Original Research

Evaluation based on Energy Consumption Reduction Policies, CO_2 Emission Education, and Economic Growth in Urban Transportation Systems using A System Dynamics Approach

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Abstract
This research examines the impact of energy consumption reduction policies, carbon dioxide (CO_2) emission reduction and economic growth in urban transportation systems. Given the increasing importance of environmental issues and sustainable development, system dynamics modeling and simulation have been chosen as the primary approach for this study. The research has been conducted in the context of Tehran, and efforts have been made to simulate the relationship between energy consumption, CO_2 emissions, and economic growth using the Vensim software. Initially, key variables and subsystems related to transportation, CO_2 emissions, and economic growth were identified, and the relationships among them were modeled. Various scenarios, such as increasing fuel prices and developing subway and bus rapid transit lines, were examined. The results showed that the development of public transportation infrastructure could have a significant impact on reducing CO_2 emissions. Additionally, rising fuel prices have negative short-term effects on household income but lead to decreased traffic and air pollution in the long term. This research emphasizes that investing in renewable energy and developing sustainable transportation plays a crucial role in reducing environmental impacts and improving quality of life. This study can assist urban policymakers in making more effective decisions for enhancing urban transportation and mitigating environmental effects, utilizing scientific approaches and dynamic system modeling.

Keywords – Carbon dioxide emissions; Economic growth; Environment; Gross domestic product (GDP); Urban transportation.

INTRODUCTION

The increase in urban population and urbanization in recent decades has created a growing demand for energy, transportation, and related infrastructure. This issue is particularly challenging in metropolitan areas like Tehran, which face heavy traffic, air pollution, and resource limitations. Urban transportation accounts for approximately a quarter of global energy consumption

and its associated carbon emissions, contributing significantly to climate change [1]. In this context, sustainable transportation and energy consumption reduction policies have become a main priority for urban policymakers. In Iran, the heavy reliance on fossil fuels and low fuel prices has resulted in the neglect of renewable energy usage and energy consumption optimization. This, along with the irrational consumption of fuel in the transportation sector, has led to excessive greenhouse gas emissions and increased air pollution [2]. Accordingly, the design and implementation of dynamic urban transportation models that consider the interactions between environmental, economic, and social variables seem essential.

This research utilizes system dynamics methodology and Vensim software to model and simulate the impacts of energy consumption reduction policies and carbon dioxide emission reduction in urban transportation systems. The main objective of the study is to identify and analyze the interactions between key indicators such as energy consumption, CO2 emissions, and economic growth, and to evaluate various scenarios such as increasing fuel prices and developing public transportation infrastructure. The results of this study can assist policymakers in designing optimal strategies for improving urban transportation and reducing environmental impacts. Furthermore, the findings emphasize the importance of investing in renewable energy technologies and strengthening public transportation infrastructure [3].

LITERATURE REVIEW

Research conducted in the field of urban transportation, carbon dioxide (CO_2) emission reduction, and energy consumption highlights the importance and necessity of addressing this issue at both national and international levels. Below is an overview of some related studies. A study conducted by Wang et al. (2021) showed that the use of renewable energy and the development of public transportation can have a significant impact on reducing CO_2 emissions and improving the quality of life in large cities. This study particularly emphasized that fuel pricing policies and subsidies for public transportation infrastructure can reduce environmental impacts [4]. Hatef Huzari and his colleagues presented a study in 2022 titled "The Impact of the Transportation Sector on Energy and CO_2 Emissions." This article primarily discusses the increase in CO_2 emissions and global warming due to fossil fuel consumption, which has risen due to fossil fuel trade. Developed and developing countries have been seeking optimal planning and appropriate methods in recent years that not only help them achieve their economic goals but also reduce the detrimental impacts on the environment caused by fossil fuel consumption. In this research, the impacts of fossil fuel trade (such as transportation and domestic production) on CO_2 emissions in selected developing and developed countries were examined for the period from 2000 to 2014. Econometric methods were employed, using a multivariate linear regression model with the ordinary least squares method for estimating the statistics. The results indicated that the impacts of fossil fuel trade in the domains of fossil fuel consumption in transportation and production (industry) have a significant relationship with carbon emissions in developed and developing countries. CO_2 emissions are a global issue that leads to global warming and ultimately causes harm to the environment (climate change), bringing unpredictable costs for both developing and developed countries.

