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System Dynamic Modeling for Assessment Transportation Policies in Greater Cairo Metropolitan Area

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ABSTRACT

Air pollution is a serious problem that harms human health and the environment. It is caused by a variety of pollutants, including gaseous pollutants, odors, and particulate matter. Air pollution is especially harmful in urban areas, where it can cause severe health problems for residents. The transportation sector is a major source of air pollution in the Greater Cairo Region, Egypt (GCR). To address this problem, the Egyptian government has implemented several transportation policies, such as investing in public transportation, and improving road networking road pricing. A mathematical model has been developed to assess the environmental impacts of different transportation policies in the GCR. The model takes into account the interactions between different components of the transportation system, such as traffic demand, vehicle emissions, and air quality. The model shows that three transportation policies evaluated can have a significant impact on air quality such (tax on industries that pollute the air and modification of relative user costs, utilizing renewable energy and fostering a shift to cleaner vehicles and enhancing vehicle maintenance and development of a public transportation system). For example, investments in public transportation can reduce traffic congestion and emissions, while road pricing can discourage car use and improve air quality. The model can be used to support decision-making on transportation policies in the GCR. It can be used to assess the environmental impacts of different policies, identify the most effective policies, and track the progress of implementation. The mathematical model developed in this paper can be utilized to inform the development of transportation policies and monitor the progress of their implementation.

1. INTRODUCTION

Transportation is a crucial component of urban development and the economy of a city, but it also has a significant impact on the environment.it is a major contributor to air pollution, noise pollution, and climate change in Greater Cairo [1].

To mitigate the environmental impacts of transportation, it is important to conduct a strategic environmental impact assessment (SEIA) [2], it is a process that identifies, evaluates, and mitigates the potential environmental impacts of a proposed project or policy.

To identify key environmental factors affecting Greater Cairo, we analyzed the local context. Our assessment revealed challenges such as limited inter-governmental cooperation, insufficient financial resources, and rapid population growth. However, opportunities also exist, including technological advancements in transportation, renewable energy, and environmental monitoring [1].

We recommend increased funding for these areas, along with public awareness campaigns and greater international collaboration.

The specific environmental issues facing Greater Cairo include land use, solid waste management, water and air pollution, and climate change [1]. From Table 1, we can identify:

Some of the main surrounding environmental themes in Greater Cairo are: (air pollution - water pollution - solid waste management - land use - deforestation and climate change).

The current state of the transport and road sector in the Greater Cairo region is characterized by the following [2]:

High traffic congestion: Traffic congestion is a major problem in the Greater Cairo region. The average speed of traffic in the city is only 15 kilometers per hour, and the average commute time is over two hours.

Poor air quality: Air quality in the Greater Cairo region is poor, due to the high levels of traffic congestion. The city has been ranked as one of the most polluted cities in the world.

High rates of traffic accidents: Traffic accidents are a major problem in the Greater Cairo region. There are over

10,000 traffic accidents each year, and over 3,000 people are killed.

Inefficient public transportation: Public transportation in the Greater Cairo region is inefficient and overcrowded. The metro system is the most popular form of public transportation, but it is still unable to meet the demand.

Lack of investment in infrastructure: The government has not invested enough in the transport and road sector in the Greater Cairo region. This has led to the deterioration of the road network and the aging of the public transportation system.

Table 1. SWOT analysis

Weaknesses	Strengths [3]
• Lack of coordination between different government agencies. • Limited financial resources. • The transportation sector is fragmented, with several different government agencies responsible for different aspects of transportation planning and management. • There is a lack of data and information on the environmental impacts of transportation projects.	• The distinct ground formation (topography - tendencies) allows for the settlement of a wide range of uses without limitations or barriers. • The study area has geological characteristics that allow for the settlement of all activities and uses. • The soil's suitability for the urban development process due to the absence of determinants or barriers to the development.
Risk	**Opportunities**
• Rapid population growth. • Increasing urbanization. • Climate change. • Political instability. • Traffic congestion. The increasing demand for transportation. • Air pollution. • Noise pollution. • Economic productivity: Traffic congestion and air pollution can lead to decreased economic productivity.	• The development of new technologies for reducing the environmental impacts of transportation. • Increased investment in renewable energy [4]. • New technologies for environmental monitoring and remediation. • Growing public awareness of environmental issues. • The increasing use of public transportation and non-motorized transport. • The growing international cooperation on environmental issues related to transportation [5].

To evaluate the environmental effects of the transportation sector, we must assess both positive and negative impacts, as well as direct, indirect, and cumulative effects. By using a checklist tool and reviewing existing literature, we've found that Greater Cairo is one of the world's most polluted cities, primarily due to traffic, industrial emissions, and construction dust. This air pollution poses significant health risks, including respiratory diseases, heart problems, and cancer [6].

The use of mathematical models to evaluate the environmental effects of transportation regulations has gained popularity in recent years. Mathematical modeling is a powerful tool that can be used to assess the environmental impact of the transportation sector. It is a complex and challenging undertaking, but it can be a valuable tool for making informed decisions about the transportation sector and its impact on the environment and transportation planning and policy [3]. This paper proposes a mathematical model for strategic environmental impact assessment (SEIA) of the transportation sector in Greater Cairo. Using a system dynamics approach, the model examines the interconnectedness of various transportation components, including traffic demand, vehicle emissions, and air quality.

We used a mathematical model to identify mitigation measures that can be taken to reduce the environmental impact of the transportation sector [7].

The use of mathematical models has increased in popularity as a useful tool for decision-making about transportation projects. It has also been used to evaluate and test various alternative strategies for urban transportation planning, according to a literature review. The outcomes of the simulation indicate that the following factors affect mobility: trip time; the effectiveness of public transportation in terms of both distance traveled and time spent traveling; the fulfillment ratio of supply and demand; and access time. Both internal and external variables might impact traffic congestion [4].

