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Deep Decarbonization of Indian Road Transportation Sector by the Implementation of Strategies based on Intelligent Transportation System using System Dynamics Simulation Model: A Step towards Carbon Neutrality

Aditi Rajput[1]* and Madhuri Jain[1]
[1]Department of Mathematics and Statistics, Banasthali Vidyapith, Rajasthan-304022, India
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*to whom all correspondence should be addressed: e-mail: aditirajput0106@gmail.com, abrma20116_aditi@banasthali.in
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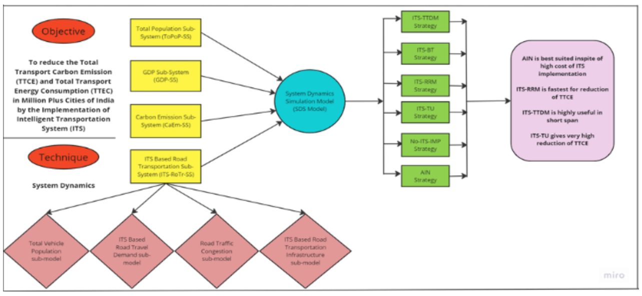
Graphical abstract



Abstract

System dynamics is a methodology whereby complex, dynamic and nonlinear interactions in real-world systems can be understood and analyzed, and new structures and policies can be designed to improve the system behaviour. This study introduces a system dynamics simulation model aimed at decreasing the Total Transport Carbon Emissions (TTCE) in million-plus cities of India through the implementation of strategies based on Intelligent Transportation Systems (ITS). The integrated model consists of four interconnected Sub-Systems: Total Population, GDP, Carbon Emission, and four sub-models enabled ITS based Road Transportation Sub-Systems, illustrating their interrelationships. The model has been validated, and a sensitivity analysis is employed for optimal management. Six strategies based on ITS: Traffic and Transportation Demand Management (ITS-TTDM), Bus Transport (ITS-BT), Rules and Regulations Management (ITS-RRM), Technology Upgradation (ITS-TU), No ITS Implementation (No-ITS-IMP), and All Integrated (AIN), are developed based on identified key parameters. The model simulation shows that, although the All Integrated (AIN) strategy has a greater implementation cost, it provides the highest 88 % decrease in TTCE, while Rules and Regulations Management (ITS-RRM) delivers the most feasible and reasonable 78 % drop in TTCE and represents the optimal critical strategy. Traffic and Transportation Demand Management (ITS-TTDM) provides a 73 % decrease in TTCE and delivers significant immediate advantages.

Keywords: Intelligent Transportation System, System Dynamics Model, Carbon Neutrality, Total Transport Carbon Emissions, Strategies Analysis

1. Introduction

In order to have a safe world with comfortable lives in the present and the future, all developing and developed countries must act immediately to address and mitigate the global warming challenge. This urgent and forward-looking futuristic approach to improve global health will undoubtedly promote safe living and ideal societies. The transportation sector, which contributes roughly 24 percent of fuel emissions and 10–15 % of carbon emissions globally, should be the primary emphasis to fulfil the target carbon emissions goals. A synergistic approach was used to integrate machine learning algorithms with a mathematical model for the prediction of CO_2 emissions and demand of energy for the transportation sector (Javanmard *et al.*, 2023). The heterogeneous effects of characteristics of firms and pilot programs to reduce carbon emissions were thoroughly analyzed (Shen *et al.*, 2020). Energy efficiency across transportation modes was estimated using a stochastic technique (Irfan *et al.*, 2024). The role of transport renewable energy consumption, considering the infrastructure of roads and transport fuel consumption, was analyzed to recommend justified policies (Dai *et al.*, 2023).

India is the third highest emitter of CO_2 in the world (Jocelyn, 2019) with annual emissions totaling 3.6 gigatons and a trajectory that could reach 7.3 gigatons per year by 2050 (Hossain *et al.*, 2023) and has a vision to reduce CO_2 emissions from industries, waste, forest, energy sector and transportation sector by the end of 2030 (Mukhopadhyay, 2021). India also announced a carbon neutrality commitment by 2070 at COP26

(Viswanathan *et al.*, 2021). To fulfil such an ambitious climate target, stricter policies and longer-term decarbonization strategies are needed for the carbon-intensive Indian road transportation sector. Due to changes in buying habits and the high living standard of the majority of Indians, the CO_2 emissions of the Indian road transportation sector will reach to dangerous level very soon, and every Indian transportation system expert and decision maker will be responsible for this. The road transportation sector of India accounts for approximately 56% of our country's transportation system emissions (O'Rourke *et al.*, 2021). The deep decarbonization of the transportation system to achieve carbon neutrality will negatively impact roads. Therefore, the primary goal now is to develop a new approach for utilizing roads to enhance mobility while also achieving carbon neutrality. This research represents an innovative step in this direction, focusing on implementing strategies based on Intelligent Transportation Systems (ITS) for the Indian road transportation sector.

ITS can create significant opportunities by transforming the Indian road network, ultimately working towards the main goal of achieving carbon neutrality. ITS relies on the intelligent input and analysis of various traffic and transportation data, which is rapidly transmitted to traffic management centres. This intelligent data is then processed into intelligent actionable information and shared with different transportation system users through a sophisticated range of electronic devices and cloud platforms supported by wireless networks. A policy has been suggested for managing the obstacles in the implementation of ITS (Susanty *et al.*, 2022). Additionally, a privacy traffic signal control system has been proposed for ITS (Ying *et al.*, 2022). A machine learning tool has been discussed for securing smart vehicles (Gupta *et al.*, 2022), and a routing scheme has been introduced to manage traffic within ITS (Khan *et al.*, 2022). The application of the metaverse in the transportation sector has been studied, along with its potential applications in ITS (Njoku *et al.*, 2023). By utilizing ITS-related data, the differences in mobility patterns among various vehicle types, including cars, medium vehicles, and long vehicles have been examined (Kraft *et al.*, 2022). In the context of cooperative ITS, security-related issues in vehicular networks have been a focus of study (Mangla *et al.*, 2023). A vehicle consensus scheme based on ITS has been proposed to manage traffic and select infrastructure options for users (Gao *et al.*, 2022). Dasgupta *et al.* (2022) introduced a fusion model to detect pedestrians in low-light conditions during nighttime driving. Furthermore, a neural network-based model has been developed to facilitate intelligent decision-making for public transportation (Alkinani *et al.*, 2022). A model aimed at enhancing road safety and reducing accidents caused by traffic jams has also been discussed (Ramesh *et al.*, 2022). Rajput and Jain (2022) presented a system dynamics simulation model to reduce traffic congestion through the implementation of ITS strategies in metropolitan cities in India.

