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DYNAMIC ANALYSIS OF SUSTAINABLE PRACTICES ADOPTION IN ROAD INFRASTRUCTURE DEVELOPMENT

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Awareness of the importance of sustainable development has made many governments prioritize the adoption of green measures. The road infrastructure sector is no stranger to this and has been transforming its processes in such a way that they incorporate more sustainable practices. However, the inclusion of this type of practice has not been an easy task, since the adoption of these practices results from a decision-making process that is affected by the context of potential adopters, as well as other external parameters such as institutional, environmental, socioeconomic factors, etc. This study aims to identify the main variables that affect the adoption of sustainable practices in the development of roadways in Colombia. Through the application of the Bass Diffusion model concept, the most influential variables were identified and a Causal Loop Diagram (CLD) was built to understand the dynamics and feedback processes between them. External variables such as the popularity of the green technique, guidelines existence, and costs associated with them are significantly influential in the inclusion of green measures. Additionally, the level of influence of each variable is assessed through the formulation of a system dynamics model and the evaluation of different scenarios. Finally, a set of recommendations to overcome barriers in the process of green measures adoption is given. This model can be used as a support tool in formulating strategies that promote sustainable practices in road development.

Keywords: Road infrastructure, Sustainability, System dynamics, Bass diffusion model, Pavements.

1 INTRODUCTION

Practitioners and scholars have been concerned with finding alternatives for materials or techniques that are more environmentally friendly, such as Warm Mix Asphalt (WMA) and Reclaimed Asphalt Pavement (RAP)(Aurangzeb and Al-Qadi 2014, Robinette and Epps 2010). A variety of methods have been employed to support decisions in road planning and development to evaluate sustainable practices, such as Life Cycle Analysis, genetic algorithms, optimization techniques, system dynamics, multi-attribute analysis (Fallah-Fini *et al.* 2014).

Most studies have characterized the different sustainable alternatives in technical, environmental, or economic terms. However, questions remain to be answered regarding how to promote the adoption of certain sustainable practices. This study aims to analyze the dynamics related to the adoption of sustainable practices in the development of roads. Specifically, by applying the Bass Diffusion model, it seeks to identify the variables that influence the inclusion of sustainable materials. Additionally, through a system dynamics model, this study analyzes different scenarios to compare rates of implementation of different materials and their impact on the road network system.

2 METHODOLOGY

In this study, System Dynamics (SD) is employed to understand the dynamics of the adoption of sustainable practices in road construction and maintenance. Specifically, a Causal Loop Diagram (CLD) was built based on the Bass Diffusion model concept to identify the most influential variables in this process. Followed by this, through a system dynamics model, different scenarios were evaluated to see how the preference between road materials (traditional and sustainable) varied over time. Additionally, variables such as Net Present Value (NPV) and CO2 emissions (associated with the construction and maintenance of roads) were calculated to analyze the impact of the adoption of sustainable practices in the system.

SD is a methodology developed by Forrester (1961) to study the behavior of complex systems over time. This approach assumes that systems are constantly changing due to a series of causal relationships between all their components. SD seeks to incorporate these relationships into a system through differential equations. SD has been widely used to solve sustainability problems in the infrastructure sector. Specifically, in the road infrastructure sector, it has been employed to examine the effects of maintenance and rehabilitation practices on deterioration (Fallah-Fini *et al.* 2014, Guevara *et al.* 2017, Ruiz and Guevara 2020b), and others have produced simulations capable of quantifying Greenhouse Gases (GHG) emissions across the pavement's lifecycle (Chua *et al.* 2018).

2.1 Bass Diffusion Model

The Bass Diffusion concept is employed to formulate the process of adoption of sustainable practices. This model proposes the rate of adoption of innovation measures is the sum of the adoptions resulting from word of mouth and adoptions resulting from external influences (Sterman, 2000). Adoptions from word of mouth are the consequence of social effects and , external influences in this study are represented by Government decisions and s (Ruiz and Guevara 2020a).

This study aims to compare the implementation rate between a traditional road material Hot Mix Asphalt (HMA), and two sustainable materials: Warm Mix Asphalt (WMA) and Reclaimed Asphalt Pavement (RAP). The variable *%Type of material* in Figure 1 (B) represents the rate of implementation for each. This variable depends on three main variables*: Visibility*, *Unit cost*, and *CO2 emissions*. As stated before, Visibility represents the adoption from word of mouth. On the other hand, Government decisions regarding road development are highly influenced by economic and environmental consequences. Because of this, the variables *Unit cost* and *CO2 emissions* were considered for the formulation of the implementation rate. Since unit cost and emissions are different for each activity (i.e., construction, maintenance, rehabilitation, and reconstruction), four different rates were calculated over time for each material. Additionally, Figure 1 (B) shows the variables *Wvisib*., *WEcon*, and *WEnv*, which represents the relative importance between the variables *Visibility*, *Unit cost*, and *CO2 emissions*, respectively.