The article also provides conclusions and policy recommendations for preventing increases in CO_2 emissions. [1] Azadeh Davudi conducted a study in 2015 titled "Decomposition Analysis of Carbon Emission Indicators (Carbon Dioxide and Carbon Monoxide) in the Transportation Sector and its Sub-sectors in Iran." The objective of this paper is to analyze the factors influencing carbon compound emissions (carbon dioxide and carbon monoxide) resulting from energy consumption in the transportation sector and its sub-sectors: road, rail, and air. This article utilized the Index Decomposition Analysis (IDA) method for the years 2009 to 2018 to examine the factors affecting carbon compound emissions. The results of this research indicate that, in the overall transportation sector, scale and economic growth have the most significant impact on the increase in carbon compound emissions. Additionally, emissions and fuel composition have also influenced emissions. The effects of price indicate that low fuel prices have led to increased carbon compound emissions. Energy intensity and structural changes in the transportation sector have also had a reducing effect on emissions. This paper shows that the use of clean fuels, development of public and rail transport fleets, and infrastructure development in all transportation sectors can help reduce carbon compound emissions. [5] Sara Balouchi and her colleagues conducted a study in 2020 titled "Electrification of the Transportation and Residential Heating Sectors as Support for Renewable Penetration: Scenarios for the Italian Energy System." One of the challenges related to integrating significant shares of renewable energy is the intermittent nature of these resources. However, there are solutions to support the integration of renewables, particularly if a smart energy system perspective is created to leverage the cooperative capabilities between different energy sectors. In this context, the transition of programmable consumption from fossil fuels to electricity is a strategy that can benefit renewable production that would otherwise be curtailed. This study evaluated the impact of simultaneously electrifying personal transportation and space heating

on the Italian energy system using Energy PLAN software. It examined how much the increase in electricity demand supports renewable development, utilizing both environmental and techno-economic indicators. The results indicated that both transportation electrification and heating can lead to a significant reduction in CO_2 emissions, about 25-30% if pursued separately.

Overall, the techno-economic optimization identified potentially optimal scenarios that could achieve a reduction of up to 47% in emissions and an increase in annual costs of up to 34% [6]. Pegah Nourouziyan Maleki and her colleagues presented a study titled "Forecasting Sustainable Urban Transport Demand for Managing and Enhancing the Safety of Road Networks Using a System Dynamics Approach." Currently, urban growth has led to population density, and residents of urban areas continually face the issue of travel demand throughout the day. This problem is particularly critical in densely populated cities like Tehran. One of the main challenges in Tehran is that the demand for travel using private vehicles consistently outweighs the use of public transportation, such as subways and buses. This leads to a high number of accidents, injuries, and increased mortality rates associated with private transport. Therefore, enhancing the safety of citizens in urban road networks is crucial. In this study, a system dynamics model was used to examine the factors influencing travel demand in Tehran. This model includes four main subsystems: population, travel demand, transportation investment, and traffic. Based on these subsystems, a flow-stock model was constructed, implemented through mathematical relationships, simulated, and validated. Additionally, various scenarios were simulated using real data from the city of Tehran. Within the context of this study, a set of proposed policies for managing travel demand and enhancing the safety of urban road networks is presented. Some of these policies include price control, development of public and rail transportation, reducing the use of private vehicles, and controlling fuel prices. The simulation results indicate that these policies are effective and are introduced as effective solutions for managing travel demand and increasing urban road safety [7].

