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DYNAMIC MODEL FOR QUALITY ASSESSMENT OF LOGISTICS CORRIDOR ROAD INFRASTRUCTURE IN COLOMBIA

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ABSTRACT

In this paper the behavior of the road infrastructure of logistics corridors in Colombia is modeled using system dynamics to assess the impact of investment policies carried out in the paved road network. Five categories are considered for assessing the quality of the paved road network as defined by the Instituto Nacional de Vías y Transporte (INVÍAS). The model contains parameters for evaluatingroad wearbased on average traffic and the investments made for road rehabilitation and maintenance.

KEYWORDS: System dynamics; Pavement wear; International roughness index; State of the road network; Logistics corridor.

MODELO DE EVALUACION DINÁMICA DE LA CALIDAD EN LA INFRAESTRUCTURA VIAL DE CORREDORES LOGÍSTICOS EN COLOMBIA

RESUMEN

En el presente artículo se modeliza el comportamiento de la infraestructura vial de los corredores logísticos de Colombia, utilizando dinámica de sistemas para evaluar los efectos de las políticas de inversión que se realizan en la red pavimentada. Para ello, se consideran cinco categorías que permiten evaluar la calidad de la red pavimentada definidas por el Instituto Nacional de Vías y Transporte – INVIAS. El modelo contiene la parametrización para evaluar el desgaste de las vías en función de tráfico promedio y de las inversiones que se realizan para la rehabilitación y el mantenimiento de las vías.

PALABRAS CLAVE: Dinámica de sistemas; desgaste de pavimentos; índice de rugosidad internacional; estado de la red vial; corredor logístico.

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MODELO DE AVALIAÇÃO DINÂMICA DA QUALIDADE EM INFRAESTRUTURA VIAL DE ESTRADAS LOGÍSTICA NA COLÔMBIA

RESUMO

Em este artigo, se modeliza o comportamento da infraestrutura rodoviária de corretores de logística da Colômbia, usando a dinâmica de sistemas para avaliar o impacto das políticas de investimento realizados na rede pavimentada. Para este fim, consideram-se cinco categorias para avaliar a qualidade da rede pavimentada definido pelo Instituto Nacional de Vias y Transporte - INVIAS. O modelo contém os parâmetros para avaliar o desgaste de estradas, dependendo do tráfego e dos investimentos, feitos para a reabilitação e manutenção de estradas.

PALAVRAS- CHAVE: Dinâmica de sistemas; Desgaste do pavimento; Índice de rugosidade internacional; Estado da rede rodoviária; Corredor logístico.

1. INTRODUCTION

Road infrastructure is one of the most important pillars in the functioning of a city and country as they facilitate communication, commerce, tourism, and economic development. Land transport (by highway) represents the highest percentage of use for the movement of merchandise and people in comparison with other existing modes of transportation available in Colombia, which makes it the object of special attention given its importance for the adequate development and functioning of logistical activities in the country (Fedesarrollo, 2013).

All transportation infrastructure, especially roads, has a basic life cycle: construction, maintenance, and dismantling (Schaffernicht, 2012). The entity responsible for assigning, regulating and supervising these activities in Colombia is the National Institute of Roads and Transport (in Spanish, *Instituto Nacional de Vías y Transporte* or *INVÍAS*), which has defined five categories for the state of the paved road network: Excellent, Good, Fair, Poor, and Very Poor. These categories correspond to the International Roughness Index (IRI), which serves as a reference parameter for measuring the ride quality of a road, and which was accepted by the World Bank in 1986 (Arriaga, Garnica and Rico, 1998) as the standard measurement for the surface regularity of a roadway.

The case study addressed in this project considers the behavior of the quality of six logistics corridors in Colombia over the course of 15 years during the maintenance stage of their life cycles. Using system dynamics as a tool, the behavior of the quality of the roads is modeled by determining the relationships established between the state of the roads in each category (Excellent, Good, Fair, Poor, and Very Poor kilometers), average daily traffic, the IRI, and different types of interventions restricted by resource availability and allocation policies.

Productive growth, infrastructure, and the logistical system of a country are determined by economic competition. As such, logistical development (such as connections between physical infrastructure and associated services) contribute to adequately facing predictions regarding foreign trade and boosting the flow of goods, thus making the structure of logistical costs and physical distribution more efficient" (Departamento Nacional de Planeación, 2013).

