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System Dynamics for Enhancing Urban Mobility in India: Solution for Traffic Congestion and Carbon Emissions

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Abstract: India is a decisive player in the global economic platform and continuing its standing as fastest-growing major economy. The rapid rise in population growth, the surge in vehicular traffic, and the establishment of small-scale industries are leading to deteriorating environment, road accidents, worsening traffic congestion and dissimilarity in access to mobility in Indian cities. Better urban mobility can play a major role in unlocking the Indian cities potential. In this paper a system dynamics based sustainable urban transportation model is designed and developed to reduce total vehicle population, carbon emissions and road traffic congestion by monitoring the impact of five formulated and generated policy scenario maps. The system dynamics approach is a computer-aided approach based on causal feedback structure and feedback dynamics. The model incorporates seven sub-models: total population, gross domestic product, environmental impact, total vehicle population, road transport demand, road transport infrastructure, and road traffic congestion. The factor of policy scenario implication is selected as a control variable within the model simulation framework. The model simulation results indicate that a powerful endorsement policy scenario map can lead to a decrease in total number of vehicles, which in turn promotes the rapid adoption of sustainable technologies, such as electric vehicles. This model also contributes to enhance urban mobility of India by creating a sustainable urban transportation system and to achieve carbon neutrality.

1. INTRODUCTION

Urban transportation is a critical component of urban development, enabling the efficient movement of goods and people within cities. According to the 2011 census, India's urban population stood at 360 million, accounting for 30% of the total population. By 2051, this figure is expected to reach 820 million, representing 46% of the total population. The rapid urbanization in fast pace expanding cities is leading to a significant increase in urban travel demand and environmental degradation. To meet high travel demand in India, various types of slow and fast transportation modes are utilized. The sustainable development of India's urban transportation system is vital for achieving an eco-friendly, resource-efficient, and people-centered society. The core of sustainable urban transportation system lies on three pillars: economic viability, environmental sustainability, and social equity. These pillars lead the expansion and implementation of lifelong and valuable critical strategies.

A well-planned, sustainable urban transport network not only improves urban mobility but also enhances economic productivity, environmental conservation, and social well-being. Sustainable urban transportation reduces greenhouse gas emissions, minimizes air and noise pollution, and promotes energy efficiency through the adoption of cleaner technologies such as electric vehicles (EVs) and renewable energy-powered transit systems. Moreover, transportation is a major contributor to climate change. While policies are shifting toward demand-driven and sustainable strategies, challenges such as inadequate governance and monitoring hinder progress. The major transportation problems, shortcomings of current policies and proposed potential solutions was highlighted by (Verma et al. 2021). The structure of India's urban system using the rank-size rule, Gibrat's law, and a primacy index, revealing a top-heavy distribution was analyzed by (Shaban et al. 2020). Although cities contribute over three-fourths of the country's GDP, they are grappling with issues such as congestion, pollution, and social polarization. This imbalance hampers regional development and limits the urban potential for economic and social transformation. To achieve sustainable urban transport, it is essential to implement eco-friendly solutions that cater to the diverse needs of all users. Using the Interval Analytic Hierarchy Process (IAHP), (Ghorbanzadeh et al. 2018) conducted a study in Mersin, Turkey, which analyzed the preferences of users, non-users, and experts. This method successfully achieved a stable consensus for future public transport planning. Additionally, urban freight transport in developing countries faces challenges such as mixed traffic and inadequate infrastructure. In their review of Indian studies, (Dhonde & Patel 2021) highlighted existing inefficiencies and suggested potential improvements for the sector.

India's urban transport system is undergoing a rapid transformation, driven by increasing urbanization and rising vehicle ownership. As of 2021, the country had 39 cities with populations exceeding one million, leading to a surge in demand for efficient and reliable transportation services. However, this expansion has brought significant challenges, including severe traffic congestion, escalating air pollution, and a growing number of road accidents. A major contributor to these issues is the transportation sector, which remains one of the largest sources of carbon emissions in the country. The steady rise in the number of vehicles, particularly those powered by fossil fuels, has led to a substantial increase in CO_2 emissions, adversely affecting local air quality and contributing to global climate change (IEA, 2023). This trend is further exacerbated by the lack of well-integrated and efficient public transportation systems in several Indian cities, making personal vehicle ownership the primary mode of commuting. As a result, India continues to face mounting environmental and public health concerns linked to urban mobility (Statista, 2023).

To address these major challenges, this study employs a system dynamics (SD) approach to model and analyze the evolution of urban transportation systems. The system dynamics modeling technique enables the simulation of complex real-world problems by integrating both qualitative and quantitative methods in a synergistic manner. It provides a holistic framework for understanding the interdependencies within the transportation sector, capturing feedback loops, and assessing the long-term impacts of various policy interventions. By incorporating system reasoning and dynamic interactions, SD modeling helps in generating scenarios that can aid in decision-making for sustainable and efficient urban mobility solutions. A SD model was developed by (Chen et al. 2022) for urban pollution, and evaluated the impact of various policies and also discussed the benefits of synergistic approach for addressing environmental problems and traffic congestion. A SD approach was applied by (Gupta et al. 2019) to measure the effectiveness of carbon tax on Indian road passenger transport. A SD model was developed by (Wang et al. 2021) for capturing feedback processes and for interactions between different sectors and various population, water quality, and resources factors. Using SD technique, (Shahsavari-

Pour et al. 2022) developed a simulated model to analyze the pollution level taking into consideration its sources and outcomes.

A SD models was proposed by (Wen et al. 2023) for the assessment of carbon emissions in transportation system sector and generations of scenarios to achieve carbon neutrality and carbon peak. A literature review on SD model was conducted by (Ghisolfi et al. 2022) related to strategies for freight transport decarbonization. Using SD technique, a methodology was discussed by (Stasinopoulos et al. 2021) to analyze the impacts of autonomous vehicle adoption on GHG emissions. For the assessment of development status of new energy vehicles, (Chen et al. 2021) combined different interdisciplinary methods with SD and analyzed the results. A dynamic interaction between consumers, manufacturers and government based SD model was developed by (Li et al. 2023) for the promotion of e-vehicle industry. A System dynamics simulation model was discussed by (Rajput & Jain 2022) to significantly reduce traffic congestion as well as to enhance safety, mobility, and reliability in metropolitan cities of India.

In this paper, a System Dynamics based Sustainable Urban Transportation (SDSUT) model is designed and developed to assess the impact of policy scenario maps on critical dynamic parameters of Indian traffic and transportation system. These critical dynamic parameters include total vehicle population, total carbon emissions and road traffic congestion. Total five policy scenario maps are formulated and generated with the basic goal of reduction in road traffic congestion, minimization of total number of vehicles and reduction in total carbon emissions. The designed and developed model also delivers a wide range of additional paybacks such as reduction in road traffic accidents, collisions, improvement in road operating efficiency, and consumption of fuel. It is very interesting to note that very limited literature is available on the reduction of total carbon emissions and traffic congestion of Indian road transportation system using SD modelling technique but the literature related to development of SD simulation model to reduce the total vehicle population, transport carbon emissions, and road traffic congestion by the implementation of policy scenarios maps simultaneously are almost negligible. Therefore, to fill this vast research gap in Indian literature, an innovative first-time effort is being made in this research work.

