System Dynamics Model For Urban Transportation System To Reduce Fuel Consumption And Fuel Emission

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System Dynamics Approach for Urban Transportation System to Reduce Fuel Consumption and Fuel Emissions

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Abstract The world today is facing a severe environmental crisis. High fuel consumption by the various categories of vehicles in urban areas causes fuel emissions, worsening environmental conditions. This study aims to investigate and analyze the scenario-based System Dynamics (SD) models to reduce fuel consumption and fuel emissions. In this study, we built an SD model, including the factors influencing the transportation system, energy system, emissions system, and environment system. A broad range of policy scenarios was constructed for Chennai city, India, which considered criteria such as model split, fuel consumption, and fuel emissions. The SD simulation-based forecasting models are built considering three scenarios, such as do-nothing scenario, do-minimum scenario, and desirable scenario to project the SD parameters for the horizon year 2030. The scenarios of augmenting the proportion of public transportation and simultaneously restricting the proportion of private transportation by a model split of 10%:90% in the do minimum scenario and 20%:80% in the desirable scenario led to substantial reduction in the number of vehicles plying on the city roads. This has eventually resulted in pursuing a significant reduction in fuel consumption and fuel emissions. The results from SD simulation findings have led to the development of policies to regulate increasing fuel consumption and fuel emissions, based on the estimated figures.

Keywords Urban transportation system · System dynamics (SD) · Scenario analysis · Vehicular fuel consumption · Vehicular fuel emission

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1 Introduction

As the urbanization cycle accelerates, developing countries are under increased pressure to make savings in energy and reduce pollution, particularly for urban regions. Furthermore, energy consumption and CO_2 emissions from the public and private transport modes plays an important role in energy conservation and emission reduction. Travel demand models that can be used to forecast travel by mode, time of day, length of travel, or travel location must be built [1] immediately to examine the impact of one factor over the other. Enhanced capacity policies, which include mobility management strategies for conservation and emission reduction in both developed nations and developing nations, are required [2]. Collective actions and coordinated government initiatives are thus the immediate requirements for addressing the problems and reducing damages to improve productivity through the usage of renewable transport systems [3]. So, it is vital to comprehend the structures and the relationships between different transportation systems, energy systems, emissions systems, and environment systems of the urban region. As a result, the quantitative analysis of behavioral characteristics and the process of complex transportation of urban travelers have become important areas of study.

This work, therefore, aims primarily to study the energy and emission factors affecting the transport sector in road transport. In addition, we have developed three scenarios based on possible policies that could be adopted by the city administration to predict their potential for both reducing vehicle fuel consumption and reducing fuel emissions. The development of different alternative scenarios based on the System Dynamics (SD) simulation models to predict potential demands for the transport, energy, and emission sectors are also conducted. Later, the SD model scenarios are critically reviewed and evaluated in such a way that could tackle and minimize losses in transport, energy, and emissions. Finally, effective transport policies to ensure the implementation of a sustainable transport system are proposed.

2 Background Literature

In the past few years, a significant number of studies have been conducted into energy consumption and emissions.

Wang et al. [4] measured CO_2 and passenger car pollutants through 2000–2005, in order to find a reduction in the potential policies. The authors predicted the future trend in pollutant emissions from passenger cars under three different scenarios. Han and Hayashi [5] used the SD model to evaluate the influence of the supply chain and examined the effects of policy scenarios on traffic volume, modal share, energy conservation, and CO_2 emissions.

Rentziou et al. [6] anticipated urban passenger transport volume, energy consumption, and CO_2 emissions based on simultaneous equations. Song et al. [7] formulated a methodology for the development of mesoscopic fuel consumption and fuel emission models to assess the environmental impacts of Intelligent Transportation Systems (ITS) strategies.

Cheng et al. [8] explored three SD scenarios, which include fuel taxation, motorcycle parking management, and free bus service to potentially reduce vehicle fuel consumption and mitigate CO_2 emissions over a 30-year timeframe (from 1995 to 2025). The author suggested that the most efficient way of curbing growth in the number of private cars, the amount of fuel usage, and CO_2 emissions was both fuel taxing and motorcycle parking management.

Malik et al. [9] have carried out a comprehensive disaggregate-level analysis to quantify freight fleet emissions in Delhi, India. The effect of freight emissions on the environment of the city was quantified. This research work revealed that freight vehicles contribute 42.3% and 45.5% of the total PM_{10} and NO_x emissions, respectively. Interestingly, the light-duty freight vehicles were found to be a significant contributor to the overall pollution with 28.71% and 33.07% PM_{10} and NO_x emissions, respectively.