Transport is a logistical function (Bowersox, Closs and Cooper, 2008; Rushton, Croucher and Baker, 2006, Chopra and Meindl, 2008) and has a direct impact on the competitiveness of a region and country (Pascua and Gento, 2010, Álvarez, Pabón and

Ortiz, 2010; CEPAL & OCDE, 2013; Kunaka and Carruthers, 2014).“[A]logistics corridor is that which connects origins and destinations in physical and functional aspects in a comprehensive manner, such as transportation infrastructure, information and communication flows, and practices for doing and facilitating business”(Departamento Nacional de Planeación, 2008). The performance of a corridor can be evaluated from three perspectives: quality of infrastructure, services, and movement of goods (National Research Council, 2000; Arnold, 2006; Muñuzuri, Grosso, Cortes, and Guadix, 2011; Arvis, Raballand Marteau, 2010).

This article is organized to first present the variables that will be used in the development and analysis of the model, which were obtained in a review of government entity documents and previous research projects. Secondly, the causal diagram that represents the relationship between the variables identified and the respective feedback loops will be presented. Following that, the stock and flow diagram that describes the mathematical formulation of the model will be developed. Finally, the results obtained will be presented, and a sensitivity analysis will be done to support action policies regarding the network to ensure its quality.

2. METHODOLOGY

Systems theory recommends conducting a holistic analysis that permits not just learning about and understanding each element of the system, but also the interrelation that exists between them and their effect on the system as a whole (Richmond, 1993). System dynamics proposes a methodology that seeks to structure and improve mental models until achieving a simulation model that reproduces historical reference system behaviors and in whose causal structures a logical coherence is maintained between system and model (Schaffernicht, 2012).

Using the methodology proposed by Sterman (2002), the relevant variables that affect the quality of the paved roads in the logistics corridors of Colombia are identified in the document *E-Transcol #10* (Universidad Nacional de Colombia, 2014). The identified variables are classified based on the categories used in system dynamics, meaning level, auxiliary, flow, and parameter variables. **Table 1** shows the variables and their classifications.

In accordance with what has been established by Roda (2009), correspondence between the IRI and the categories established by INVÍAS was identified. This correspondence is shown in **Table 2**, where the highway kilometers that make up the current national road network are classified into the categories established by the IRI.

TABLE 1. VARIABLE CLASSIFICATION IN THE SYSTEM: PREPARED BY THE AUTHOR, (2015)

Type of variable	Name of variable
Level	Excellent kilometers
	Good kilometers
	Fair kilometers
	Poor kilometers
	Very Poor kilometers
Auxiliary	Total national investment in rehabilitation and maintenance
	Investment rate for Fair corridors
	Investment rate for Poor corridors
	Investment rate for Good corridors
	Effect of periodic and routine maintenance
	Effect of investment in Very Poor kilometers
	Effect of investment in Good kilometers
	Proportion of Fair kilometers maintained
	Proportion of Poor kilometers maintained
Flow	Rehabilitation of Very Poor kilometers
	Maintenanceof Fair kilometers
	Maintenanceof Poor kilometers
	Maintenanceof Good kilometers
	Wear on Excellent kilometers
	Wear on Good kilometers
	Wear on Fair kilometers
	Wear on Poor kilometers

Parameter	Percent of investment in rehabilitation
	Cost of rehabilitation per kilometer
	Cost of maintenance per Good kilometer
	Percent of investment per corridor
	Cost perkilometer of routine maintenance
	Cost perkilometer of periodic maintenance
	Percent of investment in routine maintenance
	Percent of investment in periodic maintenance
	Rate of wear in Excellent, Good and Fair kilometers

TABLE 2. IRI CORRESPONDENCE AND CLASSIFICATION WITH INVÍAS. SOURCE: PREPARED BY THE AUTHOR APART FROM RODA (2009)

Status category	INVÍAS classification	IRI
Excellent	MB (*muy bueno*)	<2.5
Good	B (*bueno*)	<3.5
Fair	R (*regular*)	<4.5
Poor	M (*malo*)	<5.5
Very poor	MM (*muy malo*)	>5.5

Table 3 represents the state of the national road network for the year 2013, based on this classification.