It would help them to make informed decisions about transportation planning and investment that would minimize the environmental impacts of transportation identify the potential environmental impacts of transportation projects at an early stage, assess the cumulative impacts of multiple transportation projects, compare the environmental impacts of different transportation

The results of the model show that the transportation sector is responsible for a significant proportion of air pollution in Greater Cairo.

The model also shows that different transportation policies can have a significant impact on air quality. For example, investments in public transportation can reduce traffic congestion and emissions, while road pricing can discourage car use and improve air quality [8].

2. BACKGROUND ON THE STUDY AREA

For this study, Greater Cairo refers to Cairo and Giza governorates shown in Figure 1. We selected Greater Cairo for the study because there is a lack of research on the specific impacts of air pollution from transportation in Greater Cairo and, a lack of comprehensive data on the sources and impacts of air pollution from transportation in it, there is a need for research that specifically investigates the impacts of air pollution from vehicles, such as cars, buses, and trucks and there is a need for more research that takes a holistic approach to the problem.

The need for more effective methods to assess the environmental impacts of transportation projects become a top priority because traditional methods for assessing the environmental impacts of transportation projects, such as environmental impact assessments (EIAs), are often not sufficient.

Greater Cairo is an ideal case study for system dynamic modeling of transportation policies due to several key factors such Complex and Dynamic Transportation Challenges, Cairo has a relatively rich dataset on population, land use, transportation infrastructure, and traffic patterns, essential for developing and calibrating system dynamic models due to Cairo's rapid population growth has led to significant challenges in managing transportation infrastructure and traffic congestion.

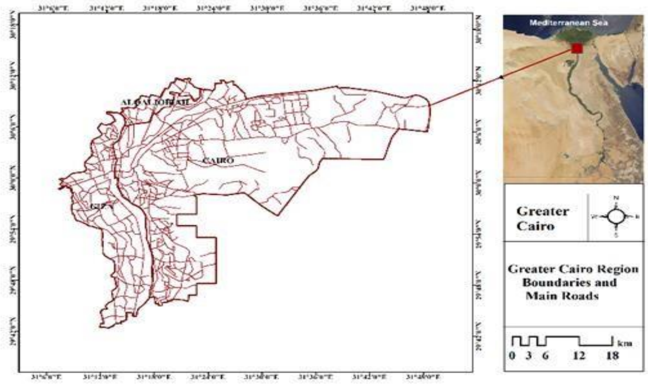

Figure 1. Greater Cairo Region (GCR), Egypt: (a) Location map, (b) The study area

Source: (a) http://glovis.usgs.gov/2023, (b) Landsat 8 Pan-Sharpened with DEM from Shuttle Radar

The city boasts a mix of public and private transportation, making it a complex system to model and analyze and Air pollution and traffic-related emissions are pressing issues in Cairo, making it a prime location to study the environmental impacts of transportation policies.

By 2030, Greater Cairo is projected to rank as the world's fifth most populous megacity [5]. At present time, the city is home to about 20 million people (about 20% of Egypt's total population) and 4 million on-road cars (45% of Egypt's fleet), 60% of which are older than a decade [6, 7]. The complex network of arterial roadways, bridges, tunnels, residential streets, and lanes that connect the various zones of Greater Cairo is illustrated by a ring road and highways [8]. The public transportation system shows features such as decreasing service frequencies, crowded carriages, and aged fleets [9]. Eighty-three percent of motorized journeys are made by commuters using shared taxis and unofficial microbuses [10]. Additionally, there aren't many defined bike lanes or pedestrian zones in the city.

In addition, there aren't many defined bike lanes or pedestrian areas in the city. Geographically, Greater Cairo is vulnerable to dust storms as it is bounded by the Eastern Desert and the Mokattam Hills on one side and the Western Desert and the Abu-Rawash Hills on the other [11]. The city experiences high temperatures (18-45℃) and low yearly precipitation (22-29 mm). Greater Cairo's transportation system has evolved significantly over the centuries, reflecting the city's growth and changing needs.

In Ancient and Medieval Times the primary mode of transportation was the Nile River, serving as a vital artery for both people and goods while Land Transportation Limited to walking, horses, and camels for short distances. In Colonial Era and Early 20th Century The construction of railways in the 19th century connected Cairo to other parts of Egypt and the wider region, Became Horse-drawn Carriages popular for urban transportation within Cairo.

Introduced in the late 19th century, Electric Trams providing a modern mode of public transport. At Mid-20th Century Post-World War II saw a rapid increase in car ownership, leading to traffic congestion public bus services were expanded to accommodate the growing population.

Construction Cairo Metro (Phase 1) began in the 1980s, with the first line opening in 1987. At late 20th Century and beyond the metro system continued to expand with new lines and stations. The city's road network was significantly expanded. Despite infrastructure improvements, Cairo faced severe traffic congestion, air pollution, and inadequate public transportation. Recent Developments focus on improving public transport, including new metro lines, bus rapid transit (BRT) systems, and promoting cycling and walking [12].

Key Challenges are Rapid urbanization and population growth, Increasing car ownership, Limited public transportation option, Traffic congestion and air pollution [13].