2. MATERIALS AND METHODS

2.1. System Dynamics based Sustainable Urban Transportation Model

A System Dynamics based Sustainable Urban Transportation (SDSUT) model is designed and developed to reduce road traffic congestion, minimize total number of vehicles and decrease total carbon emissions by monitoring the impact of five policy scenario maps. The improvement of sustainable urban transportation system involves a conceptual jump by concentrating on multifaceted approach having progression in public transit with alternative fuels or electric vehicles, transport infrastructure development, reduction of environmental repercussions and behavioural shifts. The structure of model is based on seven interconnected sub-models: Total Population (TP) Sub-Model, Gross Domestic Product (GDP) Sub-Model, Environmental Impact (ENVI) Sub-Model, Total Vehicle Population (TVP) Sub-Model, Road Transport Demand (RTD) Sub-Model, Road Transport Infrastructure (RTI) Sub-Model, and Road Traffic Congestion (RTC) Sub-Model. Fig. 1 displays the relationships among these sub-models, using arrows to indicate cause-and-effect links, and plus and minus signs signify positive and negative impacts respectively. After model validation and sensitivity analysis, total five policy scenario maps are also formulated and generated and their impact on critical dynamic parameters is monitored to improve sustainable urban transportation system. The SDSUT model is built and then simulated for all generated policy scenario maps using system dynamics Vensim PLE 10.2.2 software platform.

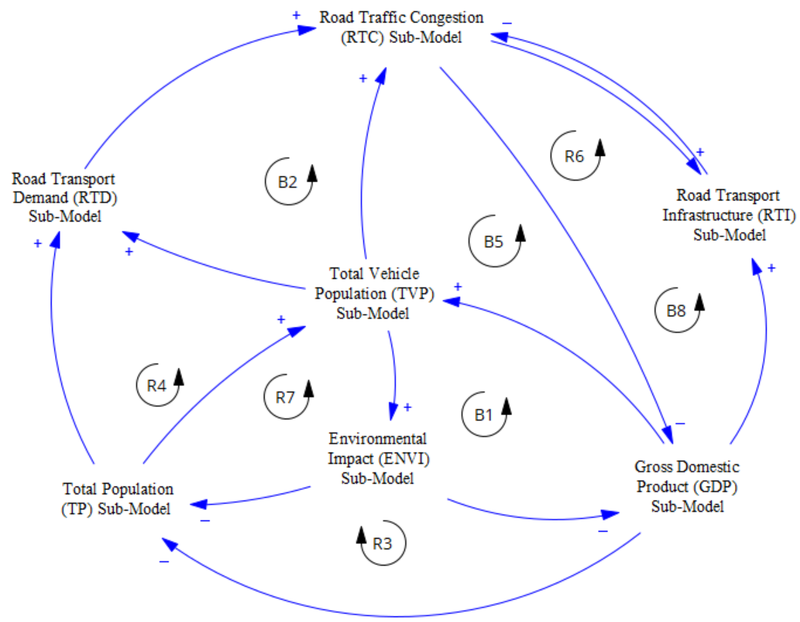


Fig. 1: Relationships among the Sub-Models

The following loops provide a detailed description of each key feedback loops of various sub-models, including its parameters, interdependent relationships between various factors, where changes in one variable influence others, creating either reinforcing (positive) impact or balancing (negative) effect and thus highlighting the feedback mechanisms that drive the system's behavior:

Loop 1(B1): Gross Domestic Product (GDP) → + Total Vehicle Population (TVP) → + Environmental Impact (ENVI) → - Gross Domestic Product (GDP) [Negative or Balancing (B) Loop]

Loop 2 (B2): Gross Domestic Product (GDP) → + Total Vehicle Population (TVP) → + Road Transport Demand (RTD) → +Road Traffic Congestion (RTC) → - Gross Domestic Product (GDP) [Negative or Balancing (B) Loop]

Loop 3 (R3): Gross Domestic Product (GDP) → - Total Population (TP) → + Road Transport Demand (RTD) → + Road Traffic Congestion (RTC) → - Gross Domestic Product (GDP) [Positive or Reinforcing (R) Loop]

Loop 4 (R4): Gross Domestic Product (GDP) → + Total Vehicle Population (TVP) → + Environmental Impact (ENVI) → - Total Population (TP) → + Road Transport Demand (RTD) → + Road Traffic Congestion (RTC) → - Gross Domestic Product (GDP) [Positive or Reinforcing (R) Loop]

Loop 5 (B5): Gross Domestic Product (GDP) → + Total Vehicle Population (TVP) → + Road Traffic Congestion (RTC) → - Gross Domestic Product (GDP) [Negative or Balancing (B) Loop]

Loop 6 (R6): Gross Domestic Product (GDP) → + Road Transport Infrastructure (RTI) → - Road Traffic Congestion (RTC) → - Gross Domestic Product (GDP) [Positive or Reinforcing (R) Loop]

Loop 7 (R7): Gross Domestic Product (GDP) → + Total Vehicle Population (TVP) → + Environmental Impact (ENVI) → - Total Population (TP) → + Road Transport Demand (RTD) → +Road Traffic Congestion (RTC) → - Gross Domestic Product (GDP) [Positive or Reinforcing (R) Loop]

Loop 8 (R8): Gross Domestic Product (GDP) → - Total Population (TP) → + Total Vehicle Population (TVP) → + Road Traffic Congestion (RTC) → - Gross Domestic Product (GDP) [Positive or Reinforcing (R) Loop]

2.1.1 Key Assumptions Behind the Model

The following key assumptions are made in the development of SDSUT model:

1. The total population mainly includes the permanent resident population not the floating population.
2. In environmental impact sub-model, the pollutants emitted by vehicles are mainly COx (with CO2 as the standard equivalent), carbon monoxide, hydrocarbons and inhalable particulate matter.
3. Setting: initial time = 2011; final time = 2040; time step = 1; unit of time: year.
4. Each policy scenario map is assigned a specific Factor of Policy Scenario Implication (FPSI) value: 1.3, 1.1, 0.5, 0.7, and 0.9, respectively.

In this framework, the sub-models for total population, gross domestic product and total vehicle population serve as foundational elements for quantitative analysis. These sub-models significantly affect the Indian traffic and transportation system and environmental outcomes. The road traffic congestion sub-model emerges from the interaction between road transport demand, which in turn influences gross domestic product. Meanwhile, the environmental impact sub model imposes critical constraints on urban transportation growth, impacting both the gross domestic product and total population sub models. Fig. 2 displays the stock and flow diagram for the SDSUT model.