2.2 Simulation Model Description

The present study used a previously developed SD model (Ruiz and Guevara 2020c). This model represents the evolution of a road network overtime considering deterioration processes, construction, and maintenance activities (using both traditional and sustainable techniques). It also quantifies the costs and CO2 emissions associated with all activities. The present study employs the aging chain of the aforementioned study to analyze the behavior of the road network. Figure 1 (A) shows an aging chain that represents the total road network. The Subscript function of the Vensim DSS software was used to model the dynamics for the three materials. Similarly, the CO2 emissions and NPV associated with construction and M&R activities are calculated (Figure 1(C)). However, in the current study, the implementation rate of each is not an exogenous parameter, it responds to the interaction of the variables *Visibility*, *Unit cost*, and *CO2 emissions*, as explained before.

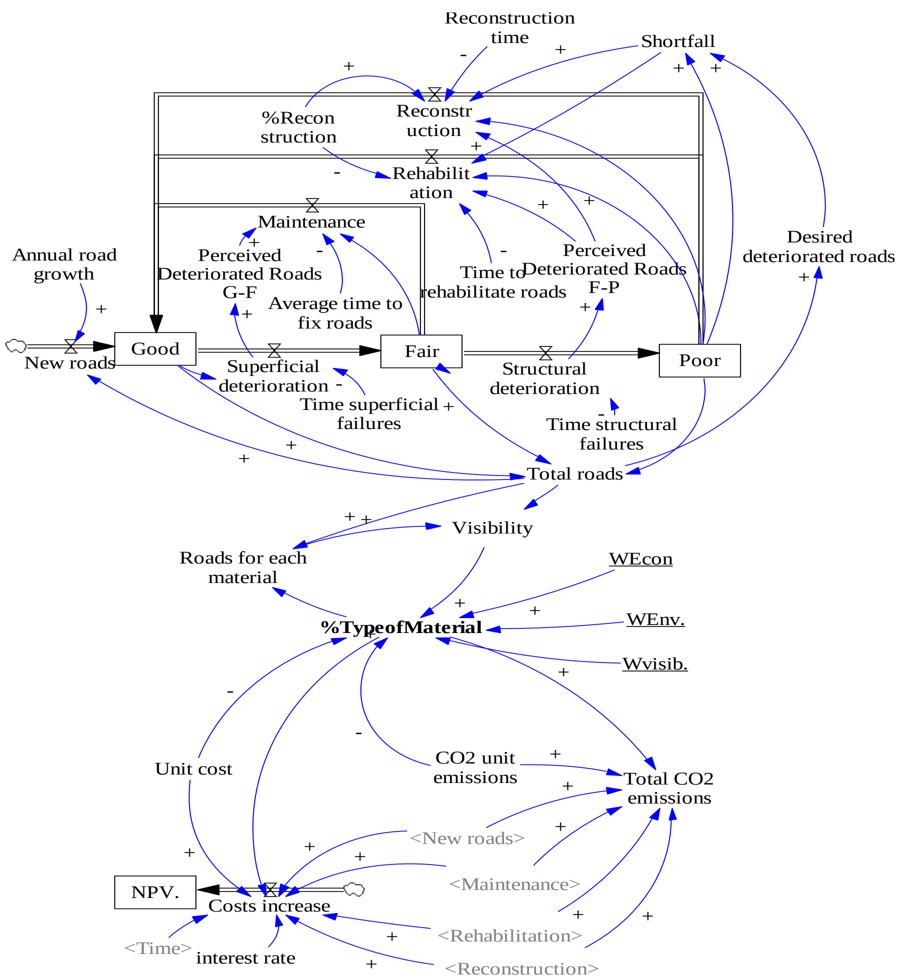

Figure 1. Simplified model; (A) Road network aging chain; (B) Rate of adoption of materials; (C) NPV and CO2 emissions.

System dynamics modelers have developed several tests for validation purposes that seek to find flaws in the model formula and ensure its efficiency (Sterman 2000). The set of tests carried out include tests of dimensional consistency, structure, integration error, extreme conditions, and sensitivity analysis. The model behaved logically and consistently in all tests run. A mathematical validation of the model was not performed due to the lack of official data regarding the implementation of sustainable materials. For future research, it is suggested to collect data to build a reference mode and strengthen the calibration and validation processes.

