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Simulation of Emissions From Fuel Consumption of Passenger Vehicles in Tehran and Proposal of Mitigation Strategies

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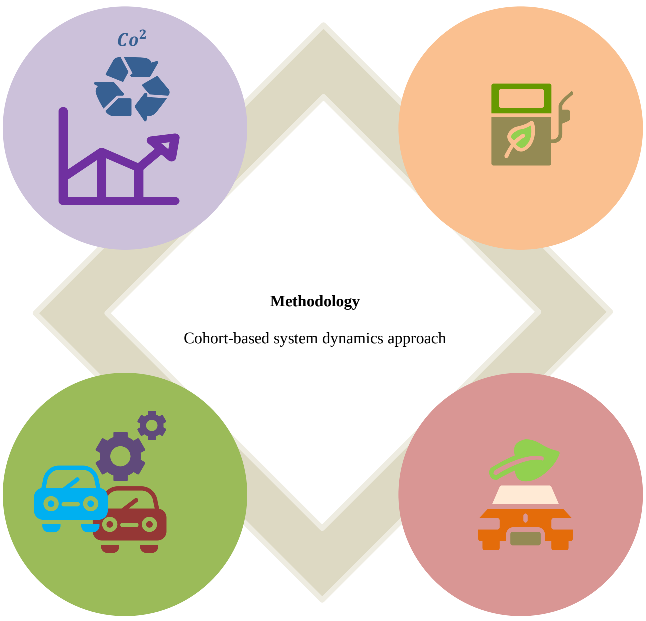
A B S T R A C T

Air pollution stands as one of the most critical challenges facing the world and Iran today, necessitating precise policy-making and systemic modeling. This study employs a cohort-based system dynamics approach to simulate both future vehicle numbers and pollutant emissions. This systemic method enables the consideration of temporal changes and dynamic factors such as vehicle age, purchase rates, depreciation, and transportation policies. A two-subsystem model is developed for Tehran's transport sector. The first subsystem simulates the number of vehicles based on vehicle cohorts (divided into five age groups), with each cohort treated as a stock variable reflecting the number of vehicles in each age group over time. The second subsystem calculates carbon dioxide (CO_2) emissions based on the number of vehicles driven, distance traveled, and emission rates per kilometer. Results indicate that population growth will lead to a rising trend in both vehicle numbers and CO_2 emissions, worsening Tehran's environmental indicators in the future. Therefore, effective policies are essential. Recommended policies include adjusting fuel prices, improving vehicle technology, modifying depreciation rates, and removing outdated vehicles. Findings show that increasing fuel prices can positively impact vehicle demand and reduce air pollution. Ultimately, a combination of these policies yields the most effective results. Based on the study, it is recommended that fuel prices be increased according to a phased plan, while also implementing targeted measures to enhance vehicle manufacturing technology and engine efficiency



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1. Introduction

One of the most significant environmental issues facing the Earth today is air pollution, which has become a major administrative concern for countries worldwide. According to the standard definition of air quality, air pollution refers to the presence and dispersion of one or more pollutants such as solids, liquids, gases, ionizing and non-ionizing radiation in the open air at levels and durations that harm air quality for humans and the environment. The most important air pollutants include carbon monoxide (CO), particulate matter (PM), ozone (O_3), nitrogen oxides (NO_x), hydrocarbons, sulfur oxides (SO_x), and carbon dioxide (CO_2).

Air pollution in major cities around the world has, over recent years, escalated into a serious crisis. The complexity of urban air pollution stems from a combination of various factors. Long-term stagnation and downward air movement, mountainous topography, lack of surface winds during certain periods of the year, temperature inversion, urban barriers, and the construction of tall buildings often built without regard to prevailing wind directions play significant roles in intensifying severe pollution events [1]. Most critically, emissions from urban and industrial sources, including vehicles and factories, are key contributors to the worsening air quality.

In large European cities, the primary focus of policy-making has been on improving air quality through urban transportation systems. In France, the importance of this issue is so great that a portion of the "Sustainable Urban Development Program" is dedicated to enhancing air quality. Therefore, it appears that one of the most effective measures to improve air quality and combat air pollution is to reorganize urban transportation. Multiple factors influence urban air pollution, and thus, a comprehensive, multidimensional approach is essential for its effective analysis and management [2].

Bagheri et al [3] investigated the influence of driving characteristics and vehicle type on fuel consumption and emissions under real-world driving cycles. Their study demonstrated that driving behavior—including acceleration patterns, braking frequency, and average speed—significantly affects both fuel efficiency and pollutant emissions. Moreover, vehicle-specific factors such as engine type, age, and daily mileage were shown to play a crucial role in determining emission levels. The results highlight that taxis and high-mileage vehicles tend to exhibit higher fuel consumption and pollutant emissions compared to private cars, largely due to increased engine wear and degradation of emission control systems. This study underscores the importance of integrating vehicle type and real driving behavior into fuel consumption and emission models, providing essential insights for designing effective urban traffic and environmental management strategies.

Kadhim and Oshchepkov [4] examined the effects of different diesel fuel types on engine performance and exhaust emissions in a single-cylinder direct-injection diesel engine. Their results indicate that fuel composition plays a significant role in improving brake thermal efficiency and reducing pollutant emissions, particularly smoke and unburned hydrocarbons. Although a slight increase in NOx emissions was observed for some fuel types, the overall findings highlight the importance of fuel quality optimization as an effective approach for enhancing energy efficiency and mitigating environmental impacts in the transportation sector.

Heidari, Bikdeli, and Daneshvar [5] developed a dynamic model to analyze CO_2 emissions from urban transportation in Mashhad, Iran, over the period 2005–2030. Their study highlighted the strong relationship between vehicle usage patterns, urban growth, and carbon emissions, showing that increases in vehicle kilometers traveled and private car ownership significantly contribute to rising CO_2 levels. The model provides a framework for forecasting urban transportation emissions and emphasizes the need for integrated policies targeting both traffic management and sustainable urban mobility to mitigate long-term environmental impacts.

Mosharafi and Ansari [6] investigated the impact of fuel price increases on passenger vehicle fuel demand and pollutant emissions in their study *"Examining the Effect of Fuel Price Increases on Passenger Vehicle Fuel Demand and Emissions."* To analyze the relationship between fuel prices, fuel demand, and emissions, they employed a vehicle travel (vehicle kilometers traveled) function that incorporates several explanatory variables, including fuel price. Their findings indicate that an increase in fuel prices leads to a reduction in vehicle travel, which in turn decreases fuel demand. Accordingly, the study concludes that higher fuel prices are an effective instrument for reducing fuel consumption.