3. LITERATURE REVIEW

The study by the US Department of Transportation (DOT) used a system dynamics model to simulate the transportation system in the San Francisco Bay Area and the study by the World Bank used it to simulate the transportation system in several cities in developing countries. The study found that transportation systems in these cities were becoming increasingly congested, and that this congestion was hurting the economy and the environment. The study also found that there we several policies that could be implemented to reduce traffic congestion, such as investing in public transportation and improving land use planning [14], the study by the US Environmental Protection Agency (EPA) used a traffic simulation model to estimate the impact of a new highway on air quality in the Los Angeles area. The study found that transportation would increase air pollution levels in the area [15]. According to a survey of the literature, mathematical models are being utilized more and more to test and assess various alternative strategies for urban transportation planning. They can be an invaluable tool for decision-making about transportation projects. The outcomes of the simulation indicate that the following factors affect mobility: trip time; the efficiency of public transportation in terms of both distance traveled and time spent traveling; the fulfillment ratio of supply and demand; and access time. Both internal and external variables might impact traffic congestion.

The papers mentioned above illustrate how the body of literature on air pollution attempted to tackle the issue from chemical or economic angles. Only a tiny percentage of them considered sustainable development, recognizing that air pollution is an increasingly pressing environmental concern in metropolitan areas, particularly in greater Cairo. A few of them applied a system dynamics approach in their works. Examining earlier studies on air pollution in the wider Cairo area reveals several research gaps that have either been ignored or have not been fully examined. Identifying a complete collection of variables and strategies that could address the issue of air pollution is one of the gaps in their knowledge [9].

From Quantify the environmental impacts of existing and proposed transportation policies and projects on air quality and greenhouse gas emissions and the need for Support policymakers and urban planners to develop and implement effective sustainable transportation strategies that prioritize both mobility and environmental well-being.

In addition to high population density, limited public transport infrastructure, reliance on private vehicles and Climate change considerations Integrating climate change scenarios and their potential impact on the transportation sector is crucial for long-term planning. By addressing these research gaps, the proposed mathematical model for SEIA has the potential to significantly contribute to the development of sustainable transportation solutions in Greater Cairo. It will provide a powerful tool for policymakers, urban planners, and stakeholders to make informed decisions that prioritize both environmental well-being and efficient mobility for the future of this mega city. The model will be tailored to address these specific challenges and provide contextually relevant insights and to assess the environmental impacts under different climate change projections.

Furthermore, there aren't many policies in place that could be able to reduce air pollution. Furthermore, it's uncertain if the variables and factors causing air pollution in the research area could have an interaction with one another. As a result, one of the novelty of this work is the application of a system dynamics approach to the problem of air pollution in greater Cairo, one of the most polluted megacities, from the standpoint of sustainable development. By looking into multiple policies that may be useful in mitigating air pollution, this study offers more trustworthy guidelines for reducing air pollution in the greater Cairo area [10].

4. DATA AND METHODOLOGY

4.1 Data used

The data used in the system dynamics model for transportation in the GCR can be divided into two categories:

Quantitative data: This data includes information on the number of vehicles, the amount of traffic, the types of vehicles, the road network, and the environmental impacts of the transport sector. This data can be collected from a variety of sources, such as government agencies, transportation companies, and environmental organizations.

Qualitative data: This data includes information on the public's views on the transport and road sector, the legal and regulatory requirements for environmental impact assessments, and the social and economic impacts of the transport sector. This data can be collected through surveys, interviews, and focus groups.

4.2 Methodology

4.2.1 Development of system dynamics model

We created a model simulation to provide integrated transportation planning. It allows us to assess various options for improving the performance of the transportation system and learn about the behavior of the transportation system, which significantly affects everyday traffic, congestion, and mobility performance. Planning tools are designed, constructed, and managed through modeling, which makes use of data and mathematical equations [16]. In various sub-models for road network capacity, vehicle fuel consumption, vehicle carbon emissions, population growth, and vehicle population growth are created for this current inquiry [17].

It will be required to construct a feedback loop to illustrate the interaction between components since the most complex behaviors in any system originate not from the complexity of its parts but rather from the interaction or feedback of those parts. In addition to simulating feedback loops and component interactions, a system dynamics technique can forecast how system interventions will behave with respect to many variables over an extended period of time [18]. Using system dynamics techniques like VENSIM and STELLA software, this study will look into a variety of factors influencing air pollution in the study area, as illustrated in Figure 2.

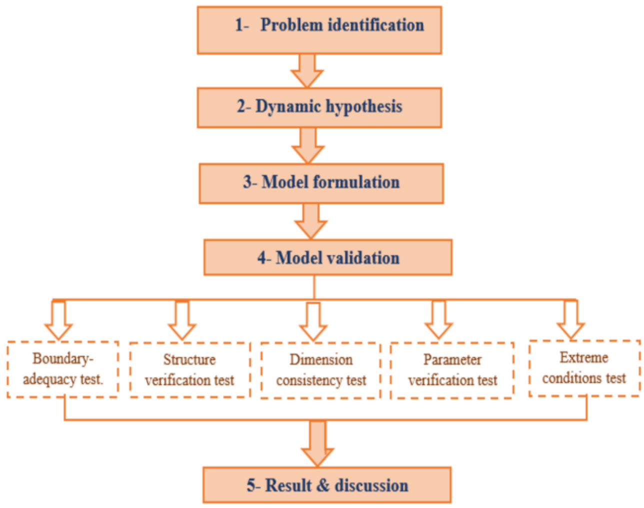

Figure 2. Methodology

4.2.2 Problem identification

We'll apply policies that might have an impact on air pollution mitigation in order to watch how it behaves in the model. In order to accurately analyze which policy continues to be the most successful, the simulation model will look at the trend over a period of twenty years. The study's 20-year horizon was chosen because the policies are acknowledged as long-term plans and to ensure that there is sufficient time to put the policies into action that will reduce air pollution. Expert opinions and government data about air pollution are used in examining the factors influencing air pollution. The above-discussed methodology can be used to evaluate Greater Cairo's air quality and determine the causes of air pollution [14].