TABLE 3. STATE OF THE NATIONAL ROAD NETWORK. SOURCE: TAKEN FROM INVÍAS (2013)

NETWORK TOTAL	Paved road network					
	MB	B	R	M	MM	Total
Length (Km)	1,837	3,021	2,530	1,253	64	8,705
%	21.1%	34.7%	29.1%	14.4%	0.7%	100%

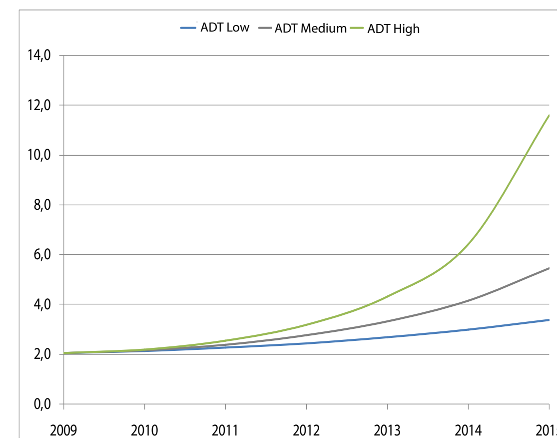
The state of a road as seen from the perspective of the IRI depends on its initial state and the wear or deterioration produced by traffic volume (Arriaga, et al., 1998), which are classified as low, medium or high depending on the quantity of vehicles that travel on the road as shown in **Table 4.**

TABLE 4. AVERAGE DAILY TRAFFIC (ADT) CLASSIFICATION. SOURCE: PREPARED BY THE AUTHOR APART FROM RODA (2009)

Vehicles/day	ADT
<2941	Low
2942-5254	Medium
>5255	High

The ex-post evaluation of the Comprehensive Road Rehabilitation and Maintenance Program (in Spanish, *Programa Integral de Rehabilitación y Mantenimiento Vial*) and the quantification of road liabilities for the National Road Network (*Red Vial Nacional*), established by INVÍAS, make it possible to identify the relationship between ADT and the value of the IRI over time, as shown in **Figure 1** (Roda, 2009).

Figure 1. Relationship between ADT and IRI. Source: Taken from Roda (2009)



The base for the determination of maintenance investment for each logistics corridor through Colombian public policy on road network maintenance in 2009 is a global allocation of 515 billion pesos, of which 34% goes to routine maintenance, 14% to periodic maintenance, 32% to rehabilitation,10% to kilometers in good condition, and 10% to the gravel road network (Roda, 2009).

Table 5 shows the length of the logistics corridors analyzed.

TABLE 5. LENGTH OF LOGISTICS CORRIDORS. SOURCE: TAKEN FROM UNIVERSIDAD NACIONAL DE COLOMBIA (2014)

Corridor	Length (Km)
Medellín - Cali	424
Bogotá - Barranquilla	948
Bogotá - Cali	464
Bogotá - Bucaramanga	394
Medellín - Bucaramanga	399
Bogotá - Villavicencio	88
TOTAL	2,717

For the development of the system dynamics model, the following assumptions were adopted:

- Distribution of the condition of the national road network according to the IRI for each of the corridors studied was shown in **Table 3**.
- Investment allocation for the different interventions, rehabilitation of the worst sections, and periodic and routine maintenance are decided in proportion with the length of each corridor.
- Investment costs by kilometer are constant during the simulation.
- Intervention periods for roads being maintained are considered constant and annual.
- The investment value in annual national maintenance is constant during the simulation period.

3. CAUSAL DIAGRAM

To determine the variation in quality of the roads in the previously mentioned categories, each quality category is treated as a level variable; the category shift of a road occurs due to the wear rate and the maintenance interventions. Maintenance interventions include routine maintenance, periodic maintenance, and rehabilitation. It is important to highlight that it is assumed that after any type of intervention the condition of the road enters the Excellent category (Arriaga, et al., 1998).

The relationships between the different variables of interest can be represented based on a causality diagram which, in addition to allowing for the visualization of the cause and effect relationships given in the system, facilitates the identification of balance and feedback loops (Kirkwood, 1998). The causal diagrams allow, in light of observing how the variables behave over time, for the system's feedback to be modeled based on its components, information flows, structure, and delays that can occur over time to achieve a behavior. They also make it possible to contemplate the non-linear relationships of the elements studied (Holling and Meffe, 1996; Sterman, 2002;Hjorth and Bagheri, 2006).

In the causal diagram developed for the road network presented in **Figure 2**, both reinforcement and balance loops are shown. The reinforcement loops produce an effect that causes a variable to increase or decrease, while the balance loops cause an asymptotic behavior in the level variable (Universidad Nacional de Colombia, 2014).

