J. Appl. Environ. Biol. Sci., 7(12)164-174, 2017
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ISSN: 2090-4274
Journal of Applied Environmental and Biological Sciences
www.textroad.com

A System Dynamics Approach in Air Pollution Mitigation of Metropolitan Areas with Sustainable Development Perspective: A Case Study of Mexico City

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Received: July 17, 2017
Accepted: October 12, 2017

ABSTRACT

Searching and identifying capable policies for mitigating air pollution in metropolitan areas has always been a serious concern due to its complexity for policy makers. Governments can play a crucial role in establishing effective policies in order to reduce the air pollution. This study investigates the fundamental variables contributing in air pollution and also evaluates applicable policies to mitigate air pollution in Mexico City using system dynamics simulation modelling. In this paper, the three important considered policies are 1) tax on industries and people that pollute the air, 2) utilizing renewable energy as a necessity, and 3) the development of public transportation system. All variables and policies are selected with a sustainable development perspective. As the result of simulation shows in this study, the development of public transportation system is the most applicable policy in mitigating air pollution in Mexico City. Finally, a substantial decrease in the air pollution amount due to applying the selected policy has been detected.
KEYWORDS: System Dynamics, Simulation Modelling, Air Pollution, Sustainable Development, Feedback loops, Environmental issue.

1. INTRODUCTION

Air pollution is a global issue and countries are struggling with this problem regardless of their location or level of economic development, from Europe to Africa. This issue is not just a matter of polluting the air, but also of side effects that could be more detrimental. In terms of areas of interest in air pollution problem, it can be investigated through its health, environmental, chemical and economic aspects [1,2,3,4]. Recently, many developed countries which are experiencing this crisis have implemented multiple solutions in order to mitigate air pollution; yet, just few of them were able to succeed in their strategies. Most European and American countries are active in investigating new procedures to mitigate the air pollution and even improving the aerial condition at some point. One of the successful solutions implemented in European countries is the framework for the deployment of Intelligent Transport Systems (ITS) which aims to reduce traffic of cities and also to mitigate the air pollution [5]. However, the application of ITS takes steps beyond regulating motor vehicle traffic, such as promulgating more public awareness and improving sustainable development. Hence, this can prompt the policy makers to plan for controlling and eliminating the main source of air pollution [6].

Based on research done with correspondent to air pollution in metropolitan areas and also based on the environmental experts' opinions on related studies, the major factors contributing in air pollution problem are industrial pollutants, deforestation, overpopulation, CO2 emission, thermal inversion, fuel consumption, traffic congestion, and quality of cars. Furthermore, researchers tend to agree that these factors require the most immediate consideration [6,7,8,9]. There might be other indirect factors contributing in air pollution; however, they might be different depending on the cities. An important point that should also be considered is that the factors are selected with a sustainable development perspective due to the fact that the air pollution problem is an environmental issue [10].

In this paper, Mexico City is chosen as the case study because it almost has all the major factors to be recognized as a polluted city such as industrial pollutants, fume and carbon monoxide emitted by cars. This city is the 11th most populated city in the world [11] and one of the most populated city in North America in 2016 by over 20 million population [12]. Another variable that plays an important role in air pollution in Mexico City could be thermal inversion which happens when a dense layer of cold air close to the earth is trapped by a layer of warm air above during the winter. Industrial pollutants affects the air quality in Mexico City by emitting the most hazardous pollutants to the air. In addition, the deforestation phenomenon also could be another contributing factor in polluting the city since Mexico City loses over 200,000 trees of forest cover each year due to the deforestation. Another effective variable in air pollution of Mexico City is traffic congestion which is very common in that city as the number of cars are much greater than the capacity of the roads [13]. Increase in fuel consumption can be another significant factor contributing in air pollution because the outdated cars are less fuel efficient and tend to emit more pollutants [14]. Quality of cars is also recognized as one of the crucial variables affecting the air pollution in Mexico City as most of the cars are outdated in that city and doesn't follow current technology in producing cars. Occasionally, when air pollution reaches an emergency state, Mexico City's local government enforces driving bans as a short-term policy that last several days [15]. The variables stated as part of the problem of air pollution in Mexico City are gathered by referring to environmental experts [8,9,11].

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There exist multiple studies regarding air pollution in Mexico City, most of which consider its chemical, economic, health, or ecological effects. However, the number studies that propose an effective policy or evaluate an ongoing policy in air pollution mitigation in Mexico City is limited. Among them, Davis (2008) [14] focused on a scenario in which Mexico City's local government banned drivers from driving for one day per week, in an effort to reduce air pollution. Having examined the effectiveness of ongoing policy by comparing the data before and after applying the policy, it is determined that there is no substantial evidence suggesting that the car ban reduced the level of air pollution in Mexico City. However, the author was unable to benefit from a tool to investigate if the policy could be effective in a longer time. In addition, the evaluation of the policy would be more valid if it could be compared with other potential policies. Also, by merely investigating the chemical concentrations in vehicles and meteorological changes to specify the most pollutant factors it cannot be surely stated that only chemical factors could contribute in the air pollution problem in Mexico City [16, 17, 18]. There should be a methodology that not only could contain a comprehensive number of variables and factors contributing to the air pollution in Mexico City, but also to evaluate the different policies together in the system that can give a sense of why one policy could be more effective. Systems dynamics modelling, as one of the best approaches to model socio-economic problems, has broad advantages when used in a system with a variety of variables since it dispels the complexity of systems and makes it easier for users to learn from them [6]. System dynamics is among the most reliable methodologies in socio-economic systems [19]. It can be used in simulating the feedback loop of variables and their possible interactions and represent the behavior of policies in terms of variables in the systems. The behavior of such complex systems cannot be assessed only by data comparison. A simulation methodology can be helpful in predicting the behavior of the system. However, it needs to be mentioned that this paper is not associated with technical or chemical facets of air pollution in metropolitan areas.

