Dynamics and learning scenarios for the road infrastructure development system: Colombian case

Dinámica y escenarios de aprendizaje para el sistema de desarrollo de la infraestructura vial: El caso de Colombia

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ABSTRACT

Studies focused on understanding the dynamics of road resources availability for the construction and maintenance of roads are useful for planning infrastructural goals to leverage the competitiveness of the products transported by this mode of transport. This paper guides action plans and achievement targets for the number of kilometers of roads in good condition within a road network in the Colombian case, through the development of a systemic model. This study disaggregates the variables that make up the road system to visualize how the use of materials such as flexible and rigid pavement, contributes to the achievement of goals of kilometers of roads in good condition. The scenarios suggest that flexible pavement shows more favorable results in the short term, and rigid pavement, in the long run. However, mixing the materials shows improvements leading to the achievement of kilometers of roads in good condition.

Keywords*: System dynamics; Infrastructure; Highway maintenance; Pavement maintenance; Scenarios*

RESUMEN

Estudios centrados en la comprensión de la dinámica de la disponibilidad de recursos viales para la construcción y el mantenimiento de carreteras son útiles para planificar los objetivos de infraestructura a fin de potenciar la competitividad de los productos transportados por este modo de transporte. Este documento orienta planes de acción y las metas del número de kilómetros de carreteras en buen estado dentro de una red de carreteras para el caso colombiano, mediante el desarrollo de un modelo sistémico.

Este estudio desagrega las variables que conforman la red vial para visualizar cómo el uso de materiales como el pavimento flexible y el rígido contribuyen al logro de las metas de kilómetros de carreteras en buen estado. Los escenarios sugieren que el pavimento flexible muestra resultados más favorables a corto plazo, y el pavimento rígido, a largo plazo, aunque la mezcla de los materiales muestra mejoras que conducen al logro de la meta de kilómetros de carreteras en buen estado.

Palabras Clave*: Dinámica de sistemas; Infraestructura; Mantenimiento de Vías; Mantenimiento de pavimento; Escenarios*

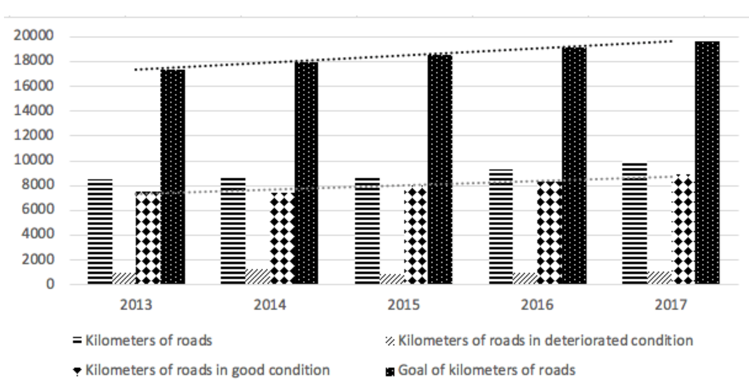
1. INTRODUCTION

Within the Colombian context, there is an evident lag in the development of infrastructure. The World Bank, with its Logistics Performance Index (LPI) in terms of infrastructure, places Colombia in the 72nd position among 160 countries [1]. Similarly, the Global Competitiveness Index (GCI) places Colombia in the 109th position for the general quality indicator of infrastructure. It is in the 110th position when comparing the quality of roads among the 137 countries evaluated [2]. One of the consequences of having infrastructure failures is showed by the high logistics cost incurred by Colombian companies, which is around 13.5 Colombian Pesos (COP) for every COP 100 sold. According to the national logistics survey [3], 35.2% of the logistics costs correspond to the transportation and distribution processes. In this scenario, it is more expensive to send products to national ports and borders than to deliver a product abroad. It is thereby influencing its competitiveness.

Infrastructure has developed at a plodding pace, slower than the needs of the market [4]. Records show that roads transport 71% of goods, 27.27% by rail, and 1.22% by rivers [5], with coal being 99% of the freight moved by rail [6]. The inadequate supply of infrastructure places Colombia in 87th place out of 137 countries, in the general indicator of infrastructure, according to the GCI [2].

Figure 1 shows the values of the inventory of roads in good and bad conditions, compared with the kilometers of roads set as a government target according to data from the national department of roads of Colombia. The gap between the target and the road values its seen, which shows the delay in the development of roads and the desire of the government to improve its results by setting challenging targets of kilometers of roads in good condition, which will benefit the competitiveness in the transport of Colombian products.

Figure 1. Statistics in Colombia's road Inventory (2013-2017) [7]



The development of infrastructure is an issue that has had an academic interest in the last decades; interest focused on the assessment of alternatives to make the planning and scheduling of activities inherent to its start-up possible [8].

There are various techniques used to address this problem. Expert systems show weaknesses in the difficulty to reach points of agreement among the experts, and the lack of tools and procedures to represent the knowledge domain [9]. Analytical models are limited to the computational capacity required by stochastic modeling [10]. Finally, systemic analysis employs system dynamics, which values uncontrollable aspects and feedback loops of the system using modeling [11].