The balance and reinforcement loops will be explained below, keeping in mind that the categories shown (Very Poor kilometers, Poor kilometers, Fair kilometers, Good kilometers, and Excellent kilometers) have a sequential order.

Balance loops

In the causal diagram of the case study, "Dynamic behavior of the quality of the road infrastructure in six logistics corridors in Colombia," two general structures appear that show balance.

- The first relationship is between the number of kilometers in a condition and their respective wear. All the kilometers found in a condition due to wear will enter a lower category, thus decreasing the kilometers found in a better condition. The cycles that demonstrate this structure are B1, B2, B3 and B8 in **Figure 2**.
- The second relationship is established between the number of kilometers in a condition and their respective intervention, which generates a second balance loop since, if more kilometers exist in a category, the required intervention will be greater.

Although restricted by the value of the budget allocated for that purpose, the effect brought about by the decrease in kilometers in that condition, regardless of the type of intervention, will mean more Excellent kilometers. The loops that demonstrate this behavior are B4, B5, B6 and B7.

Reinforcement loops

In the causal diagram shown in **Figure 2**, a general structure is depicted that defines the reinforcement loops contained therein; they are the result of the relationship between the condition of a kilometer, its maintenance and transition to the Excellent category, and in the rest of the categories the return to their initial condition due to wear. The loops that exhibit this behavior are R1, R2, R3 and R4, as shown in **Figure 2.**

4. FORMULATION OF THE MODEL

One decisive and necessary factor to ensure road maintenance is conducted, is devoting investment. In Colombia, this investment is made at the national level, which is why it is necessary to differentiate the percentage of said investment destined towards the six corridors and to distribute the value obtained among each of them (Roda, 2009).

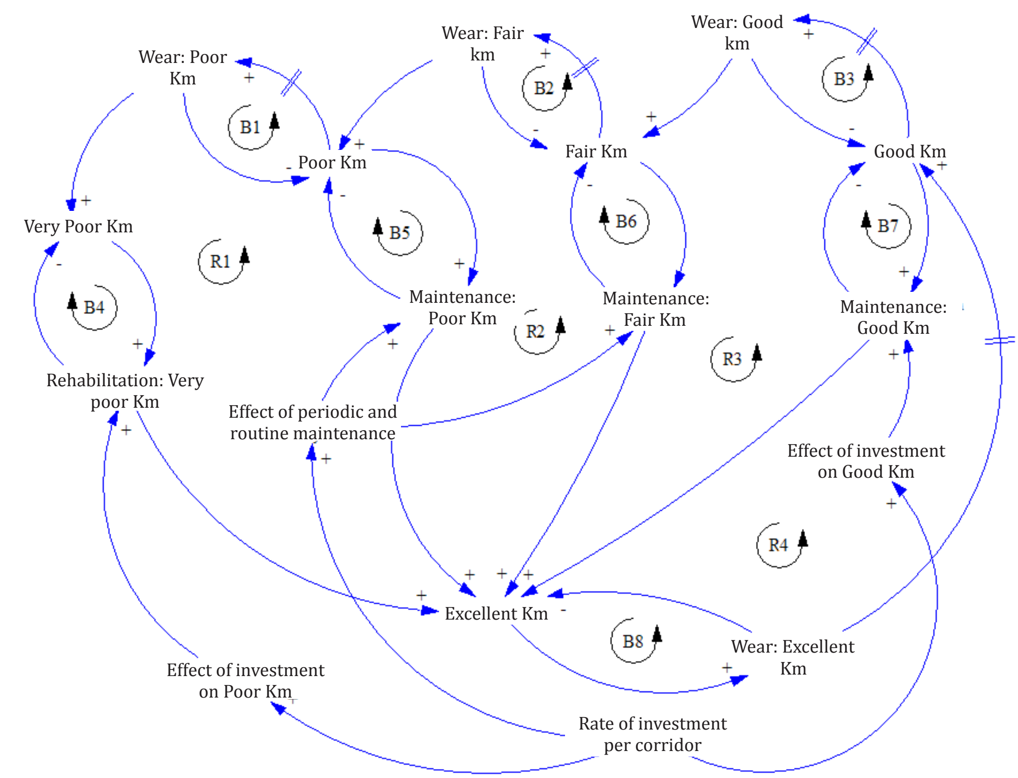
- **Equation 1** shows how to estimate the value available for a class of intervention:

$$TDIC_{ij} = (IAI)\times(\%AIC)\times PC_i \qquad (1)$$

Where:

- $TDIC_{ij}$ is the investment rate per corridor i in each class of intervention j.