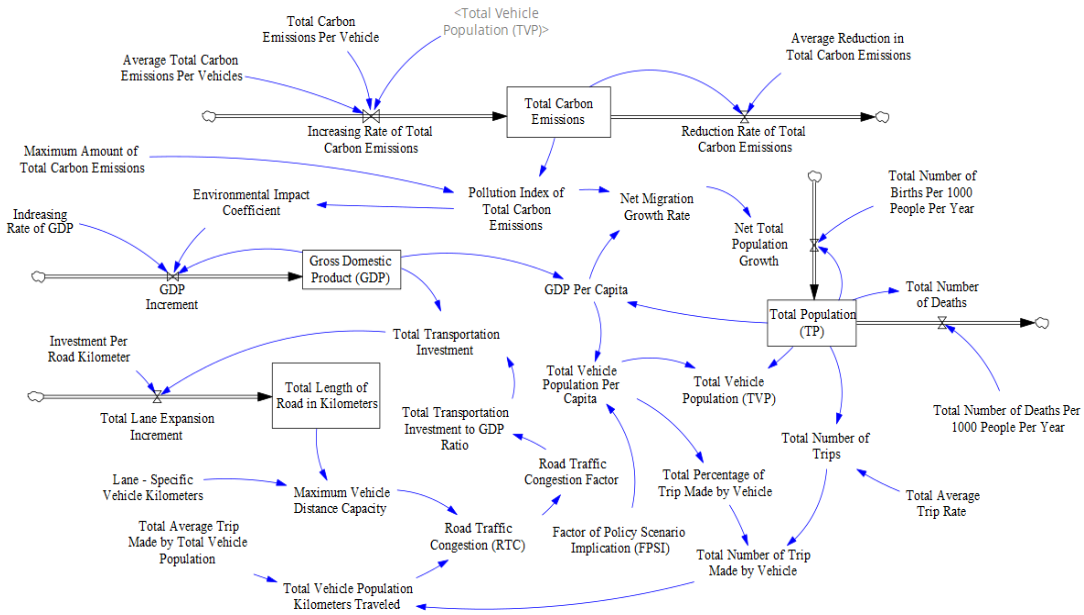


Fig. 2: Stock and flow diagram for SDSUT model

2.1.2. Total Population Sub-Model

The Indian traffic and transportation system is mainly affected by the structural pattern and magnitude of the total population. The sub-model of Total Population (TP) represents the developmental phase of different Indian cities within this framework. The total population influences total transport demand as well as economic growth. Polluted living environment due to poor air quality have a significant impact on migration of population. In this TP sub-model, the total population is designated as the main variable, i.e. stock variable, while the net total population growth, total number of deaths, and net migration growth rate serve as secondary variables. The net migration growth rate is modeled as a function of Gross Domestic Product (GDP) per capita and environmental impact coefficient, with its relationship determined through correlation analysis. The equations of TP sub-model are:

$$\mathrm{TP} = \mathrm{INTEG(Net\ Total\ Population\ Growth - Total\ Number\ of\ Deaths, 1.21)} \quad \ldots(1)$$

$$\mathrm{Net\ Total\ Population\ Growth} = \mathrm{TP} * (\mathrm{Net\ Migration\ Growth\ Rate} + \mathrm{Total\ Number\ of\ Births\ Per\ 1000\ People\ Per\ year}) \quad \ldots(2)$$

$$\mathrm{Total\ Number\ of\ Deaths} = \mathrm{TP} * \mathrm{Total\ Number\ of\ Deaths\ Per\ 1000\ People\ Per\ Year} \quad \ldots(3)$$

2.1.3. Gross Domestic Product Sub-Model

The Gross Domestic Product (GDP) sub-model outlines the key factors driving the urban transportation development. Economic growth is a crucial indicator of a city's competitiveness and has a significant impact on population migration. Due to rise in GDP/capita, the people can easily afford to buy motorized vehicles like cars, scooters, motor bikes etc. for driving or movement purpose and this will result in shift from non-motorized modes to motorized transport modes on the road. Thus, there is one to one relation between the growth of GDP/capita and the road transportation system. Furthermore, economic growth is often correlated with investments in transportation sector, as government has to allocate more funds to develop and maintain transportation infrastructure to ensure efficient road traffic conditions. In this sub model, Gross Domestic Product is defined as a stock variable, while the Gross Domestic Product increment is considered as a rate variable. The auxiliary variables include the increasing rate of GDP, total transportation investment, and environmental impact coefficient. The environmental impact coefficient measures the impact of environmental quality on Gross Domestic Product growth. The following equations within the GDP sub-model are designed to capture the relationships effectively:

$$GDP = INTEG(GDP\ increment, 92.13\ billion) \quad \ldots(4)$$

$$GDP\ Per\ Capita = \frac{GDP}{TP} \quad \ldots(5)$$

$$GDP\ Increment = GDP * Increasing\ Rate\ of\ GDP * Environment\ Impact\ Coefficient \quad \ldots(6)$$

2.1.4. Environmental Impact Sub-Model

Environmental necessities play an important limitation in shaping the development of urban transportation system. Vehicle emissions, which include CO_x (with CO_2 as the standard equivalent), carbon monoxide, hydrocarbons, and inhalable particulate matter, significantly contribute to air pollution. In this Environmental Impact (ENVI) sub-model, total carbon emissions are represented as a stock variable, while increasing rate of total carbon emissions and reduction rate of total carbon emissions are represented as a rate variable. Key auxiliary variables include average reduction in total carbon emissions, total carbon emissions per vehicle, average total carbon emissions per vehicle, and pollution index of total carbon emissions. These variables are interlinked through following equations that model their dynamic relationships, allowing for a comprehensive analysis of the environmental impacts associated with transportation:

$$Total\ Carbon\ Emissions = INTEG(Increasing\ Rate\ of\ Total\ Carbon\ Emissions - Reduction\ Rate\ of\ Total\ Carbon\ Emissions) \quad \ldots(7)$$

$$Reduction\ Rate\ of\ Total\ Carbon\ Emissions = Total\ Carbon\ Emissions * Average\ Reduction\ in\ Total\ Carbon\ Emissions \quad \ldots(8)$$

$$Increasing\ Rate\ of\ Total\ Carbon\ Emissions = TVP * Average\ Total\ Carbon\ Emissions\ Per\ Vehicles \quad \ldots(9)$$

2.1.5. Total Vehicle Population Sub-Model

The Total Vehicle Population (TVP) sub-model is the vital backbone to this research work as it represents the prime focus of the proposed SDSUT model and interacts with all other sub-models. The total vehicle population is the sum of private cars, taxies, jeeps, two wheelers, buses, goods vehicles and other vehicles. The explosive rise in the total vehicle population is primarily due to rise in GDP/capita and rising total travel demand. The segment rate of cycling and walking is decreasing continuously, and segment rate of motorization is rising with a tremendous pace. The segment rate of cars, jeeps and taxies is continuously increasing at a very fast pace and plays an important role in the road traffic congestion, accidents, air pollution and total carbon emission, which, in turn, negatively impacts economic growth and population dynamics. In this TVP sub-model, the total vehicle population is treated as a key variable. Additionally, the total vehicle population per capita and the Factor of Policy Scenario Implication (FPSI) are included as auxiliary variables to analyze their influence on the system.