Transport and infrastructure models are governed by dynamic structures [12], [13], implying that they may need to approach through a holistic perspective in order to improve their understanding and the integration of the various forms of interpretation of the different actors that are part of them [14]. Feedback govern the infrastructure development system. This system has characteristics of non-linearity, trade-offs, cause and effect relationships distributed in time, which makes it counter-intuitive, characteristics of complex systems [14], [15] that involve the use of resources following public policies aimed at achieving government objectives.

Historically, public policies have been proposed as a reaction to symptoms and not to causes. Ignoring the dynamic nature of the issues and using traditional tools with limited capabilities to confront causes, which are enough to take care of complicated problems successfully, fail when facing complex problems with multiple actors, limited rationality, unpredictable behavior, and different interpretations [16].

The difficulty with public policy problems is described by the following characteristics: (i) policy resistance, because of feedback and delays eroding its original purpose, worsening the problem even more than in its initial state. (ii) The resistance and delays that hinder experimental learning. The cost of experimentation is high, and the influence that a policy can have on the population is irreversible, giving rise to unexpected behaviors. (iii) the need to persuade stakeholders with a diversity of interests to reach a consensus. (iv) The biases of policymakers which result in conflicting benefits for stakeholders. (v) The tendency on the part of decision-makers to attribute unexpected events to exogenous sources [17].

Previous studies analyze the development of infrastructure in an aggregate way [18], leaving out factors that closely match them to real situations. Topics mainly address problems such as resistance to deterioration of the roads to the type of material used [19]; construction time [20]; maintenance and its cost [10], which makes the costs required to perform this activity not constant but variable.

The construction of roads and their maintenance depends on the mechanical characteristics of the type of material used. The literature showed that the most common materials for road construction are flexible pavement and rigid pavement, each with characteristics such as construction time, deterioration time, and investment cost. To take advantage of each material's benefits and recognize the percentage of participation of each in the road infrastructure system, as an alternative to meet the goals of kilometers in good condition grounds this study.

We used a systemic perspective to analyze road construction and maintenance as part of the infrastructure's development. Based on a simulation model that outlines the dynamics and relationships between variables, we expect to understand and learn about the system's structure [21]. In the same sense, guide decision-makers [22] about the effects that the type of material used for the construction and maintenance of roads has on the goal of kilometers of roads in good condition and the budget invested.

Subsequently, the structure of the article is as follows. Section 2 presents a literature review that offers solutions to road infrastructure development problems from the system dynamics perspective; section 3 describes a system dynamics model with its mathematical formulation. Section 4 and 5 include the results and discussions; finally, the reader will find the conclusions and future work.

2. MATERIALS AND METHODS

To improve the transport of goods by road, the Colombian national government has set targets for kilometers of primary roads in good condition in the report on the state of the roads published by the National Institute of Roads [23]. Seeking to understand the dynamics of the system of construction and maintenance of roads it is crucial to consider the variables that are part of this system such as investment, construction time, speed of deterioration, among others that explain its behavior and guide the fulfillment of the goals expected by the government.

This study disaggregates the factors involved in the construction and maintenance of roads. It shows the impact of resources allocated to these items concerning the target of kilometers of roads in good condition.

The methodology used to construct the model is system dynamics. A representation of a complex system seen from a holistic perspective, with causal relationships, with counter-intuitive effects, which allow through learning scenarios to observe the system's behavior over time and identify the structure that facilitates understanding and comprehension of the problems immersed in the system [15], [24].

2.1. Literature Review

The literature review was done on the Web of Science (WOS), and Scopus databases. Initially, the search was developed in WOS using a sentence "Highway Maintenance", refining the result to documents that included system dynamics as an analysis methodology, resulted in five documents as the initial sample. Using the same sentence in Scopus displays seven documents, of which four documents coincide with the results found in WOS. Of the remaining three, one document is available for consultation, increasing the sample to six documents. Another search was performed by changing the sentence to "Pavement Maintenance". As a result, the sample is composed of six articles and a literature review. The following is a detailed examination of the documents included in the sample.

Zhang, Jin, Li & Skibniewski [25] propose a model for the analysis of the concession period in public-private infrastructure cooperation projects, focusing their interest on the maintenance of the pavement and the impacts of shared risk to the parties concerned, as a result of the aging and the deterioration of the infrastructure. Public-private cooperation projects are a way to finance public works. The private sector acquires the responsibility of designing, constructing, maintaining, and operating a project, from which the investment is repaid directly by the public sector or through the collection of tolls for a stipulated concession period, which, in the end, gives up its rights to the public sector. A regular concession period should be enough to recover the private sector's investment, the reason why short concession periods could lead to rejection of project development, increases in toll costs, maintenance budget reduction, and increased dissatisfaction with the part of the users. On the other hand, when the concession period is long, it is beneficial for the private sector. However, it generates adverse effects on governments because of the short operation period after the concession expires. Consequently, this makes the concession period one of the most critical elements in the approach to public-private infrastructure projects.

Zhan, Zao &Tam [26] analyze the relationship between stakeholders and the road maintenance system through the Chinese case study with its well-known motorway network, which includes road recovery measures in terms of daily maintenance, prevention, rehabilitation and in extreme cases road reconstruction.