3 SCENARIOS AND RESULTS

A hypothetical case study is used to simulate different scenarios of rates of implementation of each material. This study employs the road network described in Ruiz and Guevara (2020c), which is a national road network, 17,201 km-roadway in length. The set of exogenous parameters related to unit ratios of CO2 emissions, unit costs, and time-based variables associated with pavement deterioration and preservation were taken from the same study.

Four different scenarios were simulated to analyze the behavior of adoption of materials (Figure 2) and how it impacts the NPV and CO2 emissions associated with construction and M&R activities for a period of ten years (Table 1). The baseline scenario was formulated based on the results of an Analytic Hierarchy Process (AHP) conducted with Colombian road experts (Ruiz & Guevara, 2020c). According to the AHP results, in the selection of road strategies and policy formulation, decision-makers consider that costs are significantly more important than the environmental impact. Additionally, experts affirm that the popularity or visibility of innovations is the most influential variable in their implementation. For example, it is considered that in Colombia the most widely used sustainable practices are those that have mandatory regulations or guidelines.

Table 1 shows the relative weights selected for visibility, costs, and environmental impact (Wvisib., Wecon, Wenv.) for the baseline and three alternative scenarios. Additionally, it shows the NPV and total CO2 emissions for the analysis period. Scenario 2 is an eco-friendly scenario, where the importance of the environmental impact is increased through the interchange of the relative weights between costs and CO2 emissions. Scenario 3 aims to evaluate the impact of Visibility by reducing significantly its importance, i.e. decreasing the impact of the adoption from word of mouth. Finally, Scenario 4 combines scenarios 2 and 3. According to Table 1, the impact of the adoption rates in the NPV and CO2 emissions are not significant. Regarding the NPV, the expenditures are higher in the three alternative scenarios compared to the Baseline. However, the largest increase in cost is around 8% for scenarios 3 and 4. The three alternative scenarios bring environmental benefits. Scenarios 2, 3, and 4, show reductions of CO2 emissions around 3.0E6 kg, 21.0E6 kg, and 21.0E6 kg, respectively.

Table 1. Scenario descriptions, NPV, and emissions.

	Scenario	Wvisib.	Wecon.	Wenv.	NPV (MUSD)	Emissions (M kg)
1	Baseline	0.60	0.34	0.06	-22.78	395.47
2	Ecofriendly	0.60	0.06	0.34	-22.27	392.35
3	Promotion	0.44	0.48	0.08	-21.03	374.40
4	Promotion&Eco.	0.45	0.27	0.27	-20.99	374.16

Figure 2 shows the rate of implementation for each material for the alternative scenarios vs. the baseline. Four figures per scenario are shown since the rates of implementation are slightly different for each activity (i.e., construction, maintenance, rehabilitation, and reconstruction). The baseline scenario is represented by dotted lines. In this scenario, the implementation of HMA dominates over WMA and RAP for all activities. This is because of the high importance of the Visibility factor, if additional measures are not taken to promote sustainable practices, new users are unlikely to be interested in them. Scenario 2 shows a similar situation where HMA maintains its dominance over time. Specifically, WMA and RAP do not even reach 30% of the interventions at the end of the period. On the other hand, Scenario 3 shows an equitable implementation rate among the 3 materials and a constant practitioner over time, this demonstrates the importance of promoting practices for their successful implementation, regardless of their price or environmental impact. Scenario 4 presents implementation rates like the ones of Scenario 3. This reaffirms the importance of the Visibility factor.