$$TVP = \frac{TP}{Total\ Vehicle\ Population\ Per\ Capita} \quad \ldots(10)$$

$$Total\ Number\ of\ Vehicle\ Per\ Capita = FPSI * 0.35904 * exp(-4.2324 * exp(-0.35393 * GDP\ Per\ Capita)) \quad \ldots(11)$$

2.1.6. Road Transport Demand Sub-Model

Road Transport demand (RTD) is a derived need influenced by factors such as the total population and gross domestic product. In the RTD sub-model, key auxiliary variables include total number of trips, total average trip rate, total percentage of trip made by vehicles, total average trip made by total vehicle population, and total vehicle population kilometers traveled. These variables work together to capture the dynamics of transportation demand and its relationship with urban development.

$$Total\ Number\ of\ Trips = TP \times Total\ Average\ Trip\ Rate \quad \ldots(12)$$

$$Total\ Number\ of\ Trips\ Made\ by\ Vehicle = Total\ Percentage\ of\ Trip\ Made\ by\ Vehicle * Total\ Number\ of\ Trips \quad \ldots(13)$$

$$TVP\ Kilometer\ Traveled = \frac{Total\ Number\ of\ Trip\ Made\ by\ Vehicle}{Total\ Average\ Trip\ Made\ by\ Total\ Vehicle\ Population} \quad \ldots(14)$$

2.1.7. Road Transport Infrastructure Sub-Model

Road Transport Infrastructure (RTI) reflects the quality of urban infrastructure development and maintains a dynamic balance with road transportation demand. The level of RTI is primarily influenced by investments in infrastructure construction and improvements. In this RTI sub-model, total length of road in kilometers is defined as the stock variable, while the total lane expansion increment serves as the rate variable. Auxiliary variables include total transport investment, total transportation investment to GDP ratio, investment per road kilometer, lane-specific vehicle kilometers, and maximum vehicle distance capacity. These variables describe how transport infrastructure adapts to meet the increasing demands of urban mobility.

$$Total\ Length\ of\ Road\ in\ Kilometers = INTEG(Total\ Lane\ Expansion\ Increment, Total\ Length\ of\ Road\ in\ Kilometers) \quad \ldots(15)$$

$$Total\ Lane\ Expansion\ Increment = Investment\ Per\ Road\ Kilometer * Total\ Transportation\ Investment \quad \ldots(16)$$

2.1.8. Road Traffic Congestion Sub-Model

Road Traffic Congestion (RTC) occurs when road transport demand outstrips supply, posing a significant challenge to urban transportation systems. This imbalance leads to longer travel times and frustration for commuters while worsening environmental quality through increased emissions and fuel consumption. Ultimately, it compromises the overall effectiveness of the transportation network.

$$RTC = \frac{Total\ Vehicle\ Kilometers\ Traveled}{Maximum\ Vehicle\ Distance} \quad \ldots(17)$$

2.2 Model Validity and Sensitivity

The parameters of the SDSUT model are continuously refined and adjusted throughout its development to enhance the interrelationships among various parameters. This process aims to minimize the discrepancy between actual historical data and simulated results, ultimately improving the model's reliability. The Error Rate (ER), Error Variance (EV), Mean Absolute Percentage Error (MAPE), Root Mean Square Percentage Error (RMSPE), and Mean Absolute Error (MAE) of the key parameters are determined using the following equations respectively:

$$ER = \frac{|SV - AV|}{AV} \times 100 \quad \ldots(18)$$

$$EV = \frac{|Average\ Rate\ of\ SV - Average\ Rate\ of AV|}{Average\ Rate\ of\ Absolute\ Value} \times 100 \quad \ldots(19)$$

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{SV - AV}{AV}\right| \times 100 \quad \ldots(20)$$

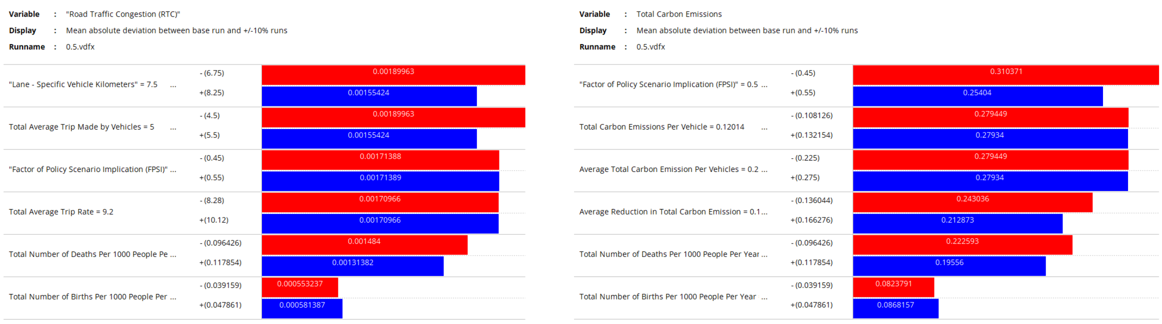
$$RMSPE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left|\frac{SV - AV}{AV}\right|^2} \times 100 \quad \ldots(21)$$

$$MAE = \frac{\sum |SV - AV|}{Number\ of\ Count} \quad \ldots(22)$$

SV and AV are simulated value and actual value respectively, the ER and EV for total carbon emissions and total population are {4.4678 % and 4.58549 %} and {7.3312 % and 5.1793 %} respectively while the MAPE and RMSPE for these parameters are {4.7523 % and 5.4610 %} and {5.8928 % and 6.2417 %} respectively. The MAE value for these parameters are {0.1060 and 0.0764} respectively. The developed SDSUT model is totally effective, valid, and generating reliable simulated results because the values of ER and EV of the key parameters are less than or equal to 5% and 30% respectively, while MAPE, RMSPE and MAE are also very close to zero which clearly shows that error is very low and model's prediction ability is best. The correlation analysis of simulated and actual data for total carbon emissions and total population are 0.9844 and 0.9845 respectively, which is close to 1 which indicates a strong positive relation between the simulated and actual data. Using 2011 as the base year, the historical data from 2011 to 2024 are utilized to verify the validity of the model. The data for the simulation has been taken from Our World in Data (https://ourworldindata.org/), which provides globally recognized datasets on various socio-economic and environmental parameters. Additionally, demographic and statistical data specific to India has been obtained from the official Census of India website (https://censusindia.gov.in/census.website/). These sources ensure reliable, comprehensive, and up-to-date information for accurate simulation modeling. The key parameters fully satisfy the validity for future projections and Fig. 3 shows the comparison between real historical and output simulated data of key parameters.