1.1. LITERATURE REVIEW

One of the most challenging issues in metropolitan areas around the world is severe air pollution. The studies focusing in the field of air pollution utilize either operational research methods with consideration of the economic, chemical aspect of air pollution in metropolitans or simulation modelling [6]. However, in a few cases, system dynamics modelling is used to simulate the behavior of air pollution and incorporate a policy-making perspective. The body of existing literature focuses on reducing air pollution by operational research methods and by simulation approaches.

Among first category of studies, Vlachokostas et al. (2009) [20] developed an integrated evaluation system to measure air pollution in Thessaloniki, Greece using cost-effectiveness analysis with respect to economic productivity. Their sensitivity analysis showed that the government need to spend about 54.5 M€ to control and mitigate air pollution in Thessaloniki. They utilized operation research models in their study to present decision support system. However, they selected certain populated areas in their case study which could lead to biased judgment. Duque et al. (2016) [21] investigated the emission of chemical particles such as NO2 that could contribute in air pollution in Porto, Portugal. He used The Air Pollutant Model (TAPM) to measure effects of NO2 reduction in air pollution and proposed four scenarios in his study but his policies are merely applicable in local areas. Sivacoumar et al. (2001) [22] considered effect of NOx emission as a substantial source of pollution in Jamshedpur in eastern part of India for their case study, by their estimation, as one of the most polluted area in the world. In the study, they utilized Gaussian Dispersion Model and their results showed 53% contribution of NOx from industries as major source in air pollution with 68% accuracy in the model performance. By introducing speed limitation of 80 km/h and the variable of speed system as two policies that could potentially lead to air pollution reduction in the city of Barcelona, Bel and Rosell (2013) [23] investigated the effectiveness of the policies. They have utilized empirical research to support their claims and results indicated that the impact of speed limit variable is more stable in air pollution mitigation in their case study.

However, there are other studies regarding air pollution that utilize simulation methods in order to investigate the behavior of air pollution and the interrelations between the variables. One of the first works corresponding to air pollution simulation was done by Ch. Kessler et al. (2001) [24]. They had used nested models in their air pollution simulation in North Rhine-Westphalia (NRW), the most populous state in Germany. The accuracy of the model was investigated by statistical indexes. Their finding presented a consensus on measuring the ozone layer which can be utilized for future air pollution research on a regional scale. However, it is worth noting that an inconsistency between their proposed model and their discussion was observed. Having proposed three different policies in order for CO2 emission reduction in the cement industry in India, Anand et al. (2006) [25] developed a system dynamics approach to evaluate the best policy. The three incorporated policies were population growth stabilization, energy conservation and structural management in cement industry. The results showed 42% reduction in CO2 emission by implementing an integrated scenario which includes mentioned policies. By looking at the negative externalities of transportation on air pollution, Armah et al. (2010) [7] applied a system dynamics approach in Accra, the capital of Ghana, to demonstrate the cause and effect correlations between the variables using causal loop diagram. However, authors did not consider a stock and flow diagram nor a time horizon in their simulation. Fong et al. (2008) [26] developed a system dynamics model in order to predict CO2 emission trend in future in Malaysia. It was determined that the model proposed could be utilized as a policy making tool in future urban planning in Malaysia. The framework presented in their study can be considered as a preliminary step in mitigating CO2 emission in Malaysia. Vafa-Arani et al. (2014) [6] predicted the air pollution behavior in Tehran City for 40 seasons using system dynamics methodology via VENSIM software. They proposed four policies which could contribute in reducing air pollution in Tehran and based on their analysis technology improvement in fuel and automobile industries as a long-term policy lead to mitigation of air pollution in Tehran City. Goodarzi et al. (2016) [8] also took Tehran's air pollution into consideration within a system dynamics perspective. They considered both causal loop diagram and stock & flow diagram in their modeling in order to track the behavior of pm 2.5 as the element of air pollution in Tehran for ten years. However, they didn't provide any literature about non-system dynamics approaches in air pollution problem the way this study did; therefore, their contribution to the benefits of system dynamics approach over non-system dynamic approaches was limited. Also, they didn't provide parameters and formulas in their results; hence, reproducing the results is hard to achieve. This shortage is eliminated in this study. Since they didn't provide model validation in their study, the accuracy and reliability of the model was not clear. This shortcoming is eliminated in this study as well. One of the first studies regarding air pollution in Mexico City had been done by G.B. Raga and Le Moyne (1996) [27]. At that time Mexico City was recognized as the most polluted city in the world. By analyzing 13 areas in Mexico City, they proposed a pattern of transportation from north-west to south-east indicating that the degree of freedom in center and west of the city is lower. Their work was done with very rudimentary assumptions.

As the above studies show, the body of studies regarding air pollution tried to address the problem from economic or chemical perspectives. A few of them utilized a system dynamics approach in their works and among them just small numbers took sustainable development into account noticing the fact that air pollution is a rapidly growing environmental issue in metropolitan areas especially in Mexico City. By investigating previous works regarding the air pollution in Mexico City, there can be seen some research gaps that have been left intact, or not investigated thoroughly. Among them, there is a lack in determining a comprehensive set of factors and policies that could intervene in the air pollution problem. Also, there is a shortage of introducing policies that could potentially mitigate the air pollution. In addition to that, it is unclear whether the factors and variables contributing in the air pollution in Mexico City could possibly interrelate to each other. Hence, one of the novelties of this study is to utilize a system dynamics approach in the air pollution problem in Mexico City for the first time as one of the most polluted megacities with a sustainable development perspective. This study provides more reliable ground rules to reduce air pollution in Mexico City by investigating on more than one policy that could potentially be effective in mitigating the air pollution. However, this study does not go through the chemical and technical facets of air pollution associated with metropolitan areas. By applying System Dynamics modeling in this study, as one of the most reliable modelling method in complex problems, major variables affecting the air pollution in Mexico City are going to be identified. This can contribute in extracting the best policy of mitigating the air pollution with respect to sustainable development perspective and investigating its behavior on air pollution within 20 years which is set as our time horizon.