Figure 2. Causal diagram on road network conditions
Source: Prepared by the author



- *IAI* is the annual investment in infrastructure directed towards the six corridors. This is obtained based on the ratio between the total length of the corridors and the total length of the paved road network in Colombia, multiplied by the total of the national investment in maintenance, which is established by public policy each year and includes both public and private parties.
- *%AIC* is the annual percentage allocated to a type of intervention defined by the national distribution policy.
- *PC* is the proportion of corridor length *i* in relation to the group of all six corridors.

The effect of these investments in each category, in kilometers, is deduced from **Equation 2** based on the investment rate for each class of intervention *j* per corridor *i* ($TDIC_{ij}$), and the cost of investment per kilometer:

$$Efecto_i = \frac{TDIC_{ij}}{costo/km\ de\ intervención_j} \quad (2)$$

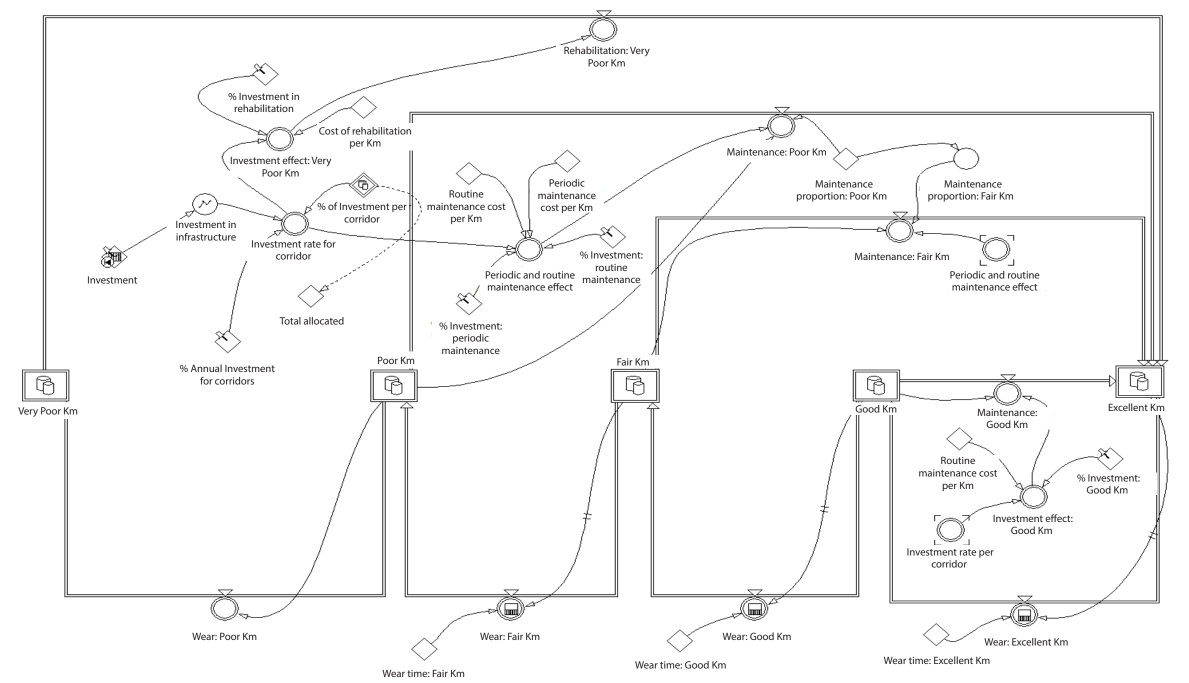
Based on **Equation 2** it is possible to define the kilometers where interventions can take place per year and per category according to the economic resources available (Universidad Nacional de Colombia, 2014).

Figure 3 shows a section of the flow and levels diagram crafted to formulate the model.

4. RESULTS

The behavior obtained for the simulation of each of the corridors present in the case study is shown in **Figure 4** (a. Medellín-Buenaventura, b. Bogotá-Barranquilla, c. Bogotá-Buenaventura, d. Medellín-Bucaramanga, e. Bogotá-Bucaramanga and f. Bogotá-Villavicencio). The simulation was conducted using Powersim 10.0 software. The conventions for each simulation can be found in **Figure 4 (g)**.