Fig. 3: Relation between Simulated Data and Actual Data

The sensitivity analysis of the SDSUT model is performed to assess how responsive the model is to changes in key parameter values and modifications in its fundamental structure. The results demonstrate that the model remains stable and well-regulated, making model suitable for simulation and monitoring impact on generated policy scenario maps. Fig. 4 presents a Tornado Diagram to illustrate the sensitivity analysis for critical dynamic parameters: road traffic congestion, total carbon emissions, and total vehicle population respectively, illustrating how these critical dynamic parameters are influenced by the changes in other variables. This analysis helps in identifying crucial variables affecting system behavior and ensures the model's reliability in predicting different policy scenario maps. Critical dynamic parameter: Road traffic congestion is influenced by lane-specific kilometers, the total average trips made by vehicles, the Factor of Policy Scenario Implication (FPSI), the total average trip rate, the total number of births per 1000 people per year, and the total number of deaths per 1000 people per year. Critical dynamic parameter: Total carbon emissions is affected by the Factor of Policy Scenario Implication (FPSI), total carbon emissions per vehicle, the average reduction in total carbon emissions, the total number of births per 1000 people per year, and the total number of deaths per 1000 people per year. Similarly, critical dynamic parameter: total vehicle population is influenced by the Factor of Policy Scenario Implication (FPSI), as well as the total number of births per 1000 people per year, and the total number of deaths per 1000 people per year. The value of factor of policy scenario implication ranges from -0.45 to +0.55, corresponding to {0.00171388 and 0.00171389} for road traffic congestion, {0.310371 and 0.25404} for total carbon emissions, and {2.16397 and 1.77144} for total vehicle population. This analysis highlights the critical dynamic parameters affecting system behavior and reinforces the model's reliability in predicting various policy scenario maps.



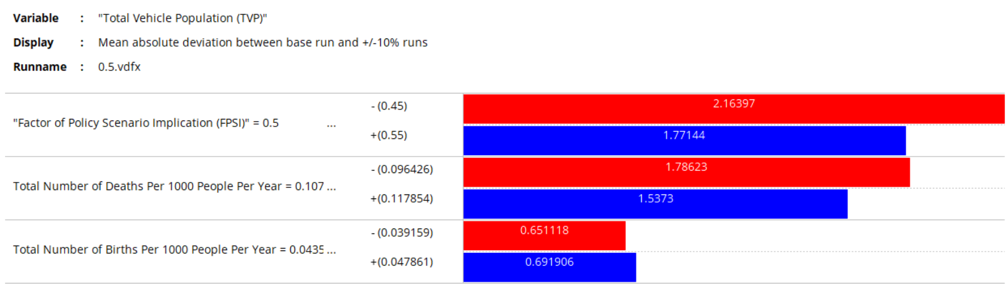


Fig. 4: Tornado Diagram for Road Traffic Congestion, Total Carbon Emissions, and Total Vehicle Population

The Coefficient of Determination or R squared method, a statistical analysis tool is used to measure the proportion of variance in the dependent variable explained by the independent variable, ranging from 0 to 1, where 1 indicates a perfect fit. The R^2 values indicate the strength of relationships between gross domestic product, total population, total vehicle population, and total carbon emissions. The R^2 value for gross domestic product and total population is 0.9265, suggesting a very strong correlation between these variables. Similarly, the R^2 for gross domestic product and total vehicle population is 0.9114, while for gross domestic product and total carbon emissions is 0.8929. Additionally, the R^2 value between total population and total carbon emissions is also 0.8929. The enumerated values demonstrate strong predictive power, indicating that the developed model is reliable and suitable for simulation and analysis. Fig. 5 shows the R^2 values for GDP-Total Carbon Emissions, GDP-Total Population, Total Population-Total Carbon Emissions and GDP-Total Vehicle Population.

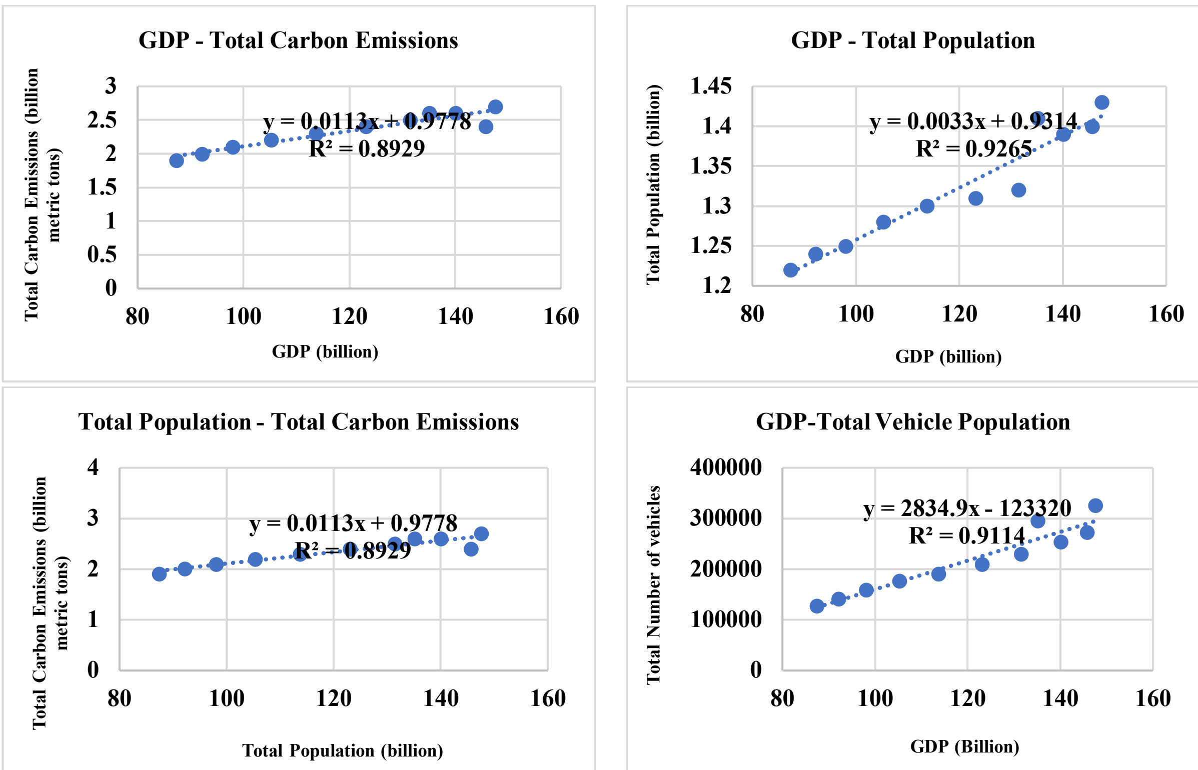


Fig. 5: R^2 for GDP-Total Carbon Emissions, GDP-Total Population, Total Population-Total Carbon Emissions and GDP-Total Vehicle Population

2.3. Model Simulation and Policy Scenario Maps

This study primarily examines the impact of various policy scenario maps on critical dynamic parameters: total vehicle population, total carbon emissions and road traffic congestion of Indian traffic and transportation system. Total five distinct policy scenario maps—Powerful Endorsement, Endorsement, Strict Regulation, Regulation and No Implication have been formulated and generated to monitor their impact with the basic goal to reduce road traffic congestion, minimize total vehicle population and to achieve carbon neutrality by reducing total carbon emissions. To achieve this, Factor of Policy Scenario Implication (FPSI) is used as a control variable within the model simulation framework, enabling the quantification of effects under different policy scenario maps. The model simulation spans 29 years starting from 2011, proceeding with a one-year time step, and providing a long-term perspective on the outcomes of different policy scenario maps. Each policy scenario map is assigned a specific FPSI value: 1.3, 1.1, 0.5, 0.7, and 0.9, respectively. These values reflect varying levels of regulatory or factor of policy scenario implication, promotional intensity, ranging from significant encouragement to strict restrictions and the absence of intervention. This approach provides a comprehensive understanding of the interplay between five distinct policy scenario maps and urban transportation dynamics, enabling policymakers to make informed decisions that foster sustainable urban transportation system and mitigate transportation related challenges.

