last years for both sections, a simple regression was applied to determine the IRI curve tendency for the first seven years of segment 2 and segment 5, then the real IRI data and its curves were incorporated in HDM-4 through the calibration factors to construct an adjusted model and forecast the behavior of the IRI curves for the next years.
- The calibration factors were applied in key characteristics like the start of distresses as structural cracking, potholes, rutting and roughness, resulting for the stabilized segment 5 calibration factors between 0.4 and 0.65, which represent a delay of the distresses mentioned, whilst for the non-stabilized segment 2 the calibration factors resulted between 1.00 and 1.10, which could mean any delay in premature distresses for the section 2.
- Overlapping both calibrated IRI curves, it can be observed that the non-stabilized segment 2 needed maintenance for an IRI value of 2.6 in 2022 (year 6) taking reference on 2.6 IRI value as the first maintenance activity, the stabilized segment 5 may would need its first maintenance in 2025 (year 9) this represents a delay of maintenance activities of about 50% due to the benefits of the stabilized base with multi-axial geogrid.
- As the IRI is directly related with the vehicle operation costs and the time of travel, an analysis was conducted in HDM-4 to calculate the road user cost (RUC), as part of the cost in a life cycle cost analysis, based on the calibrated models for segment 2 and segment 5, forecasting both sections and assuming no maintenance, the total RUC resulted in 300.68 million dollars and 263.48 million dollars respectively, until 2029, which shows a reduction

in user cost of 14% in the segment 5 regarding segment 2, due to the benefits of the mechanically stabilized granular base with multi-axial geogrid of triangular aperture.

- Even when segment 2 and segment 5 are structurally similar, is important to highlight that the segment 2 needed 145,000 m3 of imported material for construct its subbase layer, whilst the segment 5 was constructed with the existing subgrade as a poor subbase, this reduction in excavate, carrying, and laying a subbase in the segment 5, could represent about 177 tons of CO_2 whilst construct the subbase in the segment 2 could represent about 357 tons of CO_2 which could mean a reduction in CO_2 emissions of about a 50% due to the benefits of multi-axial geogrid with triangular aperture stabilized pavement, this CO_2 calculations were made with a spreadsheet with default values, and further investigation is needed to accurate calculations in this topic for future papers.

In general, the results have demonstrated that the incorporation of multi-axial geogrids in granular layers of pavements have numerous benefits in reduction of aggregate layers thickness and improved performance along the life cycle, even for conventional pavement structures that are similar in terms of structural number, which directly reduce agency and users costs as well as reducing the emissions of greenhouse gases in all the stages of a project, since production to construction and service life.

References

1 J. Wall III and M. R. Smith, US DOT FHWA, Life Cycle Cost Analysis in Pavement Design-Interim Bulletin, **FHWA-SA-98-079**, xi (1998)

2 US Deparment of transportation, Life-Cycle Cost Analysis Primer, **FHWA IF-02-047**, 7, (2022)

3 L.M. Pierce, G. McGovern, K.A. Zimmerman, US-DOT FHWA, Practical Guide for Quality Management of Pavement Condition Data Collection, 11 (2013)

4 J. Odoki and H. G. Kerali, PIARC, World Road Associ., Analytical Framework and Model Descriptions Version 2.0, **Vol. 4,** 2.2.2 A1-7 (2006)

5 AASHTO, Geosynthetic Reinforcement of the Aggregate Base Course of Flexible Pavement Structures, **R 50-09**, 5 (2013)

6 J. P. Jiroud and J. Han, Geosynth. Mgzn., Mechanism governing the performance of unpaev roads incoporating geosynthetics, **Part 1,** 29 (2016)

7 X. Peng. and J. Zornberg, Procedia Engineering, Evaluation of load Transfer in Geogrids for Base Stabilization Using Transparent Soil, **189 (2017) 307 – 314**, 308 (2017)

8 G. H. Roodi, J. G. Zornberg, M. M. Aboelwafa, J. R. Philliphs, L. Zheng and J. Martinez, Texas DOT, Soil-Geosynthetic Interaction Test to Develop Specifications, **FHWA/TX-18/5-4829-03-1**, 1-2 (2017)

9 S. R Jersey, J. S. Tingle, G. J. Norwood, J. Kwon and M. Wayne, TRB, Full-Scale Evaluation of Geogrid Reinforced Thin Flexible Pavements, 2-3 (2012)

10 Secretary of Infraestructure and Transport, HND Government, Memoria Institucional , 83 (2016)

11 ICA Inversiones, Propuesta de Refuerzo de Estructura de Pavimento Mediante Geomalla Triaxial TX, (2015)

12 Ingios Geotechnics, Automated Plate Load Test Tech Brief, 1-2 (2014)

13 P. K. R. Vennapusa, D. J. White, M. H. Wayne, J. Kwon, A. Galindo and L. García, Intern. Journ. Of Pavmnt, In situ performance verification of geogrid-stabilized aggregate layer: Route-39 El Carbón–Bonito Oriental, Honduras case study, 3,4,9,10 (2018)

14 E. Aleman, L. García and O. Ardila, UE INVEST-H, Desafío en la subrasante, BID **2155/BL-HO**, 1 (2019)

15 SOPTRAVI, Lic. 10DGC-Const., Pliegos de referencia, 28 (2008)

16 MDOT, Asset Management Background, International Roughness Index, 1 (2017)

17 C. A. Cameron, The Univ. Of Brunswick, Innovative Means of Collecting International Roughness Index Using Smartphone Technology, (2012)

18 P. Tamrakar, M. Wayne, M. Stafford, A. Galindo, C. Cameron and L. Garcia, Geoamericas 2020, Pavement Performance Evaluation of Geogrid Stabilized Roadways, **4th Pan American Conference on Geosynthetics**, 5 (2020)

19 C. R. Bennett and W. D. O. Paterson, PIARC World Road Associ., A Guide to Calibration and Adaptation, **Vol. 5**, 2,4 (2000)

20 T. Gutierrez, M. Arce, LANAMME, Índice de Regularidad Internacional, **LM-PI-PV-IN-24a-04**, 8 (2024)

21 D. M. Barbieri, B. Luo, F. Wang, I. Hoff, S. Wu, J. Li, H. R. Vignisdottir, R. A. Bohne, S. Anastasio and T. Kristensen, Transport. Res. Interdisciplinary Perspect., Assessment of carbon dioxide emissions during production, construction and use stage of asphalt pavements, 1-11 (2021)