White-box flight simulator built with system dynamics to support urban transportation decision-making and address induced travel demand

Simulador caja blanca construido con Dinámica de Sistemas para apoyar la toma decisiones de transporte urbano y lidiar con la Demanda Inducida de Transporte

J. S. Angarita-Zapata ; H. H. Andrade-Sosa , A. D. Masegosa

***Abstract*— Induced Travel Demand is a phenomenon (ITD) wherein building new road infrastructure increases private car use. ITD has been measured and corroborated through econometric models that give an account of how much travel demand can be induced after road construction. The latter without claims of causality in their inner structure (black-box approach). Beyond the contributions of black-box models, it is still needed to explain structurally ITD for understanding and identifying its causes. Thus, this approach allows policy-makers to design comprehensive policies to deal with ITD in urban context wherein new roads are still needed to guarantee connectivity. In this paper, we present a white-box flight simulator based on a System Dynamics model to support urban transportation decision-making and address ITD. Through the simulator developed, it is possible to improve the causal understanding of ITD. Besides, although the considered policies to intervene in this phenomenon have a conceptual connotation, the simulator is a means to acquire knowledge of structural complexity underlying the interaction between the policies and ITD.**

***Index Terms*— Decision making, Flight simulator, Induced travel demand, System dynamics, Traffic congestion.**

***Resumen* — La demanda inducida de transporte (DIT) es un fenómeno en el que la construcción de nuevas vías aumenta el uso de automóviles privados. La DTI se ha medido y corroborado mediante modelos econométricos que dan cuenta de cuánta demanda de viajes puede inducirse después de la construcción de nuevas vías. Sin embargo, este enfoque econométrico no tiene pretensiones de causalidad en su estructura interna (enfoque de caja negra). Más allá de las contribuciones de los modelos de caja negra, sigue siendo necesario explicar estructuralmente los DIT para comprender e identificar sus causas; así pues, este enfoque permite a los responsables políticos diseñar políticas integrales para abordar los DIT en un contexto urbano en el que todavía se necesitan nuevas vías para garantizar la conectividad. En este artículo, presentamos un simulador de caja blanca basado en un modelo de Dinámica de Sistemas para abordar los DIT y apoyar la toma de decisiones sobre el transporte urbano. A través del simulador desarrollado, es posible mejorar la comprensión causal de la DIT. Además, aunque las políticas consideradas para intervenir en este fenómeno tienen una connotación conceptual, el simulador es un medio para adquirir conocimientos sobre la complejidad estructural que subyace a la interacción entre las políticas y la DIT.**

***Palabras Clave*— Congestión vial, Demanda inducida de transporte, Dinámica de Sistemas, Simulador, Toma de decisiones.**

I. Introduction

Nowadays, in many cities around the world, road construction is no longer a predominant transportation policy to deal with traffic congestion because evidence has been found of how new road infrastructure increments private car use [1]. This phenomenon is known as Induced Travel Demand (ITD), wherein building new roads increases private car travel demand, which leads to the re-emerge of congestion [2]. Such a phenomenon calls into question the effectiveness of road construction as a single and sufficient policy to improve urban mobility.

In the transportation literature, the ITD has been measured and corroborated using econometric models that give an account of how much congestion can be induced after road construction [3], [4]. These models are built based on elasticities measures, in which new roads expressed as linear kilometers forecast the increments in the number of kilometers traveled by cars. However, despite the available evidence about ITD in North America, Europe, and Asia, we have found few works that discuss this phenomenon in Latin American (LA) cities wherein road construction is still emphasized by policy-makers when dealing with traffic congestion [5].

In the context mentioned above, quantifying the effect of ITD at the LA level could be a pertinent research endeavor to

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achieve sustainable mobility in emerging economies. However, before using econometric models that quantify ITD, it is necessary to explain structurally this phenomenon to understand and identify its causes. The latter approach will allow policy-makers to design comprehensive policies that go beyond road construction to address effectively ITD, within contexts wherein road infrastructure is still needed to guarantee connectivity.

To accomplish the purpose as mentioned above, ITD must be approached from a systemic perspective to suggest sizing up this phenomenon, placing it in a broad enough context, and thinking about it as a system in the same way that every social concern must be approached [5], [6]. This implies recognizing and defining elements that interact between road construction and motorized travel demand, as elements linked and influence each other in a whole system and whose interactions determine ITD behavior.