RESEARCH METHODOLOGY

This research is categorized as applied research in terms of nature and method, utilizing the system dynamics approach for analyzing and modeling urban transportation systems. The research method includes the following steps:

I. Type of research:

- Nature of the Research: This study is applied, as its goal is to provide practical solutions for improving urban transportation and reducing its environmental impacts.
- Research Method: This study employs the system dynamics approach, which is a tool for analyzing complex interactions between variables in nonlinear systems.

II. Data collection:

- Information Gathering Method: A combination of library and field studies was used. Library sources included articles, books, and related research reports. Field information was obtained from the opinions of experts in the fields of transportation, energy, and the environment.
- Data Collection Tools: Questionnaires, interviews with experts, and reliable statistical data from relevant organizations, such as Tehran's Transportation and Traffic Organization.

III. Research steps:

- Problem Definition: The main issue involves the complex interactions between environmental, economic, and urban transportation variables and the impact of various policies on these variables.
- Identifying Variables and Subsystems: Key variables include CO_2 emissions, energy consumption, and economic growth. Related subsystems such as rail transportation, private vehicles, and urban infrastructure were identified.
- Designing the System Dynamics Model: Using modeling tools, such as causal-loop diagrams and flow-stock diagrams, the system structure was designed.
- Simulation: The designed model was simulated using Vensim software. Different scenarios, including fuel price increases and metro line expansions, were simulated to analyze the effects of policies.
- Results Analysis: The simulation outputs were analyzed, and the effects of scenarios on key indicators were evaluated.

IV. Software and analysis tools:

- Vensim software was used for designing and simulating system dynamics models. This tool allowed for visualizing relationships between variables and analyzing simulation results.

V. Statistical population and scope of research:

- Statistical Population: The urban transportation system of Tehran.
- Spatial Scope: The city of Tehran.
- Temporal Scope: Analysis of the urban transportation system over a ten-year period.
- Model Validation: The validity of the model was assessed using conventional methods in system dynamics, including comparing simulation results with real data. Sensitivity analysis of the model was also conducted to examine the impact of parameter changes.

OVERALL FLOW DIAGRAM OF THE PROJECT

As previously mentioned, based on past experiences and the modeling done, an initial model was created. Subsequently, based on the opinions of experts and relevant specialists, some transportation-related variables were added to the model. The relationships between these variables and their corresponding formulations were then incorporated into the model. These relationships and formulas were summarized using the same method, which will be detailed in the following pages. The flow diagram is typically considered as the final diagram that assists in writing the equations. In the flow diagram, details such as the definition of variables in the form of stock, flow, and auxiliary diagrams, the definition of constant values and parameters, the definition of table functions, and the inclusion of other special functions are presented. In this research, the model's flow diagram was drawn using Vensim software, which is displayed in figure 1.

ANALYZED SCENARIOS

Two main scenarios were examined in this study:

I. Increase in fuel prices: Assessing the impact of fuel price increases the reduce use of private vehicles, decreasing CO_2 emissions, and economic growth.

II. Development of public transportation infrastructure: Increasing the length of the metro network, rapid bus transit (BRT) lines, and its impact to reduce traffic and air pollution.

III. Results of the fuel price increase scenario:

- Impact on Energy Consumption: With the increase in fuel prices, the use of private vehicles temporarily decreased. However, the impact of this policy on reducing energy consumption was limited.
- Impact on Household Income: The increase in fuel prices led to a decrease in households' disposable income; however, long-term positive effects were observed in reducing private transportation costs and increasing public transportation use.
- Reduction in CO_2 Emissions: Significant reductions in CO_2 emissions were observed starting from the third year.

IV. Results of the development of public transportation infrastructure scenario:

- Impact on Traffic: The development of metro and BRT lines led to reduced urban traffic and increased public transportation use.
- Impact on CO_2 Emissions: A significant reduction in CO_2 emissions was observed. This reduction was attributed to decreased use of private vehicles and increased public transportation system usage.

- Impact on Quality of Life: Increased use of public transportation contributed to improved quality of life for citizens and reduced stress caused by traffic.