4.2.3 Dynamic hypothesis

System dynamics modeling (SDM) is a powerful tool for understanding and analyzing complex systems. It can be used to dispel the complexity of systems and make them easier to learn from. SDM is often used as a "strategy and policy laboratory" in socioeconomic systems. This is because it allows researchers and policymakers to evaluate the different impacts of chosen policies before they are implemented in the real world [19].

CLDs (Causal Loop Diagram): This is a qualitative modeling technique that uses arrows to show the causal relationships between different variables in a system. CLDs can be used to visualize how changes in one variable can lead to changes in other variables. To show the interrelationships between the variables affecting air pollution in greater Cairo, at the first step it is needed to identify variables. To do so, an interview has been done with an environmental expert and also previous works regarding air pollution especially the ones done regarding the study area [11]. As our results reveal, the key variables in polluting air in greater Cairo are CO_2 emission, traffic Congestion, private car community, Population, fuel consumption, travel demand and Quality of Cars. There might be other factors contributing to air pollution in the study area, but we tried to introduce the most important ones. Thus, the positive and negative feedback interactions between variables are shown in Figure 3.

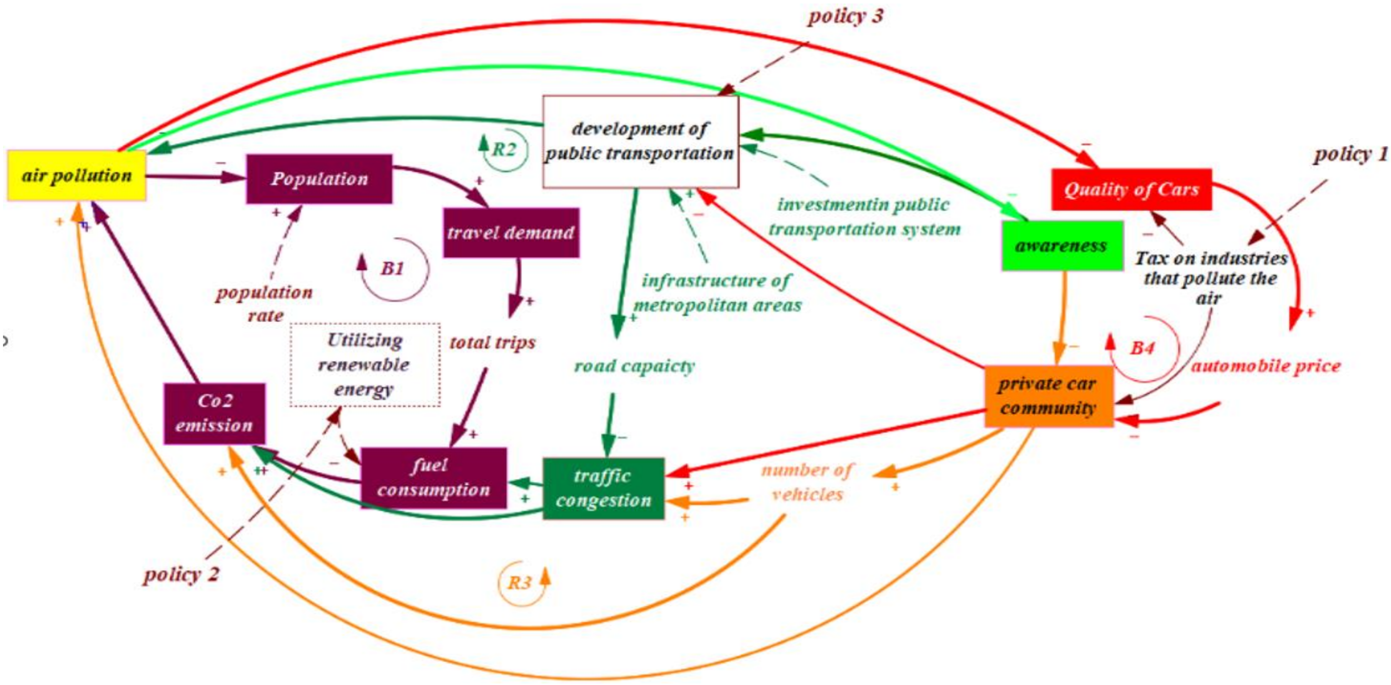

Figure 3. Causal loop diagram of endogenous variables affecting air pollution

In this paper, three policies have been selected that could potentially mitigate air pollution in Greater Cairo according to studies and reports to the World Bank and Economic Research Forum (ERF):

Tax on industries that pollute the air and modification of relative user costs: by raising fuel prices, increasing licensing fees for vehicles, and imposing congestion or fuel charges to dissuade private car use [20] and implement stricter vehicle emission standards for new and existing vehicles and discourage the use of older, more polluting vehicles through taxes or other financial incentives [21].

Utilizing renewable energy: Promote the use of cleaner fuels, such as compressed natural gas (CNG) and electricity [22] and fostering a shift to cleaner vehicles and enhancing vehicle maintenance by encourage the adoption of cleaner vehicles like electric vehicles (EVs) and hybrid electric vehicles (HEVs) through incentives like tax breaks, subsidies, preferential parking. Implement regular vehicle inspection and maintenance programs to ensure vehicles are operating efficiently and within emission standards.

Development of a public transportation system: Invest in expanding and improving public transportation options, such as buses, metros, and light rail, Make public transportation more affordable and accessible, Integrate public transportation with other transportation modes, such as walking and cycling, to make it easier for people to get around without using a car and Build and maintain safe and accessible infrastructure for pedestrians and cyclists.

It is important to note that the best policy for reducing air pollution will vary depending on the specific circumstances of each city or country. However, system dynamics can be used to evaluate the potential impacts of different policies and to identify the best policy for a given situation.

The figure above shows how different factors interact with each other to affect air pollution. When one factor increases, it can cause other factors to increase (positive feedback loop), or it can cause other factors to decrease (negative feedback loop).