System Dynamics (SD) models can propose representations about the structural complexity of ITD from which it is possible to formulate statements of how this phenomenon is generated. SD models are built on understanding why certain phenomena occur using a feedback structure that explains the occurrence of ITD over time. The latest means that the feedback structure produces behavior similar to ITD behavior corroborated and estimated by econometric methods. Therefore, the feedback mechanism can be conceived as a dynamic hypothesis of ITD based on a fundamental premise of the systems dynamics paradigm: to similar causal structures correspond similar behaviors [7]

In this paper, our objective is to continue deepening the research line proposed in [5] wherein a SD model, as a dynamic and structural hypothesis of ITD's behavior, was proposed. Specifically, we design and introduce a flight simulator that supports decision-makers in two different aspects. On the one hand, understanding the causes that determine the behavior of ITD, based on the SD model proposed by [5]; and on the other hand, designing and implementing transportation policies to deal with ITD's effects in the medium- and long-term. In the latter case, these policies were added to the mentioned SD, generating a new version of it.

The proposed flight simulator is a white-box simulation environment (Angarita-Zapata, Vásquez Cardozo, & Andrade-Sosa, 2019) that works based on a SD model and allows experimenting with the dynamic and complex relationship between road construction, ITD, and traffic congestion. This approach complements black-box econometric simulators, whose objective is to reproduce ITD's behavior and forecast it over short-term horizons. In this sense, traditional black-box simulators do not focus on explaining why ITD occurs and, consequently, makes hard formal learning that is a valuable asset for policy-makers when designing mobility urban policies [8].

In the context above, the main contributions of this paper are:

- A white-box flight simulator that accounts and structurally explains the causal factors that determine ITD to make decisions based on the understanding of its dynamic and systematic complexity.
- A new SD model in which the feedback structured proposed by [5] is integrated into a set of structural mobility policies able to deal with the counterintuitive behavior of ITD.
- A simulation tool for decision-makers to have a dynamic and systemic vision when selecting alternatives to address ITD and traffic congestion, which in turn allows detecting potential effects of their possible decisions in the process of seeking sustainable urban mobility.

The rest of this paper is structured as follows. Section II presents the state-of-the-art of econometric and SD research papers that have approached the quantification and causal explanation of ITD. Section III shows the methodology used to design and develop the flight simulator with SD. Then, Section IV presents the simulation tool and its application on a particular LA urban context. Finally, Section V presents conclusions and discusses future research endeavors.

II. Related Work

The phenomenon of ITD was recognized even before the automobile age [9]; nevertheless, serious attention began only in the 1980s, especially in the UK [10]. During that time, scholars in the USA carried out statistical works to discuss and corroborate this phenomenon. Since the 1990s, several studies using econometric models have produced substantial evidence about the existence of ITD [1], [3], [4]. These confirmations contradict the long-term benefits of road construction on mobility. As a result, road construction within consolidated economies is no longer an exclusive policy to deal with traffic congestion.

Several works have approached ITD with econometric models that use elasticities as a measure to estimate how much-motorized travel demand can be induced by new roads [3]. Those models are built with forecasting purposes to match sets of outputs between specified ranges of accuracy without claims of causality in their structure. Therefore, these techniques neither deepen the structural complexity of ITD nor report information (knowledge) useful for making decisions based on the underlying causes of ITD.

On the other hand, opposite to the econometric approach, white-box models can propose representations about the causal-structural complexity of ITD; however, a few research has been carried out under this paradigm. In the area of SD, [5] proposed a SD model based on a feedback mechanism to explain structurally ITD but without either discussing or proposing transportation policies to deal with this phenomenon. Similar to this research line, [11], [12] discussed what most car users, transport planners, and politicians assume as true in the old transport planning paradigm: reducing congestion by permanently road construction is an effective policy that improves mobility. Those authors state that every time road capacity is increased, traffic volumes will go up and settle around previous levels of congestion; however, they explicitly did not address the modeling and simulation of ITD effects, which were accounted by

Summarizing, all papers reviewed were made under an econometric approach. Although a few of the works have stated structural explanations to the counterintuitive behavior in which mobility tends to be saturated despite building new roads, we only found one paper with a white-box approach that models explicitly the causes that generate ITD. In this context, our paper complements the state-of-the-art by introducing a flight simulator based on the structural and dynamic explanation of ITD. It is a proposal that supports the reflection of decision-makers and guides the intervention in the medium and long term of the complicated relationship between ITD, road congestion, and road construction.

III. Methodology

In this section, first, we present SD methodology used to build the simulation model of ITD and the transportation policies to deal with it. Then, we introduce the software development methodology to develop the white-box flight simulator and to integrate it into the SD model. Finally, we summarize the study case considered to assess the flight simulator with real data.

A. System Dynamics methodology

SD is a methodology based on feedback theory equipped with mathematical simulation models by computer, which uses linear and non-linear differential equations and the concept of delay for modeling postponed effects, i.e., situations when the impact of a decision requires time for it to manifest. Jay Forrester at Massachusetts Institute of Technology developed this approach in the 1960s. Since then, it has been employed to address complex social issues in various fields such as urban dynamics [13], business and management [14], education and learning [15], [16], agroindustry [17], management of natural resources [18], among others. The purpose of SD in these areas has focused on explaining structure and modeling complex phenomena that are represented as systems for understanding their behavior over time rather than concentrating on accurate forecasting purposes.