2.3.1. Powerful Endorsement

The transportation system decision makers and policymakers must encourage and implement aggressive policies to promote electric vehicles (EVs) adoption.

- Subsidies: Substantial financial incentives for electric vehicle (EV) buyers, including subsidies and direct cash benefits.
- Infrastructure: Swift expansion of charging stations in both urban and rural areas.
- Awareness Campaigns: Nationwide publicity initiatives through television and newspapers to promote the environmental and economic advantages of EVs.
- Tax Policies: Significant tax exemptions for both EV manufacturers, suppliers and users.

2.3.2. Endorsement

The policymakers and transportation system decision makers must promote and support improvement in public transportation, carpooling, travelling at non-peak hours and using alternate routes.

- **Incentives:** Limited tax benefit for individuals who use public transport or participate in carpooling programs.
- **Investment:** Gradual investment in public transport infrastructure, including the introduction of new buses and development of online carpooling portal.
- **Awareness:** Targeted awareness campaigns to encourage behavioural changes among commuters.
- **Tax Rebates:** Moderate tax exemptions for private bus operating companies and carpooling agencies which are supporting mass and shared mobility solutions.

2.3.3. Strict Regulation

The transportation system decision makers and policymakers must strongly restrict older, high-emission vehicles by imposing a ban to curb urban air pollution and total carbon emissions.

- **Bans:** Prohibition of petrol vehicles older than 10 years and complete ban on diesel vehicles in major cities.
- **Fines:** Strict fines imposed on vehicles that do not comply with emission standards.
- **Traffic Rules:** Implementation of odd-even vehicle rule in major polluted cities.
- **Quotas:** Restriction on vehicle registration in a periodic time span to control the total vehicle population.

2.3.4. Regulation

The policymakers and transportation system decision makers must restrict vehicle usage or controlling of total vehicle population by introducing congestion pricing in highly congested urban areas.

- **Dynamic Tolling System:** Area-wide pricing: fees for driving within a designated zone; Cordon pricing: charging for targeted congested hotspots of a city; Dynamic pricing: tolls based on real-time traffic conditions; High-occupancy toll lanes: single-occupancy vehicles have to pay to enter reserved lanes for high-occupancy vehicles.
- **Vehicle Standards:** Incentives for using low-emission and high standard vehicles.
- **Parking Limitations:** Limited parking spaces in central business locations to discourage the use of private cars.
- **Flexible Quotas:** Periodic restrictions on registration of SUVs to control the total vehicle population.

2.3.5. No Implication

The transportation system decision makers and policymakers are not taking any proactive measures for controlling total vehicle population or their usage.

- **Market Trends:** The adoption of vehicles and levels of traffic congestion are influenced by market dynamics.
- **No Regulations:** No regulations on high-emission vehicles or private car ownership.
- **Infrastructure:** Stagnation state in transportation infrastructure investment and only minimal maintenance investment.
- **Public Transport:** Continuation of poor, inefficient and neglected public transportation systems, the key decarbonizing strategy.

3. MODEL SIMULATION RESULTS AND DISCUSSION

Fig. 6(a) displays the Effect of Factor of Policy Scenario Implication on Total Vehicle Population while Fig. 6(b) presents Effect of Factor of Policy Scenario Implication on Total Vehicle Population with Confidence Interval. The model simulation using formulated and generated five distinct policy scenario maps with FPSI significantly influences the growth of critical dynamic parameter: total vehicle population. The most notable effect is that the growth rate of the curve changes depending on the type of factor of policy scenario map implication, shifting from endorsement to regulation. Under powerful endorsement policy scenario map, the growth of total vehicle population increases at a fast pace in the beginning but after a gap of approximately fourteen years, the growth of parameter is very slow. In contrast, when strict regulation policy scenario map is applied, the growth is very fast in the beginning but after a gap of fifteen years the growth of total vehicle population is slow. This indicates that powerful endorsement policy scenario map can lead to a decrease in total vehicle population or vehicle ownership, which in turn promotes the rapid adoption of sustainable technologies, such as electric vehicles (EVs). Additionally, this model simulation contributes to a sound reduction in total carbon emissions also. Fig. 6(b) shows the confidence intervals for five distinct Factor of Policy Scenario Implication (FPSI) from 2011 to 2040. In 2026, the strict regulation policy scenario map has a predicted value of approximately 20, with an error range of about ±1.2 whereas with regulation policy scenario map, the predicted value is around 15, with an error margin of ±1.0. The upward trends indicate the impact of policy scenario maps over time, and the relatively small error bars suggest stable predictions with moderate variability in the model's outcomes.

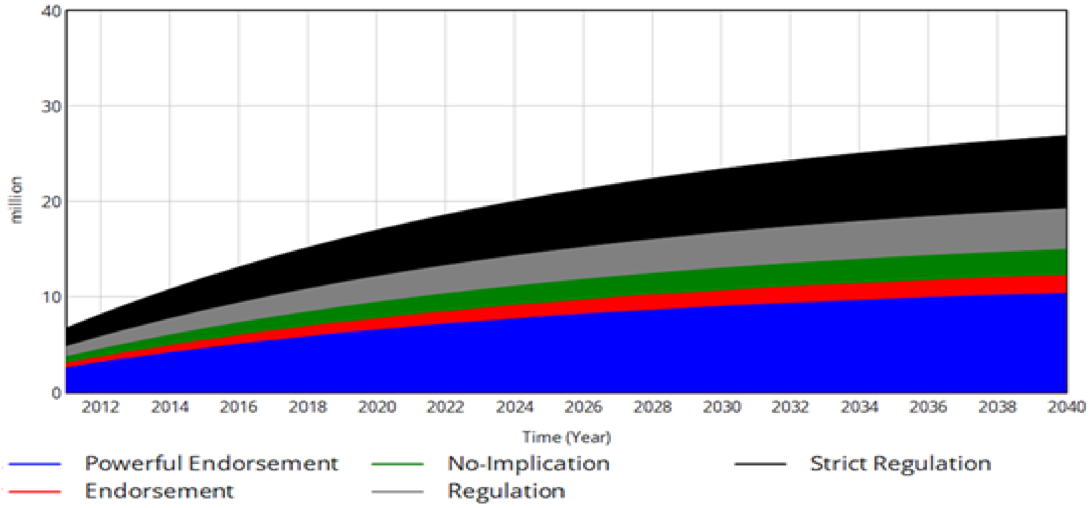


Fig. 6(a): Effect of Factor of Policy Scenario Implication on Total Vehicle Population