V. Comparison of scenarios:

- Reduction in CO_2 Emissions: Both scenarios led to a reduction in CO_2 emissions, but the public transportation infrastructure development scenario had a more significant long-term effect.
- Improvement in Economic Growth: The scenario involving the expansion of the metro and BRT networks contributed more to improving GDP growth, as it resulted in lower costs for citizens and facilitated access to new jobs.

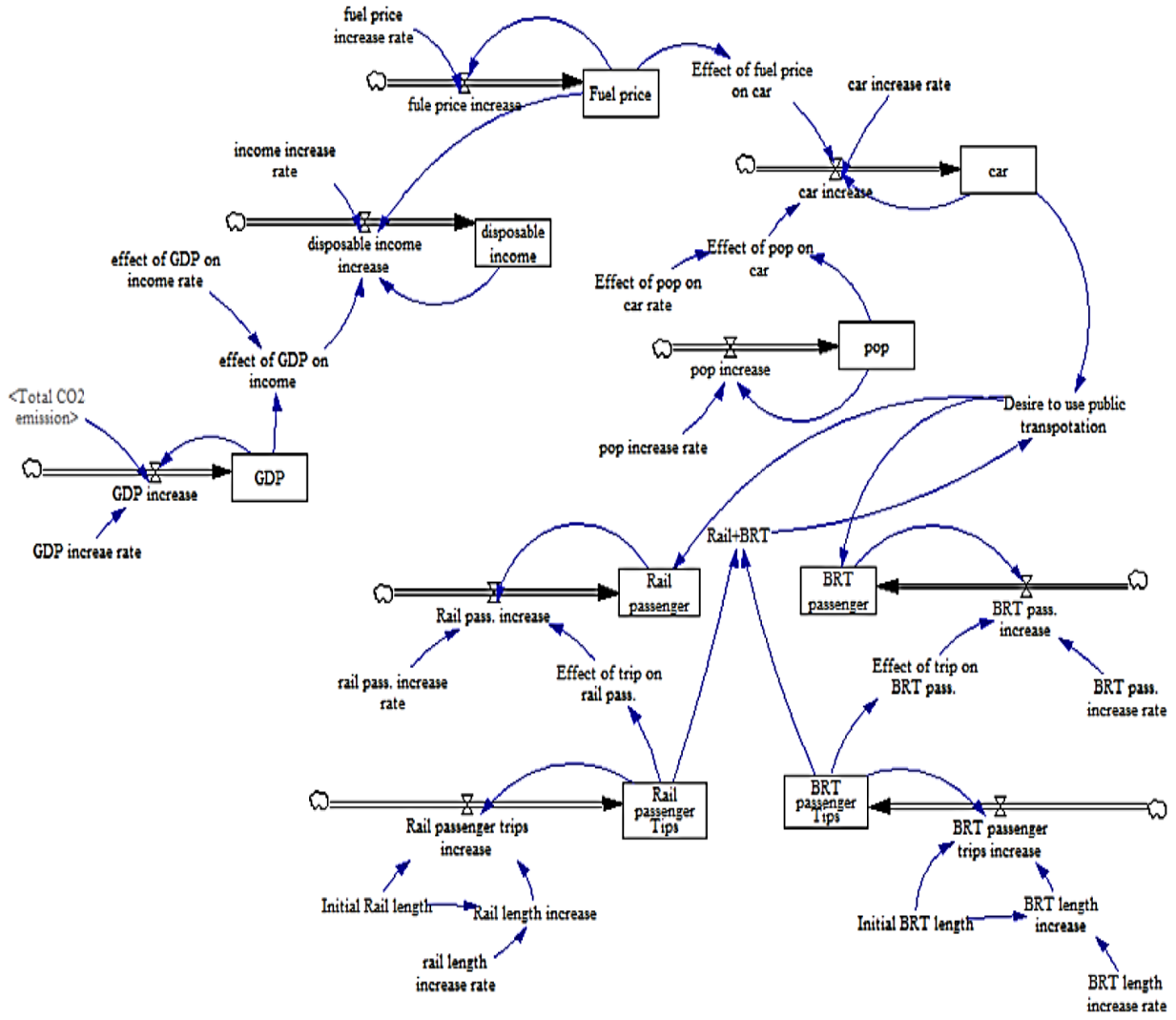

FIGURE 1

FLOW DIAGRAM OF THE URBAN TRANSPORTATION SYSTEM MODE

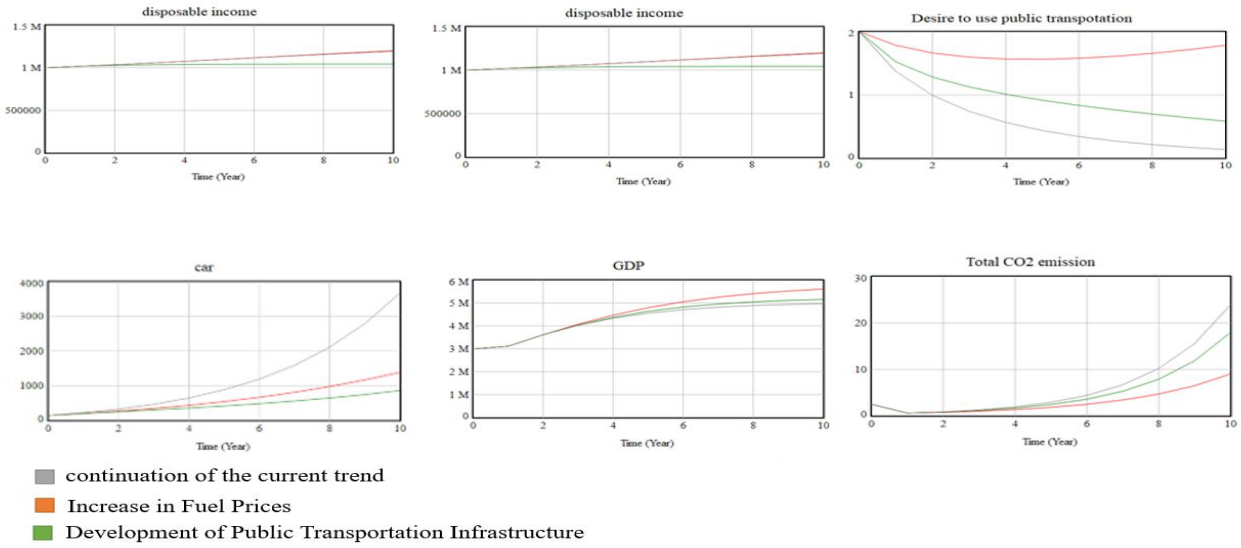

FIGURE 2
COMPARISON OF SCENARIOS

SENSITIVITY ANALYSIS OF THE MODEL

The model demonstrated that minor changes in fuel prices or the development of public transportation infrastructure could significantly impact reducing air pollution and improving quality of life.

OVERALL RESULTS

I. Investment in public transportation: Findings indicated that developing public transportation infrastructure, particularly metro lines, has a greater impact on reducing traffic and air pollution compared to increasing fuel prices.

II. Importance of combined policies: Combining fuel pricing policies with infrastructure development could simultaneously create greater economic and environmental benefits.

DISCUSSION

The findings of this research examine the impact of various policies on reducing energy consumption, decreasing carbon dioxide (CO_2) emissions, and improving economic conditions within Tehran's urban transportation system. This section analyzes the results obtained in various areas and compares them with similar studies.

I. Impact of fuel price increases: Fuel price increases led to reduced use of private vehicles and decreased CO_2 emissions; however, this impact was limited in the short term. In similar studies [4], emphasized that fuel pricing policies should be combined with the development of public transportation infrastructure to achieve more long-term effects. Additionally, the reduction in household incomes due to rising fuel prices creates challenges for citizen acceptance of this policy. These results align with findings from [1].