Building an SD model involves an iterative process. In the progression from one step to the next, the modeler moves backward and forward through each methodological tool that SD offers to create a model as an abstraction of a real phenomenon [14]. For this paper, we assumed these methodological tools as a set of languages that each represent a particular view of the model [7]. This methodological assumption corresponds to the modeling methodology of "five languages" proposed by [7], which is shown in Fig. 1. The model was built with Evolución 4.5, a software platform developed by the SIMON research group at Universidad Industrial de Santander (Colombia) to build SD models.

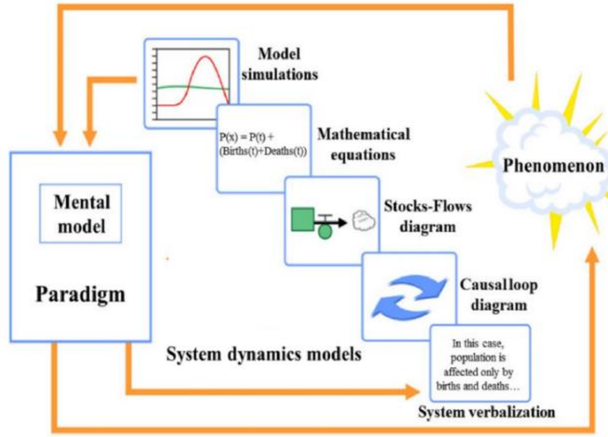

Fig. 1. Methodology of "five languages" used to build the SD model. Source: adapted from [7]. The main steps of the methodology are: (1) System verbalization (description of the system at hand), (2) Causal loop diagram (identifying main variables of the system and their relationships, (3-4), Stocks-Flows diagram (translating the causal loop diagram into a simulation model of linear and non-linear differential equations), (5) Model simulations based on the model built between steps (3) and (4).

B. Software development methodology for the white-box flight simulator

For this research, we assumed a prototype methodology as a software development approach for the flight simulator presented. The latter decision is because there were no previously defined customer requirements, and the simulator is instead a technological research product. The prototyping methodology is defined as a software development guideline model in which a prototype is built, test, and then reformulated until an acceptable prototype is obtained [19].

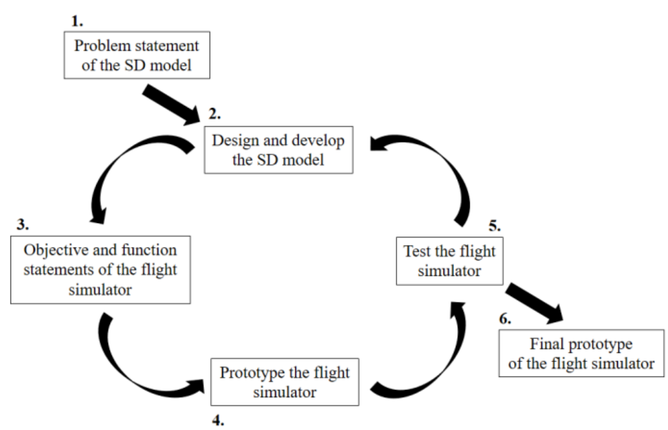

Fig. 2. Methodological guidelines composed of 6 steps to design, develop, and integrate the SD model and the flight simulator.

Having introduced both the SD and software development methodologies, Fig. 2 presents the methodological guidelines designed and followed to integrate the SD model of ITD, which includes two transportation policies described in Section IV, and the flight simulator. Specifically, Fig. 2 shows how steps 1 and 2 are focused on using the methodology of "five languages" to build the SD model. These steps include using the model of ITD proposed by [5] as a starting point; and then developing a new version of it in which two transportation policies are included to deal with ITD and traffic congestion.

Having an initial version of the SD model, steps 3 and 4 are centered in designing and developing the flight simulator, based on the software mentioned above prototype methodology, which works using the SD model. In this case, the primary purpose of the simulator is to enable policy-makers to interact with the model at a level of abstraction in which is not needed to modify it directly for proposing simulation scenarios and deploying simulations. This interaction between the user and the SD model through the flight simulator does not mean that the user is not aware of how the feedback loops of the model condition the simulations results. The latter is because the flight simulator also allows the user to explore and understand the SD model as explanation that puts in a context where the simulation results come.

Finally, step 5 is focused on testing the prototype of the flight simulator using the guidelines proposed by [14] to assess and validate SD environments. In this step, the results of the testing process could lead to either reformulate the SD model or simulator until an acceptable prototype is achieved in step 6.