This article indicates that the funds for road maintenance in China come mostly from tolls, investing 10% in this item. They allocate the remaining 90% to suppliers, taxes, debts, and other administration costs, which makes the resources limited to maintain the roads since policies such as the increase in the value of tolls could lead to user dissatisfaction, which would result in a decrease in traffic on the road. The analysis evaluates the relationships and dependencies of multiple factors systemically overtime to plan policies for road maintenance, including road operators, government, and users.

The article written by Guevara, Garvin & Ghaffarzadegan [27] looks at the deterioration of highways caused by delays and inefficient planning in the allocation of public funds meant for their recovery and rehabilitation, by focusing efforts on responding reactively and on a short-term basis, instead of planning proactive long-term actions. This document generates knowledge and learning of the dynamics of investments and maintenance expenses in the case of the United States Highway system, through a simulation model of systems dynamics. The proposed model evaluates three policies: promoting maintenance, promoting rehabilitation, and combining maintenance and rehabilitation. The results obtained from the simulation indicate that the maintenance policy generates better results than the others on a short-term basis. On the other hand, by having an appropriate combination of maintenance and rehabilitation, the network's capacity grows as the construction of new roads increases.

Liu & Mu [28] assessed truckload regulation measure's sustainability through a systemic perspective in the Chinese context, on a highway where the iron supply chain is predominant. The problem of truck overloading and its impact on the quality of roads overtime gave rise to the proposal of load regulation policies, which were evaluated based on scenarios as compared to the initial situation. The first policy delivers a plan of zero tolerance to the overload. Overload of up to 100% is the second policy proposal. The third policy brings a scenario without load restriction. The results obtained from the simulation of the first policy showed increases in transport costs and the increase in the number of trucks on the roads to withstand the demand, causing more significant congestion, increased transport time, and reduced road maintenance costs. The simulation of the second scenario shows a reduction of the pavement maintenance cost concerning the initial situation until a 50% overload is reached, due to the reduction of trucks to the first policy, overloads greater than 50% make the cost of road maintenance increase, as in the first policy. The third policy's application noted that accidents and their associated cost increase the more the truck overloaded. Regarding transport costs and the accumulated cost of mobilization,130% overload achieved the minimum cost, the latter being the policy that best achieves sustainability.

The case of the impact of overloaded trucks on Brazilian roads was also analyzed using system dynamics [29]. The imbalance between investments and road use has caused Brazilian roads to be in precarious conditions, leading to reduced vehicle life, increased fuel consumption, and increased risk of accidents. The case study analyzed in this article is that of ornamental stone transport. Data shows that 77% of the transporters carry more than the sanctioned load, which reduces the useful life of the pavement by 40%, which leads to the search for the relationship between excess weight in transport and the operational costs of transport with accidents on the roads and pavement maintenance. They proposed an analysis based on scenarios, simulated variables, and the impacts that these variations caused in the system. The results were that overloading trucks reduce operating costs, but the social cost increases in the same proportion as the overloading. In conclusion, overloading brings benefits in economic terms. It brings social disadvantages such as deterioration of the pavement, increased need for maintenance, costs associated with maintenance, and decreased road safety since road deterioration increases accident rates.

Shepherd [8] did a review in which he reveals studies in the area of transportation that have used system dynamics as a research methodology. This review includes the period between 1995 and 2013, taking the article by Abbas & Bell [14] as a starting point, which evaluates the relevance of system dynamics for modeling in transport cases. Within the articles that the author mentions with road maintenance and construction, not included in the initial sample, one finds the document by Fallah- Finni, Rahmandad, Triantis & De la Garza [11]. Modeling the impact of maintenance postponement on a road system, which concluded that preventive maintenance policies of roads generate cost reductions against corrective maintenance measures due to postponement, additionally holistically providing benefits to the system.

The review includes research by Honggang, Mashayekhi, & Saeed [30], which analyses the problem of insufficient costs in the construction of infrastructure projects and their impact on the quality of roads and delays in scheduled deadlines. The policies assessed to address the problem are (i) the introduction of pre-feasibility studies to the projects, (ii) loan financing to projects with cash constraints, and (iii) the increase in the payment for end users. The scenarios determined that the first policy might be beneficial for projects, but organizational constraints make it impossible to implement. In the second policy, the results were positive in terms of the development of projects. However, in the long run, it creates dependence on loans rather than the sustainable development of these. The third policy determined that by increasing the charges on end-users as an effect of paying the cost of project inefficiency by end-users, there are positive results for the construction budgets, reducing delays and improving the quality and efficiency of the projects.

Friedman [31] questions the counter-intuitive effect that regional development represents on infrastructure, road conditions, existing budgets, and vehicular accidents. The study concentrates on the effects of road conditions and road maintenance policy on accidents. The author considered the need to re-evaluate the concept of maximizing road repair due to its relationship with the number of accidents. Even though experts consider that the problem is related to educating users, this has not shown any effect over time.