The implementation of strategies based on ITS will facilitate a rapid dynamic transition toward carbon neutrality. The system dynamics (SD) modelling technique allows for the simulation of intricate real-world issues by harmoniously combining qualitative and quantitative approaches. It provides a holistic framework for understanding the interdependencies within the transportation sector, recognizing feedback loops, and evaluating the long-term effects of different policy measures. Through the integration of system reasoning and dynamic interactions, SD modelling generates scenarios that support decision-making for efficient and sustainable urban mobility solutions. Chen *et al.* (2022) utilized SD modelling to address urban pollution and evaluated the impact of various policies, and also highlighted the benefits of a synergistic approach for tackling environmental challenges and traffic congestion. A SD approach was applied to assess the effectiveness of a carbon tax on road passenger transport in India (Gupta *et al.*, 2019). A SD model was developed to capture feedback processes and for interactions between different sectors and various population, water quality, and resource factors (Wang *et al.*, 2021). A simulated model was developed by using the SD technique to analyze pollution levels, taking into account both sources and outcomes (Shahsavari-Pour *et al.*, 2022). A SD model was proposed for assessing carbon emissions in the transportation sector, and scenarios aimed at achieving carbon neutrality and peak carbon levels were also discussed (Wen and Wang, 2023). A literature review on SD models related to strategies for decarbonizing freight transport was presented (Ghisolfi *et al.*, 2022). A methodology using SD to analyze the impacts of autonomous vehicle adoption on greenhouse gas emissions was also discussed (Stasinopoulos *et al.*, 2021). A SD model was developed to investigate the interactions between the economy, population, urban traffic, energy consumption, and carbon emissions (Wen and Bai, 2017). Various interdisciplinary methods were combined with SD to assess the development status of new energy vehicles (Chen *et al.*, 2021). A SD model was developed to explore the dynamic interactions between consumers, manufacturers, and government for promoting the electric vehicle industry (Li *et al.*, 2023). To predict emissions from hinterland transportation, a system dynamics model was developed (Liu *et al.*, 2019). Using the SD approach, the effects of economic growth rates and various carbon reduction technology policies on carbon emissions and the carbon intensity of GDP were investigated (Du *et al.*, 2019).

This research presents the design and development of a system dynamics model aimed at reducing total transport carbon emissions and total transport energy consumption in the road transportation sector in Million plus Cities of India (MCOI), through the implementation of ITS-based strategies. A total of six critical ITS based strategies are formulated and generated, and the model offers innovative policy recommendations based on simulation, validation, and sensitivity analysis, along with a range of additional benefits. Notably, there is limited literature on reducing carbon emissions and energy consumption in the Indian road transportation sector using the SD modeling technique but the literature related to development of SD simulation model to reduce the total transport carbon emissions and total transport energy consumptions of the road transportation sector in MCOI by the implementation of six strategies based on ITS simultaneously are almost negligible. This research seeks to fill this significant gap in literature through this innovative first-time effort.

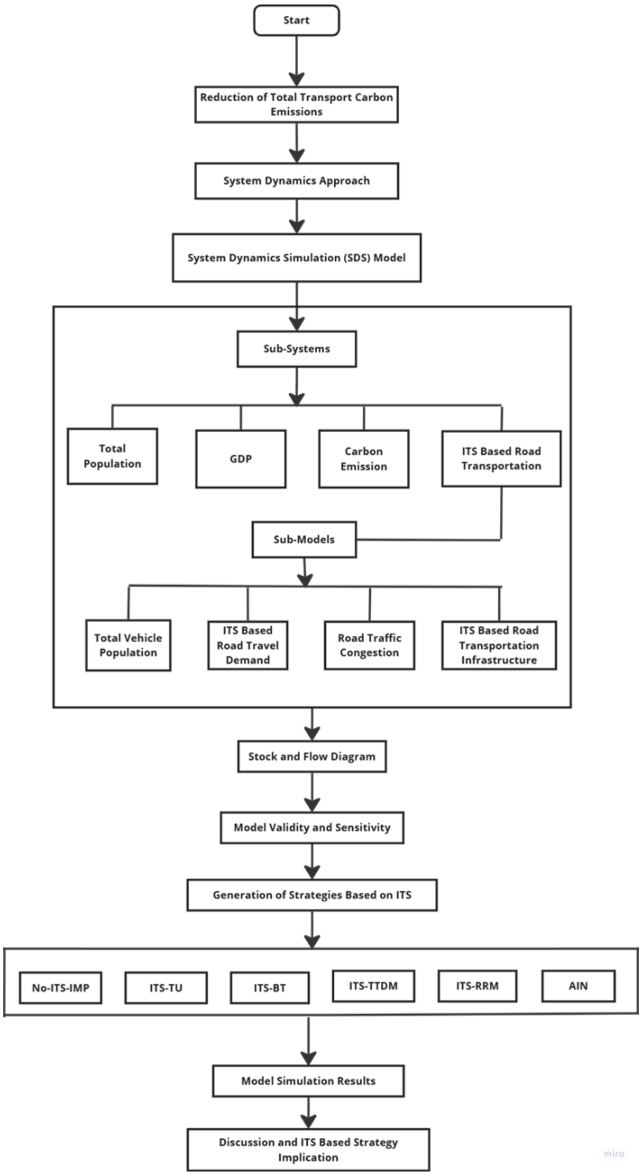


Figure 1. Detailed SDS Model Structure

2. System dynamics simulation model

A System Dynamics Simulation (SDS) model is designed and developed to reduce the total transport carbon emissions and total transport energy consumption of the road transportation sector in MCOI by the implementation of strategies based on ITS. The model also generates six ITS based critical strategies and policy implementation recommendations on the basis of validation and sensitivity analysis to reduce the Total Transport Carbon Emissions (TTCE) and Total Transport Energy Consumption (TTEC), and also delivers a wide range of additional paybacks. The relationship of critical variables affecting the TTCE and TTEC is depicted in the model. **Figure 1** shows the detailed SDS model structure.

The structure of the model is based on four main Sub-Systems: GDP Sub-System (GDP-SS), Total Population Sub-System (ToPoP-SS), Carbon Emission Sub-System (CaEm-SS) and ITS based Road Transportation Sub-System (ITS-RoTr-SS). ITS-RoTr-SS consists of four sub-models: Total Vehicle Population sub-model, ITS based Road Travel Demand sub-model, Road Traffic Congestion sub-model, and ITS based Road Transportation Infrastructure sub-model and all these four sub-models of ITS-RoTr-SS are totally linked with GDP-SS, ToPoP-SS and CaEm-SS. The relations between three Sub-Systems and four sub-models based ITS-RoTr-SS of the SDS model are shown in **Figure 2**.

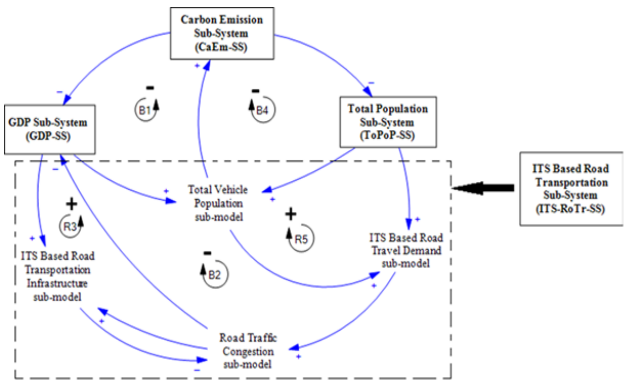


Figure 2. Relationship between three Sub-Systems and four sub-models based ITS-RoTr-SS of the SDS Model

The following loops provide a detailed description of each key feedback loop of various Sub-Systems and sub-models, and their interdependent relationships, where changes in one sub-model and Sub-Systems influence others, creating either Reinforcing (R) or Balancing (B) effect and thus highlighting the feedback mechanisms that drive the system's behaviour:

Loop 1(B1): GDP Sub-System (GDP-SS) → + Total Vehicle Population sub-model of ITS-RoTr-SS → + Carbon Emission Sub-System (CaEm-SS) → — GDP Sub-System (GDP-SS) [Negative or Balancing (B) Loop]

Loop 2 (B2): GDP Sub-System (GDP-SS) → + Total Vehicle Population sub-model of ITS-RoTr-SS → + ITS Based Road Travel Demand sub-model of ITS-RoTr-SS → + Road Traffic Congestion sub-model of ITS-RoTr-SS → — GDP Sub-System (GDP-SS) [Negative or Balancing (B) Loop]

Loop 3 (R3): GDP Sub-System (GDP-SS) → + ITS Based Road Transportation Infrastructure sub-model of ITS-RoTr-SS → — Road Traffic Congestion sub-model of ITS-RoTr-SS → — GDP Sub-System (GDP-SS) [Positive or Reinforcing (R) Loop]