C. *Study Case*

To assess the flight simulator with real data, we have chosen the study case of the Metropolitan Area of Bucaramanga (MAB) in Santander, Colombia. MAB is a metropolitan zone located in the department of Santander, Colombia, with an estimated population of around 1.160.272 people. It comprises four cities: Bucaramanga (the capital city of Santander), Floridablanca, San Juan de Girón, and Piedecuesta. They are linked geographically and commercially, and transportation is a key element that influences how people do their daily activities through the MAB. The fleet of the MAB consists mostly of private vehicles (cars, vans, and campers).

Additionally, there is a motorization rate of 285 vehicles per 1,000 people [20]. Meanwhile, road supply has built approximately 1,300 kilometers of road, and several road construction projects are underway that require significant budgets to increase the number of kilometers available [20]. However, according to the evidence reviewed of induced travel demand in cities abroad, we suggest that this one-side policy will generate, at best, modest results in MAB.

IV. Results

We integrated the SD model to the flight simulator to conceive the white-box technological tool shown in Fig. 2 (the source code can be found in the GitHub repository available in [21]). In this context, the white-box aspect is due to the simulator utility in (i) the processes of understanding ITD through the SD model, and (ii) the process of simulated experimentation through the simulator user interface that works upon the feedback-causal explanation of ITD, which is also provided by the SD model.

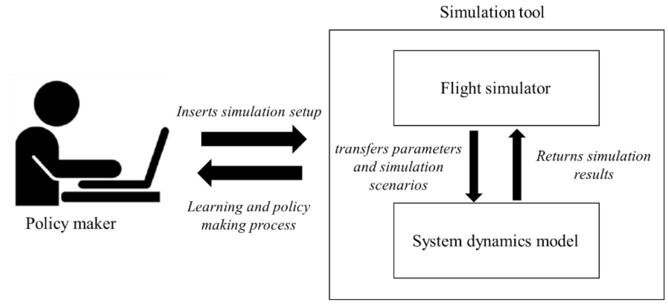

Fig. 3. White-box flight simulator architecture whose main engine to perform simulations is the System Dynamics model.

As can be seen in Fig. 3, the architecture of the flight tool is composed of two main components, which are presented below in sub-sections A and B. Besides, sub-section C presents the policy analysis and simulations of the flight simulator, whose current version is only available in Spanish.

A. *With-box Flight Simulator*

The policy-maker, as the main user of the simulator, can study and understand the structural complexity of ITD and the transportation policies consulting the causal loop and the stock-flows diagrams of the SD model. This function is available for the user in the menu bar of the user interface shown in Fig. 4.

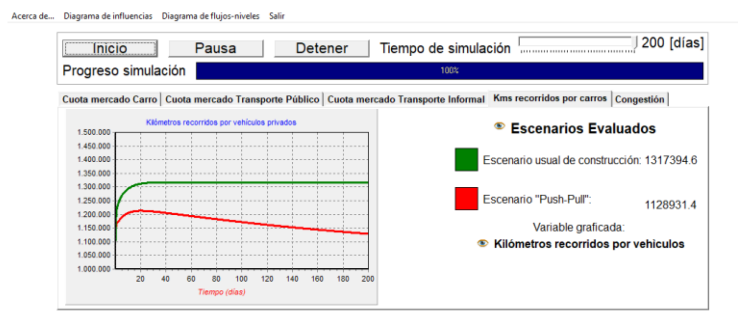

Fig. 4. Main user interface of the flight simulator composed of bar controls and simulation interfaces.

As shown in Fig. 4, the user inputs the simulation time between 5 and 200 days. This time option in the SD model represents the time horizon in which the variables of interest change in a simulation. For instance, if the user sets up a time horizon of 100 days, the simulation results show over this time horizon how enhancing public transportation can reduce the effect of ITD.

The user can also consult the simulation results for five different variables of interest: total linear kilometers traveled by cars, traffic congestion, market share of private vehicles, market share of public transportation, and market share of no-legalized transport. In the context of the SD model, the three market shares mentioned above represent the proportion of use of each means of transportation within the travel demand of the particular urban context under study.

Moreover, these five variables can be evaluated (employing the control bars shown in Fig. 5) in two policy scenarios focused on addressing the effects of ITD within urban contexts where road construction is still needed to guarantee connectivity. The two simulation scenarios are: 1) "Business as usual" scenario, which depicts how as roads built for connectivity become congested due to ITD, more road capacity is added to remain free flow conditions; and 2) "Push-Pull" scenario in which high-quality public transportation (PT) and congestion pricing (CP) are tested. In this second scenario, adding more road capacity is discarded, and the two policies mentioned above have the goal of addressing ITD to guarantee free-flow conditions on connectivity roads.

Fig. 5. Bar controls in the user interface to interact with the "No policies" scenario and the "Push-Pull" scenario.