Najafpour et al. [7], in their study titled "Modeling Air Pollution (Carbon Monoxide and Nitrogen Oxides) Emitted from Passenger Vehicles in Mashhad," modeled air pollution generated by passenger vehicles in Mashhad in 2010. Their results suggest that policy measures aimed at reducing vehicle-related emissions should prioritize increasing vehicle scrappage rates. Based on the outputs of the applied modeling software, this approach yielded the greatest reduction in pollutant emissions compared to alternative strategies.

In major European cities, urban transportation is a key focus of air quality policies. In France, for example, the *Urban Sustainable Development Program* dedicates a significant component to improving air quality, highlighting the importance of managing urban transport. In developing countries, road vehicles are the main contributors to sudden increases in urban pollution. Effective evaluation of mitigation strategies requires integrated fuel consumption and emission models, as fuel quality, environmental conditions, vehicle type, mileage, road gradient, traffic, and driving behavior all influence emissions.

High-mileage vehicles, such as taxis, experience greater wear, sensor failures, and emission control degradation, resulting in higher fuel consumption and pollutant emissions than private cars. Aggressive driving patterns, frequent acceleration and braking, and suboptimal combustion control—especially under natural gas operation—further increase emissions. Notably, emissions rise sharply at low speeds (<30 km/h), emphasizing the need for traffic-based solutions to reduce urban air pollution and excessive fuel consumption.

2. Method

Studies show that every unit of economic growth requires one and a half to two units of growth in the transportation sector. This sector is the foundation of economic development, and progress in it is considered one of the indicators of a country's development. On the other hand, a long-standing relationship exists between economic development and the environment, which began in the 1970s with studies on growth limitations and sustainability. The relationship between per capita income and income inequality Kuznets in the form of an inverted U is one of the most well-known economic relationships, which has been further studied by other economists. In the 1990s, after observing evidence of a relationship between environmental degradation and per capita income, the Kuznets curve was introduced into these studies and named the environmental Kuznets curve. The concept of the new Kuznets curve is as follows: as per capita income increases in an economy, environmental degradation initially increases and reaches a maximum. Then, these effects decrease, and a U-shaped inverse relationship between per capita income and environmental pollution is observed.

Air pollution in the context of energy consumption and environmental quality is considered a flow variable in Foster's model. For example, while smoke is released from a vehicle, its pollution does not occur instantaneously and does not accumulate as a long-term reservoir. However, in other types of pollution, such as radioactive waste leakage and oil spills, pollutants appear as reservoirs and cause long-term effects. The formula in which Foster has defined pollution as a reservoir is:

$P = \alpha E - \beta A - \delta P$

Where:

- P is the pollution reservoir.
- E is energy consumption.
- A is pollution control activity.
- α, β, and δ are parameters.

Assuming that A can reduce the pollution reservoir in a proportional manner, we have:

$P = -\beta A - \delta P$

Furthermore, if the pollution reservoir decays exponentially with a rate $\delta > 0$, we have:

$P/P_0 = -\delta$

Where P_0 is the initial pollution reservoir.

Therefore, we can write:

$P = -\delta P_0$

From the other hand, the implementation of anti-pollution activities A requires energy. That is, A causes a reduction in S, the reservoir of energy. If a proportional relationship can be established between A and S, it can be written as S = -A - E. Since S is also affected by energy consumption in other economic activities, we can have:

$S = -E$

From the combination of these relationships, we can derive:

$S = -A - E$

Since S and P are the state variables in the dynamic system, and considering that they are subject to non-negative constraints:

$[P(T) \geq 0]$

$[S(T) \geq 0]$

$[E \geq 0]$

$[0 \leq A \leq \hat{A}]$

We need to find the optimal values of E and A to minimize pollution and energy consumption.

Furthermore, implementing anti-pollution activities A inherently requires energy consumption. This means A leads to a reduction in S, the energy source reservoir. If a proportional relationship exists between A and S, it can be expressed as S = -A with proper unit selection for A. However, since S is also reduced through energy use in other economic activities, we have: S = -E. Combining these relationships, we get:

S = -A - E

Given that the above relationships represent the dynamic changes in P and S, these equations can be used as equations of motion in this model. Accordingly, the model refers to P (pollution reservoir) and S (fuel reservoir) as state variables. Upon re-examining the relationships, it becomes clear that E (energy consumption) and A (anti-pollution activities) should play the role of control variables in this analysis.

Based on this, the utility function is as follows:

U=U[C(E),P] (Uc>0, Up<0, Ucc<0, Upp<0, C'>0, C"<0)

In this case, the dynamic optimization problem can be expressed as:

$$\int_0^T U[C(E)، P]dt$$

Subject to the constraints:

P=αE- βA- δP

S= -A-E

(T given) [P(T)≥0] Free P(0)=P0>0

[S(T)≥0] Free S(0)=S0>0

And E≥0 0≤A≤Â

This problem must be explained from two aspects. First, while the initial values of S and P are the same as their values at the end time T, the final values of pollution reservoir P and energy source reservoir S are free and only subject to the non-negativity constraint. The concept of this is that there is a vertical cutoff line cut for P and a vertical cutoff line for S. Second, both control variables E and A are confined to their respective control regions. For E, the control region is [0,∞] and for A, the control region is [0,Â], where Â refers to the maximum possible level of anti-pollution activities. Given that budgetary considerations and other factors may prevent unlimited environmental purification efforts, the assumption of an upper limit Â does not seem unreasonable.

Therefore, the process of reaching the solution begins by writing the Hamiltonian function:

H=U[C(E),P]+λp(αE-βA-δP)-λs(A+E)

In this relationship, the index of each co-state variable λ refers to the state variable associated with it. To maximize H with respect to the control variable E (where E≥0), the Karush-Kuhn-Tucker (KKT) condition is:

∂H/∂E≤0

With this complementary-auxiliary condition that E(∂H/∂E)=0, the extreme case E=0 (where consumption is generally stopped) is tried to be disregarded as much as possible. E>0 should be considered as a postulate. In this case, the complementary-auxiliary condition implies that the following condition must be satisfied:

∂H/∂E=UcC'(E)+αλp-λs=0

It should be noted that H must be maximized with respect to A. H is linear in the variable A and is given as follows:

∂H/∂A = -βλp - λs

Furthermore, E is constrained to the closed control set [0,Â]. Therefore, to maximize H, if ∂H/∂A is negative, the left boundary solution A* = 0 must be chosen, and if ∂H/∂A is positive, the right boundary solution A* = Â must be selected. In other words:

$$\beta\lambda p+\lambda s \binom{>}{<} 0 \quad \text{---->} \quad A^*=\binom{0}{\hat{A}}$$

By substituting the relation λs = UcC'(E) + αλp, which was previously derived, into the above relation, we obtain the other complementary condition:

$$UcC'(E) \binom{>}{<} - (\alpha+\beta)\lambda p$$

$$> A^*=\binom{0}{\hat{A}} \quad \text{---}$$

Thus, the optimal choice of A depends primarily on λp.