Akbari et al. [10] developed six scenarios using the SD technique and quantitatively analyzed them to figure out the best-performed scenario. They found that the comprehensive policy SD scenario-based model performed the best compared to all the other individual policies.

As can be seen from the abovementioned literature, not many studies have been made in the past that focused on the interconnection between transport, energy, emissions, and environmental systems. Furthermore, the implications of various transport policies have still not been studied through a systemic approach covering more facets of the urban transportation system. This has instigated the need for this research work considering the importance of co-existence among the 4E systems—'Engineering', 'Energy,' 'Emission,' and 'Environment.'

3 Study Methodology

A research approach to evaluate and examine the interrelationships among the transport, the energy, the emissions, and the environment is proposed in accordance with the principles of the SD methodology. In this study, using the SD technique, the effect of different scenarios on future fuel consumption and fuel emissions is predicted for 2018–2030. The three possible scenarios are the do-nothing scenario, do-minimum scenario, and desirable scenario. The collected data from the different sectors are used for the SD model conceptualization to establish the relationship between the variables of the urban road transportation system (public and private), fuel consumption, fuel emissions, and the environment sector. The analyses of the three different scenarios were carried out by assuming the modal split ratio between public and private modes of transport as 10:90 and 20:80 for the do-minimum scenario and desirable scenario, respectively. The results were compared under different scenarios to determine the benefits of the policy measures. In addition, based on the results

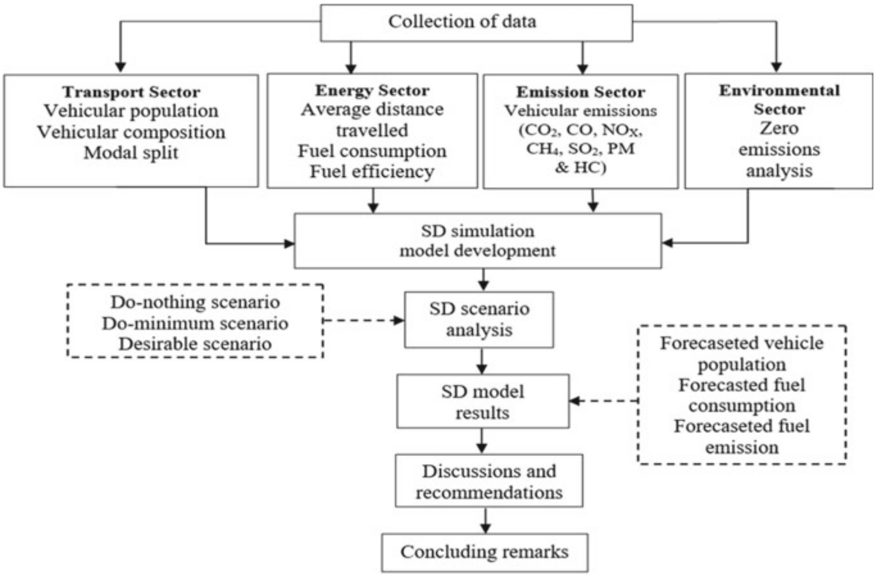

Fig. 1 Flowchart showing the study methodology

obtained and comprehensive discussions, important and relevant recommendations have been made for policy adoption. Figure 1 illustrates the study methodology.

4 Study Area

The city of Chennai, India, has been selected as the case study city to illustrate the application of proposed scenarios. The road traffic in the city is majorly occupied by private vehicles like Two-Wheelers (TW) and Cars (CR) and marginally by public transport vehicles like Metropolitan Transport Corporation Buses (BUS). However, the city roads are permanently hit by heavy traffic due to the density of the population and the frequency of TWs and CRs, which intensifies the concentration of emissions and energy consumption. Additionally, the rapid increase in the growth rate of the vehicular population, especially private vehicles (TW and CR), has increased fuel demand and emission levels. This has resulted in increased fuel prices due to fuel imports from other nations. Hence, it is considered alarming and imperative to study the impact of the increase in vehicles on fuel consumption and fuel emissions through a System Dynamics (SD) approach.