In the "Push-Pull" scenario, we provide policy insights into the dynamic effects of PT and CP on ITD. In the case of PT, we are talking about bus rapid transit systems, with an exclusive road line for their circulation, which is a kind of transportation system widely implemented in Latin American countries. Therefore, in dealing with ITD, it is feasible to use the existing alternative means of transportation to address this phenomenon. Second, although CP has not been fully deployed at the Latin American level, policy-makers are discussing the prospects and implications of applying this policy, taking international cases as a point of reference.

Having presented the flight simulator's user interface that interacts with the policy-maker, the next sub-section introduces the SD model that allows us to understand and put in context the simulation results.

B. System Dynamics model: Core of the Flight simulator

According to the literature available about ITD, after building new roads to reduce congestion, two different effects of ITD arise. In the short term, private vehicles usually traveling on roads experience better flow conditions. Therefore, they tend to remain more time on roads, and more kilometers are traveled. This effect is known as direct induced travel demand [22]. On the other hand, car drivers who previously to road construction did not use their vehicles due to perceived flow congested-conditions, in the medium term, will decide to travel again by private vehicle. The latter means that more cars will be on roads than the number before building the new routes. This effect reinforces the increment of kilometers traveled and is known as indirect induced travel demand [22].

The expressions above of ITD were represented in a SD model proposed by [5], and it is described in the feedback structure shown in Fig. 6.

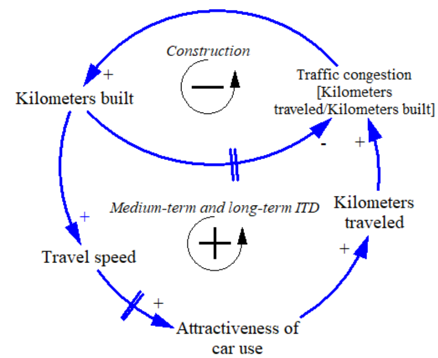

Fig. 6. Causal loop diagram of ITD composed of two main feedback loops that determine the behavior of ITD over time [5]

The feedback mechanism of Fig. 6 puts the relationship between kilometers traveled and kilometers built inside a structure of cyclical influences that translated to the stocks-flows diagram allows dynamically simulate the effects of ITD. Nevertheless, this causal loop representation does not consider structural transportation policies to deal with this phenomenon. Therefore, in this work, we moved a step forward based on the results achieved by [5]. Specifically, we designed and implemented a SD model that includes transportation two policies identified as suitable strategies in the state-of-the-art to deal with ITD. The causal loop diagram of our SD model can be seen in Fig. 7.

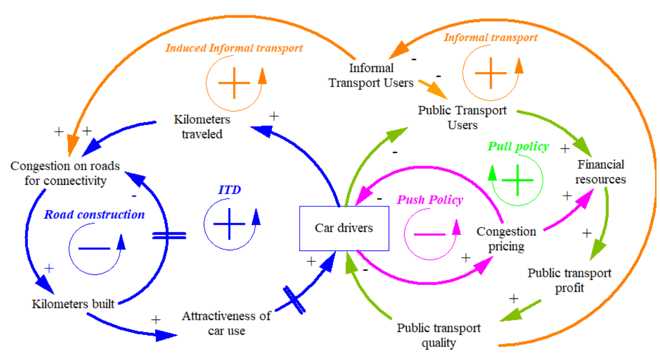

Fig. 7. Structural policies, public transport (green feedback loop), and congestion pricing (purple feedback loop) to address induced travel demand (blue feedback loops) in a context with informal transportation (orange feedback loop).

As stated before, we provide policy insights into the dynamic effects of PT and CP over ITD (purple, green, and blue causal loops, respectively, in Fig. 7). Besides, we included informal transport (people traveling by motorcycles) as a characteristic phenomenon of many Colombian cities that appears as a consequence of low-quality public transportation (orange feedback loop in Fig. 7).

The feedback loops of Fig. 7 are described below:

- "Road construction": this balancing loop represents the intuitive decision-making process of adding more road capacity to guarantee connectivity. However, hen free flow conditions disappear on these roads, more kilometers are built, and congestion is released temporarily. In this context, this policy is a partial solution with only significant results in the short-term horizon as congestion after a while again appears. Such a delay effect is represented in Fig.s 6 and 7 with two small and parallels links.