The optimal choice of anti-pollution activities A* can be either an interior or a boundary solution. Foster shows that in the current model, an interior solution is not feasible. To see this, consider the motion equations for the state variables:

λp = -∂H/∂P = -Up + δλp

λs = -∂H/∂s = 0 —> λs = constant

If A* is an interior solution, then:

βλp + λs = 0

Since λs is a constant, the last equation implies that λp must also be a constant, which means:

λp = 0 —> δλp = Up

However, the constancy of λs implies the constancy of Up as well. Since U is monotonic in P, only one value of P can exist such that Up takes on a specific constant value. Therefore, if A* is an interior solution, P must also be constant.

Assuming an initial pollution reservoir P0 > 0, for P to be constant, the final pollution reservoir must also be constant at P(T) = P0 > 0. For a problem with a free terminal line, the transversality condition includes the following relation:

P(T)λp(T) = 0

With a constant P(T), it is necessary that λp(T) = 0. Since λp is constant, this implies:

λp(t) = 0

It should be noted that the zero value for λp implies UcC'(E) = 0, which contradicts the assumption that both Uc and C' are positive. Therefore, the interior solution for A* in the current model must be discarded.

Thus, the only feasible policies are the boundary solutions A* = 0 (no anti-pollution actions taken) or A* = Â (pollution control actions taken at the maximum possible rate).

The research methodology employed in this study is system dynamics, utilizing cohort-based modeling. Recently, to overcome the limitations of conventional methods, system dynamics has been applied to study sustainable transportation systems. This approach is used to simulate the dynamic behavior of biological, biophysical, and social systems, based on relationships between stock and flow variables organized in feedback loops. It has gained attention for addressing long-term sustainable transportation issues, as conventional methods—such as econometrics and other statistical techniques—rely on past data and are less reliable. These methods do not account for necessary structural changes and interactions between the transportation system and the economy, society, and environment over time. In contrast, system dynamics examines cause-and-effect relationships within an integrated system. This approach became prominent in transportation research when researchers recognized the long-term limitations and unreliability of past-oriented models, which fail to capture structural changes and interactions between transportation, technology, and the environment over time.

Air pollution is a concerning and growing problem worldwide, particularly in urban areas. Today, hundreds of millions of people live in areas where air pollution exceeds safe levels. One of the sources of urban air pollution is the presence of light and heavy vehicles. Cars burn gasoline or diesel fuel and emit CO, various nitrogen oxides (NOx), burned hydrocarbons (HC), and other toxins. To better understand the role of pollution from mobile sources, it is necessary to develop a model that can estimate the total emission of pollution from these sources and, with the help of this model, examine the list of pollutants. [8,9]

A cohort can be a group of individuals, vehicles, trees, buildings, etc. The cohort model is based on dividing a population (cars, people, animals, etc.) into several subgroups or different cohorts with different ages. The cohort model practically enables us to identify the exhaust gases from vehicles with different age groups. Therefore, with the help of cohort models, we can identify that part of the total vehicle population that contributes the most to the total pollution from mobile sources. Cohort models are usually used to study populations where either tracking the activity of a specific group within the population is of interest, and the relative size of the cohorts changes dynamically over time and these changes are important to us [10]

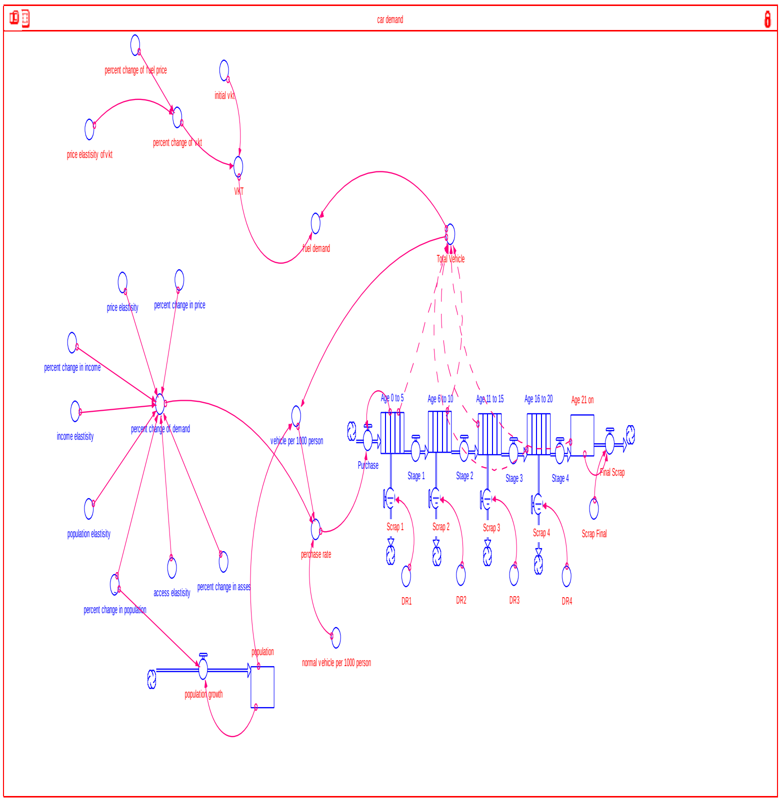
Due to the distinctive feature of the system dynamics approach—learning during modeling—gradually, with experience gained from the process using real data, the system's behavior can be tested. This enhances the model's accuracy throughout the modeling process and prior to its final validation. Generally, no model is entirely reliable, as every model will have shortcomings compared to the real system and the primary objective. Therefore, in practice, the focus should be on assessing the model's usefulness based on the problem's context and the defined objectives, rather than proving its complete accuracy. Hence, before using the model to determine and test policy options, confidence in its correct functioning must be established. If the model's output reflects the observed behavior of the problem, it can be assumed that the model includes the key elements and mechanisms responsible for generating the desired behavior. For this purpose, various tests, such as structural testing and comparing the model's output results with the observed behavior of the problem in studies, are employed. It is also essential to note that the degree of confidence in the model's accuracy depends on the modeler's perspective based on the designed dynamic model and the objectives the modeler intends to achieve with it [11]

Structural testing is conducted by comparing the causal and mathematical relationships between variables with existing knowledge about the real system.