Table 1 Base year vehicle population

Class of vehicle									
Particulars	BUS	AR	TX	LCV	HCV	PB	MB	TW	CR
Count	7517	81,147	51,941	49,237	42,814	1677	3095	3,999,354	808,291
Percentage composition (%)	0.15	1.61	1.03	0.98	0.85	0.03	0.06	79.27	16.02

Source District statistical handbook Chennai district, 2016–2017 [11]

5 Data Collection

5.1 Transport Sector

The classified vehicle population data for the base year 2016–17 was acquired from the State Transport Department, Chennai, to forecast the horizon year (2030) vehicle population. The different classes of vehicles consist of public transport buses (BUS), auto-rickshaws (AR), taxis (TX), private buses (PB), mini-buses (MB), light commercial vehicles (LCV), heavy commercial vehicles (HCV), two-wheelers (TW), and cars (CR). Table 1 shows the various classes of vehicles along with their population of vehicles and the percentage composition in the city of Chennai.

Table 1 shows that the model split between public transport and private transport is 0.15%:95.29%. The present share of public transport is less than 1%, which is alarming. This classified vehicle population data is used to develop three different scenarios, such as a do-nothing scenario, a do-minimum scenario, and a desirable scenario. Furthermore, the SD models are developed on the basis of these data, and forecasts of fuel consumption and fuel emissions for the respective vehicle population have been made till the horizon year 2030.

5.2 Energy Sector

The energy sector is an important part of the transportation system's driving mechanism. However, there are concerns about this now and in the near future, given the limited availability of energy. The fuel consumption is measured according to the average journey distance and fuel efficiency. In the SD-model building and simulation development process presented in Table 2, the average distance traveled by the various classes of vehicles in km/day, the efficiency of fuel in km/liters, and the liter-year consumption of fuel are taken into account.

Table 2 Data regarding fuel efficiency and fuel consumption by different vehicle types

Parameter	BUS	AR	TX	LCV	HCV	PB	MB	TW	CR
Average distance traveled (km/day)	151	96	21	51	55	111	22	18	24
Fuel efficiency (km/liter)	4.1	21	13	14	4.33	5.0	8.7	53	12.9 (Petrol) 15.6 (Diesel)
Fuel consumption (liters/year)	13,415	1669	534	1330	4637	11,863	897	124	684 (Petrol) 652 (Diesel)

Source Ministry of Petroleum & Natural Gas, Government of India, Report of The Expert Group on a Viable and Sustainable System of Pricing of Petroleum Products [12]

Table 3 Pollutants emitted from the different vehicle types in grams/km

Class of vehicle									
Type of pollutant	BUS	AR	TX	LCV	HCV	PB	MB	TW	CR
CO_2	515.2	60.3	208.3	423.84	423.84	515.2	515.2	26.6	223.6
CO	3.60	5.10	0.90	1.61	1.61	3.60	3.60	2.20	1.98
NO_X	12.00	1.28	0.50	10.96	10.96	12.00	12.00	0.19	0.20
CH_4	0.09	0.18	0.01	0.05	0.05	0.09	0.09	0.18	0.17
SO_2	1.42	0.02	10.3	1.39	1.39	1.42	1.42	0.01	0.05
PM	0.56	0.20	0.07	0.33	0.33	0.56	0.56	0.05	0.03
HC	0.87	0.14	0.13	0.50	0.50	0.87	0.87	1.42	0.25

Source Ramachandra and Shwetmala [13]

5.3 Emissions Sector

India's transportation sector is the third-largest emitting sector for greenhouse gas (GHG), with the largest contribution from the highway transport sector. Chennai city, with a population of around 10 million, and more than 75% ownership of cars, is one of the largest emitters of various forms of pollutants. Table 3 provides data on the types of pollutants emitted from different vehicle types.

5.4 Environmental Sector

A clean vehicle strategy and a mobility management strategy can be adopted to reduce energy consumption and emissions of vehicles to zero levels. However, the implementation of both such strategies requires proper and comprehensive analysis and involvement of policymakers, government, and other stakeholders. Other emission mitigation measures can be the use of public bicycle sharing system, especially during winters, and improvement in the walking environment by setting up special driveways and pedestrian lanes, to meet the requirement of short-distance travel.

6 System Dynamics (SD) Model Development

System dynamics (SD) was first proposed by Forrester [14] to analyze dynamic complex system feedbacks. Based on computer simulation technology, this tool can analyze the relationships between various factors, simulate quantitative data, and provide information about the feedback structure and system behavior. This simplifies the understanding of the overall system and various relationships associated with policies related to the dynamic performance control of the system [15]. The SD model is not only capable of analyzing a system with several interrelated variables but is also capable of defining its complex patterns based on a limited collection of details [5]. The SD incorporates qualitative analysis with quantitative analysis and uses system synthesis logic to explain unknown behavioral features, making SD a better choice when dealing with non-linear, high-level dynamic time-varying processes. The SD models embodied the complex cycle of energy consumption and emissions and expressed the unpredictable nature of the key issues associated with urban transport systems. For these reasons, we have chosen an SD model to analyze the energy and emissions of the urban transportation system in Chennai city, India.