For B1: an increase in Population can lead to an increase in travel demand which can lead to an increase in total trips, fuel consumption and CO_2 emission which can further increase air pollution (balance feedback loop).

For R2: applying policy 3 (developing public transportation) investment in the public transportation system and infrastructure in metropolitan will lead to the development of road capacity thus will decrease in traffic congestion, CO_2 emission and fuel consumption and solving air pollution problems.

For R3: an increase in awareness can lead to a decrease in the private car community, which can lead to a decrease in several vehicles, traffic congestion, fuel consumption and CO_2 emissions, which can further decrease air pollution (positive feedback loop).

For B4: improving the quality of cars will increase automobile prices so will decrease car private communities and then decrease traffic congestion, fuel consumption, CO_2 emissions, air pollution problems.

System dynamics is a powerful tool for understanding and managing complex systems, such as air pollution problem. It allows us to see how the different factors interact with each other and how they affect air pollution levels over time [18, 23].

When choosing policies to reduce air pollution, it is important to consider the following factors:

Sustainability: The policies should be environmentally friendly and should remain effective for a long period.

Economic and political feasibility: The countries or cities that are implementing the policies should have the right infrastructure and resources to do so.

4.2.4 Model formulation

Based on the causal loop diagram, all the key variables that affect the choice of suitable policy are identified. The conceptual causal loop diagram is converted to a quantitative model to facilitate the running of the model [12]. To this end, the causal loop diagram is converted into a stock-flow diagram using STELLA software. Figure 4 depicts a stock-flow diagram of the model [6, 24].

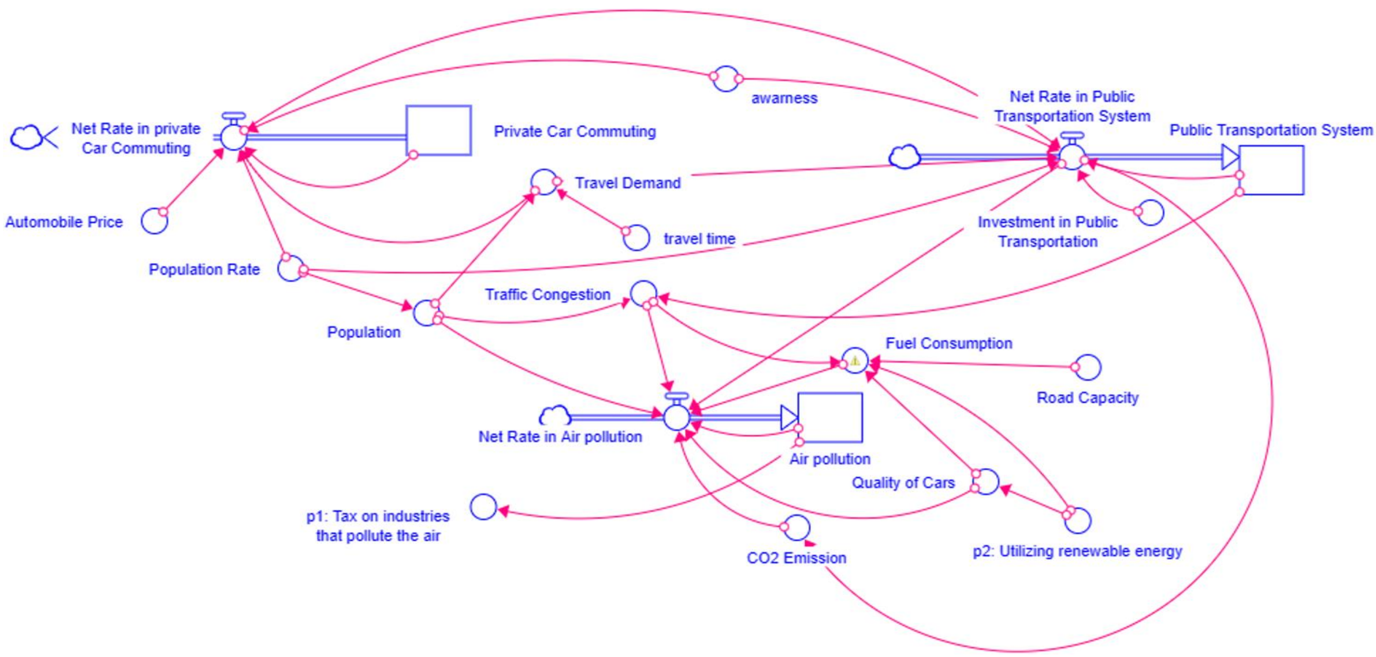

Figure 4. Stock & flow diagram of air pollution showing dynamics between variables

Stock and flow equations for air pollution, private car commuting, and public transportation. They are a type of differential equation that is used to model dynamic systems. These systems are characterized by the fact that their state changes over time in response to inputs and outputs.

Stock and flow equations are typically used to model systems that can be divided into two types of variables: stocks and flows. Stocks are variables that accumulate over time, such as the amount of air pollution in the atmosphere or the number of people commuting by private car. Flows are variables that represent the rate of change of a stock, such as the rate of CO_2 emissions or the rate at which people are switching to public transportation.