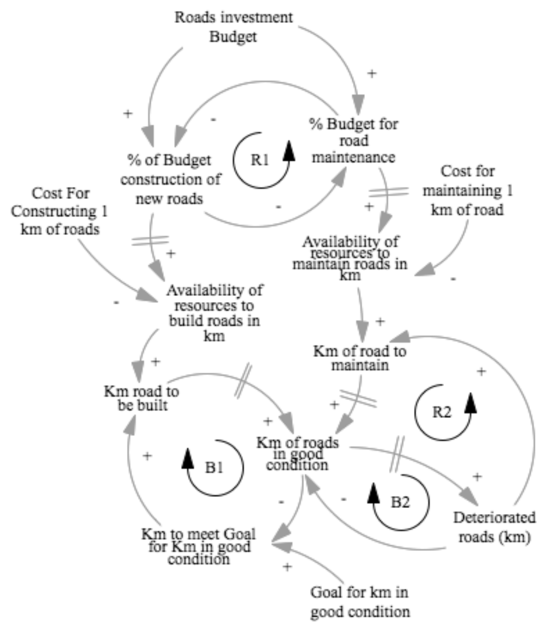
In conclusion, there are different ways in which the authors have sought answers to the development and maintenance of road infrastructure, describing public policies sometimes aimed at favoring the development of roads or, at other times, purely for purposes of understanding. Within the sample of articles analyzed, the use of flexible pavement or rigid pavement for road construction and maintenance is not a decision variable, it is precisely the mixture of materials and their impact on the goals of kilometers in good condition that will analyze this document seeking to provide understanding and knowledge of the system's behavior over time as a support for decision-makers.

2.2 Proposed Model

To understand and interpret the dynamics of the infrastructure's development system, we did a causal loop diagram that shows the cause and effect relationships between the variables and the feedback processes; this diagram is known as a dynamic hypothesis [32] (Figure 2).

The model consists of two balancing loops (B1-B2) and two reinforcing loops (R1-R2). The exogenous variables of road's investment budget, the goal of kilometers in good condition, the cost of building roads, and the cost of maintaining roads fed the model. The value of the road's investment budget is determined annually, depending on the infrastructure development plans and the infrastructure budget defined by law at the end of each year. The infrastructure budget is part of the national budget, defined as a rate of the total gross domestic product (GDP). A delay represents the time needed for the money budgeted by the government for road construction or maintenance to be available to contractors. This delay comes in monthly terms based on work reports and public contract documents. It is caused by the paperwork and bureaucracy to formalize the release of these resources and audited by state spending control agencies. The percentage awarded for construction or maintenance of roads divided by the cost of construction or maintenance of 1 kilometer of roads determines the value of resources available to build or maintain roads in terms of kilometers.

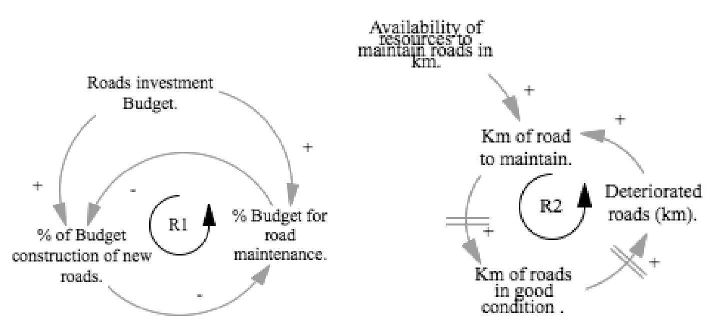
Figure 2. Dynamic hypothesis of the development and maintenance of road infrastructure



This representation tries to illustrate how the achievement of the goal of kilometers in good condition is affected by the availability of resources designated to the construction of new kilometers or roads' maintenance. The characteristics, variables, and relationships of the loops that are part of the infrastructure development system structure are part of the next paragraphs.

R1 draws out the competition between the percentage of the budget meant for the construction of new routes and the percentage of the budget meant for the maintenance of the roads (Figure 3). This competition suggests that the budget breaks down between these two objectives. By increasing the percentage of money to one of them, the other is negatively affected by reducing the value of the percentage of money budgeted.

Figure 3. Reinforcing loops 1-2

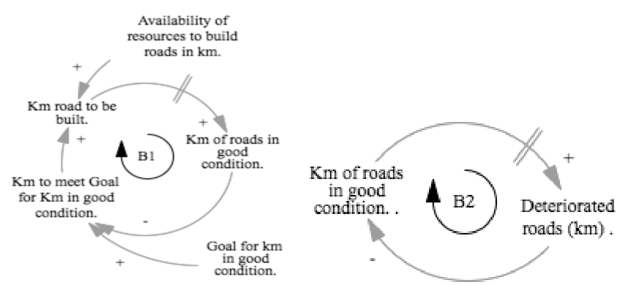


R2 aims to explain the relationship among kilometers of roads in good condition, deteriorated roads in kilometers, and the availability of resources to maintain roads in kilometers (Figure 3). The relationship between kilometers of roads in good condition and kilometers of deteriorated roads is positive if one follows the premise that as the number of kilometers of roads in good condition increases, the number of kilometers of deteriorated roads will increase over time. A delay represents this dynamic because the roads have a limited lifespan that will determine when the roads stop being in good condition and become deteriorated. The relationship between the number of kilometers of deteriorated roads and the value of the kilometers to be maintained is positive, the higher the number of deteriorated kilometers, the greater the number of kilometers to be maintained. The value of the kilometers of deteriorated roads and the availability of resources to maintain roads in kilometers determine the number of kilometers of roads to maintain. This value comes from the highest value among these variables.