In other words, the causal relationships in the feedback loop diagrams must be defined based on prior studies and existing theories in the field. In this study, the system structure has been designed based on research conducted in the areas of fuel demand models in transportation and vehicle emission models studies are among the systematic studies in vehicle emission modeling that have considered various components of vehicle demand and pollution in their modeling. In this study, efforts have also been made to pay attention to the literature when designing causal relationships [12]

In Graph (1), the stock and flow of vehicle demand in Tehran city is presented. In the designed stock and flow diagram, the number of vehicles in Tehran is divided into five groups based on their usage levels, with the depreciation rate of each group considered different from the others. In other words, it is expected that as the number of years of vehicle operation increases, its depreciation rate will also increase. On the other hand, the rate of change in vehicle demand is considered based on price, income, population, and road accessibility elasticities. The price and income elasticities used in the model are defined based on previous studies, while the population and road accessibility elasticities for vehicle demand in Tehran are incorporated into the model based on estimates made for the study area. In Figure (2), the subsystem for vehicle-generated pollution is presented.

Graph 1. Vehicle Demand and Flow Dynamics in Tehran



In the carbon dioxide production stock and flow diagram, the amount of pollution generated is defined as the product of the number of vehicles, the average distance traveled, and the rate of carbon dioxide production per kilometer traveled. The fuel consumption and average carbon dioxide production per kilometer for the passenger vehicle fleet were considered based on the study by [13].

Among the variables affecting the vehicle purchase rate in Tehran, income and price are key factors. The impact of changes in these variables on consumer behavior can be tracked through the price and income elasticities of vehicle demand in a study showed that demand for passenger cars falls within the category of durable goods, where demand depends on the price of the good, prices of complementary and substitute goods, income, and the existing stock of the good. The author estimated the demand function for passenger cars based on available data, considering vehicle demand in year t as a function of vehicle price in that year, income, and the existing vehicle stock in the previous period. Based on the results, the price elasticity of demand was reported as -2.47% and the income elasticity of demand as 3.05%.[14].

Table 1. Estimated coefficients of the vehicle demand model

variable	factor	probability	variable	factor	probability
width of source	***-58.08	0.00	width of source	0.73	0.70
population logarithm	***2.60	0.00	log accessed	***1.98	0.00
MA(1)	0.99	0.99	AR(1)	0.04	0.92
AR(1)	0.34	0.57			
	0.99	R^2		0.96	R^2
	1.84	DW		1.87	DW
(0.00)	223.09	F-Statistic	(0.00)	43.51	F-Statistic

source : research findings

The percentage change in the relevant variables (price, income, population, and road accessibility) has been calculated and calibrated based on the available data from the base period. In other words, the average rate of change of these variables in different periods was calculated and adjusted according to the model's performance. Therefore, based on the available data, the average annual rate of change in vehicle price was determined as 12.02%, the average annual income growth rate of Tehran households as 14.80%, and the average annual road accessibility growth rate as 2.22%. Additionally, according to statistics published by the Statistical Center of Iran, the population growth rate of Tehran city was reported as 0.80% during 1385–1390 and 1.3% during 1391–1395.

Behavioral Test

The model's ability to simulate the system's structure is evaluated by examining the system's past behavior and conducting sensitivity analysis. Once the model is validated, it can be used to study the system's behavior over a specific time period. In this study, the geographical boundary of the model is set to Tehran city, and the time period is a 24-year span (1386–1410). In the first step, the behavior of the designed system is simulated over the period 1386–1395 to be used for testing its behavioral performance. In this model, price, income, population, and accessibility elasticities of vehicle demand are considered as rate variables. Carbon dioxide emissions are modeled as a function of the number of vehicles, distance traveled, and average CO_2 emissions per kilometer. Initial population and population growth rate are based on data published by the Statistical Center. It should be noted that the population growth rate is entered into the model as a time series. Among the variables in the model, population and number of vehicles are used as reference variables for behavioral testing.

The behavioral test focuses on the model outputs by comparing the data generated by the model with historical data to assess how closely the model's data trends match the historical data. Since each statistical tool has advantages and disadvantages in comparing observed and simulated data, in this test, the observed and simulated data are first plotted, and then statistical tools such as the coefficient of determination and the correlation between the model's behavior and the actual behavior of the variables are examined.

Table 2 .Statistical test results of selected variables of model

statistics / variable	number of cars in tehran	population of tehran
(R^2)	0.94	0.99

source : research findings

Analysis of the Behavior of the Vehicle Pollution Production System

Number of Vehicles in Tehran

In this section of the study, the simulation results of key variables in each subsystem under the base scenario, assuming constant conditions, are reported.

The simulation results for the number of vehicles in Tehran are presented in Table (3). As observed, the number of vehicles in Tehran at the beginning of the simulation period is projected to be 6.009 million vehicles, and it increases by 2.26% annually to reach 6.139 million vehicles by year 1400. During the study period, this variable continues to grow and reaches 7.042 million vehicles at the end of the simulation period. Overall, the average annual growth rate of this variable from 1398 to 1410 is estimated at 1.33%.

Table 3. Projected Number of Vehicles in Tehran (in Millions)

averag e annu	2019	2021	2023	2025	2027	2029	2031	variable
1.33	6.99	6.139	6.306	6.510	6.664	6.799	7.042	total car numbers

source : research findings

The subsequent figure (4) illustrates the trend of the number of vehicles in Tehran over time. As can be observed, this variable exhibits positive changes and an upward trend throughout the study period, ultimately reaching its highest level by the end of the simulation.

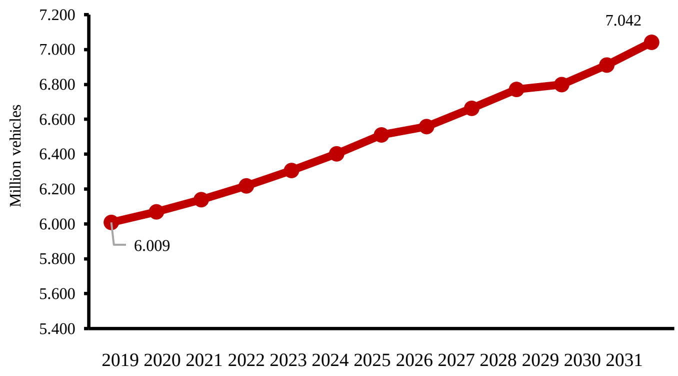


Figure 4 .the trend of predicting the number of car accidents

source : research findings

Population and road accessibility and driving comfort are also among the variables affecting vehicle demand. Based on the available data in this study, efforts were made to calculate the response of vehicle demand to changes in population and accessibility. The results of the estimation of the model are presented in the table below. The estimated coefficient for the logarithm of population is 2.60, which is significant at the 1% level. Additionally, the estimated coefficient for the logarithm of accessibility is 1.98. Given the logarithmic form of the model, these coefficients are used as elasticities in the designed model.