Loop 4 (B4): Carbon Emission Sub-System (CaEm-SS) → — Total Population Sub-System (ToPo-SS) → + Total Vehicle Population sub-model of ITS-RoTr-SS → + Carbon Emission Sub-System (CaEm-SS) [Negative or Balancing (B) Loop]

Loop 5 (R5): Carbon Emission Sub-System (CaEm-SS) → — Total Population Sub-System (ToPo-SS) → + ITS Based Road Travel Demand sub-model of ITS-RoTr-SS → + Road Traffic Congestion sub-model of ITS-RoTr-SS → —

GDP Sub-System (GDP-SS) → + Total Vehicle Population sub-model of ITS-RoTr-SS → + Carbon Emission Sub-System (CaEm-SS) [Positive or Reinforcing (R) Loop]

The resulting outcome in the total variation in the Sub-Systems and sub-models, and the quantitative relations between the various parameters with the overall system basic characteristics are shown in the form of a Stock and Flow (SF) diagram of the SDS model, and this SF diagram mainly revolves around ToPoP-SS, GDP-SS, CaEm-SS and four sub-models based ITS-RoTr-SS. **Figure 3** depicts the SF diagram of the SDS model.

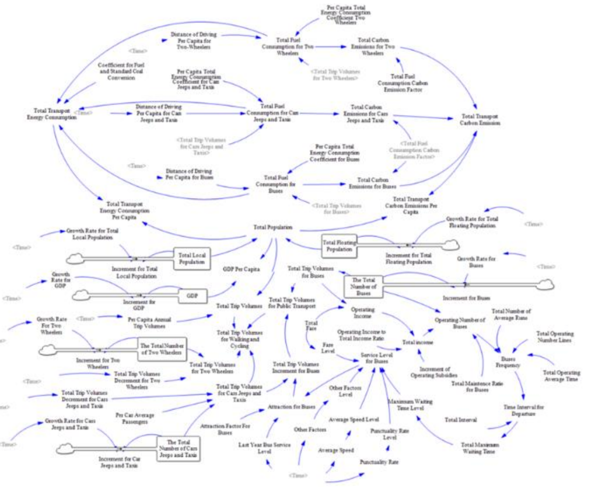


Figure 3. SF Diagram of the SDS Model

2.1. Total Population Sub-System (ToPoP-SS)

The road transportation sector of MCOI is mainly affected by the structural pattern and magnitude of the total population. Due to the expansion in cities of India, the total floating population phenomenon plays an important role in the total population and is slightly different from other natural displacements of the total population. This population is basically a group of people who reside in the border area of the cities but study or work etc. in a different place and thus affect both the origin cities as well as destination cities, and is one of the major problems in the road transportation sector of MCOI. The rise in this total floating population is bound to drastically affect the road transportation sector of these cities. The total floating population is treated like an incremental parameter of the GDP/capita, and its effect on the total floating population is evaluated. The stock variable total local population and the stock variable total floating population will synergistically affect the total population of the cities.

2.2. GDP Sub-System (GDP-SS)

Due to rise in GDP/capita, the total population of MCOI can easily afford to buy motorized vehicles like cars, scooters, motor bikes etc. for driving or movement purposes, and this will result in a shift from non-motorized modes to motorized transport modes. Thus, there is one to one relation between the growth of GDP/capita and the road transportation system of MCOI.

2.3. ITS based Road Transportation Sub-System (ITS-RoTr-SS)

The residents of MCOI are changing their mode of road transportation due to their high living standard, from non-motorized to motorized and using two-wheelers, cars, taxis, jeeps, and public transport. The segment rate of cycling and walking is decreasing continuously, and the segment rate of motorization is rising at a tremendous pace. The segment rate of cars, jeeps, and taxis is continuously increasing at a very fast pace and plays an important role in the road traffic congestion, accidents, and rise in TTCE and TTEC. Due to improvement of punctuality, travel time and comfort, reduction in waiting time, and cheaper mode of transportation in comparison of cars, jeeps, and taxis, the majority of commuters are slowly switching over and using the bus transportation system in MCOI. The important parameters like quantity of vehicles – two-wheelers, cars, taxis, jeeps, and buses; vehicles mileage driven, and vehicles energy efficiency are directly affecting the TTEC. The fuel consumption is increasing at a fast pace despite of price rise, and the demand for private jeeps and cars is also continuously growing due to the rise in people's living standards and growth in economy. The promotion of the usage of ITS based new energy efficient vehicles and the development of ITS based green bus transport are very strong measures for the reduction of TTCE.

2.4. Carbon Emission Sub-System (CaEm-SS)

Reduction of TTEC and TTCE of the road transportation sector in MCOI is the major goal of the SDS model. The Total Transport Energy Consumption due to particular modes of transport m for different types of total transport energy consumption n can be calculated from the following equation:

$$TTEC_{m,n} = TTECC_{m,n} \times DD_m \times TV_m \qquad (1)$$

where, $TTECC_{m,n}$ = Total Transport Energy Consumption Coefficient per Capita, DD_m = Distance of Driving per capita for particular modes of transport m , TV_m = Trip Volumes per year for particular modes of transport m

NTotal Transport Carbon Emissions due to particular MODES of transport m. for different types of total transport energy consumption n. can be calculat from the following equation.

$$TTCE_{m,n} = TTECC_{m,n} \times DD_m \times TV_m \times Ef_n \qquad (2)$$

w, Ef_n = Emission factor from total transport energy cmption n. Similarly, Total Transport Energy Consumption *TTEC* can be calculated from t following equation.

$$TTEC = \sum_{m,n} TTECC_{m,n} \times DD_m \times TV_m \times ECC_n \qquad (3)$$

(re, ECC_n = Energy Conservation Coefficient from energy type n. to standard coal and Per Capita Transport Energy Consumption $PCTEC$ can be calcuted fm the following equation:

$$PCTEC = \frac{\sum_{m,n} TTECC_{m,n} \times DD_m \times TV_m \times ECC_n}{TP} \qquad (4)$$

where, TP. = Total Population

Now Total Transport Carbon Emission *TTCE*. can be calculated from the following equation:

$$TTCE = \sum_{m,n} TTECC_{m,n} \times DD_m \times TV_m \times Ef_n \quad (5)$$

and finally, Per Capita Transport Carbon Emission *PCTCE.* can be calculated from the following equation:

$$PCTCE = \frac{\sum_{m,n} TTECC_{m,n} \times DD_m \times TV_m \times Ef_n}{TP} \quad (6)$$

2.5. SDS Model Validity and Sensitivity

The parameters of the SDS model are continuously modified a adjusted during the course of development of the interrelation between different parameters to reduce the error between actual historical and simulated data, and ultimately to improve t reliability of the model. The Mean Absolute Percentage Error (MAPE), Root Mean Square Percentage Error (RMSPE), Error Rate (ER), and Error Variance (EV) of the key parameters are calculated using the following equations respectively:

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{Simulated\,Value - Absolute\,Value}{Absolute\,Value}\right| \times 100 \quad (7)$$

$$RMSPE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left|\frac{Simulated\,Value - Absolute\,Value}{Absolute\,Value}\right|^2} \times 100 \quad (8)$$

$$ER = \frac{|\,Simulated\,Value - Absolute\,Value\,|}{Absolute\,Value} \times 100 \quad (9)$$

$$EV = \frac{|\,Average\,Rate\,of\,Simulated\,Value - Average\,Rate\,of\,Absolute\,Value\,|}{Average\,Rate\,of\,Absolute\,Value} \times 100 \quad (10)$$

The MAPE and RMSPE for Total Population, GDP, The Total Number of Two Wheelers, The Total Number of Cars Jeeps and Taxis, and The Total Number of Buses are {0.4635, 1.3409, 0.7141, 2.7628 and 0.2826} and {1.0767, 1.8021, 1.4003, 3.6653 and 1.1925} respectively while the ER and EV for these parameters are {0.4266, 1.3604, 0.9001, 3.1206 and 0.2711} and {10.3593, 0.8505, 3.9265, 10.6186 and 3.3509} respectively.he developed SDS model is effective, valid, and generates 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 and RMSPE are also very close to zero, which clearly shows that error is very low and model's prediction ability is best. Using 2011 as the base year, the historical data from 2011 to 2019 (Ministry of Road Transport and Highways, Government of India; Census Division, Government of India; Economic Survey, Government of India) were utilized to verify the validity of the method. The key parameters fully satisfy the validity for future projections, and **Table 1** depicts the comparison between the actual value and simulated value of key parameters.