The rest of our work is organized as follows: Section 2 focuses on the methodology and the explanation of the interrelationships between variables that contributes to the air pollution problem using Causal Loop Diagram (CLD), Stock and Flow Diagram (SFD) and introducing the potential applicable policies. Important findings and results are discussed in section 3. Finally on section 4 a model validation and on section 5 the conclusion is presented.

2. MATERIALS AND METHODS

Since the most complex behaviors in each system derive from the interaction or feedbacks of the elements of that system rather than the complicacy of its parts itself, designing a feedback loop to represent the interaction between components will be necessary. A system dynamics approach can engage to simulate the feedback loops and the interaction between components; moreover, it is able to predict the behavior of interventions in the systems with respect to different variables in a long period of time [6]. In this study, several factors affecting the air pollution in Mexico City will be investigated using system dynamics tools through VENSIM software. In addition, policies that could potentially affect the mitigation of air pollution will be applied in order to observe its behavior in the model. In order to properly study which policy remains the most effective, the simulation model will investigate the trend in a 20-year horizon. The 20-year horizon is selected in this study due to the policies are recognized as long-term plans and also to make sure that there is enough time for implementing policies to mitigate air pollution. In investigating the variables affecting air pollution, experts' opinions and official data with respect to air pollution are used [8, 12,14].

2.1. System Dynamics Methodology

System dynamics mostly includes two-steps of modeling: first, it is a qualitative modeling known as causal loop diagram (CLD) to show how different variables in a system are interrelated; and second, it is the stock and flow modeling to provide a better understanding of the behavior of the system by visualizing a richer representation. It is also worthy to note that System Dynamics is often identified as a “strategy and policy laboratory” in Socio-economic systems, since it creates a method of evaluating the different impacts of chosen policies in a socio-economic system [28].

2.2. Causal Loop Diagram

The Causal Loop Diagram (CLD) is a crucial tool in providing the structure of a system. By using it, the model is able to indicate the relationships between the variables. The relationship between two variables that are shown by arrows can be either positive, which reinforces the loop, or negative, which balances the loop [29]. In order to show the interrelationships between the variables affecting the air pollution using system dynamics, the first step is to identify the variables. In order to do so, an interview has been conducted with an environmental expert, and also a study of previous works was conducted in relation to air pollution in metropolitan areas especially the ones in Mexico City. As shown by the results, the key variables in polluting the air in Mexico City are: thermal inversion, CO_2 emission, population, road congestion, industrial pollution, deforestation, and quality of cars. There might be other factors contributing in air pollution in Mexico City directly, but this study will focus on the most important ones. There are also other variables that can contribute in air pollution indirectly which is going to be presented in stock and flow section. After identifying the direct and indirect factors contributing in the air pollution, a comprehensive causal loop diagram (CLD) with positive and negative feedback interactions between variables is shown in Figure 1:

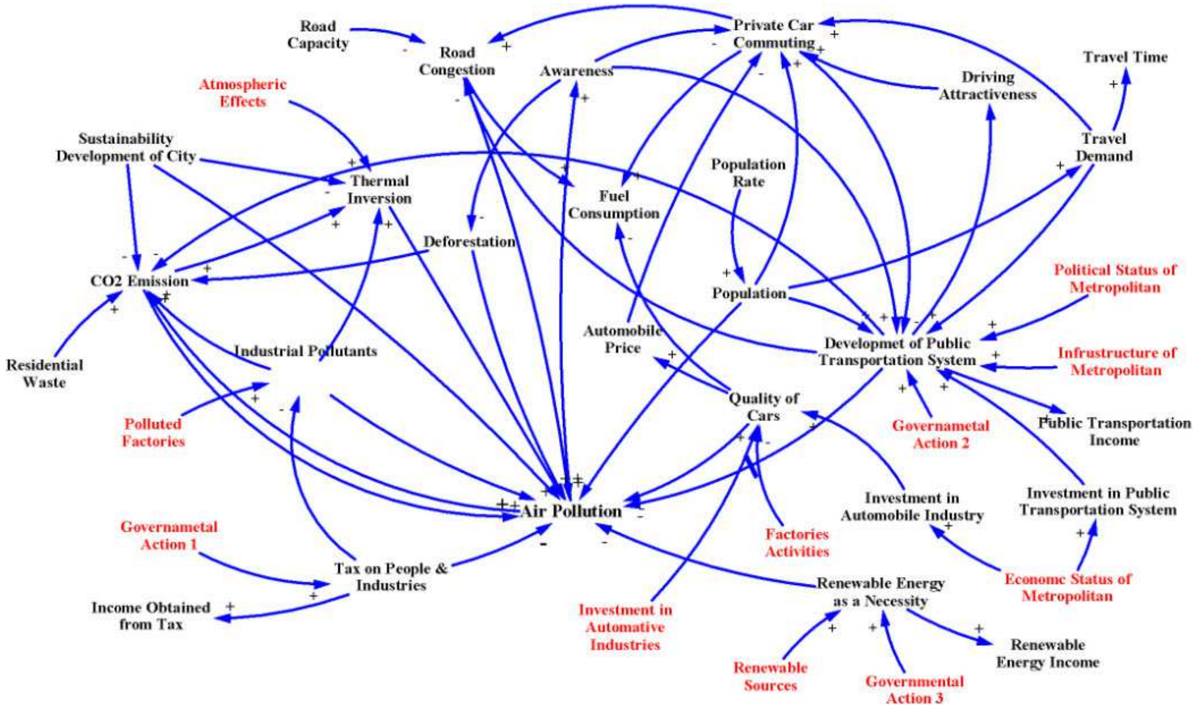

Fig. 1: Causal loop diagram of endogenous variables affecting air pollution

The red variables in Figure 1 are not considered in the final presented stock and flow diagram since they are not quantifiable. The above figure represents the interrelationship between different variables as well as their interaction with air pollution problem. The increase in some variables results in growth in others which is showed by positive polar; however, their increase may results in reduction in variables which is represented by negative polar. These interactions can be better assessed in causal loops. Loops divided into reinforcing loops and balancing loops in cause and effect diagram. Reinforcing loops results in growth or decline in the whole loop such as Air pollution-CO2 emission-Thermal inversion loop which increase in one variable results in growth in air pollution. Balancing loops attempt to move the current state into a desired goal such as Air pollution-Awareness-Private car commuting-Public transportation system loop that Air pollution is going to be decreased as the result of increase in public transportation. Based on what has been discussed regarding the features of system dynamics, it is apparent that utilizing system dynamics approach could be more advantageous when investigating the factors affecting the air pollution. Since air pollution is an environmental issue, the policies should be selected with correspondent to a sustainable development perspective to make sure that they are environmentally friendly and they remain effective for a long period of time. It is important to note that the political and economic status of countries or cities should be considered when selecting the policies as well, in order to see whether they have the right infrastructure to implement the policies [12]. In this paper, three policies have been selected that could potentially mitigate the air pollution in Mexico City: 1) tax on Industries and people that pollutes the air, 2) utilizing renewable energy as a necessity, and 3) the development of public transportation system. However, only one policy might play the most crucial role and have the most effective contribution on reducing the air pollution.

2.3. Stock and Flow Diagram

The causal loop diagram is an initial step of system dynamics that is used to represent feedback loops and the interrelationships between the variables. It is sufficient in representing the effect of policies in the air pollution problem; however, by utilizing the stock and flow diagram, the understanding of the model is enriched and simplified. As mentioned beforehand in introduction section, there are eight key factors contributes in air pollution problem in Mexico City which are industrial pollutants, deforestation, overpopulation, CO2 emission, thermal inversion, fuel consumption, traffic congestion, and quality of cars. As each of these factors increases, it results in increasing of air pollution accordingly. Also, as shown in Figure 1, some of these variables have interactions with respect to each other as well as affecting air pollution. For instance, as quality of cars, one of the main factors affecting air pollution, increases, fuel consumption decreases reversely. Or thermal inversion is affected by CO2 emission and industrial pollutants which are two main factors in air pollution problem in Mexico City and the increase in these two factors results in growth of thermal inversion accordingly. Other interactions between main variables are presented the same way in causal loop diagram.

Other than the key variables affecting the air pollution, there are other factors introduced in the model that indirectly affect the air pollution in Mexico City. Residential waste is one of the main sources of CO2 emission which recently Mexico City governors put their focus on. Sustainability of the city introduced in the model as a relative factor is associated with CO2 emission, thermal inversion and air pollution in the city. Its increase results in reduction of the main factors contributes in air pollution. Likewise, awareness is defined as a relative factor that can affect private car commuting negatively, and public transportation positively. As awareness about air pollution increases, public transportation usage increases and private car usage decreases. We have utilized automobile price as an auxiliary variable that as it increases, people will be less interested in using their own cars. Travel demand and travel time are also introduced as variables to show the number of people and the time they spend in commuting from home to other places. Road capacity indicates the capacity of streets, highways, and roads that can hold cars in the case of traffic congestion and as the capacity of roads increases, the traffic congestion will be reduced respectively. Population rate shows the growth rate in population. Automobile price is introduced as a variable that directly affect the rate of private car commuting and as the automobile price increases, the interest to use private car commuting decreases respectively. Capital spent on automobile industry in order to increase the quality of cars is shown as investment in automobile industry. Similarly, investment on public transportation system is considered for development of public transportation. The revenue obtained from public transportation is defined as public transportation income and as the public transportation usage increases, the income obtained from that increases as well.

If the data regarding increase rate and decrease rate is unknown, the net rate or the difference between increase and decrease rate can be utilized interchangeably. The stock and flow diagram as a part of the system dynamics modeling is shown in Figure 2. It is also worth mentioning that in order to create a system dynamics simulation, the data was gathered from previous official records and experts' opinions [9, 11, 12].