As shown in the designed storage-flow system diagram, the total number of vehicles in Tehran has been divided into 5 age groups. In the first age group, 0 to 5 years, the number of vehicles in Tehran at the beginning of the simulation period is projected to be 769,000 vehicles. This figure decreases to 720,000 vehicles in the year 1400 by 3.67%, and then increases to 838,000 vehicles in the year 1402. Overall, the average of this variable, defined as a storage in the modeling, is calculated to be 1,068,000 vehicles. More specifically, the number of vehicles in the 0 to 5 age group is expected to increase from 769,000 vehicles in the year 1400 to 662,000 vehicles in the year 1410. It is expected that the increase in the number of vehicles in Tehran will increase fuel consumption and consequently, the pollution caused by the emission of carbon dioxide.

According to Table (4), the number of vehicles simulated in the 6 to 10 age group in the year 1398 is 774,200 vehicles, which decreases to 1,030,000 vehicles at the end of the simulation period. Overall, there are fluctuations in the behavior of this variable during the simulation period, but the average is predicted to be 1,105,000 vehicles during the years 1395-1410. Similarly, the number of vehicles simulated in the 11 to 16 age group has shown an increasing trend at the beginning of the study, from 656,100 vehicles in the year 1398 to 719,200 vehicles in the year 1404. Subsequently, the behavior of this variable experienced a downward trend and reached 744,000 vehicles at the end of the simulation period. As shown in the designed model's results, the average number of 11 to 16 year old vehicles during the study period is calculated to be 924,100 vehicles.

Finally, the number of vehicles in the 16 to 21 years and older age group is projected to be 646,000 and 164,000 vehicles respectively at the beginning of the simulation period, which will be 591,200 and 1,015,000 vehicles at the end of the period, i.e., in the year 1410. Overall, the average of these two variables during the study period is 549,100 and 547,000 vehicles respectively.

Table 4 . Car numbers in different ages in tehran (million vehicles)

variable	2019	2021	2023	2025	2027	2029	2031	average car number
0 to 5 years	0.769	0.720	0.838	1.041	1.218	1.379	1.662	1.068
6 to 10 years	2.774	2.308	1.650	0.761	0.712	0.829	1.030	1.405
11 to 16 years	1.656	1.865	2.148	2.719	2.257	1.610	0.744	1.924
16 to 21 years	0.646	0.963	1.273	1.557	1.777	2.081	2.591	1.549
Higher	0.164	0.283	0.362	0.415	0.700	0.890	1.015	0.547

source : research findings

Figure (5) illustrates the trend of changes in the simulated number of vehicles in different age groups. The vehicle stock variable for the 0–5 years age group experiences an upward trend throughout the simulation period. However, the number of vehicles in other age groups exhibits fluctuations. For example, the number of vehicles aged 11–15 years initially shows a positive growth rate at the beginning of the simulation period. Then, it follows a declining trend until the year 1405, after which it increases again. However, the minimum value of this variable is observed at the end of the simulation period. According to the plotted graph, it can be stated that the vehicle stock variables for the 6–10 years, 16–20 years, and over 20 years age groups experience an increasing trend at the end of the simulation period, i.e., during the years 1406–1410.

As observed in the designed system, the changes in the number of vehicles in different age groups are influenced by the depreciation rate and the number of scrapped vehicles each year. Therefore, by changing the depreciation rate in different age groups, the number of vehicles also changes, and their movement trend will be accompanied by variations. In addition to these factors, the number of vehicles per 1000 people also plays a crucial role in defining the vehicle purchase growth rate.

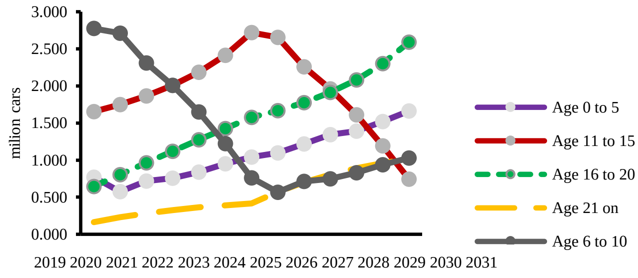


Figure 5. The predicted trend of the number of vehicles in different age groups.

source : research findings

The increase in the number of vehicles in Tehran has been accompanied by rising traffic congestion. Traffic is one of the major social issues in modern societies and large cities. Currently, a significant portion of household expenses is related to transportation and traffic costs. Moreover, the irreversible negative impacts of traffic on environmental pollution are a matter of serious concern. Developing countries are particularly vulnerable to pollution caused by traffic. The continuous rise in the number of vehicles and the need for mobility in our country—especially in its major cities—has intensified this problem. Tehran is no exception and has a unique situation. The city experiences heavy traffic and severe related problems, particularly in the city center, stemming from inadequate transportation infrastructure, excessive use of private cars, and insufficient public transport facilities.

According to the latest air pollution data for Tehran in 2017 (1396), passenger cars contribute to the emission of particulate matter in the city's air through four main pathways. Some particles are released directly from the exhaust of passenger cars, while others result from brake pad, tire, and road surface wear. Based on the source breakdown of pollutants in Tehran, passenger cars alone account for 14% of particulate matter emissions in the city. Additionally, exhaust gases from gasoline-powered passenger cars directly influence the formation of secondary particulate matter in the atmosphere. Passenger cars also contribute approximately 38% of total air pollutants in Tehran, indicating that gasoline-powered passenger cars are among the most significant pollution sources in the city. Reducing their traffic volume in the city will undoubtedly lead to a decrease in Tehran's air pollution.

The simulated results of Tehran's resident population are presented in Table (5). As observed, the population at the beginning of the study period is 9.005 million, and it increases to 9.242 million by the year 1400. It is expected that this variable will reach 10.522 million by the end of the study period, with an average annual growth rate of 1.3%. Overall, population growth is expected to accompany rising demand for transportation. Urban expansion in recent decades has led to an increase in the number of vehicles. Especially in large cities, traffic pollution is among the issues that threaten citizens' health. Cars, buses, and trucks play a significant role in air pollution.

Table 5. Prediction of Tehran's population during the study period (million people)

variable	2019	2021	2023	2025	2027	2029	2031	average annual growth (%)
Population	9.005	9.242	9.485	9.734	9.990	10.253	10.522	1.3

The population of Tehran increases during the study period through two main factors: natural population growth and migration into the city, with migration playing a significant role in population growth. One of the primary reasons for the high migration rate into Tehran is the availability of better job opportunities, due to the presence of industries and improved healthcare and medical facilities.