- “ITD”: this reinforcing loop depicts how new roads improve flow conditions. This loop induces more car use and leads to congestion on roads built for connectivity in a medium and long-term time horizon due to the delay effect in the link that connects the variables “Attractiveness of car use” and “Car drivers”.
- “Pull Policy”: this reinforcing loop depicts how public policy can improve public transport quality, ensuring efficient operation as well as high management performance of the transportation system. More public transport use generates more revenue coming from fares paid by users. More revenue poses more possibilities to reinvest and improve service quality. More public transport quality influences more users to travel in this transportation mode.
- “Push Policy”: this balancing loop shows how congestion pricing focused on discouraging car use can reduce the number of private vehicles traveling on roads. More car use implies more private vehicles subject to congestion pricing. More cars subject to pricing means more money that can be invested in public transport to improve its quality. More public transport quality increases public transport use, and finally, it decreases car use.
- “Informal transport” and “Induced informal transport”: these two reinforcing loops show how the existence per se of public transportation does not guarantee the success of the pull policy. If public transport has low quality due to a lack of investment, more users will travel using informal transportation, which means less public transportation use. Besides, more informal transport increments the level of congestion on roads built for connectivity.

The feedback structure in Fig. 7 gives a qualitative representation that is useful for describing the causes that generate ITD and the influences of PT and CP on this phenomenon. Besides, it is essential to highlight the role of delays within the feedback structure because without considering them, policies focused on short-term time horizons could lead to wrong conclusions that encourage unfavorable long-term effects.

Finally, as the main contribution of the flight simulator presented is to allow decision-makers to experiment with the feedback structure of Fig. 7 easily, the next sub-section presents a policy evaluation analysis.

C. Policy analysis scenarios using the white-box flight simulator

Having formulated the causal loop diagram, this section presents a policy evaluation analysis that required generating a stocks-flows diagram based on Fig. 7. This diagram provides the necessary tools to generate the simulations of the policy analysis that are observed in the flight simulator. Specifically, behaviors observed in this policy analysis emerge from the dynamic relationships between the feedback loops in Fig. 7.

Such as was observed in the user interface of the flight simulator, we defined two policy scenarios that can be seen in Table 1. In this table, there are two scenarios and four public policies. The green symbol represents the inclusion of a policy in a scenario, while the red mark means that a policy is not included in the scenario.

TABLE I
POLICY ANALYSIS ASSESSMENT CONSIDERING TWO MAIN SCENARIOS: A BUSINESS AS USUAL SCENARIO AND A PUSH-PULL SCENARIO

Scenarios	Road construction to address ITD	Public transport	High quality of public transport	Congestion pricing
Business as usual scenario	X	X	X	X
Push and Pull scenario	X	X	X	X

Each scenario in Table I is described below:

- Business as usual scenario: this scenario depicts how once the roads built for connectivity become congested due to induced travel demand effect, new and better roads is the only policy to address this phenomenon. Besides, although there is public transport, it does not have economic support from the push policy, which means that trying to become more attractive this means of transportation is not a policy in this scenario.
- Push and Pull scenario: in this scenario high-quality public transportation and CP policies are tested. In this context, added more road capacity is discarded, and now both the push and pull systems have the goal of addressing ITD to guarantee free-flow conditions on the road infrastructure built for connectivity.

Using the scenarios in Table 1, we performed simulations with the flight simulator reproducing a time horizon of 150 days using the data available from the urban study context (the MAB). It is pertinent to clarify that the purpose of the flight simulator is not focused on reaching any level of accuracy. On the contrary, its purpose is to explain and understand how the dynamic behaviors observed in the graphs emerge from the explanation of ITD, which is represented in the SD model. From this last comes the “white-box” characteristic of the flight simulator.

To analyze to what extent the described scenarios manage to mitigate ITD, it is pertinent to graph the kilometers traveled by cars in use. Increases or decreases in the total kilometers traveled imply variations in the number of people who use the private vehicle. Therefore, the variable market share of such means of transport is also plotted together with the market shares of public transportation and informal transportation. In this way, it is also possible to analyze the migration of passengers between the three means of transport under the two scenarios proposed in Table 1.

The market share of a means of transportation represents the percentage fraction of the total transportation demand that said means has with respect to the other means of transportation. In our SD model, the market shares of private vehicles (MS_{car}), public transport (MS_{PT}) and informal transport (MS_{IT}) are calculated using (1). This approach is based on the approach proposed by (Sterman, 2000, p. 392) wherein the total transportation demand (TD) is equal to the sum of each of the three MS observed in (2).

$$(1)\quad MS\ of\ transportation\ mean\ "i" = TD\ x\ \frac{Average\ attractiveness\ of\ transportation\ mean\ "i"}{\sum_{j=1}^{3} Average\ attractiveness\ of\ transportation\ mean\ "j"}$$

$$(2)\ TD = MS_{car} + MS_{PT} + MS_{IT}$$

In the current version of our flight simulator, the total TD has a constant value and does not change in the simulation time horizon. This is intended to reduce the complexity associated with variations in TD due to factors not considered within the SD model, such as immigration, tourism, employment, among others. Based on (1), the market shares for each of these means of transportation are defined in (3), (4), and (5).