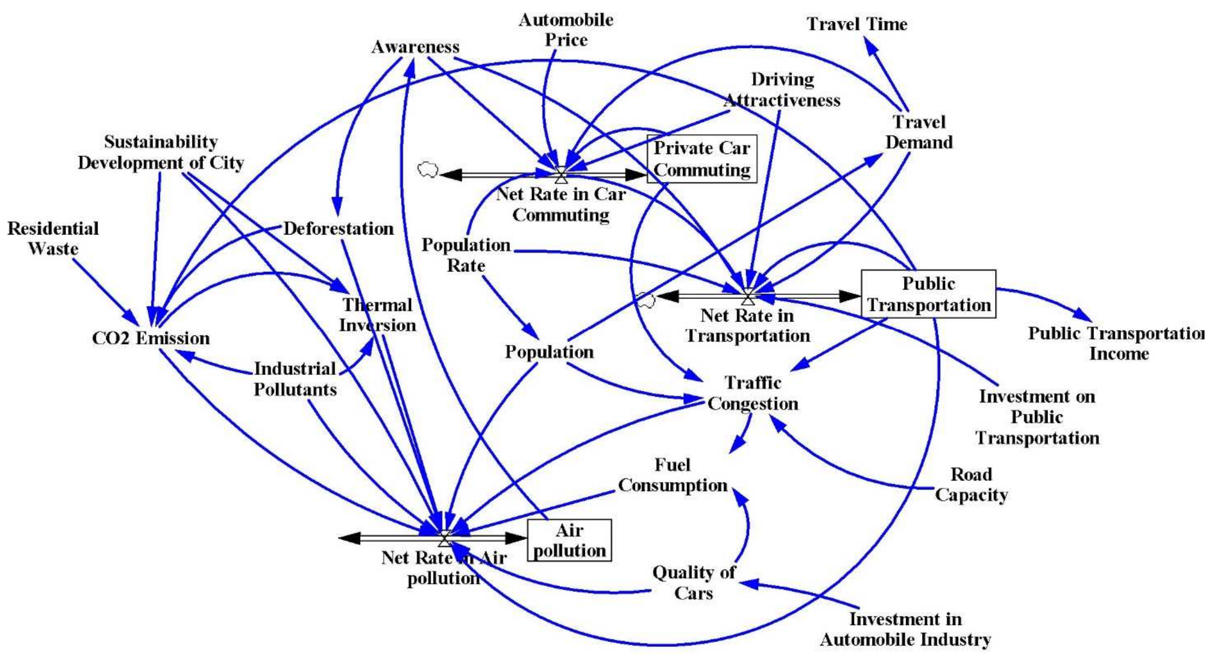

Fig. 2. Stock & Flow Diagram of air pollution showing dynamics between variables

To setup Stock and Flow Diagram, as shown in Figure 2, the state of the system which is represented by stocks and rate of changes in the system (flows) should be defined beforehand [8]. There are three stock variables and three flows accordingly associated with them identified in the presented modeling. The flows or net rates are specified as major equations in the modeling which are rate of public transportation, rate of private car commuting, and rate of air pollution. The equations of these rates are as follows:

Net Rate of Air Pollution (t) $= Net(0) + \int_0^t \big((Industrial\ Pollutants + CO2\ Emission + Thermal\ Inversion + Air\ Pollution) + (Population + Traffic\ Congestion + Deforestation + Fuel\ Consumption)\big)\, d(t) / \int_0^t (Public\ Transportation + Quality\ of\ Cars + Sustainability\ Development\ of\ City)\, d(t)$

Net Rate of Private Car Commuting(t) $= Net(0) + \int_0^t ((Private\ Car\ Commuting \times Population\ Rate \times Travel\ Demand \times Driving\ Attractiveness) d(t) / \int_0^t (Automobile\ Price + Awareness))\, d(t)$

Net Rate of Public Transportation (t) $= Net\ (0) + \int_0^t ((Public\ Transportation \times\ Population\ Rate \times Travel\ Demand \times\ Investment\ on\ Public\ Transportation)d(t) / \int_0^t (Net\ Rate\ in\ Car\ Commuting \times Driving\ Attractiveness \times\ Awareness))d(t)$

Net (0) is current amount of the variable which is set by historical data. The integral from the intervals between 0 to t shows the cumulative amount of each variable as a function of other variables between the years 2016 to 2030. For example, the prediction of Net Rate of Air Pollution is calculated through its current amount plus the integral of the interaction between variables affecting the Net Rate positively divided by the interaction of the variables negatively affected the Net Rate. The variables associated to each rate are both explained and represented earlier in stock and flow section. Moreover, the parameters used in stock & flow diagram are in three types of stock, rate and auxiliary variables. All the specification of parameters shown in Figure 2 are categorized in Table 1 with their units. Some variables that couldn't own any units are shown as relative factors. These relative factors mostly used when the data in terms of variables are not existed or they are qualitative variables that are not receptive to units. The values of these variables are determined with the help of experts' opinions. Also, as mentioned before, rates are determined as the major equations in the modeling. The real data in terms of each variable contributing in air pollution was gathered from annual report of Mexico City transportation from the year 2010 to 2016 and the previous official literatures in terms of air pollution [9, 11, 12].

Table 1. List of Parameters (Variables) Used in Stock and Flow Diagram

Variable Type	Variable Name	Variable Value	Unit
Stock	Air pollution	61.7	µg/m3
	Development of Public Transportation System	2.9	million passenger/year
	Private Car Commuting	5.5	million/year
Rate	Net Rate in Air pollution		1/year
	Net Rate in Transportation		1/year
	Net Rate in Car Commuting		1/year
Auxiliary	Population Rate	0.016	1/year
	Population	21	million people
	Deforestation	0.27	million/year
	Thermal Inversion	1.3	Celsius/m3
	Industrial Pollution	-0.05	million ton reduction/year
	CO2 Emission	30.7	million ton/year
	Traffic Congestion	1.9	trip/km
	Fuel Consumption	2.1	lit/year
	Investment in Automobile Industry	0.53	Million dollar/year
	Investment in Public Transportation	0.75	Million dollar/year
	Public Transportation Income		million dollar/year
	Road Capacity	9.25	kilometer
	Travel Demand	3.7	million passenger/year
	Travel Time		
	Driving Attractiveness	1	
	Awareness	1	
	Automobile Price	1	
	Residual Waste	17.5	Million ton/year
	Sustainability of the City	1	
	Quality of Cars	1	