With the increase in the number of households in Tehran, pollution emissions rise in two ways: directly and indirectly. Direct emissions result from the consumption of energy sources such as electricity, heating fuels, diesel, and gasoline. Indirect emissions occur through industrial production, where households are the final consumers of products such as clothing, appliances, services, and food. Urban production is influenced by three main factors: labor concentration, structural changes, and replacing traditional energy sources with new energy types, all of which affect energy demand and consumption. As urbanization increases, so does the use of infrastructure, transportation, and energy. The shift from agriculture to industry also contributes to pollution in cities, including Tehran. The rapid population growth in Tehran, along with the consequent increase in private vehicle use, has made this source the most significant factor influencing air pollution in the city. Major consequences of the unchecked increase in private vehicles in Tehran include reduced vehicle speeds, engine idling at traffic lights, unnecessary braking, excessive street space occupation due to longer travel distances resulting from horizontal urban expansion, increased fuel consumption—especially of leaded gasoline, which is cheaper in our country—and consequently, higher air pollution.

Figure (6) illustrates the trend of population changes in Tehran. As shown, this variable exhibits a positive growth rate and reaches its highest level at the end of the simulation period.

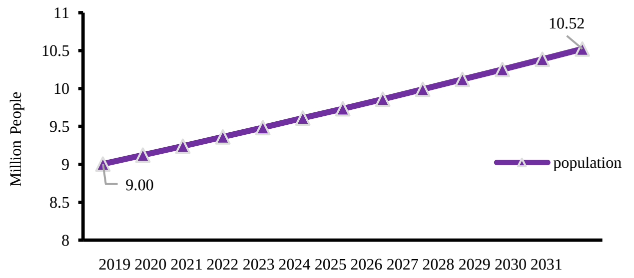


Figure 6. Trend of the predicted population of Tehran city

Due to the study's objective, this section reports the results of the simulation regarding carbon dioxide emissions resulting from vehicle traffic. As observed in the results of Table (6), the emission level in 2019 (1398) is projected to be 27,215 kilograms, increasing to 28,535 kilograms in 2021 (1400) with a 4% growth rate. The average annual growth rate for this variable during the years 2019-2021 (1398-1410) is estimated at 1.822%. The volume of carbon dioxide emitted at the end of the simulation period is projected to be 33,797 kilograms.

Table (6). Predicted level of emitted pollution during the study period (thousand kilograms)

average annual growth (%)	2019	2021	2023	2025	2027	2029	2031	Variable
1.822	27.215	28.355	29.460	30.660	31.797	32.645	33.797	carbon dioxide emissions

source : research findings

The change in the pollution variable in Tehran is defined in the designed dynamic system as a function of the number of vehicles, average distance traveled, and average carbon dioxide emissions per kilometer traveled. Generally, examining the trend of vehicle sales in Iran reveals that since around 1347, when vehicle production began in Iran, sales have followed an upward trend. After the Islamic Revolution and during the war period, this trend declined, but it resumed a rising trajectory from the beginning of 1368. In 1371, when the vehicle law was enacted, a significant shift occurred in the automotive industry, and growth between 1377 and 1384 was particularly rapid. Consequently, vehicle production in the country has increased in recent years, and manufacturers and importers continue to seek entry into this market. The most important variables influencing the prediction of future vehicle stock behavior are economic growth and population growth. In other words, vehicle demand, like other economic demands, is a function of relative vehicle price, income, fuel price, per capita income, population growth, road network, and urbanization rate. Analysis of published statistics confirms that Tehran's population has shown a growth trend. On the other hand, given the price and income elasticities of vehicle demand reported in various studies, it can be expected that an increase in price, assuming other conditions remain constant, will lead to a decrease in vehicle demand in the city. Conversely, due to the positive income elasticity of vehicle demand, an increase in household income in Tehran will be accompanied by higher demand for vehicles. Based on the calculated elasticities in this study and the growth rates of population, income, price, and accessibility variables, the annual percentage change in vehicle demand in Tehran has been estimated at 23%. Therefore, with the annual increase in the number of vehicles in Tehran, pollution emissions will also rise, and the city will face worsening environmental indicators compared to the past.

Figure (7) shows the trend of change in the carbon dioxide emission variable. As observed, emissions from vehicles in Tehran show an increasing trend. Overall, the average annual percentage change in this variable is predicted to be 1.822%.

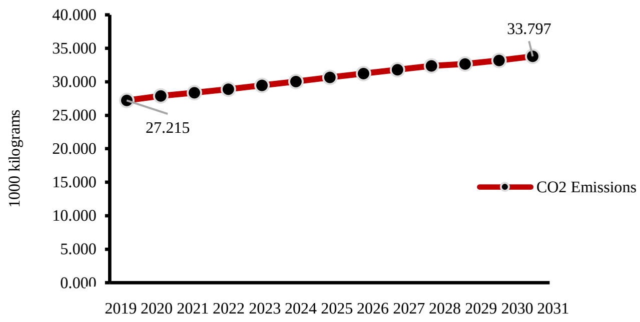


Figure 7. Trend of predicted pollution

source : research findings

Analysis of Pollution Control Policies

Effects of Increasing the Relative Cost of Vehicle Use (Fuel Price Increase)

In economics, deviations of relative prices from equilibrium values lead to inefficient resource allocation. In our country, due to abundant oil and gas reserves, energy carriers such as gasoline are available to consumers at prices significantly lower than global market prices. Currently, the price of energy carriers like gasoline is about half of the global market price, while the prices of crude oil, gas, and furnace oil are approximately one-fifth, and white oil is about one-seventh, and liquefied gas and natural gas are about one-third of the FOB (Free On Board) price of the Persian Gulf. This has led to excessive consumption of energy carriers in the country. The environmental issues arising from this growing consumption are concerning. Although environmental pollution in Iran is not solely due to low prices, and has non-monetary roots such as equipment wear and tear, weak and environmentally incompatible technology, and outdated, inefficient vehicles, studies indicate that prices play a crucial role in encouraging energy efficiency and the use of clean fuels. [15]

Among different economic sectors, transportation holds a significant position due to its essential role in economic development and accounts for 25% of the country's total final energy consumption, ranking second after the household and industrial sectors. Additionally, the high share of gasoline and gas oil in road and urban transportation, compared to other energy carriers, has created expectations that optimal energy consumption policies and investments in this sector could significantly reduce greenhouse gas emissions. A review of empirical studies in this field shows that in most studies, a significant inverse relationship exists between energy prices and emissions and greenhouse gases in various economic sectors. [16]