B1 represents the logic of the construction of new kilometers of roads through the availability to build roads in kilometers and the kilometers to meet the goal for kilometers in good condition (Figure 4). The goal for kilometers in good condition as an endogenous variable fed this loop. When compared with the kilometers of roads in good condition, determine the kilometers to meet the goal for kilometers of road in good condition. Having more kilometers to meet the goal for kilometers in good condition will increase the gap between the goal and road network inventory, making it necessary to build new kilometers of roads to pursue the goal. A delay represents the time taken to the construction of new kilometers of road. That will make the kilometers of roads in good condition increase after the construction period, generating a relationship which indicates that by increasing the number of kilometers of roads in good condition, there will be a reduction in the number of kilometers to meet the goal.

B2 shows the relationship between kilometers of roads in good condition and kilometers of roads in poor condition (Figure 4). B2 represents the dynamics that arise from the roads built or repaired and that over time deteriorate, reducing the inventory of roads in good condition, which serves as a trigger to start R2 directly and indirectly B1 by influencing the value of the kilometers to reach the goal of kilometers in good condition.

Figure 4. Balancing loops 1-2



The dynamic hypothesis (Figure 2) shows in an aggregated way the development of road infrastructure. It is the basis of the stock and flow diagram (Figure 5) that presents a novel characteristic that offers alternatives for the analysis and interpretation of the dynamics of the road development system focusing on the construction material used for the roads. Several variables and technical criteria defined the design decision to opt for concrete-based rigid pavements or asphalt-based flexible pavements, such as material sources, environmental conditions, wear resistance, soil types, and traffic types [33].

It is generally argued that the cost of the asphalted pavement is lower than that of concrete, which sometimes is not entirely true, since the asphalt, being a bitumen, depends on the prices of crude oil. In contrast, cement, the main component of the rigid pavement, has had cost reductions [34]. The cost of flexible pavements used to be up to three times less than rigid pavements, a currently matched value after a comprehensive cost analysis, including maintenance and construction operation [33].

The model shown in this article takes as a reference mode the statistics of the Colombian road inventory (Figure 1). The figure shows the situation of lag in the development of roads in good condition over time so that the values used to parameterize this model proceed from the Colombian case of road development (Table 1 and Table 2).

The information used to parameterize the model comes from different sources: the GDP from 2004 to 2017 from the Colombian Central Bank [35], the percentages of the GDP to determine the values of investment in infrastructure emerge from the National competitiveness Report 2017-2018 [36]; the costs of road construction, highway maintenance, construction time and maintenance from Gómez [37]; deterioration times, according to construction material, from the manual on the design of concrete pavement for low, medium and high traffic flow [33] and the values of the number of kilometers in good condition and kilometers for infrastructure goals from the National Roads Institute of Colombia and their report on the condition of road networks [23] (Monetary data is included in dollars at constant 2017 prices with an exchange rate of COP 3000 per dollar since original values are in COP).

Table 1. Model parameters (GDP, Investment and Goal of km of roads in good condition)

Year	GDP (Thousands of Millions of dollars)	Percentage of GDP Invested in roads	Budget to build roads (Thousands of Millions of dollars)	Goal for Km of roads in good condition (Km)
2005	$ 171.42	0.48%	$ 0.82	12,782
2006	$ 183.04	0.50%	$ 0.92	13,357
2007	$ 195.57	0.46%	$ 0.90	13,932
2008	$ 201.96	0.36%	$ 0.73	14,507
2009	$ 204.38	0.51%	$ 1.04	15,082
2010	$ 213.26	0.47%	$ 1.00	15,657
2011	$ 228.97	0.68%	$ 1.56	16,232
2012	$ 237.90	1.06%	$ 2.52	16,807
2013	$ 248.77	1.02%	$ 2.54	17,382
2014	$ 260.53	0.93%	$ 2.42	17,957
2015	$ 268.16	1.50%	$ 4.02	18,532
2016	$ 273.50	1.80%	$ 4.92	19,107
2017	$ 278.39	2.00%	$ 5.57	19,682

For the development of the proposed model, the construction and maintenance of rigid pavement will be twice the cost for the construction of flexible pavement. Besides, the resistance of roads is five times greater for those with rigid material versus those with flexible material. Maintenance time shows no differences between the two options. The construction time variable varies according to the material. This variable follows a normal distribution that adds randomness to the model (Table 2).

The road infrastructure development model, through road construction and maintenance, is a tool that seeks to identify trends and long-term effects, through the simulation of scenarios that describe the system. It is necessary to clarify that for this article the meaning of scenario corresponds to changes in the parameters and conditions of the simulation runs, not to the sequence or development of events over time [38]

This paper contemplates the effects of different scenarios on the construction of roads to achieve the goal for kilometers in good condition by varying the fractions of flexible and rigid pavement in road construction, where construction costs, maintenance costs, and deterioration times determine the dynamics of the system.

Table 2. Model parameters by type of pavement.