Figure 3. Flow-levels diagram for road network conditions
Source: Prepared by the author

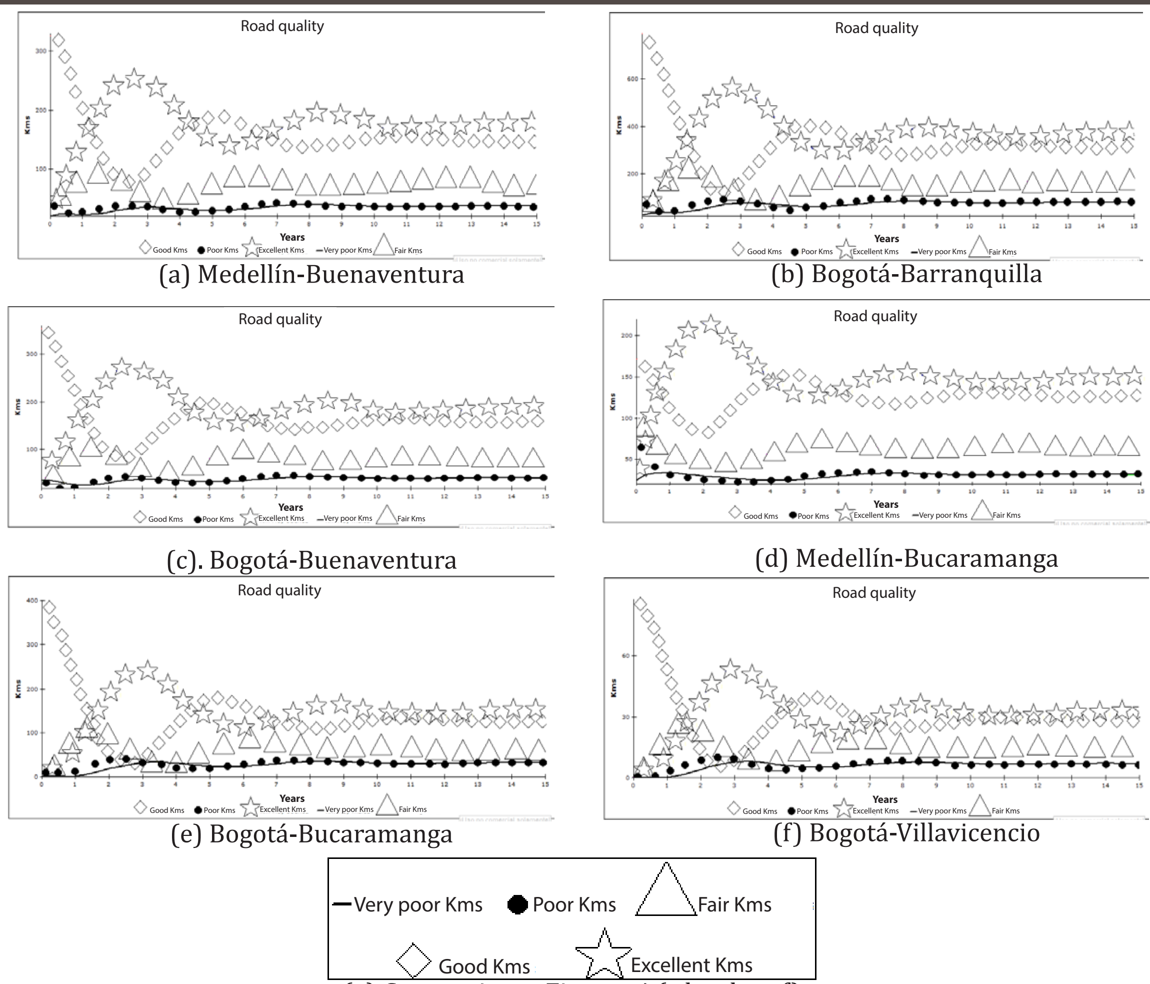


In each of these figures, how the performance of Very Poor, Poor, Fair, Good, and Excellent kilometers behaves can be observed over the course of the 15 years used for the simulation, with further observations that the values for each of the classifications tend to stabilize as time goes by.