Table 1. Comparison between Simulated Value (SV) and Actual Value (AV) of Key Parameters

Year	Total Population (crore)			GDP (crore)			The Total Number of Two Wheelers (thousand)			The Total Number of Car Jeeps and Taxis (thousand)			The Total Number of Buses (thousand)		
	SV	AV	Error %	SV	AV	Error %	SV	AV	Error %	SV	AV	Error %	SV	AV	Error %
2011	1.25	1.25	0.00	8736330	8736329	0.00	101865	101865	0.00	19231	19231	0.00	1604	1604	0.00
2012	1.28	1.27	0.01	9190620	9213017	0.00	113274	115419	0.02	21616.2	21568	0.00	1684.89	1677	0.00
2013	1.31	1.28	0.02	9686910	9801370	0.01	128340	127830	0.00	24243.1	24056	0.01	1761.62	1814	0.03
2014	1.33	1.32	0.01	10297200	10527675	0.02	142072	139410	0.02	27039.6	25998	0.04	1905.61	1887	0.01
2015	1.36	1.35	0.01	11059200	11369493	0.03	154859	154298	0.00	29222.3	28611	0.02	1982.33	1971	0.01
2016	1.39	1.37	0.01	11932900	12308193	0.03	171274	168975	0.01	32159.3	30242	0.06	1737.61	1757	0.01
2017	1.41	1.43	0.01	12911400	13144582	0.02	187545	187091	0.00	33992.4	33688	0.01	1845.69	1864	0.01
2018	1.44	1.45	0.01	13776400	14003316	0.02	207612	202755	0.02	37864.3	36453	0.04	1958.15	1943	0.01
2019	1.46	1.47	0.00	14671900	14569268	0.01	224844	221270	0.02	40971.9	38433	0.07	2041.18	2049	0.00

The sensitivity analysis of the SDS model is also performed to assess how responsive the model is to changes in key dynamic parameter values and modifications in its fundamental structure. This sensitivity analysis helps in identifying critical dynamic parameters affecting system behavior and reinforces the model's reliability in predicting different generated ITS based strategies. **Figure 4** presents a sensitivity analysis of the total transport carbon emissions, and the model indicates that several parameters exert proportional effects on the output. A ±10% change in the total fuel consumption carbon emission factor resulted in a corresponding ±10% change in the model outputs. Similarly, a ±7.31% change in the per capita total energy consumption coefficient for two-wheelers produced a proportional ±7.31% change in total transport carbon emissions. Furthermore, a ±2.67% change in per-car average passengers as well as in the car energy consumption coefficient per capita resulted in equivalent ±2.67% changes in the outputs. These results suggest that the model exhibits unitary sensitivity for these parameters, implying that variations in these factors translate directly into proportional percentage changes in total transport carbon emissions, and the developed model is totally under control and is totally fit for simulation to generate ITS based strategies.

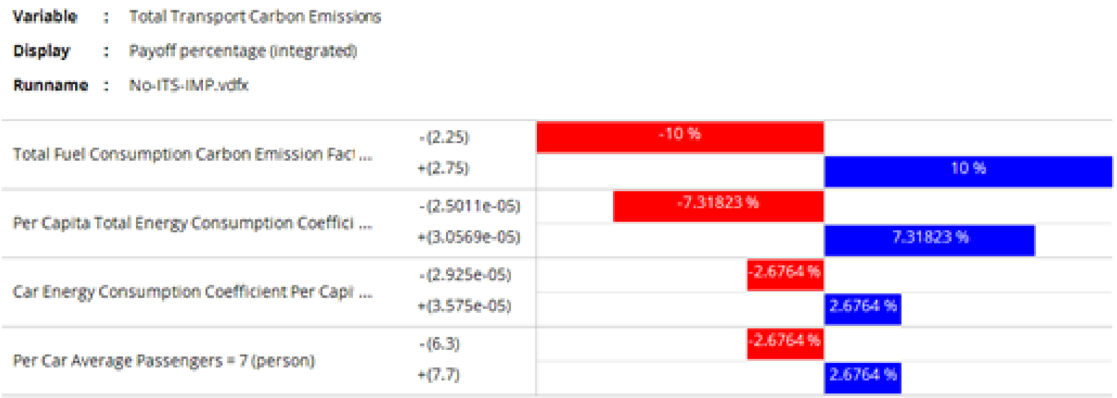


Figure 4. Sensitivity analysis of the total transport carbon emissions

3. Generation of strategies based on intelligent transportation systems

ITS integrates information technologies- like cloud computing, mobile internet, Internet of Things and big data with communication technologies and by effectively utilizing the present transportation infrastructure can drastically reduce TTCE and TTEC, road accidents, traffic congestion, and improve traffic and transportation services. The ITS fosters a symbiotic relationship between environment, vehicles, roads and commuters, making it a growing market with significant potential. Advanced Public Transportation Systems (APTS), Advanced Traveler Information Systems (ATIS), Advanced Traffic Management Systems (ATMS), Advanced Vehicle Control Systems (AVCS), Emergency Vehicle Services (EVS), and Commercial Vehicle Operations (CVO) are major functional areas of ITS. APTS increases the efficiency of public transportation network and APTS solutions include Smart Bus Core, Smart Bus Camera, Driver Status Monitoring, Blind Spot Detection, Ultrasonic Sensors and Smart Card IC Scanners, while ATIS is the most extensively used ITS application area that provides real time information to the travellers to enhance their mobility. ATIS solutions include Personal Digital Assistants, Onboard Electronic Maps, Electronic Route Guidance, GPS, En Route Driver Information, Wireless Devices, Variable/Changeable Message Signs, Weather-related Messages, Travel Times, Emergency Alerts, and Alternate Routes.

ATMS is another ITS application platform that covers monitoring, controlling and safety on roads and highways. ATMS solutions include Signal Optimization and Innovative Ramp Metering, Real Time Traffic Information, Incident Detection and Rapid Accident Response, Signalized Arterial Networks, Highway Advisory Radio, Adaptive Signal Control, Real Time Decision Support while Advanced Vehicle Control Systems solution include Longitudinal Assistance Systems preventing Rear-End and Front-End Collisions, On-Board Radar, LiDAR, Computer Vision Technology, Dedicated Short Range Communication Radios to enable Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Infrastructure-to-Vehicle (I2V) to improve safety. EVS solution includes Drones and Unmanned Aerial Vehicles, Green Wave system, Visual Road Side Units, and Emergency Vehicle Lighting and Sirens, while CVO application area of ITS deals in regulating and transporting freight in commercial vehicles and includes Fleet Administration, Freight Administration, Electronic Clearance, Commercial Vehicle Administrative Processes, Weigh-In-Motion, Roadside CVO Safety, On-Board Safety Monitoring, CVO Fleet Maintenance, Hazardous Material Planning and Incident Response, Freight In-Transit Monitoring and Freight Terminal Management (**Figure 5**).