Concept		Flexible Pavement	Rigid Pavement
Cost to construct a Km (thousand dollars)		$433,33	$866.66
Cost to Maintain a Km (thousand dollars)		$300	$600
1 km Construction time (Months) (normal distribution)	Min	3	7

	Max	5	11
	Mean	3,8	9
	StanDev	1	1
Maintenance time per Km (Months)		1	1
Deterioration time (Months)		15	75

The first scenario proposes constructing 100% of the roads in flexible pavement. The second scenario proposes constructing 100% of the roads in a rigid material. The third scenario illustrates the combination of materials in which 80% of roads correspond to the flexible material and 20% to the rigid material. The fourth scenario shows 80% of road construction in rigid and 20% flexible material (Table 3).

Table 3. Proposed Scenarios

Scenario	Flexible pavement	Rigid pavement
Scenario 1	100%	0%
Scenario 2	0%	100%
Scenario 3	80%	20%
Scenario 4	20%	80%

It is necessary to mention that from the budget allocated for the development of roads, 50% goes to the construction of new roads and the remaining 50% to the maintenance of existing ones. The simulation step is in months. Even though there are annual values such as road infrastructure budget, variables such as money availability time, construction time, maintenance time, and deterioration time, which are fundamental to represent the dynamics of the model, are defined in months. The simulation time is 12 years.

The most relevant equations that leverage the dynamics of the system and feed the stock and flow diagram shown in Figure 7 are below: Although the rates between flexible and rigid pavement are different, the relationship between the variables is equivalent to the two types of pavement. For this reason, and to abbreviate the number of equations, we generically include them.

Kilometers of roads in good condition ($KGC_{Flex/Rig}$) depend on the construction rate ($CR_{Flex/Rig}$), recovery rate ($RR_{Flex/Rig}$), and deterioration rate ($DR_{Flex/Rig}$). (eq. 1)

$$KGC\ (t) = KGC(0) + \int_0^t CR(t) - DR(t) + RR(t)dt. \quad (1)$$

Deteriorated roads in kilometers ($DK_{Flex/Rig}$) is related to the deterioration rate ($DR_{Flex/Rig}$) and the maintenance rate ($MR_{Flex/Rig}$) (eq. 2)

$$DK\ (t) = DK(0) + \int_0^t DR(t) - MR(t)\, dt. \quad (2)$$

Maintained roads in kilometers ($MK_{Flex/Rig}$) is subject to maintenance rate ($MR_{Flex/Rig}$) and the recovery rate ($RR_{Flex/Rig}$) (eq. 3)

$$MK\ (t) = MK(0) + \int_0^t MR(t) - RR(t)\, dt. \quad (3)$$

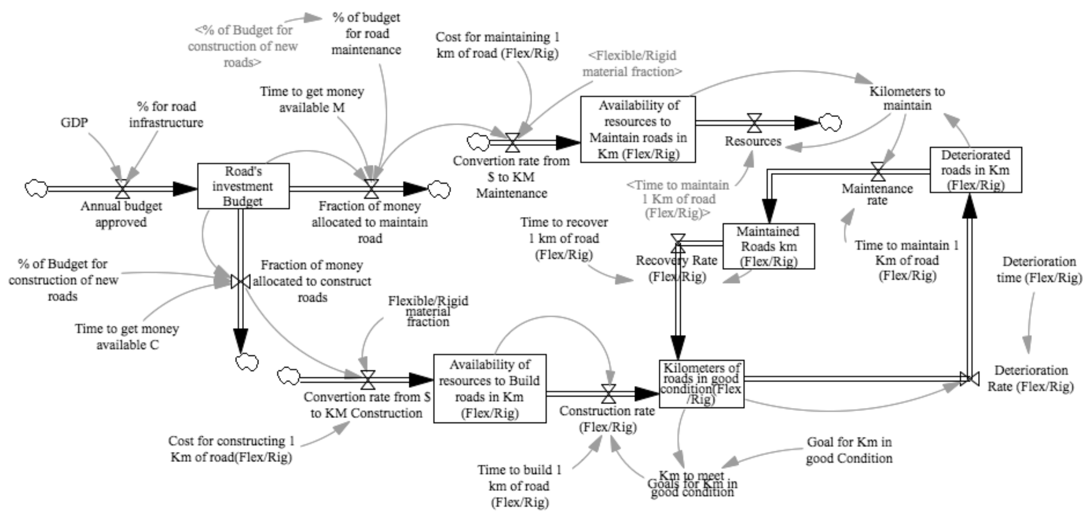
Kilometers to meet the goal of kilometers in good condition (KMG) obtains its value by subtracting from the goal of kilometers in good condition (GKGC) the sum of the results kilometers in good condition

(KGC_{Flex}) of the rigid pavement and the Kilometers in good condition (KGC_{Rig}) of the flexible pavement (eq. 4).

$$KMG\ (t) = GKGC - (KGC_{Rigid}(t) + KGC_{Flexible}(t))\ (4)$$

A stock and flow diagram helps to understand and define the state of the system by generating pieces of information that support the actions and decisions regarding the behavior of the system [39]

Figure 5. Stocks and flows system diagram



The model validation includes a series of tests following the procedure proposed by Barlas[40]. Previous existing studies based on the development of infrastructure in Colombia, included in tables 1 and table 2, validate the structure of the model concerning the boundary adequacy and the parameter rationality of the SD. In the same sense, the causal diagrams and the stock and flow diagrams facilitate the identification of the exogenous constants that can be considered variables in the model. Additionally, we tested the dimensional consistency of the measurement units using the VENSIM software utility and its "Check Units" command, which facilitated the identification of inconsistencies adjusted in their totality. Comparing the results with reference modes such as historical road inventory data in the Colombian case [7] validate de model's behavior.