2.4. Data Validation

In order to show the validity of the model, a comparison between historical data and the estimation of the model with respect to air pollution between the years 2010 to 2016 in Mexico City has been performed. The target of data validation is to investigate the behavior of the air pollution from the year 2010 to 2016 and compare it with the exact amount of air pollution in each year gathered from historical data. The baseline for comparison between real data and model estimation was set in 2010 and the amount of air pollution from historical data by 2010 was about 74µg/m3 in Mexico City. However, since both real data and estimation of the model start from the same point in 2010, the comparison was performed from the year 2011 so that it doesn't affect the accuracy of the model validation. Therefore, the blue line is the real data obtained from official sources and literatures in terms air pollution in Mexico City from the year 2010 to 2016 and the orange line is the model estimation of air pollution in Mexico City after inputting data for each variable, showed in stock & flow diagram, in the year 2010 as the baseline in Vensim software [9, 11, 12]. As the Figure 3 represents, the proposed model could approximately follow the behavior of the real data on air pollution. To ensure that the gaps between the estimated data and historical data in Figure 3 is not significant, a statistical validation test is run. Since real data contains outliers and do not follow normal distribution, a non-parametric test should be performed to investigate whether the gap between the graphs associated with real data and estimated data is significant. Wilcoxon Signed-Rank test is chosen as the most appropriate non-parametric test, since the data are not normally distributed and have relatively the same shape. This test is mainly used when it is required to run two sample t-test but the samples do not follow normality [33]. Therefore, the statistical hypothesis with respect to the non-parametric test is as follows:

$$\begin{cases} H0: Median\ of\ real\ and\ estimated\ data\ are\ equal \\ H1: Median\ of\ real\ and\ estimated\ data\ are\ not\ equal \end{cases}$$

The results of Wilcoxon Signed-Rank test shows that p-value is equal to 0.178 (greater than 0.05) proving the fact that the gap between the graphs associated with historical data and estimated data is not significant. Hence, system dynamics can be utilized as a reliable estimator of the behavior of the air pollution in the future in Mexico City.

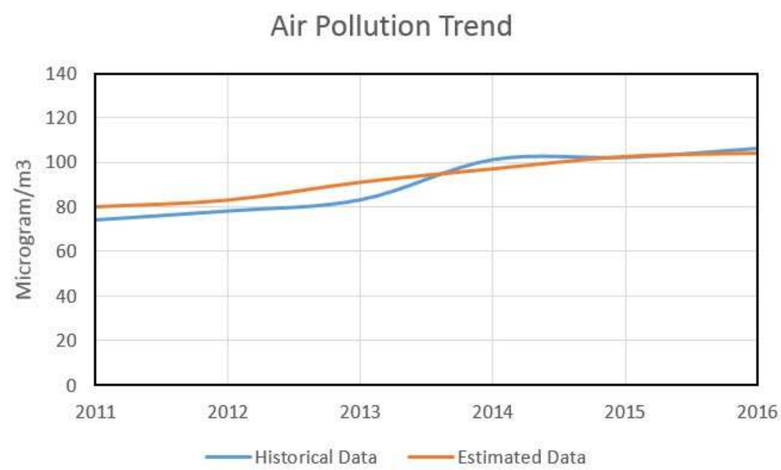

Fig. 3. The air pollution behavior by comparison between historical and estimated data

After ensuring about the validity of the presented model, policies can be added to the model as an intervention in order to investigate their effects on air pollution. It is common to consider some alterations on Stock and Flow diagram such as shrinking the model (as the red variables are removed), adding shadow variables, and removing insignificant policies to simplify the model or to prevent confusion. As mentioned before, three different policies which are 1) tax on industries and people that pollute the air, 2) utilizing renewable energy as a necessity, and 3) the development of public transportation system proposed to investigate their effectiveness in reducing air pollution in Mexico City. In order to determine which policy is going to remain the most effective one during the simulation, a sensitivity analysis of selected policies using historical data in terms of each policy was performed in VENSIM software. The sensitivity analysis showed that Tax on Industries and Renewable Energy as a Necessity are not going to affect the air pollution substantially in Mexico City the way the Development of Public Transportation does at least within 20 years which is set as the considered horizon. By using previous data with respect to Tax on Industries as one of the policies that could potentially mitigate the air pollution in Mexico City, a simulation is performed to present the behavior of the air pollution while this policy is implemented in the model [13]. In order to do so, Tax on Industries and People and its associated variables are added to the model and the Public Transportation and its interactions are neutralized in order to just investigate the policy of Tax on Industries and People on air pollution. By looking at Figure 1, only one variable which is income obtained from tax is associated with Renewable energy policy. This policy has some interactions with other variables in the stock and flow diagram. It affects air pollution, industrial pollutant and income obtained from tax as a variable and it is affected by governmental action. Governmental action is shown as a red variable; therefore, it is not considered in the stock and flow model. The interrelations between this policy and its associated variables is shown in Figure 4.

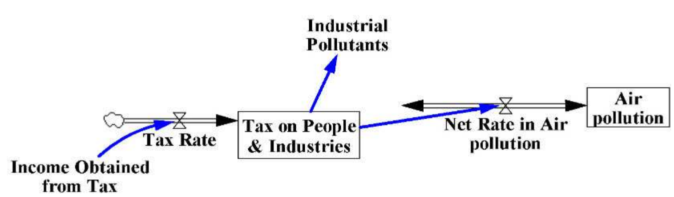

Fig. 4. Tax on people & industries interrelations system

As the Tax on Industries increases, the factories are less interested in producing excess industrial pollutants and as a result the industrial pollutant and the air pollution should be reduced accordingly. In order to run the simulation, the values for the new variables should be determined. Tax on industries initial amount is set as zero and the rate of tax in Mexico City was set as 35% per year and the income was set as relative factor between zero and one since the data regarding the amount of tax revenue from people and industries in terms of reducing air pollution was not available. Except for these variables, all other values of variables are set the same as shown in Table 1.