The vehicle population, fuel consumption, and fuel emission models have been established based on the proposed SD approach, which is presented in this section. The developed SD simulation models for scenario I (do-nothing scenario), scenario II (do-minimum scenario), and scenario III (desirable scenario) are shown in Figs. 2 and 3, respectively.

7 Scenario Analysis and Results

7.1 Forecasted Vehicle Population

The population is one of the key factors that affects passenger transport. The population growth has been one of the main contributors to average distance traveled, fuel consumption, and fuel emission. The existing growth rates in various vehicle groups have been assumed to continue up to the year 2030, according to the do-nothing scenario. On the basis of this, the vehicle population, fuel consumption, and fuel emissions values have been simulated and predicted.

The development of these scenarios focuses on reducing the use of personal TWs and CRs while increasing the use of BUS. The growth rate values of BUS (public): TW and CR (private) have been modified to 10:90 modal split for the horizon year 2030, in the do-minimum scenario. To achieve the 10:90 modal division between

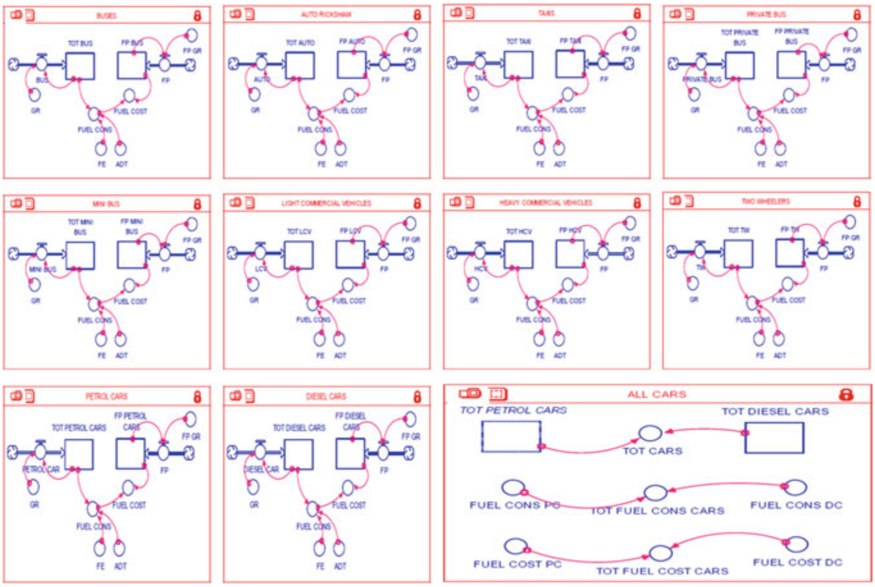

Fig. 2 SD simulation models for scenario I (Do-nothing scenario)

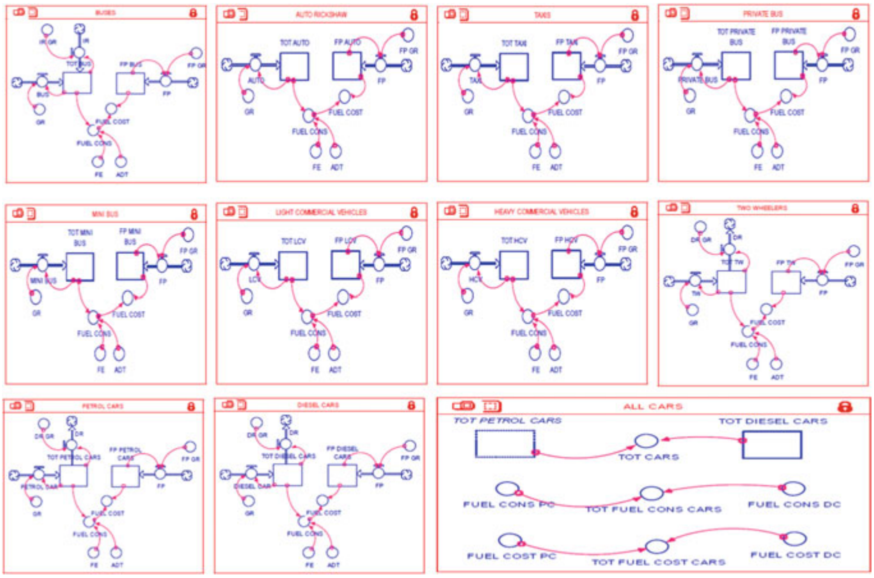

Fig. 3 SD simulation models for scenario II (Do-minimum scenario) and scenario III (Desirable scenario)

public and private modes of transport, the former has been increased to 12.63%, but the latter is limited to 6.98% and 8.24%, respectively. In the meantime, growth rates for other transport modes, including the AR, TX, LCV, HCV, PB, and MB, are slightly increased based on historical data.