The system state, represented by the stocks, and the rate of system changes, or flows, should be determined in advance in order to build up the Stock and Flow Diagram, as seen in Figure 4. The modeling that is being provided identifies 3 stock variables and three flows that are correspondingly related with them. The three main equations in the modeling are the flows, or net rates, which are the rates of air pollution, private vehicle commuting, and public transportation usage. These rates' formulas are as follows:

Define the equations [25-27]:

$$\text{Net Rate of Air Pollution (t)} = Net(0) + \int t((Emission + Air\ Pollution) + (Population \times Traffic\ Congestion \times Fuel\ Consumption \times \text{Investment in infrastructure Transportation})) \, d(\text{t}) \,/\, \int t(Public\ Transportation + Quality \text{ of } Cars + \text{private car communing}) \, d(t) \tag{1}$$

$$\text{Net Rate of Private Car Commuting (t)} = Net(0) + \int t((Private\ Car\ Commuting \times Population\ Rate \times Travel\ Demand) \, d(t) \,/\, \int t(Awareness)) \, d(t) \tag{2}$$

$$\text{Net Rate of Public Transportation (t)} = \text{Net}\ (0) + \int t((Public\ Transportation \times Population\ Rate \times Travel\ Demand \times Investment\ on\ Public\ Transportation) \, d(t) \,/\, \int t(Net\ Rate\ in\ Car\ Commuting) \, d(t) \tag{3}$$

4.2.5 Model validation

Building confidence in the model is achieved through conducting some tests after identifying and defining all variables and functions [28]. This ensures the accuracy of the model for reflecting the real world in a meaningful way. Another study listed five tests that are used for the structural validation of a system dynamics model.

(a) Boundary-adequacy test

The purpose of this test is to determine whether or not the model's degree of detail variables is appropriate for the intended research goal. In the meantime, by looking at every variable that has been represented in the stock-flow diagram, it ensures that the model incorporates all pertinent structure linkages and parameters. Each of the variables in the system dynamics model was determined to be essential for research purposes in order to assess the efficacious approaches for decreasing air pollution from the transportation sector.

(b) Structure verification test

This test's objective is to assess whether the model's structure aligns with pertinent descriptive information about the system it is meant to represent. In the whole validation process, structural verification is crucial [29]. The data in the causal loop diagram's structure and every cause-and-effect chain depicted in Figure 3 is taken from a variety of publications in this field. Because of this, the model's structure makes sense and closely resembles the system in real life.

(c) Dimension consistency test

This test ensures the consistency of variable dimensions of each mathematical equation in the model. STELLA software has the possibility of dimension checking after defining the measurement units of all the variables. Consequently, the model has been validated for dimensional consistency. The variable "traffic congestion" (shown in Figure 4), for instance, is defined using several different equations that can be used to measure traffic congestion. One common equation is the following

$$\text{Traffic congestion (t)} = (\text{Number of vehicles on road})\ (\text{t} - \text{dt}) \,/\, \text{road capacity} \times \text{dt} \tag{4}$$

Vehicle hours per kilometer (vhc/km) = No. of vehicles/ km

This equation calculates traffic congestion as the ratio of the number of vehicles on the road to the capacity of the road. The capacity of the road is the maximum number of vehicles that can travel on the road at a given time without causing congestion. It is worth noting that the variable dimensions on the left-hand side are consistent with the variable dimensions on the right-hand side.

(d) Parameter verification test

The objective of this test is to determine whether the model's parameters conceptually and numerically match actual values. The suggested model's parameter values are derived from actual situations reported in the literature. Table 2 lists some of the parameters, their values, and the source as an example. Table 1 lists all of the parameter specifications, along with their corresponding units, that are displayed in Figure 5. Certain variables that are not unit-neutral are displayed as relative factors. These relative factors are typically employed in situations when there is a lack of variable data or when the variables are qualitative and unresponsive to unit conversion. Also, as mentioned before, rates are determined as the major equations in the modeling.

(e) Extreme conditions test

Using the year 2010 as the baseline in STELLA software, the model's predictions were compared with actual air pollution data from 2010 to 2016 as shown in Figure 5. The outcomes demonstrated that the model could roughly mimic the characteristics of the actual data. The Wilcoxon Signed-Rank test, a statistical validation test, when two sample t-tests must be performed but the samples deviate from normality, this test is typically utilized [30, 31]. Consequently, the following is the statistical hypothesis related to the non-parametric test:

H0: *Median of real and estimated data are equal.*
H1: *Median of real and estimated data are not equal.*

Additionally, tests were conducted to ensure that the discrepancies between the estimated data and historical data were minimal. The test results indicated that these gaps were insignificant, confirming that system dynamics can be effectively used as a reliable estimator for predicting future air pollution trends.

In other words, the model is valid because it can accurately predict air pollution levels based on historical data. This is important because it means that the model can be used to simulate different scenarios and predict how air pollution levels will change in the future. This information can then be used to develop policies and interventions to reduce air pollution.

Table 2. List of parameters (variables) used in stock and flow diagram [13]

Variable Type	Variable Name	Variable Value	Unit	Source
Stock	Air pollution	61.7	μg/m^3	Egyptian Environmental Affairs Agency (EEAA). (2023). Air quality monitoring stations. https://www.devex.com/organizations/egyptian-environmental-affairs-agency-20329. World Health Organization (WHO). (2023). Air quality in Greater Cairo, Egypt. https://www.iqair.com/egypt/cairo/cairo-c
	Public transportation system	2.9	million daily riders	Greater Cairo Transport Authority (GCRTA), Transport for Cairo, 2023. Data - Transport for Cairo
	Private car commuting	5.5	million/year (70% of all trips)	Greater Cairo Urban Transport Master Plan (CREATS, 2003)
Rate	Net rate in air pollution		1/year	
	Net rate in transportation		1/year	
	Net rate in car commuting		1/year	
Auxiliary	Population rate	0.02	1/year	Egyptian Central Agency for Public Mobilization and Statistics (CAPMAS, 2023) https://www.capmas.gov.eg. Accessed on 5/5/2023
	Population	21,750	million people	
	CO_2 emission	13	million tons/year	World bank2023.
	Traffic congestion	100	Vehicles / 1km (Ring road)	Cairo Traffic Congestion the study - Phase 1 - World Bank Document
	Fuel consumption	1 billion	lit/year	Egyptian Ministry of Petroleum and Mineral Resources (MOEMR, 2023)
	Investment in public transportation	20000	Million EGP/year	Ministry of Transportation, Egypt (2022-2023) http://www.mot.gov.eg/
	Public transportation income	10000	Million EGP/year	National Authority for Tunnels (2022) www.nat.gov.eg
	Road capacity	80,000	vehicles per hour (Ring Road)	Greater Cairo Urban Transport Master Plan - CREATS, 2003
	Travel demand	12	million trips per day (2022)	
	Awareness	1	unit less	
	Automobile price	1	unit less	
	Quality of cars	1	60% of vehicles fail inspection (2023)	Egyptian Vehicle Inspection Authority (EVUA)