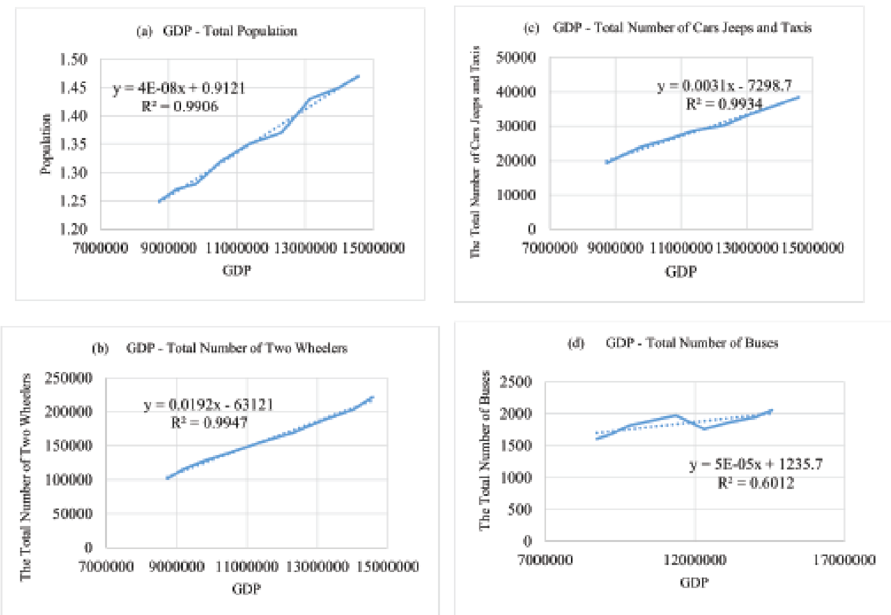


Figure 5. R^2 for (a) GDP-Total Population, (b) GDP- Total Number of Two Wheelers, (c) GDP- Total Number of Cars, Jeeps and Taxis and (d) GDP- Total Number of Buses

Total six strategies based on ITS-- ITS based Traffic and Transportation Demand Management (ITS-TTDM) strategy, ITS based Bus Transport (ITS-BT) strategy, ITS based Rules and Regulations Management (ITS-RRM) strategy, ITS based Technology Upgradation (ITS-TU) strategy, No ITS Implementation (No-ITS-IMP) strategy and All Integrated (AIN) strategy are formulated and generated to monitor the TTCE and TTEC in MCOI using the output of the sensitivity analysis of key dynamic parameters of the SDS model. The developed robust model is simulated for generated strategies based on ITS to reduce the TTCE and TTEC. The outcome pattern of TTCE and TTEC is analyzed and simulated from 2011-2020 (pre-COVID period), during the Covid period, and post Covid period from 2022 to 2030 to observe the effect of generated strategies based on ITS.

3.1. No ITS Implementation Strategy

In No-ITS-IMP, there is no change in the TTCE and TTEC pattern in MCOI because it follows the current national developmental trend, and also there is no implementation of ITS as well as no addition of any new policy to the four main Sub-Systems and four sub-models of ITS-RoTr-SS. Thus, the TTCE and TTEC will continuously increase in the near future and reach a new height.

3.2. ITS based Bus Transport Strategy

The basic aim of ITS-BT is to provide intelligent and innovative services to enhance the mobility, safety, efficiency, and environment of the public bus transport of the MCOI. ITS-BT cannot cover all the dense points of cities, but can only cover all the major and important locations and will definitely play attention mode to reduce the TTCE and TTEC. The share of public bus transport equipped with ITS must increase by 60 percent, while a serious effort should be made to reduce the personal motorized four and two-wheelers to reduce the TTCE.

3.3. ITS based Traffic and Transportation Demand Management Strategy

The majority of cities of India are already implementing traffic and transportation demand management policy planning in a phased manner but there is an urgent need to implement strategy ITS-TTDM not only to reduce the TTCE and TTEC but also to develop an ITS based green, human-centered and hi-tech public transportation. This ITS-TTDM mainly focus on promoting and increasing the use of ITS based bus transport in MCOI and to discourage and reduce the use of private cars, taxis, and jeeps by implementing ITS based odd-even rule; ITS based traffic and transport management plan; and ITS based traffic congestion charging fee rule. The ITS-TTDM strategy is crucial for strategic and tactical planning. It determines how, when, why and where people in MCOI travel, aiming to make their travel patterns more sustainable. This strategy is designed to change travel patterns, making them more effective, efficient and equitable. ITS-TTDM is built on four pillars for an integrated approach. The first pillar involves travel disincentives and incentives, such as parking fees and transit charges. The second pillar promotes supportive land-use practice to reduce the need for travel. The third pillar focuses on sustainable travel options like cycling, walking and public vehicles, making travelling more enjoyable, safer, and comfortable. The fourth pillar is about raising awareness and promoting a culture of sustainable transportation. By formulating and implementing such innovative education and awareness programs, individuals can make informed choices about their travel modes and feel more comfortable.

3.4. ITS based Technology Upgradation Strategy

The role of ITS-TU in cities of India will play a very important role in reducing TTCE and TTEC by eliminating the use of highly polluting vehicles, and very old two and four-wheelers, and introducing ITS based hi-tech vehicles. The health of children and adults is slowly entering the danger zone in MCOI due to heavily polluted traffic and transport environments. The only solution to prevent escalating environmental pollution is the introduction of ITS based hi-tech e-vehicles. Road transportation is mainly dominated by diesel and petrol-based vehicles. The introduction of ITS based hi-tech e-vehicles will improve quality, efficiency, performance and reduce fuel consumption and carbon emissions.

3.5. ITS based Rules and Regulations Management Strategy

The goal of ITS-RRM is to implement ITS based guidelines in the road transportation sector of MCOI to reduce TTCE and TTEC patterns. This involves controlling the purchase and use of new two-wheelers and four-wheelers, managing the inflow of floating population and balancing the ITS based infrastructure development in small villages, towns and MCOI. Introduction of the Indian government sponsored ITS based two and four wheelers scrap page policies will generate an ecosystem to attain a net zero emission footprint by phasing out very old, polluting and unfit two and four-wheelers on the roads of cities. This will also encourage citizens of India to buy ITS based safe, advanced, and eco-friendly hi-tech e-vehicles. The strict implementation of ITS based vehicle fitness testing regulations using automated testing stations for light and heavy commercial vehicle populations and private vehicle populations should be immediately introduced. The implementation of ITS based odd-even rule as a road traffic rationing yardstick will not only reduce the TTCE but also road traffic congestion of MCOI by intelligently scanning the registration number plates of private vehicles ending with an odd digit on odd dates of months or even digit on even dates of months. The introduction of ITS based traffic congestion charging fee rule during morning and evening peak hours will also reduce traffic congestion as well as TTCE and TTEC.

3.6. All Integrated Strategy

The AIN strategy combines ITS-TTDM, ITS-BT, ITS-RRM and ITS-TU along with all their restrictions. Due to the multiple effects of these four strategies, an accumulated decreasing pattern of TTCE and TTEC is observed in MCOI.