3. RESULTS AND DISCUSSION

Figures 6, 7, 8, and 9 show the results of the simulation runs. The figures are composed of 3 graphs. The first one represents the distance to achieve the goal of kilometers in good condition, which compares the value of kilometers in good condition and the goal of kilometers in good condition. The second and third graphs display the value of kilometers in good condition of flexible pavement and rigid pavement.

Figure 6 represents the scenario 1, which outlines the situation in which all the investment goes to road construction with flexible asphalted material. For the first 10^{th} months, the value of the kilometers in good condition is approaching the goal. This increase in the number of kilometers in good condition caused by the flexible pavement cost allows construction and maintenance of kilometers higher than the increase in the goal of kilometers in good condition. After the 10^{th} period, the number of kilometers in good condition tends to move away from the goal due to the speed of deterioration of roads emphasizing B2 (balancing loop 2). It presents moments of the dominance of the kilometers of road in good condition. It balances with the dominance of the deteriorated kilometers. The number of kilometers of rigid pavement in good condition decreased over time since the development of flexible pavement roads has all resources. Some oscillations accentuate over time due to the delay between the construction, deterioration, and maintenance of the roads. Towards the end of the simulation, the number of kilometers in good condition increases, maintaining the oscillations. This increase is due to the rise of the budget allocated for the development of roads (table 1).

Scenario 2, represented in Figure 7, shows the situation of road construction exclusively dedicated to the rigid concrete pavement. The kilometers to reach the goal of kilometers in good condition gradually increases over time, until it shows a small recovery, after which some periods begin to present fluctuations that diminish over time. The behavior of this scenario shows that the value of the construction of roads in rigid concrete pavement has a direct influence on achieving the goal of kilometers in good condition. Especially in the first few months, it presents long-term improvements caused by the prolonged duration of the roads built with this type of material, counterbalancing the number of kilometers built by reducing deteriorated kilometers over time.

Scenario 3 (Figure 8) behaves similarly to scenario 1. However, by including 20% of roads built with rigid concrete pavement, it shows improvements in this scenario compared to scenario 1 concerning the values of kilometers to reach the goal of kilometers in good condition. This scenario, like scenario 1, shows a significant advance in the short term, which is explained by the costs of building flexible material. However, it similarly shows that in the long term, the deterioration rate's effect causes the gap to increase and overtime to have fluctuations, which show recoveries and deteriorations caused by the relationships among the kilometers of roads, the deterioration rate, and the maintenance rate.