II. Development of public transportation infrastructure: The results indicated that expanding metro and BRT lines had a more significant impact on reducing air pollution and traffic than increasing fuel prices. This finding is consistent with studies by

[2], which emphasize the development of public transportation infrastructure to reduce air pollution. Moreover, increased access to public transportation contributed to improving citizens' quality of life and reducing traffic-related stress.

III. Comparison of Scenarios

- Fuel Price Increase Scenario: Had a limited impact in the short term and primarily contributed to reducing the use of private vehicles.
- Infrastructure Development Scenario: Demonstrated more positive effects in the long term, especially in reducing CO_2 emissions and improving economic growth.

These results indicate that to achieve sustainable development, combining these two policies is essential.

Importance of Investing in Renewable Energy

One of the key findings of this research is the importance of investing in renewable energy and its use within the urban transportation system. This finding aligns with Forster's [8] research, which emphasizes the use of renewable energy as a strategy to reduce dependence on fossil fuels.

Limitations and Challenges

I. Public Acceptance of Policies: Changing the urban transportation pattern to promote greater use of public transportation requires changing citizens' attitudes and educating them about the benefits of this shift.
II. Financial Resource Constraints: Implementing combined policies requires significant initial investment, which may encounter budgetary constraints in the short term.

Suggestions for Future Studies

I. Examination of Combined Policies: The combination of fuel pricing policies and the development of public transportation infrastructure should be studied more comprehensively.

II. Long-Term Analysis: Long-term simulations can provide more insights into the sustainability of these policies.

III. Expansion to Other Cities: Utilizing similar models in other metropolitan areas to analyze the effects of localizing policies.

Overall, the results of this research indicate that for reducing air pollution and energy consumption in the urban transportation system, combining fuel pricing policies and the development of public transportation infrastructure is more effective than implementing these policies separately. This research can serve as a model for urban policymakers in Iran and other developing countries.

Conclusion

This study aimed to assess the impact of policies aimed at reducing energy consumption, lowering carbon dioxide (CO_2) emissions, and promoting economic growth within Tehran's urban transportation system using a system dynamics approach. The results obtained from simulations conducted in the Vensim software indicated that various policies can have differing effects on improving urban transportation conditions and reducing environmental impacts.

Key findings

I. Fuel price increase scenario: This policy led to a reduction in private vehicle usage and fuel consumption in the short term. However, its negative effects on household incomes and living costs make it difficult for citizens to accept. Long-term positive effects included reduced traffic and air pollution.

II. Public transportation infrastructure development scenario: This policy significantly reduced traffic, decreased CO_2 emissions, and improved citizens' access to public transportation. Additionally, this scenario contributed to economic growth in the long term by lowering transportation costs and increasing productivity.
III. Policy combination: The results showed that combining fuel pricing policies and infrastructure development could simultaneously reduce environmental impacts, improve quality of life, and enhance the efficiency of the urban transportation system.

IMPORTANCE OF FINDINGS

- Investment in the development of public transportation infrastructure, particularly metro and BRT lines is one of the most effective strategies for reducing environmental impacts and enhancing urban sustainability.
- Energy and transportation policies should be implemented in a combined manner, considering social and economic impacts.

POLICY RECOMMENDATIONS

- Developing public transportation systems should be prioritized as a key strategy for reducing fuel consumption and CO_2 emissions.
- Increasing public awareness about the benefits of public transportation and the negative effects of private vehicles can aid in better acceptance of these policies.
- Utilizing renewable energy in the transportation sector should be recognized as one of the main policy objectives.

LIMITATIONS AND FUTURE DIRECTIONS

- Data and financial resource limitations for implementing the proposed policies were among the main challenges of this research.
- Future research should examine the effects of these policies in other metropolitan areas in Iran and conduct long-term simulations.

Ultimately, this research demonstrated that achieving sustainable transportation and reducing environmental impacts requires a combination of fuel pricing policies and public transportation infrastructure development, along with investments in renewable energy. These findings can provide valuable guidance for urban policymakers in pursuing sustainable development.

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