$$(3)\quad MS_{car} = Attractiveness_{Car} * \left(\frac{MS_{CaR} + MS_{PT} + MS_{IT}}{Attractiveness_{Car} + Attractiveness_{PT} + Attractiveness_{IT}}\right)$$

$$(4)\quad MS_{PT} = Attractiveness_{PT} * \left(\frac{MS_{CaR} + MS_{PT} + MS_{IT}}{Attractiveness_{Car} + Attractiveness_{PT} + Attractiveness_{IT}}\right)$$

$$(5)\quad MS_{IT} = Attractiveness_{IT} * \left(\frac{MS_{CaR} + MS_{PT} + MS_{IT}}{Attractiveness_{Car} + Attractiveness_{PT} + Attractiveness_{IT}}\right)$$

Having introduced the considerations above for the policy scenarios, Fig. 8 shows the total kilometers traveled by cars. In the Business as usual scenario, blue trend line, it is observed that after the initial construction of roads for connectivity, the permanent construction policy to deal with ITD generates greater car use. Consequently, the kilometers traveled tend to increase until they reach a state of equilibrium that represents that most of the transportation demand is making use of the private vehicle as a means of transportation. This equilibrium point is because the total demand within the model is constant. In the case of Push and Pull scenario, the CP policy increases the cost of using the private vehicle. As a result, the use of this means of transportation is discouraged, and this is reflected in the reduction of kilometers traveled by cars, such as is shown by the red line of Fig. 8.

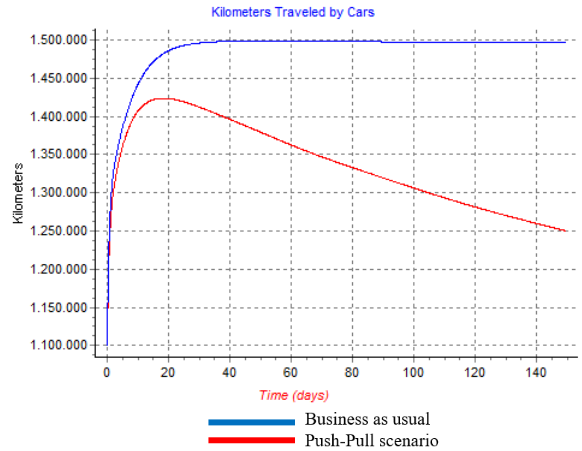

Fig. 8. Behaviour of Kilometers traveled for Business as usual scenarios and Push-Pull scenario over a time horizon of 140 days.

Fewer kilometers traveled by cars means less use of the private vehicle. This is evidenced in the decrease of the market share of this means of transportation, as can be seen in Fig. 9. In the Push-Pull scenario, once CP discourages the use of car, the high quality of PT attracts all those car drivers who have decided to change their means of transportation. The opposite occurs with the Business as usual scenario where the constant construction to mitigate ITD continues to strengthen the private vehicle as a predominant means of transportation.

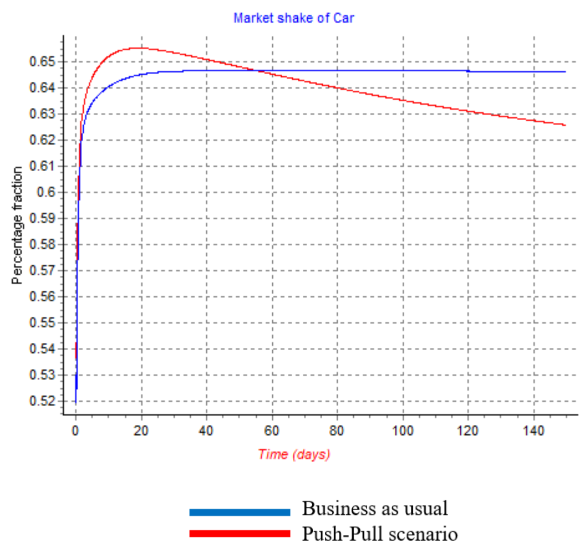

Fig. 9. Behavior of Market share of car over a time period of 140 days and evaluated under two simulation scenarios: Business as usual and Push-Pull scenario.

Applying the CP policy generates economic resources that can be reinvested to improve the service quality of the TP. Assuming that this decision is made, these resources allow more reinvestments in this means of transportation to attract both car drivers and people who use of informal transportation. Higher quality of TP increases its attractiveness and, consequently, more people use it. The latter is reflected in the increase in its market share, as seen in the Push-Pull scenario blue trend line of Fig. 10.