Because current conditions (corridor characteristics) and investment (established amounts) allocated to each of the corridors are different, the values for the types of kilometers within the quality classification are different in each of the corridors. **Figure 4** shows how, in the six corridors, the Excellent and Good kilometers predominate (higher quantities of these kilometers); however, the Poor and Very Poor kilometers do not reach zero, which would be ideal, due precisely to the increase in transport flows and the lack of planned investment to counteract this increase in transport.

Particularly for the Excellent kilometers, upon analyzing the behavior of this category in each of the corridors, a temporary increase can be observed with a tendency to stabilize at a slightly higher level than the current one due to the annual investments made in each of the different types of intervention with the level of investment.

Figure 4. Simulated behavior of logistics corridors
Source: Prepared by the author



(a) Medellín-Buenaventura
(b) Bogotá-Barranquilla
(c). Bogotá-Buenaventura
(d) Medellín-Bucaramanga
(e) Bogotá-Bucaramanga
(f) Bogotá-Villavicencio
(g) Convenciones Figuras 4 (a,b,c,d,e y f)

5. SENSITIVITY ANALYSIS

To evaluate the consistency of the model against changes in its key parameters, a sensitivity analysis is conducted in which the effect of modifying infrastructure investment with regard to road quality is analyzed (Santa-Catalina, 2010).

The estimated portion of national investment in maintenance intended for the logistics corridors studied was originally 32%. To evaluate the numeric sensitivity of the model, it was decided that a range between 5% and 10% of the original value in each logistics corridor would be established. In **Figures 5** and **6** the results for the Bogotá-Barranquilla corridor are assessed, where it can be observed that with said investment values the number of Poor kilometers predominates in the corridor over time, which is most notable when the investment in the corridor is as little as 5% (**Figure 6**).

Figure 5. Results obtained with 10% investment. Source:Prepared by the author

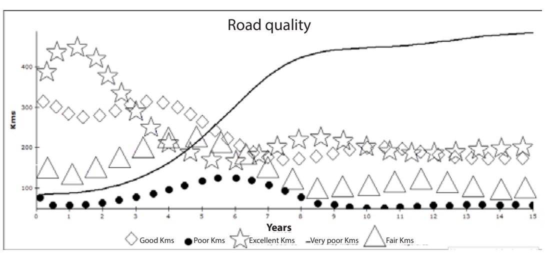
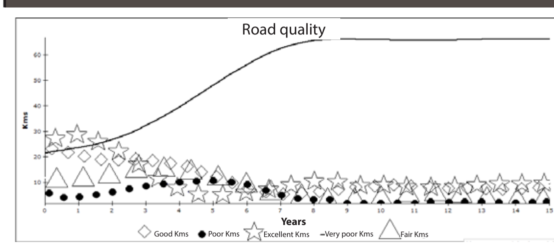


Figure 6. Results obtained with 5% investment. Source: Prepared by the author



Behavior sensitive to the investment percentage in the Figures above can be observed given that the resources are not sufficient for instituting the necessary interventions in such a way that the Very Poor kilometers rise up to a higher rate than the rest of the categories. It is also evident that the model produces coherent results despite the severity in the change of the value in the parameter used.

6. CONCLUSIONS

In this article a model was presented that, through system dynamics, makes it possible to evaluate the quality of the roads of a logistics corridor based on key variables like investment in the maintenance of the network and its average use. Based on this model, the effect of public policy investment on road infrastructure in Colombia can be evaluated.

Considering the results, it can be concluded that both the investment rate per corridor and the percentage of the same, in as much as it is allocated to maintenance, are determining factors for the optimum functioning of a logistics corridor.

From the results obtained, it can be concluded that, under the established assumptions, the behavior of the condition of the road network of the six logistics corridors tends in an asymptotic manner towards a slight majority in Good and Excellent kilometers, which is to say that they have an IRI less than or equal to 3.5.

However, it is notable that the asymptotic tendency expected with the established assumptions in the model described in this article tends to maintain a Fair or Poor quality level, which together make up 32% of the total kilometers of the Bogotá-Barranquilla corridor and 45% of the Bogotá-Bucaramanga corridor, which indicates an evident necessity to improve maintenance investment at the national public policy level.

Upon analyzing the sensitivity of the investment data in the model, it is found that a decrease in the values (economic resources) creates a situation in which a higher percentage of Fair and Poor quality kilometersis produced in the corridors, which is directly related to some dominant specifications and a difficult recovery in Good and Excellent quality kilometers in future years.

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