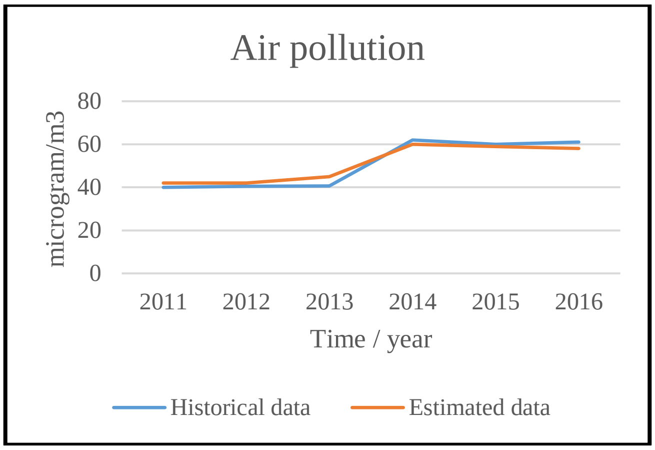

Figure 5. Air pollution behavior by comparison between historical and estimated data

4.2.6 Policy formulation

Stock and flow equations are a powerful tool for understanding and managing complex systems. They can be used to simulate the behavior of systems over time, evaluate the impact of different policies, and design new systems.

Once we are sure that the model is valid, we can add policies to it to see how they affect air pollution. We often need to change the stock and flow diagram slightly when we do this, such as by removing variables that are no longer relevant, adding shadow variables, or removing policies that are not important.

While we explored various strategies to combat air pollution in Greater Cairo, including taxation and renewable energy, our analysis suggests that investing in public transportation is the most effective approach. Using STELLA software and historical data, we found that public transportation development can significantly reduce air pollution within a 20-year timeframe [32].

We used historical data on taxing industries to simulate how air pollution would behave if this policy were implemented in the model. To do this, we added the tax on industries and people and its associated variables to the model and disabled the public transportation system and its interactions. Figure 1 shows that the only variable associated with the renewable energy policy is income obtained from tax. This policy interacts with other variables in the stock and flow diagram, affecting air pollution, industrial pollutants, and income obtained from tax.

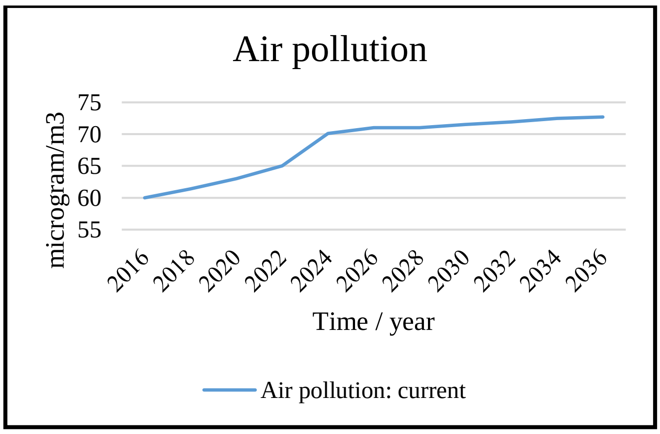

Figure 6. Air pollution amount by applying a tax on industries and people as a policy

Figure 6 shows that imposing a tax on industries as a policy to reduce air pollution increased air pollution from 61.7 μg/m^3 to 71 μg/m^3. This suggests that while taxing industries and people can slow the growth rate of air pollution, it cannot reduce the amount of air pollution in the short term. Similarly, modeling the use of renewable energy as a policy to reduce air pollution showed that it does not lead to a reduction in air pollution in the short term.

Figure 7 shows that air pollution starts to decrease within 20 years of the policy being implemented, which proves that the policy is effective. The results of a sensitivity analysis also show that this equilibrium will remain stable even after 20 years. Air pollution is a gradual process, and it takes many years to see the full effects of any policy. Therefore, the policy must be sustainable over the long term. Additionally, if one of the factors that contributes to air pollution (such as CO_2 emissions, industrial pollutants, or traffic congestion) is reduced in the future by implementing appropriate regulations, air pollution could be drastically reduced.

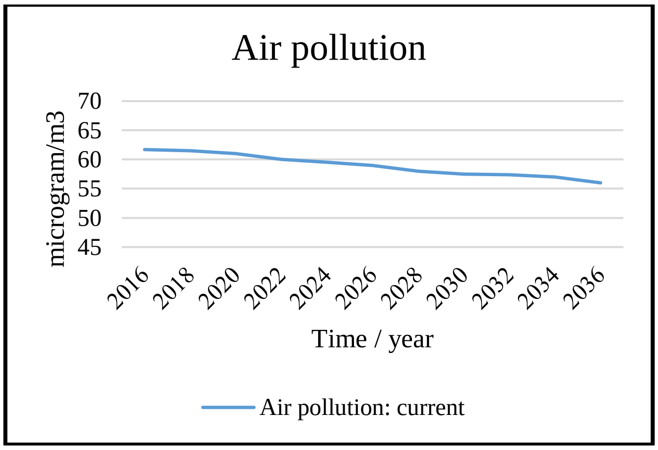

Figure 7. Air pollution amount by applying the development in public transportation as a selected policy