4. Simulation results

The simulation results of SDS model for generated strategies based on ITS are shown in **Figure 6** to reduce the TTEC and TTCE of the road transportation sector in MCOI. **Figure 6(a)** depicts TTEC pattern in MCOI for different strategies. The value of the TTEC under AIN is minimum in the base year 2011 and has the lowest rising outcome pattern of all strategies upto the Covid-19 period, and after the aggressive implementation of ITS from the post-Covid-19 time period, has the highest continuous decline pattern among the six strategies. The output pattern of AIN is the most effective strategy pattern among all six strategies in reducing the TTEC in both long as well as short periods. In ITS-RRM, the value of the TTEC has one of the lowest rising patterns of all five separate strategies upto the Covid-19 period, but after the aggressive implementation of ITS-RRM from the post-Covid-19 period, it has the second highest continuous decline pattern and thus a very realistic strategy for the short duration reduction of TTEC. In No-ITS-IMP, there is a maximum rising pattern from the post-Covid-19 period in comparison to all other strategies and in the ITS-TU, there is a minimum decline pattern in the TTEC before and after Covid-19 period. There was a less rising pattern in TTEC before the Covid-19 period, due to ITS-BT and ITS-TTDM in comparison of No-ITS-IMP and ITS-TU, but after the Covid-19 period, there is a continuous minor decline pattern in TTEC due to ITS-BT and ITS-TTDM. The ITS-TTDM looks very realistic strategy for the short duration reduction of TTEC.

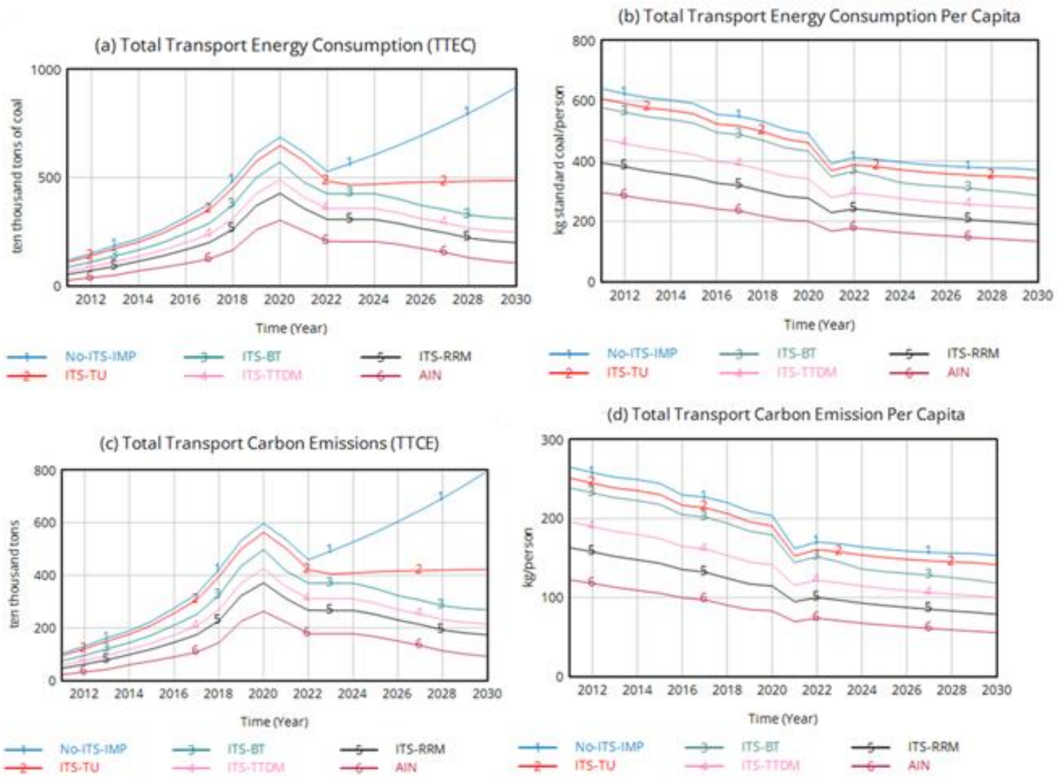


Figure 6. (a) TTEC pattern, (b) Variations in TTEC per capita, (c) TTCE pattern, and (d) Variations in TTCE per capita in MCOI for different strategies based on ITS.

Figure 6(b) depicts the variations in TTEC per capita in MCOI for different strategies based on ITS. There is very minor decline pattern in TTEC per capita under ITS-TU, primarily due to less short duration progress in energy consumption economy of urban transportation in India, mainly due to constraints of advanced technology and finance before the Covid-19 period. There is also a very slow paced decline pattern in TTEC per capita under ITS-TTDM before the Covid-19 period, but during the Covid-19 period, there is a very sharp decline, but after the Covid-19 period, there is a faster decline pattern in TTEC per capita. In the ITS-BT, the pattern of TTEC per capita depicts a bit sharp decline behaviour before the Covid-19 period, but after the Covid-19 period, the decline pattern depicts a gradual slow pace decline. In ITS-RRM, the TTEC per capita has the lowest value of all the specific strategies. In ITS-RRM and ITS-TTDM, before the Covid-19 period in comparison to all other strategies, have a tremendous initial decline pattern in the TTEC per capita, but ITS-BT depicts a drastic decline pattern in totality in the TTEC per capita, not only before the Covid-19 period but also in post Covid-19 period. The model simulation clearly shows that the ITS-BT is the best suited strategy for the reduction of TTEC per capita from the public bus transport. The TTEC per capita depicts the lowest level value at the start for the AIN, and there is a continuous fall in its values before and after the Covid-19 period. It is interesting to note that the decline of the TTEC per capita under AIN is very fast in the beginning but after a passage of time slows down.

Table 2. Variation in Percentage between the Base Run No-ITS-IMP strategy and the other five strategies

Strategies	Variation (%) compared from Base Run No-ITS-IMP strategy
No-ITS-IMP	0
ITS-TU	47
ITS-BT	66
ITS-TTDM	73
ITS-RRM	78
AIN	88

Table 3. Time Series Trends of TTCE and TTEC

	Total Transport Carbon Emissions				Total Transport Energy Consumption			
Strategy	2024	2026	2028	2030	2024	2026	2028	2030
No-ITS-IMP	526.72	604.15	693.58	796.95	605.73	694.77	797.62	916.49
ITS-TU	408.44	416.88	420.49	422.02	469.70	479.42	483.57	485.33
ITS-BT	370.36	322.98	284.60	269.08	425.91	371.43	327.29	309.44
ITS-TTDM	311.12	269.79	231.79	214.58	357.79	310.26	266.55	246.76
ITS-RRM	266.70	229.90	192.18	173.70	306.70	264.38	221.00	199.76
AIN	177.85	150.11	112.957	91.95	204.53	172.63	129.90	105.75

The TTCE pattern in MCOI for six different strategies based on ITS is shown in **Figure 6(c)**. The value of the TTCE under AIN has the lowest rising pattern of all six strategies up to the Covid-19 period, and after the aggressive implementation of ITS from 2023 to 2030, again has the highest continuous decline pattern of all six ITS based strategies. Under the ITS-RRM, the TTCE pattern after the aggressive implementation of ITS-RRM from the post-Covid-19 period has the second highest continuous steady decline pattern, and thus again a highly realistic strategy for the short duration reduction of TTCE. Variations in TTCE per capita in MCOI for six different strategies based on ITS are shown in **Figure 6(d)**. The simulation pattern for TTEC per capita shown in **Figure 6(b)** and TTCE per capita shown in **Figure 6(d)** is very similar for the ITS-TTDM, ITS-BT, ITS-RRM and AIN.

Table 2 shows the variation in percentage between the base run No-ITS-IMP strategy and the other five generated strategies derived from the simulation results of the SDS model. **Table 2** illustrates that in comparison to the base run No-ITS-IMP strategy, AIN achieves the greatest 88% decrease in TTCE, despite incurring higher implementation costs, while ITS-RRM offers the most feasible and reasonable 78% decrease in TTCE and represents the best critical strategy. The other strategies, ITS-TTDM, ITS-BT, and ITS-TU, decrease TTCE by around 73%, 66%, and 47% respectively.