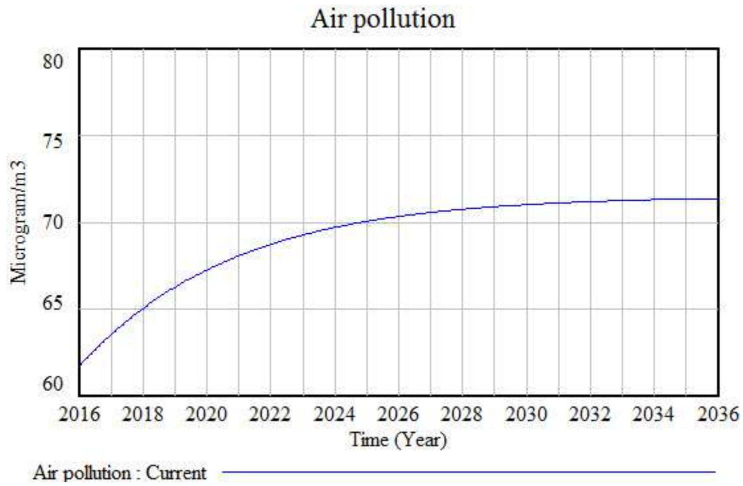

Fig. 5. Air pollution amount by applying tax on industries and people as a policy

As it is showed in Figure 5, by utilizing Tax on industries as a potential selected policy, the air pollution amount increased from 61.7µg/m^3 to 71 µg/m^3. Therefore, although the policy of Tax on Industries and People could reduce the growth rate of air pollution to make it more stable, it was unable to reduce the air pollution amount within the considered period. Similarly, Renewable Energy was examined in the model as a potential selected policy and the results of simulation showed that applying this policy does not lead to reduction of air pollution amount in Mexico City either.

By observing at Figure 1, renewable energy income, renewable energy sources and governmental action are associated with Renewable Energy policy. This policy also has an interaction with air pollution. Governmental action, renewable energy sources are shown as red variables in Figure 1; therefore, they are not considered in the stock and flow model. The interrelations between this policy and its associated variables is shown in Figure 6. Similarly, Public Transportation and its interactions are neutralized from the stock and flow diagram in order to obtain the result only in terms of Renewable Energy policy. Renewable energy initial amount is set as zero and the number of energy system was determined by the income obtained from renewable energy and the renewable energy income was set as relative factor between zero and one since the data regarding the portion of income was not available. Except for these variables, all other values of variables are set the same as shown in Table 1.

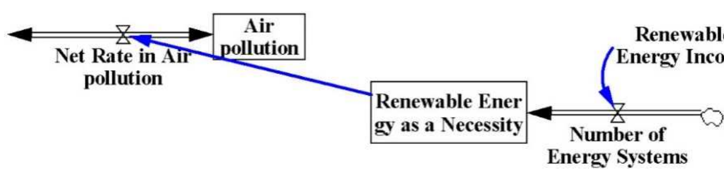

Fig. 6. Renewable energy as a necessity interrelations system

Additionally, findings from literature reviews in terms of Mexico City air pollution and major proceedings of other countries with respect to the same problem validate that the first two potential policies don't have remarkable effects on air pollution [30, 31]. However, results from previous literatures showed that utilizing Public Transportation as a long term policy could mitigate air pollution in other megacities [8, 9, 32]. That is why the Development of Public Transportation System has been chosen as the only selected policy and the leverage variable in the Stock and Flow Diagram in Figure 2. Goodarzi et al. (2016) [8] also attempted to select one desired policy to reduce air pollution in Tehran, but they didn't provide any solid ground rules on how to select the best policy and eliminate other insignificant ones. However, this point also needs to be mentioned that the Public Transportation System already exists in Mexico city but it is not widely used as people still find private commuting faster and more accessible than public transportation. Private commuting is considered as another stock preventing the public transportation to be effective in air pollution mitigation. Therefore, the focus is on the Development of Public Transportation as the selected policy rather than continuing with present public Transportation system.

3. RESULTS

By applying Development of Public Transportation System as the selected policy in Mexico City, the results of simulation in Figure 7 shows the decrease in air pollution amount which proves that the assumption on choosing this policy as an intervention in the model is acceptable. Since this policy is recognized as a long-term plan in mitigating the air pollution, it may take longer to see its actual effect because of setting up the infrastructure and investment; however, the effects of the policy are more stable and permanent [6]. As shown in Figure 7, by applying the selected policy, the air pollution will decrease from 61.7 µg/m^3, which is its current amount in the year 2016 by looking at historical data, to less than 55 µg/m^3 within 20 years. This reduction in air pollution is considered substantial within 20 years which is set as the time horizon in this study. Goodarzi et al. (2016) [8] also utilized Public Transportation System as their selected policy in order to reduce air pollution in Tehran but, their results showed that this policy could only stabilize the air pollution amount within 10 years rather than being able to reduce it. Moreover, the trend in Figure 7 shows that the air pollution won't involve in any major amplification effect when the policy is implemented. Also, the delay between applying the policy and the time to observe its real effect can be explained by the delay in setting up the infrastructure and investment on the public transportation system as the chosen policy to reduce air pollution in Mexico City.

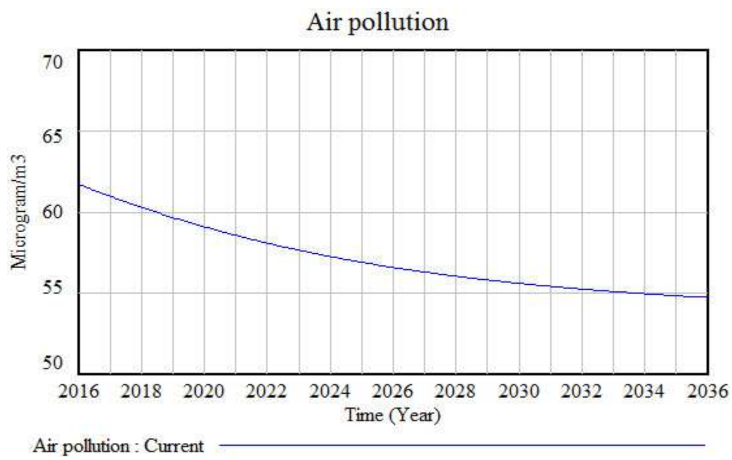

Fig. 7. Air pollution amount by applying the selected policy

Also, the trend in Figure 7 demonstrates that the air pollution begin decreasing within 20 years verifying the effectiveness of the policy in mitigating the air pollution problem. Moreover, the results from sensitivity analysis show that this equilibrium will be stable even after the established horizon. Air pollution is a gradual procedure that takes many years to observe its actual effect. That is why sustainability of the selected policy to mitigate air pollution over the years is essential. It is also plausible that if one of the factors (CO_2 emission, industrial pollutant, deforestation, etc.) contributing in air pollution decreases in the future by implementing sufficient ground rules, the air pollution will be reduced drastically.