Since high energy consumption in the country is a key factor in the emission of air pollutants, designing policies to reduce these emissions must lead to reduced consumption of these carriers. Therefore, in this section of the study, an attempt has been made to examine the impact of fuel price increases on pollution levels in Tehran. Given that energy carriers are recognized as the primary source of air pollutants, it is expected that their emissions will also change following energy price adjustments. It should be noted that the term "fuel price increase" refers to a real increase, not a nominal one, as the persistent inflation in Iran's economy would neutralize the effect of price growth over several years. Thus, in this study, a stable and real increase in fuel prices is intended. [17-19]

The results of a 50%, 75%, and 100% increase in fuel prices on pollution levels are reported below. As observed in Table (7), the projected carbon dioxide emissions from vehicles at the beginning of the simulation period after the price increases are 27.13, 27.09, and 27.05 thousand kilograms, respectively. Implementing the price increase policy in this year results in a 0.30%, 0.44%, and 0.59% reduction in carbon dioxide production in Tehran. As expected, the increase in fuel prices, due to the low price elasticity of fuel demand, leads to a small change in the pollution variable.

According to the results, the pollution emission at the end of the simulation period after a 50% fuel price increase will be 33.70 thousand kilograms, which was 33.80 thousand kilograms before the scenario implementation. The results of the 75% and 100% fuel price increase scenarios also show that after implementing the scenarios, pollution emissions at the end of the simulation period will be 33.65 and 33.60 thousand kilograms, respectively. Although vehicle-related pollutant emissions exhibit an increasing trend throughout the study period, after a 100% fuel price increase, this variable reaches its lowest level.

The trend of pollution emissions after implementing the fuel price increase scenario is presented below. As observed, in the baseline scenario (Business as usual), pollution emissions are at their highest level, while after implementing the scenario of doubling the fuel price, they reach their lowest level.

Overall, the effectiveness of the fuel price increase policy under different scenarios is predicted to be -0.30%, -0.44%, and -0.59%, respectively. In other words, a 50% fuel price increase is expected to reduce annual carbon dioxide emissions by 0.30% on average. The average reduction in pollution production per year after implementing the second and third scenarios is predicted to be 0.44% and 0.59%, respectively.

The results of implementing the fuel price increase policy indicate that greenhouse gas emissions have decreased. Therefore, the second hypothesis of the study, which posits an inverse relationship between the relative cost of vehicle use (fuel price increase) and pollution emissions, is accepted. The increase in fuel prices, due to the price elasticity of fuel demand, leads to reduced energy carrier consumption and lower vehicle travel. Since pollutant emissions are directly related to travel distance, this policy is expected to reduce pollution emissions.

Effects of Improving Vehicle Engine Technology

In another section of this study, the impact of improving vehicle engine technology on pollution emissions was examined. To this end, the parameter EF in the designed system, representing the average carbon dioxide emissions per kilometer, was adjusted under the policy of engine technology improvement, and its effect on the target variable was tracked.

As shown in Table (8), a 10% reduction in the EF parameter resulted in pollution emissions of 24.49 thousand kilograms in 1398 and 30.42 thousand kilograms at the end of the simulation period. These values were previously 27.22 and 33.80 thousand kilograms, respectively, before the scenario implementation. Therefore, based on the results, it can be expected that implementing the proposed scenario will help reduce pollution emissions.

As a result, a 20% reduction in the EF parameter in the designed dynamic model predicts pollution production at the beginning of the simulation period to be 21.77 thousand kilograms, which will increase by 24% by the end of the period to reach 27.04 thousand kilograms. As illustrated in Figure (4-11), improving technology leads to lower pollution emissions throughout the simulation period compared to the baseline scenario.

As reported in Table (8), after implementing the policy of a 30% reduction in the EF parameter, carbon dioxide emissions, which were 19.05 thousand kilograms at the beginning of the simulation period, are projected to reach 23.66 thousand kilograms by the end of the simulation period.

Figure (10) illustrates the trend of pollution emission changes resulting from the technology improvement policy. As observed, improving vehicle engine technology leads to a reduction in pollution emissions, and it is expected that Tehran will improve its environmental indicators as a result.

Effects of Disposal Rate Changes on the Number of Vehicles and Pollution Emissions

In this section of the study, attention is given to the changes in the disposal rate for older vehicle age groups. In the initial conditions of the model, the base depreciation rate for vehicles aged 16 to 21 years and above was set at 7% and 20%, respectively. Under the scenario of increasing the disposal rate and removing older vehicles from the active cycle, as a strategy to reduce pollution, the disposal rate for these two groups of vehicles was increased to 10% and 25%, respectively, and its impact on the level of pollution emissions and fuel consumption is analyzed.

As shown in Table (9), the total number of vehicles after implementing the policy at the beginning of the simulation period was 5.991 million, of which 0.637 million vehicles belong to the 16 to 21 years age group and 0.139 million vehicles belong to the age group of 21 years and above. Implementing the policy in this year led to a 0.294% reduction in the total number of vehicles in Tehran.

As the simulation moves toward the final years, the effectiveness of the policy on the number of vehicles in Tehran increases. After implementing the policy of increasing the vehicle disposal rate, the number of vehicles in Tehran decreases by 0.514% compared to the baseline conditions. More specifically, it is expected that the total number of vehicles in Tehran in 1410, after implementing the scenario, will be 7.006 million, of which 2.556 million vehicles will be in the 16 to 21 years age group and 0.843 million vehicles will be in the older age group.

Table 9. Forecast of the impact of changing the depreciation rate on the number of vehicles (million vehicles)

2031	2029	2027	2025	2023	2021	2019	variable
2.556	2.054	1.753	1.551	1.257	0.952	0.637	16 to 21 years old
0.843	0.753	0.601	0.346	0.308	0.245	0.139	Higher
7.006	6.849	6.650	6.507	6.300	6.169	5.991	All vehicles
-0.514	0.737	-0.240	-0.057	-0.097	0.479	-0.294	Percentage change

source : research findings

Given that pollution emissions are assumed to be a function of the number of vehicles and the average emission per kilometer traveled, it is expected that a reduction in the number of vehicles in Tehran will lead to lower pollution emissions, while an increase in the number of vehicles will result in higher emissions.

More specifically, the results of implementing the depreciation rate policy on pollutant emissions from vehicles are reported in Table (10). As shown, under the baseline scenario, carbon dioxide emissions in 1398 are projected to be 27.215 thousand kilograms, which decreases by 0.553% to 27.065 thousand kilograms after the implementation of the depreciation rate policy. A reduction in carbon dioxide emissions is observed throughout the study period. The effectiveness of the increased depreciation rate policy increases over the years from 1398 to 1410, ultimately leading to a 1.839% reduction in pollution emissions by the end of the simulation period. As noted, the level of pollution in this year under the baseline scenario is 33.797 thousand kilograms, which decreases to 33.175 thousand kilograms after implementing the proposed scenario.