Table 3 displays the Time Series Trends of TTCE and TTEC from 2024 to 2030, derived from the simulation results of the SDS model for the formulated and developed six strategies. The expedited decrease phase after 2024 indicates a clear downward trajectory as a result of the AIN strategy, with TTCE declining from 177.852 to 150.109 between 2024 and 2026 and from 112.957 to 91.9527 between 2028 and 2030. However, the most feasible and logical decreasing trend arises from the application of the ITS-RRM strategy, with TTCE falling from 266.699 to 229.895 and from 192.176 to 173.702 during the same periods.

5. Discussion and ITS based strategy implications

The modelled timeframe was segmented into two intervals: the initial five years from 2019 to 2024 and the subsequent five years from 2025 to 2030, to illustrate and analyze the aggregate impact of TTCE, TTCE per capita, TTEC, and TTEC per capita in AIN, ITS-RRM, ITS-TTDM, ITS-BT, ITS-TU, and the No-ITS-IMP strategy. **Figure 7(a)** illustrates the overall impact of TTCE across six varying strategies, while **Figure 7(b)** represents the overall impact of TTEC across six distinct strategies. It is evident that AIN consistently shows the greatest impact, while No-ITS-IMP consistently shows the least effect in decreasing TTCE and in conserving TTEC.

It's worth mentioning that the ITS-RRM consistently achieves the best results among all individual strategies for both reducing TTCE and saving TTEC. **Figure 7(c)** demonstrates the total effect of TTCE per capita across six different strategies, whereas **Figure 7(d)** shows the total effect of TTEC per capita across six separate strategies. A comparable trend can be observed here as well because of AIN, No-ITS-IMP, and ITS-RRM.

Figure 7. Overall impact of (a) TTCE, (b) TTEC, (c) TTCE per capita and (d) TTEC per capita across various strategies

The optimal order of implementing different strategies can be determined through precise calculations for each strategy, taking into account the influence of the remaining strategies and their multiple combinations. **Table 4** details the comprehensive calculations for different combinations of all four strategies— ITS-BT, ITS-TU, ITS-TTDM, and ITS-RRM— alongside their descriptions, which include Δ(ITS-BT), Δ(ITS-TU), Δ(ITS-TTDM), Δ(ITS-RRM) for the implementation of individual strategies; Δ[(ITS-BT) + (ITS-TTDM)], Δ[(ITS-BT) + (ITS-TU)], Δ[(ITS-BT) + (ITS-RRM)], Δ[(ITS-BT) + (ITS-TU)], Δ[(ITS-TTDM) + (ITS-TU)], Δ[(ITS-TU) + (ITS-RRM)], and Δ[(ITS-TTDM) + (ITS-RRM)] for the implementation of paired strategies; Δ[(ITS-BT) + (ITS-TTDM) + (ITS-TU)], Δ[(ITS-BT) + (ITS-TTDM) + (ITS-RRM)], Δ[(ITS-BT) + (ITS-TU) + (ITS-RRM)], and Δ[(ITS-TTDM) + (ITS-TU) + (ITS-RRM)] for the implementation of triple strategy combinations; and finally ΔAIN represents the reduction of TTCE achieved by ITS-BT, ITS-TU, ITS-TTDM, ITS-RRM, [(ITS-BT) + (ITS-TTDM)], [(ITS-BT) + (ITS-TU)], [(ITS-BT) + (ITS-RRM)], [(ITS-BT) + (ITS-TU)], [(ITS-TTDM) + (ITS-TU)], [(ITS-TU) + (ITS-RRM)], [(ITS-TTDM) + (ITS-RRM)], [(ITS-BT) + (ITS-TTDM) + (ITS-TU)], [(ITS-BT) + (ITS-TTDM) + (ITS-RRM)], [(ITS-BT) + (ITS-TU) + (ITS-RRM)], [(ITS-TTDM) + (ITS-TU) + (ITS-RRM)], and AIN strategy relative to the **No-ITS-IMP**.

Table 4. Effect on Reduction of TTCE due to separate implementation of (a) ITS-BT, (b) ITS-TU, (c) ITS-TTDM and (d) ITS-RRM Strategy and their integrations.

Strategy	Strategies Combination	Description of Strategies Combination
(a) ITS-BT	#1 ITS-BT — (No-ITS-IMP) = Δ(ITS-BT)	The effect on reduction of TTCE from the implementation of ITS-BT after the former implementation of (No-ITS-IMP)
	#2 ITS-BT— (ITS-TTDM) = Δ[(ITS-BT) + (ITS-TTDM)] – Δ(ITS- TTDM)	The effect on reduction of TTCE from the implementation of ITS-BT after the former implementation of (ITS-TTDM)
	#3 ITS-BT— (ITS-TU) = Δ[(ITS-BT) + (ITS-TU)] – Δ(ITS-TU)	The effect on reduction of TTCE from the implementation of ITS-BT after the former implementation of (ITS-TU)
	#4 ITS-BT— (ITS-RRM) = Δ[(ITS-BT) + (ITS-RRM)] – Δ(ITS-RRM)	The effect on reduction of TTCE from the implementation of ITS-BT after the former implementation of (ITS-RRM)
	#5 ITS-BT — [(ITS-TTDM) + (ITS-TU)] = Δ[(ITS-BT) + (ITS-TTDM) + (ITS-TU)] – Δ[(ITS-TTDM) + (ITS-TU)]	The effect on reduction of TTCE from the implementation of ITS-BT after the former implementation of (ITS-TTDM) and (ITS-TU)
	#6 ITS-BT—[(ITS-TTDM) + (ITS-RRM)] =Δ[(ITS-BT) + (ITS-TTDM) + (ITS-RRM)] – Δ[(ITS-TTDM) + (ITS-RRM)]	The effect on reduction of TTCE from the implementation of ITS-BT after the former implementation of (ITS-TTDM) and (ITS-RRM)
	#7 ITS-BT—[(ITS-TU) + (ITS-RRM)] = Δ[(ITS-BT) + (ITS-TU) + (ITS-RRM)] – Δ[(ITS-TU) + (ITS-RRM)]	The effect on reduction of TTCE from the implementation of ITS-BT after the former implementation of (ITS-TU) and (ITS-RRM)
	#8 ITS-BT—[(ITS-TTDM) + (ITS-TU) + (ITS-RRM)] = ΔAIN – Δ[(ITS-TTDM) + (ITS-TU) + (ITS-RRM)]	The effect on reduction of TTCE from the implementation of ITS-BT after the former implementation of (ITS-TTDM), (ITS-TU) and (ITS-RRM)
(b) ITS-TU	#1 ITS-TU — (No-ITS-IMP) = Δ(ITS-TU)	The effect on reduction of TTCE from the implementation of ITS-TU