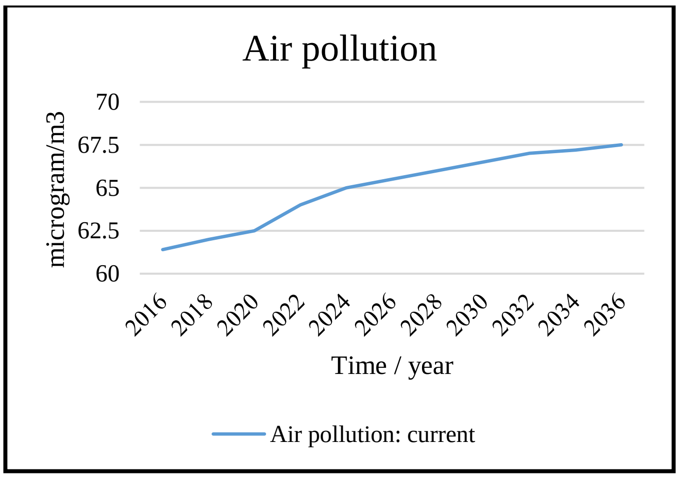

Figure 8. Expected air pollution increase without applying the policy

To highlight the policy's importance, we simulated a scenario without it. Figure 8 clearly shows that air pollution levels would dramatically increase, posing serious health risks. The average pollution level over 20 years would reach 66 μg/m^3, significantly higher than the 2016 baseline of 61 μg/m^3.

The relationship between our selected policy, developing a public transportation system, and air pollution shows that as more people use public transportation, air pollution decreases. To realize significant air pollution reductions, public transportation usage must surpass 3.5 million annual passengers, as shown in Figure 9. This ambitious goal will require strong government commitment and substantial investments to implement the policy on a large scale. The stability of Figure 9 indicates that the selected policy is sustainable over the 20-year timeframe, contributing to a more sustainable future [33, 34].

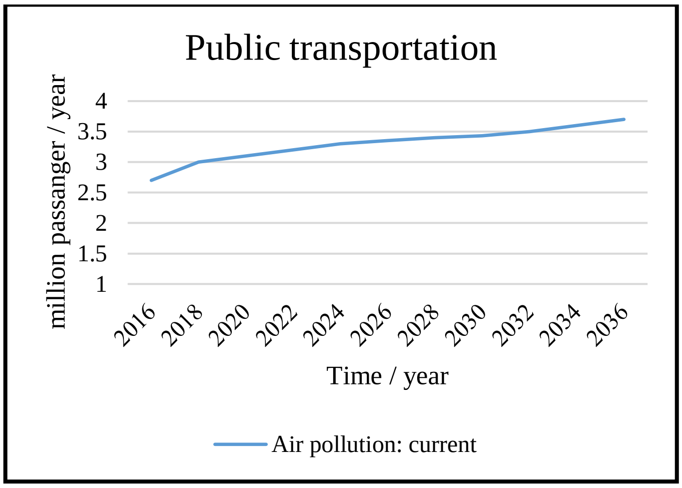

Figure 9. Public transportation as the selected policy trend

5. CONCLUSION

The transportation sector in Greater Cairo contributes notably to air pollution. This paper demonstrates how various transportation policies can significantly affect air quality. The model presented can assess the environmental impacts of these policies, identify the most effective ones, and monitor their implementation progress.

In this study, we explored key factors affecting air pollution in Greater Cairo and identified effective policies for its reduction. Due to the complex interactions among numerous factors, we employed a system dynamics approach for simulation. We used a causal loop diagram to illustrate the contributing factors and their interactions, and a stock and flow diagram to model their relationships.

We proposed three policies aimed at sustainable development and assessed each within our model. Our findings indicate that developing a public transportation system is the most effective and sustainable strategy for reducing air pollution in Greater Cairo.

The application of mathematical models to determine potential mitigation strategies to lessen the transportation industry's negative environmental effects is also covered in this study. A mathematical model for the strategic environmental impact assessment (SEIA) of Greater Cairo's transportation sector is presented in this research. Based on system dynamics, the model considers how several elements of the transportation system interact, including air quality, car emissions, and traffic demand. Greater Cairo's transportation policy decisions can be aided by the mathematical model this research presents. The model can be used to evaluate how various policies would affect the environment, determine which policies are most effective, and monitor the implementation process. In this study, we examined the key variables influencing air pollution in the greater Cairo area and then offered potential policy solutions. Because there are numerous variables that contribute to air pollution and these variables interact in intricate ways, the researchers employed a system dynamics approach to model the issue. To illustrate the possible causes of air pollution and how they interact, we constructed a causal loop graphic. Subsequently, a stock and flow diagram was produced in order to simulate the relationships between the variables. We presented three possible air pollution reduction strategies with an emphasis on sustainable development. After analyzing every policy in the model, they concluded that the best long-term solution for lowering air pollution in greater Cairo is to create a public transit system.

6. FUTURE RESEARCH

Several avenues for future research exist. One possibility is to assess the economic viability of the selected policy. Another is to develop a comprehensive policy framework combining multiple strategies for metropolitan areas. This could lead to innovative policy solutions that can be applied not only in Greater Cairo but also in other urban areas worldwide. Additionally, refining the proposed model by developing a policy-making framework could enhance future research and policy development efforts.

This study significantly advances our understanding of air pollution in Greater Cairo and provides a promising policy solution with the potential to significantly reduce air pollution. The researchers' recommendations for future research are promising, potentially leading to the development of more comprehensive and effective policies to address this global challenge.

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