Overall, the results indicate that removing outdated vehicles from the transportation system holds promise for controlling pollution. The World Bank estimated in 2018 that the health-related damage caused by particulate matter (PM2.5) in Tehran amounted to $2.6 billion, and considering indirect costs such as the closure of offices and schools, the total damage would be even higher. Therefore, it is essential to take serious measures to reduce the emission of this pollutant in Tehran's air.

Table 10. Forecast of pollution emissions throughout the study period (thousand kilograms)

2031	2029	2027	2025	2023	2021	2019	variable
33.797	32.645	31.797	30.666	29.460	28.355	27.215	Carbon dioxide emissions in the baseline model
33.157	32.427	31.477	30.424	29.257	28.330	27.067	Carbon dioxide emissions after scenario implementation
-1.839	-0.669	-1.009	-0.790	-0.687	-0.083	-0.553	Percentage change

source : research findings

appearance and exacerbating traffic problems, results from their lack of pollution control systems and outdated technology dating back many years. This leads to unnecessary and wasteful fuel consumption, particularly gasoline (a significant portion of which is imported), and increases air pollution in urban areas. Therefore, a plan to retire outdated vehicles appears necessary, especially considering that these vehicles were produced when vehicle numbers were minimal and domestic production was very low.

Combination of Fuel Price Increase and Depreciation Rate Policy

In this section of the study, the combined effect of the fuel price increase and depreciation rate policy was examined. As shown in Table (11), the effectiveness of Scenario 1 (a 50% fuel price increase combined with an increased depreciation rate) at the beginning of the study period results in a 0.847% reduction in pollution emissions. More specifically, implementing the combined policy reduces emissions from 27.215 thousand kilograms to 26.985 thousand kilograms. At the end of the simulation period, this reduction is estimated at 2.129%. As observed, in year 1410, pollution emissions after implementing Scenario 1 are projected to be 33.078 thousand kilograms, which is 2.129% lower than the baseline scenario.

Under Scenario 2, pollution emissions at the beginning and end of the simulation period are projected to be 26.945 thousand kilograms and 33.029 thousand kilograms, respectively, which are 0.993% and 2.273% lower than the baseline.

With a higher fuel price increase under Scenario 3, the policy's effectiveness increases, resulting in a 1.140% reduction in pollutant emissions at the beginning of the period and 2.418% by year 1410. In other words, carbon dioxide emissions are projected to be 26.905 thousand kilograms and 32.980 thousand kilograms in these years, compared to 27.215 thousand kilograms and 33.797 thousand kilograms in the baseline scenario, respectively.

Table 11. Forecast of pollution emissions throughout the study period (thousand kilograms)

variable	Base	Scenario 1	Percentage change	Scenario 2	Percentage change	Scenario 3	Percentage change
2019	27.215	26.985	-0.847	26.945	-0.993	26.905	-1.140
2021	28.355	28.247	-0.382	28.205	-0.529	28.163	-0.676
2023	29.460	29.171	-0.980	29.128	-1.127	29.085	-1.273
2025	30.666	30.334	-1.083	30.289	-1.229	30.244	-1.375
2027	31.797	30.384	-1.301	31.337	-1.447	31.291	-1.953
2029	32.645	32.331	-0.962	32.283	-1.108	32.235	-1.255
2031	33.797	33.087	-2.129	33.029	-1.273	32.980	-2.417

source : research findings

Scenario 1: 50% increase in fuel price and change in depreciation rate

Scenario 2: 75% increase in fuel price and change in depreciation rate

Scenario 3: 100% increase in fuel price and change in depreciation rate

3.Conclusion

Given the complexity and dynamism of the transportation system and its multidimensional effects on the environment, the System Dynamics approach has been recognized as a powerful analytical tool for long-term transportation studies in recent years. This approach allows for more accurate analysis than retrospective and linear models, which mainly deal with one-dimensional and direct changes, due to its ability to model dynamic interactions, feedback loops, and structural changes over time.

In this study, by employing a two-subsystem System Dynamics model, not only the trend of changes in the number of vehicles over time but also their direct and indirect effects on the emission of carbon dioxide and other pollutants in Tehran have been simulated. The importance of this approach lies in its ability to more accurately model the impact of vehicle age cohorts, considering factors like depreciation, purchase rates, obsolescence, and the scrapping of old vehicles.

From a policy perspective, considering Article 50 of the Constitution and the approvals of the Parliament and the Guardian Council regarding the prevention of air pollution, a legal and standard framework has been established for pollution control. These laws, including clean air standards, permissible exhaust limits for vehicles, and industry standards, indicate attention to environmental challenges at political and executive levels. However, given the increasing concentration of pollutants in Tehran, especially in areas heavily reliant on transportation, there is a need for dynamic, combined, and modeling-based policies.

The presented model demonstrates that policies such as increasing fuel prices, improving vehicle technology, changing depreciation rates, and phasing out outdated vehicles can have a significant impact on reducing CO_2emissions. Specifically, the combination of these policies can act as a coordinated and effective solution for urban transportation policymaking.

Ultimately, this study shows that achieving sustainable and data-driven reductions in air pollution requires systemic approaches that can account for the complex interactions between the economy, technology, policy, and consumer behavior. This model can be utilized as a decision support tool for transportation and environmental protection policymaking in major Iranian cities, especially Tehran.

Suggestions:

1. Given the effectiveness of the policy to improve vehicle engine technology, it is recommended that the technology level in the vehicle's technical system, which leads to reduced fuel consumption and consequently lower pollutant emissions, be prioritized by automakers.
2. Considering the high volume of outdated vehicles throughout the simulated period and the role of their operation in pollution generation, phasing out old vehicles and paying close attention to vehicle technical inspections can significantly reduce carbon dioxide emissions.
3. The study results indicate that an increase in fuel price is substantially effective in reducing fuel consumption and pollutant emissions. Given the effectiveness of the fuel price increase policy in reducing greenhouse gas emissions in the road transport sector, it is suggested that this fuel price increase be implemented gradually until it reaches the FOB Persian Gulf price.
4. Finally, hope can be placed on the role of public awareness campaigns promoting optimal fuel use by citizens, reducing the use of private vehicles, and increasing the use of public transportation in controlling pollution. In other words, no matter how much the fuel price increases or how much new investment is made in transportation, if members of society do not commit to the optimal and appropriate use of fuel resources and vehicles, the implementation of these policies will not yield desirable and effective results.

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