4. DISCUSSION

In order to demonstrate how the behavior of the air pollution would be changed without the selected policy, the policy was eliminated from the model to investigate how it can affect the air pollution. As shown in Figure 8, a substantial increase in the amount of air pollution is observed which could lead to an interminable hazard in the future. The average amount of air pollution within 20 years in Figure 8 is about 66 µg/m3 which is higher than the initial amount of air pollution in mid-2016 (about 61 µg/m3) representing a significant increase in air pollution without implementing the selected policy.

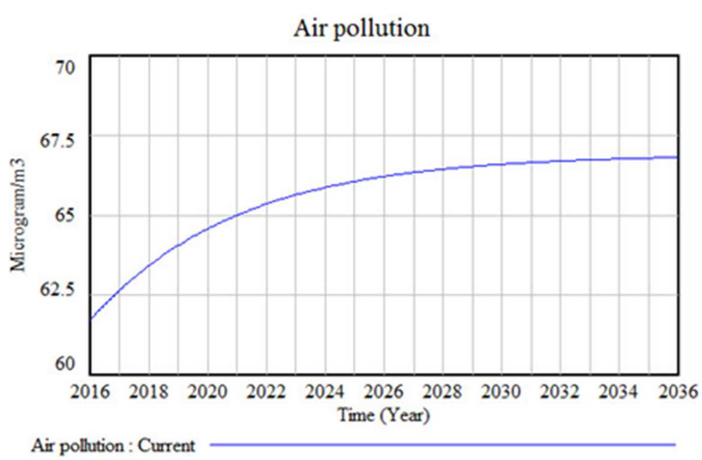

Fig. 8. Expected air pollution increase in without applying the policy

The relationship between the Development of Public Transportation System as our selected policy and air pollution shows that as the number of people using the public transportation increases, the amount of air pollution tends to decrease and as a result, the air pollution rate will decrease as well. As shown by Figure 9, the number of people using the public transportation as an intervention should increase roughly to more than 3.5 million passengers per year leading to a trend of lower air pollution. Reaching to that point needs the governmental support and action since this policy should be implemented in large scale. The stability in Figure 9 demonstrates the sustainability of the selected policy within the considered horizon since sustainable development typically investigates a stable balance between the environment and human activities [10].

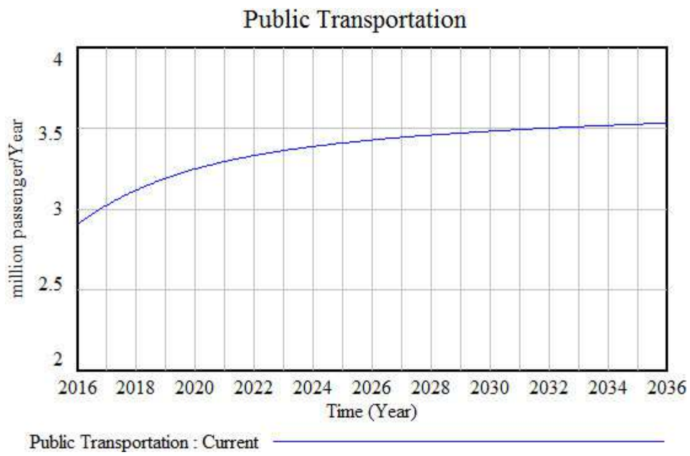

Fig. 9. Public Transportation as the selected policy trend

5. CONCLUSION

In this study, the significant variables affecting the air pollution were investigated and then the applicable policies that could contribute in air pollution mitigation in Mexico City were specified. Due to the existence of multiple variables, several interrelationships and time delays involved in the air pollution problem which makes it perplexing to analyze, a system dynamics approach was applied to simulate the behavior of the air pollution. As the first part of the system dynamics approach, a comprehensive causal loop diagram was proposed to represent the potential factors and their possible interactions contributing in the air pollution. At the second step, a stock and flow diagram was utilized to model the interactions between the variables. Accordingly, three potential applicable policies to reduce air pollution with sustainable development perspective were introduced. After the evaluation of each policy in the model, the Development of Public Transportation System was selected to be the applicable policy that could affect the air pollution significantly in Mexico City. Results of the simulation in the model showed that by having more than 3.5 million passengers per year using public transportation, a significant reduction in the amount of air pollution will be observed. Although it took a few years to sense the remarkable effect of the proposed policy in the air pollution due to the delay between the implementation of policy and its actual impact, yet it turned out that the selected policy was more stable over time and did not involve oscillation during the simulation. Since this study encompasses a wide range of variables, there are several opportunities to extend this paper. One of the areas of the future studies would be investigating the selected policy to see if it is economically affordable. Furthermore, choosing an integrated policy consist of multiple applicable policies in metropolitan area would be another interesting areas that future works can focus on. By doing so, they may come up with different policies in air pollution problem which could be applied not only in Mexico City but in other metropolitan area. Finally, the proposed model can be modified or improved by developing a policy-making framework in future research.

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