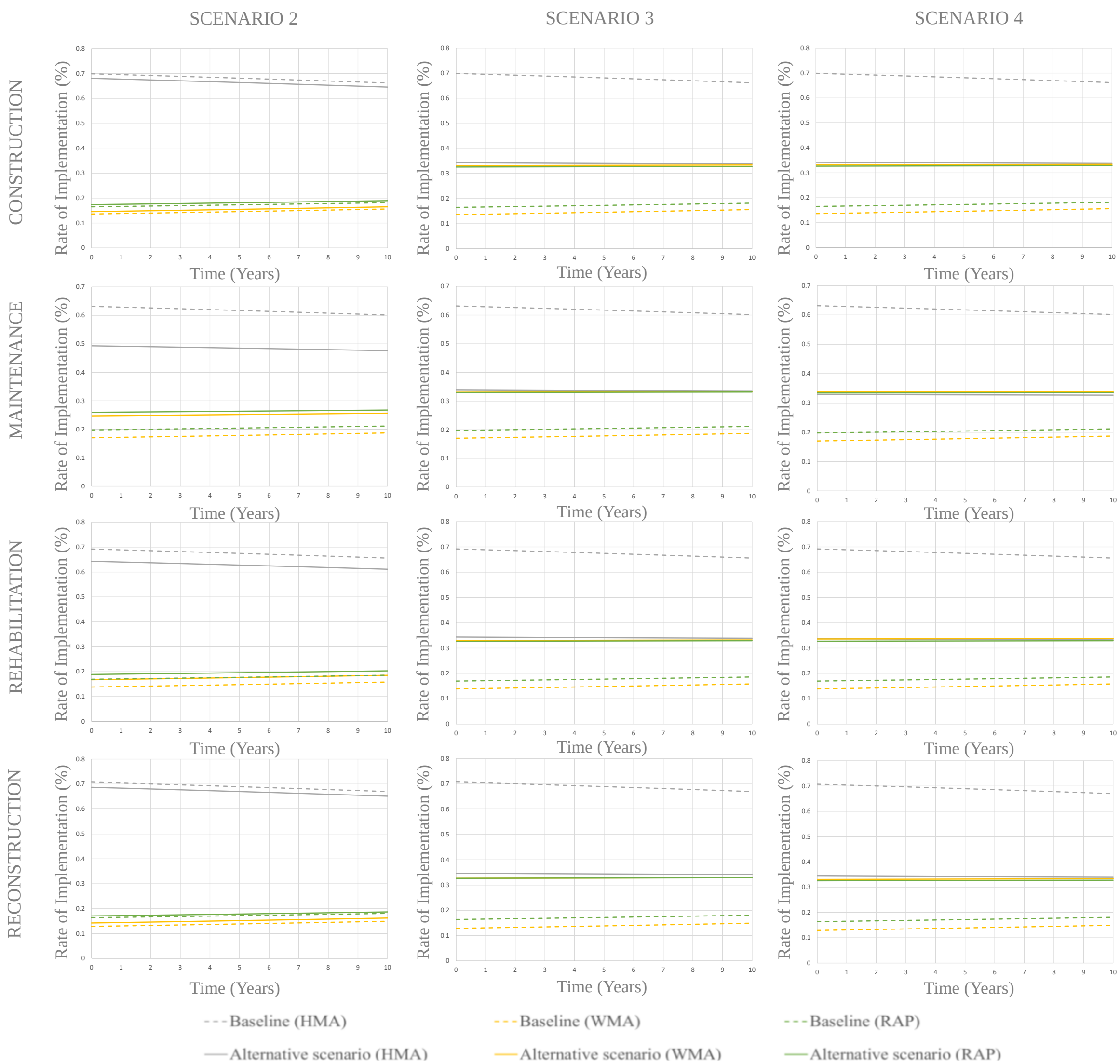

Figure 2. Rates of implementation for each material.

4 CONCLUSIONS

This work aims to analyze the adoption of sustainable innovations in the road infrastructure sector. This study shows the great impact of the visibility variable in the implementation of materials. Scenarios results show how factors that influence decision-makers in the formulation of policies (like costs of implementation and environmental impact) do not determine which materials are implemented. The more visible the material is, the greater number of users will want to use it, however for this to happen an initial impulse is necessary through other measures.

That is why most projects in the country employ traditional materials. According to experts, in Colombia, most stakeholders are unaware of the sustainable alternatives in road materials. The few that have been implemented are the result of a mandatory use imposed by regulations.

Based on the results, it is also possible that the inclusion of sustainable measures does not increase significantly the costs associated with construction and M&R processes. This reflects a misperception about sustainable practices; practitioners believe that including sustainable materials requires higher expenditures. Results show that costs are not increased by more than 8% when including sustainable materials, and the CO2 emissions are reduced. It is true that the implementation of sustainable measures will require investments in technologies, however, if long-term analyzes are carried out it is possible to see that these measures are not necessarily more expensive. This means that sustainable materials could be included if the short-term mentality is changed among stakeholders.

Efforts in the country should be aimed at socializing the benefits of sustainable practices. Financial concerns are not the only barrier to implementing these innovations. In the Colombian context, only sustainable practices that have regulations are common. This reflects ignorance on the part of the industry and the fear associated with the uncertainty of new practices. Therefore, it is necessary that the government, through tools such as incentives, public policies, guidelines, education, contribute to changing the mentality of decision-makers and users. In this way, the existing misperceptions around sustainable practices will be fought and will give that initial impetus to the implementation of sustainable materials. Once tools are used to promote sustainable materials, the social effects associated with adoption from word of mouth will be responsible for increasing the implementation rates of sustainable materials.

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