The desirable scenario seeks to improve the attractiveness of public transport to optimize the structure of public transport qualitatively and quantitatively. However, total city trips cannot be covered by public transport while they can receive a considerable amount of trips. In this scenario, the growth rate values of BUS (public): TW and CR (private) have been altered in which a 20:80 modal split between public and private transport modes is assumed. In order to achieve a 20:80 modal split between public and private transport modes, the growth rate of BUS has been increased to reach 20.66%, whereas the growth rate of TW and CR is restrained from being 4.21% and 4.52%, respectively. Meanwhile, the growth rates of the other modes of transport like AR, TX, LCV, HCV, PB, and MB are assumed to be marginally incremented based on the historical data.

Additionally, it is hypothesized in this study that 30 TW and 15 CR with vehicle occupancy values 1.5 and 2.3, respectively (Chennai Comprehensive Transportation Study [16]), could replace one single BUS. Hence, a single BUS could have the capacity to accommodate a maximum of 80 persons. However, CCTS-2010 [16] reported that 'during peak hours, the buses operate with more than 100 passengers per bus indicating substantial overcrowding'.

7.2 *Forecasted Fuel Consumption*

It is well known that as the population of vehicles rises, the fuel consumption and fuel emissions also increase for different vehicle classes, and vice versa. Figure 4

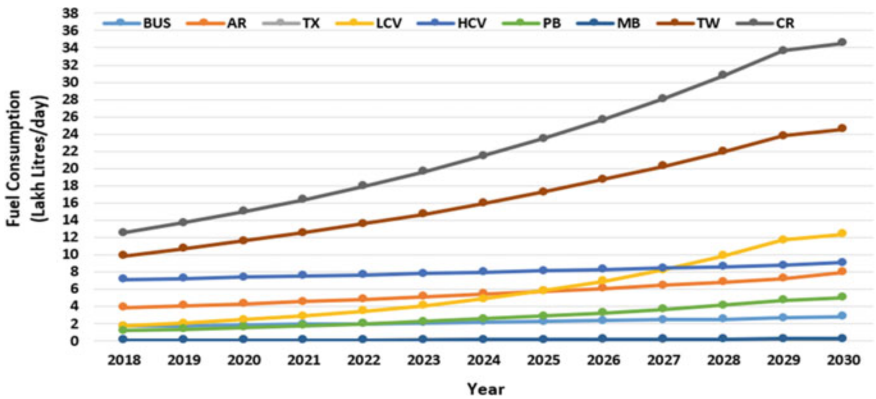

Fig. 4 Scenario I results—consumption of fuel till the horizon year

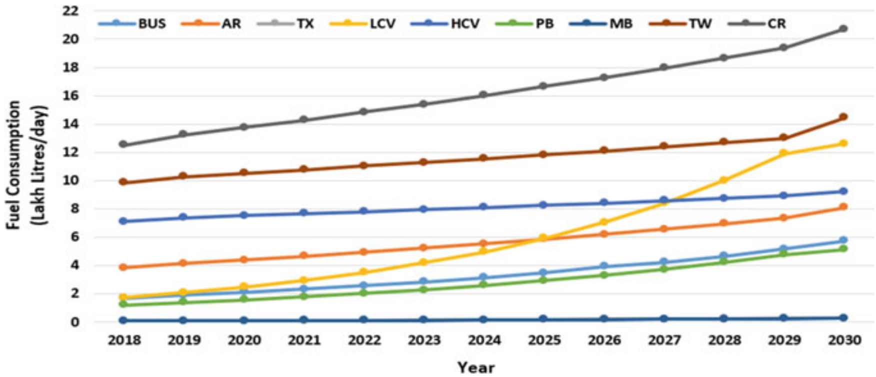

Fig. 5 Scenario II results—consumption of fuel till the horizon year

illustrates the results of scenario I (do-nothing scenario) in which the forecasted fuel consumption by each class of vehicle is represented.