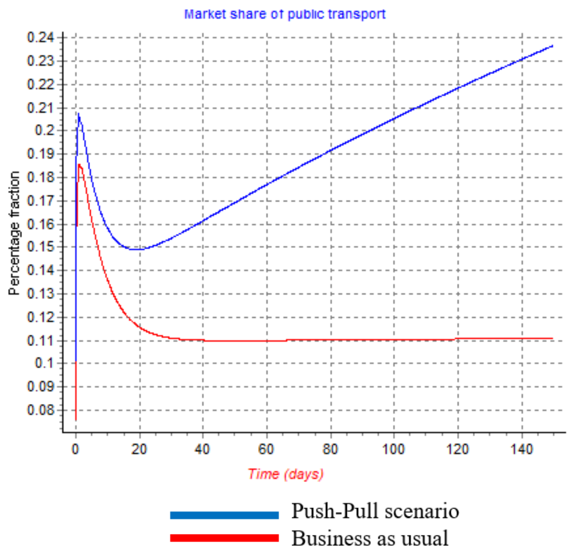

Fig. 10. Behavior of Market share of public transportation over a time period of 140 days and evaluated under two simulation scenarios: Business as usual and Push-Pull scenario.

However, in the Business as usual scenario where the quality of the TP is not improved, Informal transportation gains strength and increases its demand, as shown in the Business as usual scenario of Fig. 11. Therefore, when the quality of the TP is improved, not only private vehicle drivers are attracted, but it is also possible to mitigate informal transportation, which in the Business as usual scenario increases its market share causing more people to stop using public transport.

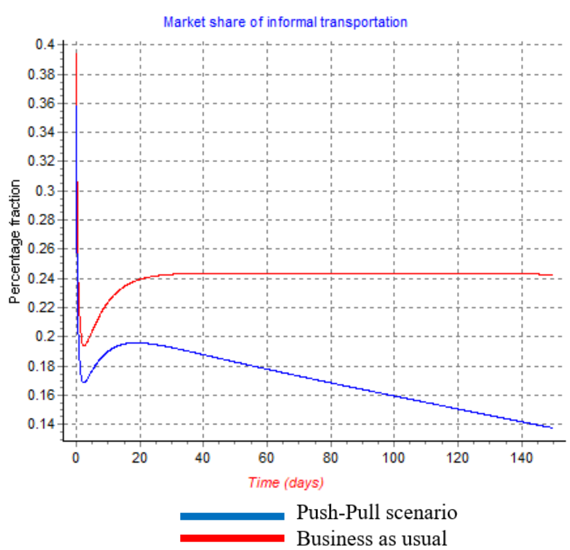

Fig. 11. Behavior of Market share of informal transportation over a time period of 140 days and evaluated under two simulation scenarios: Business as usual and Push-Pull scenario.

According to the simulation results observed in the previous Fig.11, it is clear that the Push-Pull scenario brings better results in dealing with ITD. Mitigating this phenomenon also implies avoiding the congestion of the roads built to ensure connectivity.

V. Dicussion And Conclusions

The fundamental component of social systems is feedback [23]. Every social system is inherently dynamic and complex. If feedback and delays are not assumed to study the system, its behavior in the short, medium, and long term cannot be explained.

For the reason exposed above, using SD is a relevant approach to address the study of ITD. This enables us to make decisions based on understanding the dynamic-systemic complexity of the phenomenon. However, to accomplish this purpose, it is needed a “test laboratory” where simulated experimentation can be performed, and from which can be discussed how different policies made to intervene in the system generate a set of possible futures [23].

Such "test laboratory" contributes to the exploration of policies in groups of people that make decisions for transportation planning. However, the field of expertise of these decision-makers does not necessarily include knowledge of SD. Therefore, a technological tool that operates the proposed SD model is required because it provides a level of abstraction that frees the user from interacting directly with the mathematical complexity of the model.

In the context described above, we integrated the SD model to the flight simulator to conceive a white-box technological tool that facilitates simulated experimentation. In this "virtual testing laboratory", the independent variables are PT, CP, and the reinvestment of money between them. These policies can be evaluated in different scenarios due to the user interface of the simulator that allows decision-makers to adjust parameter values associated with those policies, without directly inspecting the SD model.

Through the white-box flight simulator developed, it is possible to improve the causal understanding of ITD. Although the considered policies to intervene in this phenomenon have a conceptual connotation, the simulator is a means to acquire knowledge of the structural complexity underlying the interaction between the policies and ITD. This interaction is dynamic and is represented using a complex set of equations and the feedback structure, which allows a qualitative understanding using the cycles, delays, and nonlinearities of the SD model. Such systemic knowledge leads to identifying critical elements that must be prioritized in the implementation of policies currently discussed in Colombia regarding intelligent transport solutions.

Further research lines that we aim to explore in the future represent the discussed transportation policies in a more realistic way. The latter implies to include the policies in the SD using more operational details of them to know how they actually would work in the context of Latin American countries. Then, it would be possible to formulate a more robust simulation tool that supports a change from the old transport planning paradigm to the new one. The latter approach has been successfully implemented in countries wherein road construction is no longer a predominant transportation policy.

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