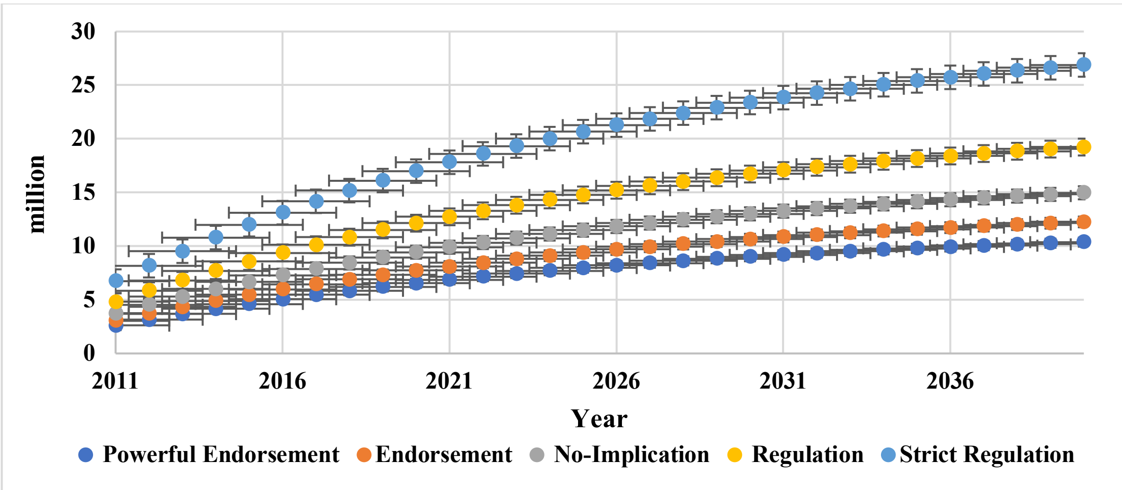


Fig. 6(b): Effect of Factor of Policy Scenario Implication on Total Vehicle Population with Confidence Interval

Fig. 7(a) presents the Effect of Factor of Policy Scenario Implication on Total Carbon Emissions while Fig. 7(b) displays Effect of Factor of Policy Scenario Implication on Total Carbon Emissions with Confidence Interval. The model simulation using generated five distinct policy scenario maps with FPSI significantly influences the total carbon emissions. In Fig. 7(a), the critical dynamic parameter: total carbon emissions follow a slightly "S curve" over time. The most distinctive effect is that the growth rate of the curve changes depending on the type of policy scenario map applied, shifting from endorsement to regulation. To effectively reduce carbon emissions, it is advisable to implement powerful endorsement policy scenario map on total vehicle population or vehicle ownership. This model simulation not only helps in decreasing total carbon emissions but also alleviate road traffic congestion. Fig. 7(b) shows the confidence intervals for five distinct policy scenario maps on total carbon emissions. In 2031, the strict regulation policy scenario map predicts a value of approximately 4.2, with an error range of about ±0.15 whereas regulation policy scenario map predicts a value near 3.0, with an error margin of ±0.12. The upward trends observed in all policy scenario maps indicates the impact of policy scenario maps over time, while the larger error bars in the earlier years suggest a higher level of uncertainty at the beginning of the period.

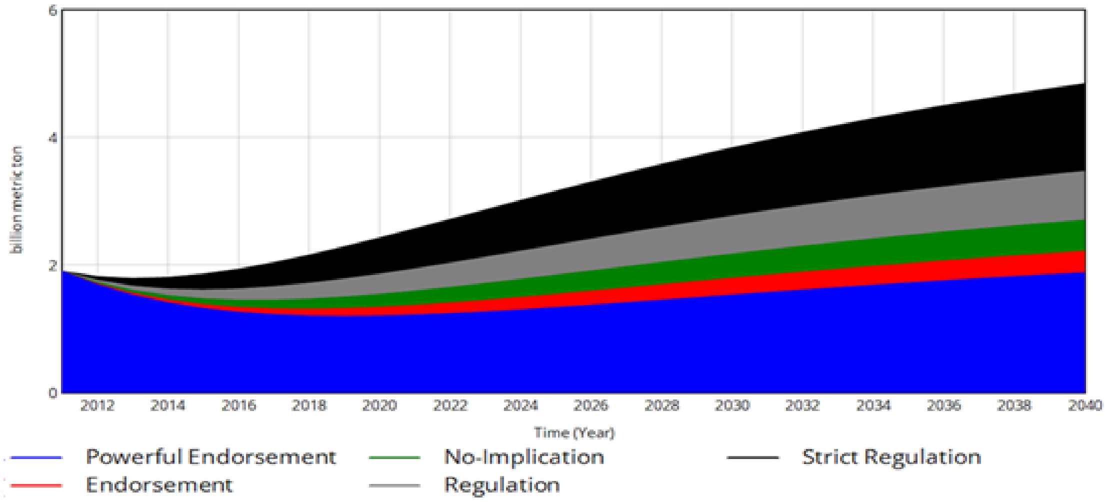


Fig. 7(a): Effect of Factor of Policy Scenario Implication on Total Carbon Emissions

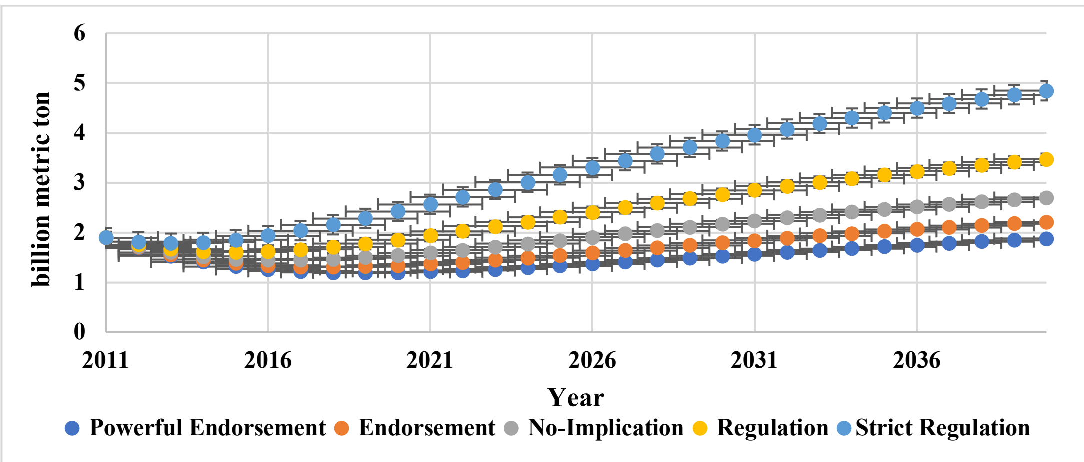


Fig. 7(b): Effect of Factor of Policy Scenario Implication on Total Carbon Emissions with Confidence Interval