The scenario of do-nothing indicates a rise in fuel consumption, following the increase in the number of vehicles in the public and private transport. CR has an expected fuel consumption of 34.02 lakh liters a day, TW has 24.11 lakh liters a day, and BUS has a forecasted fuel consumption of only 2.61 lakh liters a day over the horizon year 2030. Finally, all vehicles will consume 104.81 crore liters per day in the horizon year 2030. That will contribute to the annual fuel consumption of 382.55 crore liters annually.

In the do-minimum scenario, the changes in the share rate of different transport modes such as BUS (public): TW and CR (private) were kept at 10:90. Due to this, fuel consumption decreased, and this is shown in Fig. 5.

Adjustments in the growth rate of the number of vehicles between public and private transport have shown that fuel consumption varies accordingly for each vehicle type. The fuel consumed by CR is reduced to 20.42 lakh liters per day from 34.02 lakh liters per day (scenario I) for the year 2030. TW consumes 14.20 lakh liters per day of fuel when compared to the scenario I's 24.11 lakh liters per day in the year 2030. The fuel consumption for CR and TW is down by 39.98% and 41.10%, respectively. The fuel consumption by BUS mode of transport increases from scenario I's 2.61 lakh liters per day to 5.98 lakh liters per day in 2030, which is about 129.12%.

It can be said from these results that the fuel consumption of BUS has increased, but when we take the fuel consumption per person traveling in BUS into account compared to that of people who combinedly use TW and CR, it can be said that the former modes of transportation's consumption of fuel is considerably less than that of the latter. Compared to the outcome of scenario I, it can be seen that the total fuel consumed by all vehicles in scenario II has reduced to 308.61 Crore liters per year from 382.55 Crore liters per year in 2030, showing that all vehicles' fuel consumption in scenario II gets reduced by 73.94 Crore liters per year. Therefore, annual fuel consumption savings amount to 23.95%.

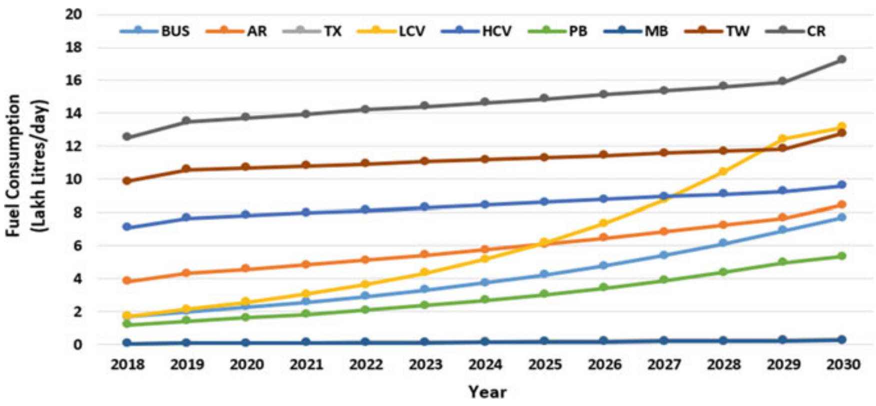

Fig. 6 Scenario III results—consumption of fuel till the horizon year

In the desirable scenario, the changes in the share rate of different transport modes such as the BUS (public): TW and CR (private) were kept at 20:80. Due to this, fuel consumption decreased, and this is shown in Fig. 6.

The CR fuel consumption reduces to 16.94 lakh liters per day in scenario III from 20.42 lakh liters per day (scenario II), and from 34.02 lakh liters per day (scenario I). The TW fuel consumption reduces to 13.01 lakh liters per day in scenario III from 14.20 lakh liters per day (scenario II), and 24.11 lakh liters per day (scenario I). The BUS fuel consumption increases to 7.98 lakh liters per day from scenario II's 5.98 lakh liters per day, and from scenario I's 2.61 lakh liters per day. The combined fuel consumption of CR and TW transport is 54.44 lakh liters per day, while that of BUS is just 7.98 lakh liters per day.

The fuel consumption in BUS has been increased, but when we take account of the fuel consumption of individuals who travel in the BUS in comparison to those who use both TW and CR, it can be assumed that the fuel consumption in the former modes of transportation is considerably lower than in the latter modes. The consequence of this scenario analysis is a combined increase. Comparing the results of scenarios II and I, with scenario III, it was found that the total fuel consumed by all the vehicles decreased to 276.44 crore-liters annually from scenario II's 308.61 crore-liters annually and to scenario I's 382.55 crore-liters annually in the year 2030. It indicates an annual fuel consumption saving of 106.11 crore-liters, which resulted in 38.38% fuel consumption reduction as compared to scenario I's fuel consumption.