Figure 6. Scenario 1 simulation results

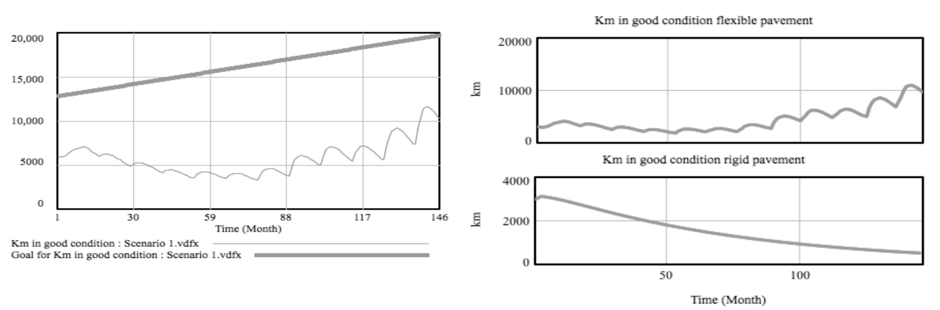


Figure 7. Scenario 2 simulation results

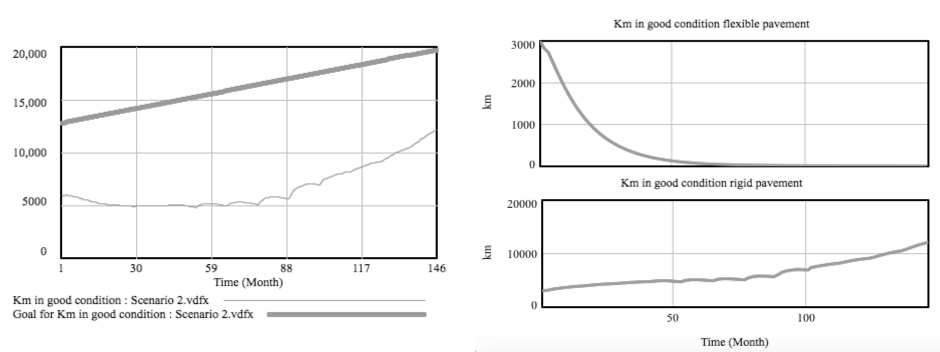
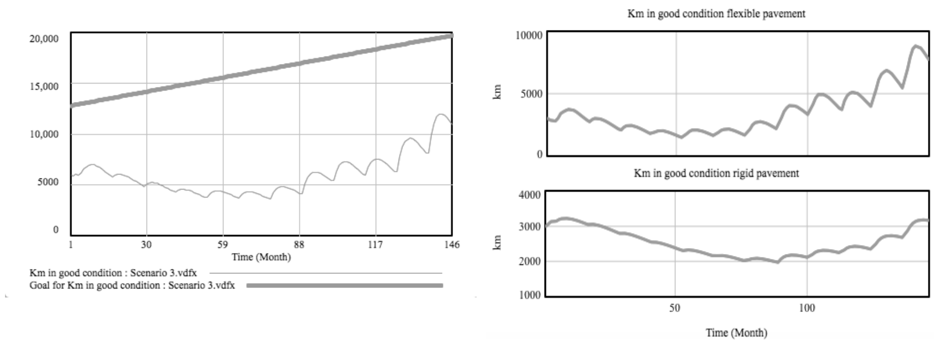
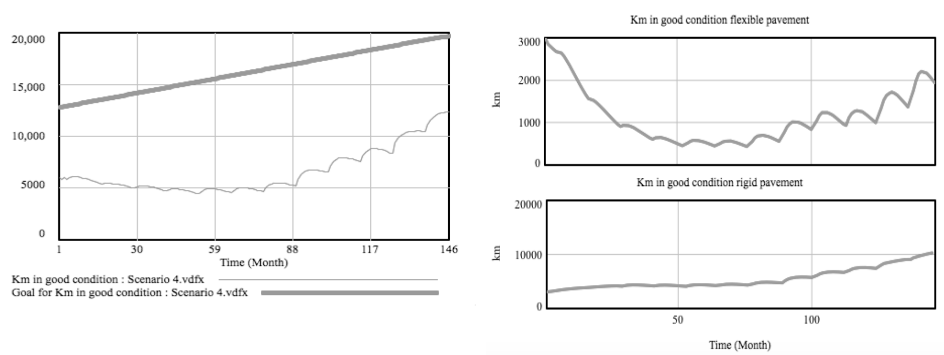


Figure 8. Scenario 3 simulation results



Scenario 4, symbolized in Figure 9, presents the best long-term behavior. The results of this scenario are closer to the goal of kilometers in good condition compared to the other three scenarios during the 143rd period. However, the fraction of flexible pavement used for the construction and maintenance of roads makes that due to delays between construction, deterioration, and maintenance, produce oscillations that lead it away from the goal in kilometers expected.

Figure 9. Scenario 4 simulation results



The scenarios obtained by simulation suggest that the materials used and their characteristics, cost, and duration, affect the development of the road system. Flexible pavement shows results more favorable in the short term. However, due to its useful life and deterioration rate, it requires investment and regular maintenance, directly affecting meeting the goals for kilometers in good condition. The use of rigid pavement (scenario 2) in all the roads and the scenario in which this material predominates (scenario 4) suggest that in the long run, they are more appropriate, reinforcing what was said by the theoretical basis [33]. Over time it is more profitable to use rigid pavement due to the aggregate costs of construction, operation, and maintenance; however, the results indicate that mixing flexible and rigid materials presents improvements that lead to the achievement of the goal of kilometers proposed by the national government.

4. CONCLUSIONS

- The problems of infrastructure development have had different approaches to seek alternatives that provide the best benefits; expert systems, analytical models, and holistic approaches have been used for this purpose, showing that holistic approaches as systems dynamics tackle the complex nature of the system.

- Road construction using flexible asphalt provides better results intending to achieve short-term goals, because of its cost that helps to achieve rapid progress in construction, with the main drawback, that over time and due to its durability characteristics, it does not present the best long-term results as shown within the base scenario.

- From the assessment of scenarios, we concluded that the use of rigid pavement, in its entirety or more significant proportions, in the long-term, provides results that are approaching the goal of kilometers in good condition because of the durability of this material, the aggregate cost of construction, maintenance and operation. The proposed model presents results consistent with the results mentioned by Londoño et al. (2008) for the long-term advantages of rigid pavement. However, the results indicate that mixing flexible and rigid materials present improvements that lead to the achievement of the goal of kilometers proposed by the national government.

- The development of simulation tools, from the methodology of systems dynamics, guides decision-makers to glimpse trends and expected and unexpected effects of the interaction of variables in a system. Furthermore, it offers conceptual bases that provide a structured way to understand and learn the behavior of complex systems.

- The assessment of public policies provides the opportunity to experience systems and configurations that allow for the orientation in decision making, planning of investments, and resources.

5. FURTHER RESEARCH

The study of the construction and maintenance of road makes part of a work that seeks to encourage the development of intermodal transport systems. Therefore, after the model is validated, it must be integrated into infrastructure development models for other modes of transport, such as rail and waterways.

The immediate step to follow for the model of stocks and flows corresponds to the validation of its structure with the use of information from other countries to compare if the results obtained from the Colombian case's parameterized data provide relevant results for other contexts.

Future studies of road infrastructure may include the development of roads divided into primary, secondary, and tertiary roads since construction material and deterioration behave differently because of traffic on the road.

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