Fig. 8(a) shows the Effect of Factor of Policy Scenario Implication on Road Traffic Congestion while Fig. 8(b) illustrates the Effect of Factor of Policy Scenario Implication on Road Traffic Congestion with Confidence Interval. The model simulation using formulated and generated five distinct policy scenario maps with FPSI significantly influences the critical dynamic parameter: road traffic congestion. The growth rate of road traffic congestion varies depending on the type of policy scenario map implemented, ranging from endorsement policy scenario map to strict regulation. Under powerful endorsement policy scenario map, road traffic congestion increases at a very fast pace in the beginning but after some time the growth of parameter is very slow. In contrast, when strict regulation policy scenario map is applied, the road traffic congestion is increasing at a fast pace but there is a reduction in road traffic congestion after approximately twenty years due to increase in compliance and adaptation. This indicates that powerful endorsement policy scenario map can effectively mitigate road traffic congestion. Additionally, this model simulation contributes to a sound reduction in total carbon emissions, emphasizing the dual benefit in improving traffic conditions and promoting environmental sustainability. Fig. 8(b) shows the confidence intervals for five distinct policy scenario maps from 2011 to 2040. In 2031, the strict regulation policy scenario map has a predicted value of approximately 0.6, with an error range of about ±0.04 whereas with regulation policy scenario map, the predicted value is around 0.5, with an error margin of ±0.035. The upward trends indicate that the impact of policy scenario maps is increasingly effective over time, and the relatively small error bars suggest stable predictions with moderate uncertainty in the model's outcomes.

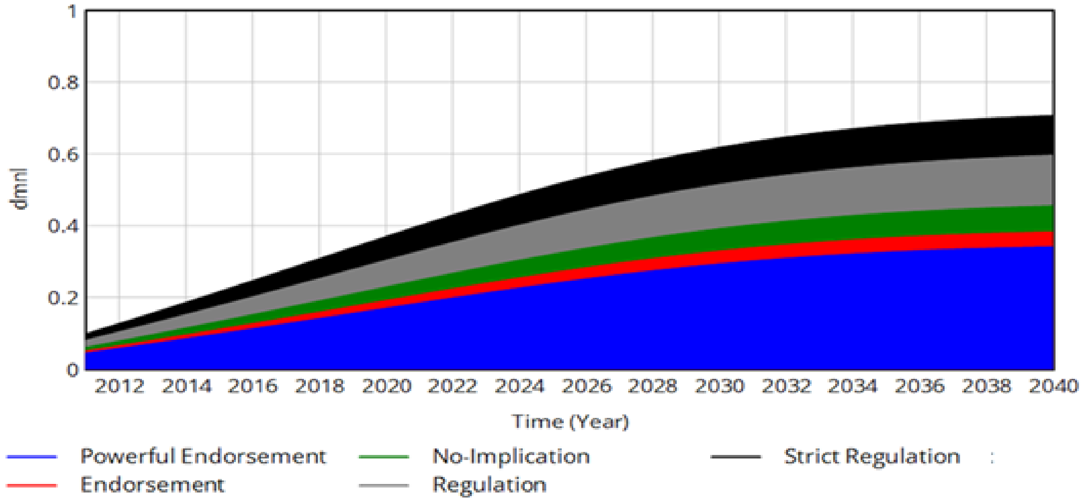


Fig. 8(a): Effect of Factor of Policy Scenario Implication on Road Traffic Congestion

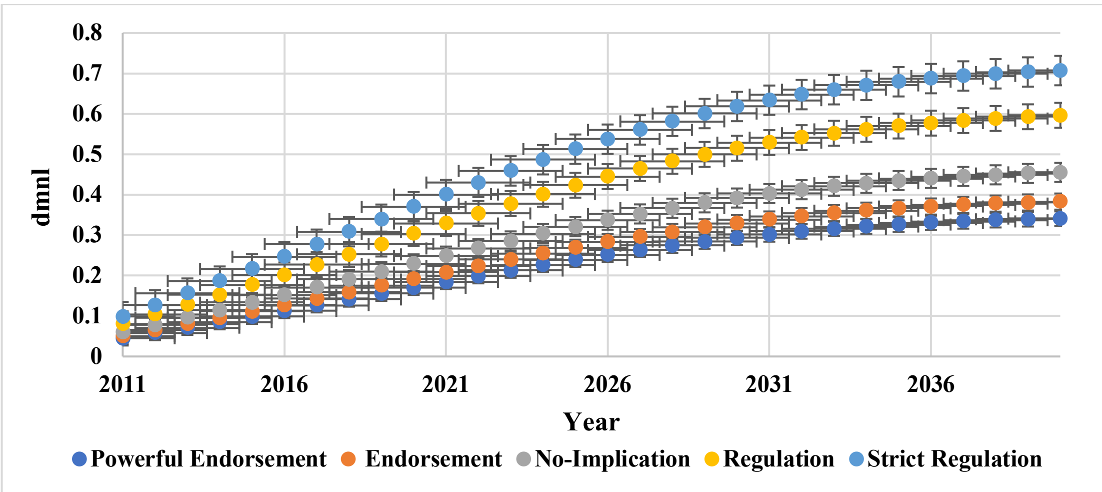


Fig. 8(b): Effect of Factor of Policy Scenario Implication on Road Traffic Congestion with Confidence Interval

4. CONCLUSIONS

A System Dynamics based Sustainable Urban Transportation (SDSUT) model is designed and developed to assess the impact of formulated and generated total five policy scenario maps on critical dynamic parameters of Indian traffic and transportation system with the basic goal of reduction in road traffic congestion, minimization of total vehicle population and reduction in total carbon emissions. The model also delivers a wide range of additional paybacks such as reduction in road traffic accidents, collisions, improvement in road operating efficiency, and consumption of fuel. The model simulation results clearly shows that effective policy scenario maps, especially those aimed at restricting vehicle ownership or total vehicle population are essential for reducing traffic congestion and lowering carbon emissions. This model simulation result indicates that powerful endorsement policy scenario map can lead to a decrease in total number of vehicles or total vehicle population, which in turn promotes the rapid adoption of sustainable technologies, such as electric vehicles (EVs). This model simulation also contributes to enhance urban mobility of India by creating a sustainable urban transportation system and to achieve carbon neutrality by reducing total carbon emissions. This research highlights the potential of system dynamics modeling as a valuable tool for policymakers to develop and implement effective solutions that support India's objectives for sustainable urban development and environmental preservation. The Indian urban planners and policymakers should focus on green transport solutions including EVs, smart mobility and carbon neutrality to avoid explosive disaster due to carbon emissions. This research work is an innovative initial step and has its limitations. Further research work will be pursued in the direction of hybrid policy approach, smart mobility, smart cities and net-zero emissions.

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