7.3 Forecasted Fuel Emissions

When contemplating the do-nothing scenario, the difference in the growth rate of the number of vehicles and the fuel consumption of each type of vehicle between the public and private modes of transport has been found to have a significant direct impact on fuel emissions. Figure 7 shows this.

Figure 7 reveals that the fuel emissions of CR, TW, and BUS would hit 13.15 Gg/day, 7.89 Gg/day, and 0.82 Gg/day, respectively, if the present pattern is permitted up to the horizon year 2030. Consequently, all the vehicles could produce a total of 30.62 Gg/day of fuel emissions, which would result in a total annual fuel emission of 11,176 Gg/annum. This impact must be minimized by effective policies and preventive measures, which are to be developed and evaluated with immediate effect. Hence, the study further considers two main SD-based simulation scenario models. The following sections discuss these SD models.

In the do-minimum scenario, Fig. 8 illustrates that the fuel emissions by CR decrease to 9.30 Gg/day from scenario I's 13.15 Gg/day and the fuel emissions by TW decrease to 4.66 Gg/day from scenario I's 7.89 Gg/day while the fuel emissions

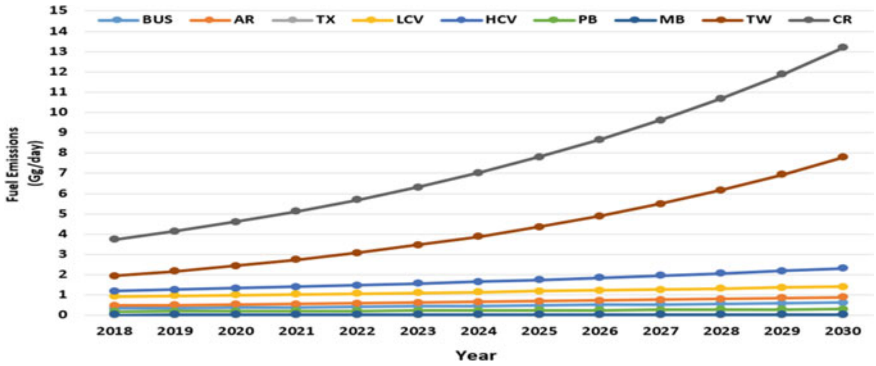

Fig. 7 Scenario I results—fuel emissions till the horizon year

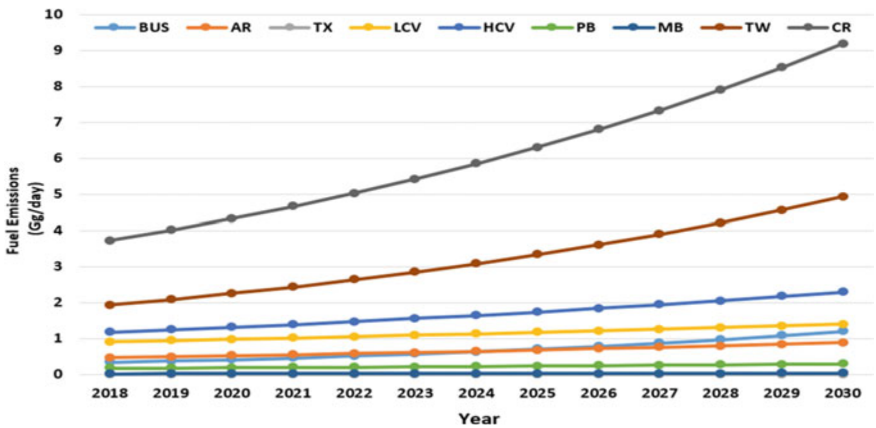

Fig. 8 Scenario II results—fuel emissions till the horizon year

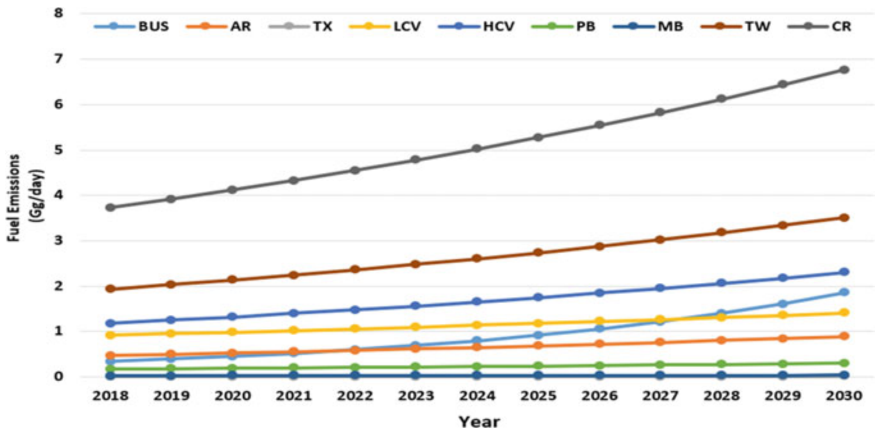

Fig. 9 Scenario III results—fuel emissions till the horizon year

by BUS increases to 1.28 Gg/day from scenario I's 0.82 Gg/day for the horizon year 2030. The private transport emissions are 12.55 Gg/day, while public transportation emissions only amount to 1.28 Gg/day.

It is evident from the above that while BUS' fuel emissions have risen, it can be said to be much lower than in the former transport mode if we consider the fuel emissions per person traveling in BUS as regards those using CR and TW combinedly. The cumulative fuel emission vehicles in scenario II have reduced to 3094 Gg/annum from scenario I's 8082 Gg/annum and from scenario II's 11,176 Gg/annum in the 2030 horizon. Therefore, fuel emissions have been reduced by 38.28%.

In the desirable scenario, the results from the contribution rate of different transport modes to fuel emissions are shown in Fig. 9.

In the desirable scenario, the fuel emission by the fuel emissions by CR decreases to 6.87 Gg/day from scenario II's 9.30 Gg/day, and from scenario I's 13.15 Gg/day. Similarly, TW decreases to 3.65 Gg/day in scenario III from scenario II's 4.66 Gg/day and from scenario I's 7.89 Gg/day, while the fuel emissions by BUS show a slight upward trend which increases to 1.88 Gg/day scenario III from scenario II's 1.28 Gg/day and from scenario I's 0.82 Gg/day. The private transport emissions are 10.52 Gg/day, while public transportation emissions are 1.88 Gg/day.

When these resulting values are compared with the results of scenarios II and I, it can be seen that the overall fuel emissions of all vehicles in scenario III dropped to 6572 Gg/annum from scenario II to 8082 Gg/annum and scenario I to 1176 Gg/annum by 2030. As a result, the annual reduction in fuel emissions relative to scenarios I and II was equivalent to 6572 Gg/annum and 1510 Gg/annum, respectively, resulting in a reduction of 41.19% and 18.68% in fuel emissions in scenario III by 2030.

As 'prepare and prevent is better than repent and repair,' promoting fuel-efficient vehicles on a larger scale can be obtained by enhancing and encouraging the use of the public transport system innovatively and systematically. Further, this scenario can bring significant amounts of annual economic savings to the people and governments by reducing energy consumption and adverse environmental effects. However, implementing this scenario requires the huge potential of cooperation and coordination from the top-down and bottom-up authorities.

8 Discussions and Recommendations

This study recommends that the increase in the BUS fleet size of the urban public transportation with greater efficiency and reliability and restriction in private transport may be implemented on a pilot basis for a zone or area to achieve sustainable development. It should be remembered that it might not be possible to enforce the desired scenario immediately. The main reason is that, because of resource and technology constraints, urban transport is difficult to make significant strides in the short term. However, the public transportation sector should be emphasized and enhanced due to its importance. Besides, 'it is believed that improving the quality of vehicles and their performance can greatly decrease fuel consumption and CO_2 emissions' [10].

Finally, this study recommends that besides implementing the conventionally applied and the recommended mitigation measures to the 4E systems—'Engineering', 'Energy,' 'Emission,' and 'Environment', calculated and strategic actions are to be taken with immediate effect considering the additional 3E's also, i.e., the Education, Ethical values, and Enforcement into the 4E systems for a prosperous and sustainable development of the city. All strategies, therefore, need tremendous cooperation and teamwork capacity from the highest and lowest governments. These policies will eventually reduce fuel consumption, fuel emissions, and environmental impacts considerably to ensure that the Sustainable Development Goals (SDG), which are adopted globally, are met.

9 Concluding Remarks

This study used SD models to understand the interrelationship between the transport system, energy system, and emission system. The SD simulation model predicted the fuel consumption and fuel emission levels when the share rate of transport was considered as business as usual or in the do-nothing scenario, 10:90 in the do-minimum scenario, and 20:80 in the desirable scenario. These policy measures will eventually lead to a considerable reduction in fuel consumption, fuel cost, and fuel emissions in the city. The study concluded that the desirable scenario gives the best results in terms of reduction in fuel consumption and fuel emissions. The presented approach and prediction results will help the transport planners and decision-makers to assess the potential needs of energy expenditure and transport infrastructure needs.

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