		after the former implementation of (No-ITS-IMP)
	#2 ITS-TU— (ITS-BT) = Δ[(ITS-BT) + (ITS-TU)] – Δ(ITS-BT)	The effect on reduction of TTCE from the implementation of ITS-TU after the former implementation of (ITS-BT)
	#3 ITS-TU— (ITS-TTDM) = Δ[(ITS-TTDM) + (ITS-TU)] – Δ(ITS- TTDM)	The effect on reduction of TTCE from the implementation of ITS-TU after the former implementation of (ITS-TTDM)
	#4 ITS-TU— (ITS-RRM) = Δ[(ITS-TU) + (ITS-RRM)] – Δ(ITS-RRM)	The effect on reduction of TTCE from the implementation of ITS-TU after the former implementation of (ITS-RRM)
	#5 ITS-TU — [(ITS-BT) + (ITS-TTDM)] = Δ[(ITS-BT) + (ITS-TTDM) + (ITS-TU)] – Δ[(ITS-BT) + (ITS-TTDM)]	The effect on reduction of TTCE from the implementation of ITS-TU after the former implementation of (ITS-BT) and (ITS-TTDM)
	#6 ITS-TU—[(ITS-BT) + (ITS-RRM)] =Δ[(ITS-BT) + (ITS-TU) + (ITS-RRM)] – Δ[(ITS-BT) + (ITS-RRM)]	The effect on reduction of TTCE from the implementation of ITS-TU after the former implementation of (ITS-BT) and (ITS-RRM)
	#7 ITS-TU—[(ITS-TTDM) + (ITS-RRM)] = Δ[(ITS-TTDM) + (ITS-TU) + (ITS-RRM)] – Δ[(ITS-TTDM) + (ITS-RRM)]	The effect on reduction of TTCE from the implementation of ITS-TU after the former implementation of (ITS-TTDM) and (ITS-RRM)
	#8 ITS-TU—[(ITS-BT) + (ITS-TTDM) + (ITS-RRM)] = ΔAIN – Δ[(ITS-BT) + (ITS-TTDM) + (ITS-RRM)]	The effect on reduction of TTCE from the implementation of ITS-TU after the former implementation of (ITS-BT), (ITS-TTDM) and (ITS-RRM)
(c) ITS-TTDM	#1 ITS-TTDM — (No-ITS-IMP) = Δ(ITS-TTDM)	The effect on reduction of TTCE from the implementation of ITS-TTDM after the former implementation of (No-ITS-IMP)
	#2 ITS-TTDM — (ITS-BT) = Δ[(ITS-BT) + (ITS-TTDM)] – Δ(ITS-BT)	The effect on reduction of TTCE from the implementation of ITS-TTDM after the former implementation of (ITS-BT)
	#3 ITS-TTDM — (ITS-TU) = Δ[(ITS-TTDM) + (ITS-TU)] – Δ(ITS-TU)	The effect on reduction of TTCE from the implementation of ITS-TTDM after the former implementation of (ITS-TU)
	#4 ITS-TTDM — (ITS-RRM) = Δ[(ITS-TTDM) + (ITS-RRM)] – Δ(ITS-RRM)	The effect on reduction of TTCE from the implementation of ITS-TTDM after the former implementation of (ITS-RRM)
	#5 ITS-TTDM — [(ITS-BT) + (ITS-TU)] = Δ[(ITS-BT) + (ITS-TTDM) + (ITS-TU)] – Δ[(ITS-BT) + (ITS-TU)]	The effect on reduction of TTCE from the implementation of ITS-TTDM after the former implementation of (ITS-BT) and (ITS-TU)
	#6 ITS-TTDM —[(ITS-BT) + (ITS-RRM)] =Δ[(ITS-BT) + (ITS-TTDM) + (ITS-RRM)] – Δ[(ITS-BT) + (ITS-RRM)]	The effect on reduction of TTCE from the implementation of ITS-TTDM after the former implementation of (ITS-BT) and (ITS-RRM)
	#7 ITS-TTDM —[(ITS-TU) + (ITS-RRM)] = Δ[(ITS-TTDM) + (ITS-TU) + (ITS-RRM)] – Δ[(ITS-TU) + (ITS-RRM)]	The effect on reduction of TTCE from the implementation of ITS-TTDM after the former implementation of (ITS-TU) and (ITS-RRM)
	#8 ITS-TTDM —[(ITS-BT) + (ITS-TU) + (ITS-RRM)] = ΔAIN – Δ[(ITS-BT) + (ITS-TU) + (ITS-RRM)]	The effect on reduction of TTCE from the implementation of ITS-TTDM after the former implementation of (ITS-BT), (ITS-TU) and (ITS-RRM)
(d) ITS-RRM	#1 ITS-RRM — (No-ITS-IMP) = Δ(ITS-RRM)	The effect on reduction of TTCE from the implementation of ITS-RRM after the former implementation of (No-ITS-IMP)
	#2 ITS-RRM — (ITS-BT) = Δ[(ITS-BT) + (ITS-RRM)] – Δ(ITS-BT)	The effect on reduction of TTCE from the implementation of ITS-RRM after the former implementation of (ITS-BT)
	#3 ITS-RRM — (ITS-TTDM) = Δ[(ITS-TTDM) + (ITS-RRM)] – Δ(ITS-TTDM)	The effect on reduction of TTCE from the implementation of ITS-RRM after the former implementation of (ITS-TTDM)
	#4 ITS-RRM — (ITS-TU) = Δ[(ITS-RRM) + (ITS-TU)] – Δ(ITS-TU)	The effect on reduction of TTCE from the implementation of ITS-RRM after the former implementation of (ITS-TU)
	#5 ITS-RRM — [(ITS-BT) + (ITS-TTDM)] = Δ[(ITS-BT) + (ITS-TTDM) + (ITS-RRM)] – Δ[(ITS-BT) + (ITS-TTDM)]	The effect on reduction of TTCE from the implementation of ITS-RRM after the former implementation of (ITS-BT) and (ITS-TTDM)
	#6 ITS-RRM —[(ITS-BT) + (ITS-TU)] =Δ[(ITS-BT) + (ITS-TU) + (ITS-RRM)] – Δ[(ITS-BT) + (ITS-TU)]	The effect on reduction of TTCE from the implementation of ITS-RRM after the former implementation of (ITS-BT) and (ITS-TU)
	#7 ITS-RRM —[(ITS-TTDM) + (ITS-TU)] = Δ[(ITS-TTDM) + (ITS-TU) + (ITS-RRM)] – Δ[(ITS-TTDM) + (ITS-TU)]	The effect on reduction of TTCE from the implementation of ITS-RRM after the former implementation of (ITS-TTDM) and (ITS-TU)
	#8 ITS-RRM —[(ITS-BT) + (ITS-TTDM) + (ITS-TU)] = ΔAIN – Δ[(ITS-BT) + (ITS-TTDM) + (ITS-TU)]	The effect on reduction of TTCE from the implementation of ITS-RRM after the former implementation of (ITS-BT), (ITS-TTDM) and (ITS-TU)

Figure 8(a) depicts the outcome changing pattern in the reduction of TTCE due to the implementation of the ITS-BT strategy under different strategy combinations #1, #2, #3, #4, #5, #6, and #7 shown in **Table 4**. Here #5: (ITS-BT) — [(ITS-TTDM) + (ITS-TU)] represents the outcome pattern in the reduction of TTCE due to the implementation of (ITS-BT) after the prior implementation of (ITS-TTDM) and (ITS-TU). Now the outcome pattern #5: (ITS-BT) — [(ITS-TTDM) + (ITS-TU)] is prominent in all and depicts that the outcome pattern of (ITS-BT) is superb, but only after the implementation of (ITS-TTDM) and (ITS-TU). Now, comparison of three pairs #3: (ITS-BT) — (ITS-TU); #2: (ITS-BT) — (ITS-TTDM); and #4: (ITS-BT) — (ITS-RRM), clearly shows that (ITS-BT) is most effective after the implementation of (ITS-TU). Now #8: (ITS-BT) —[(ITS-TTDM) + (ITS-TU) + (ITS-RRM)] has always outcome pattern positive, while #7: (ITS-BT) —[(ITS-TU) +(ITS-RRM)] and #3: (ITS-BT) — (ITS-TU) have always outcome pattern negative. These conflicting patterns indicate that the (ITS-RRM) has a very strong effect on the implementation behaviour of (ITS-BT). Hence, the correct order is first of all implement (ITS-BT) and then (ITS-RRM). Therefore, the optimal order to maximise the effect of (ITS-BT) is (ITS-TU) → (ITS-TTDM) → (ITS-BT) → (ITS-RRM).

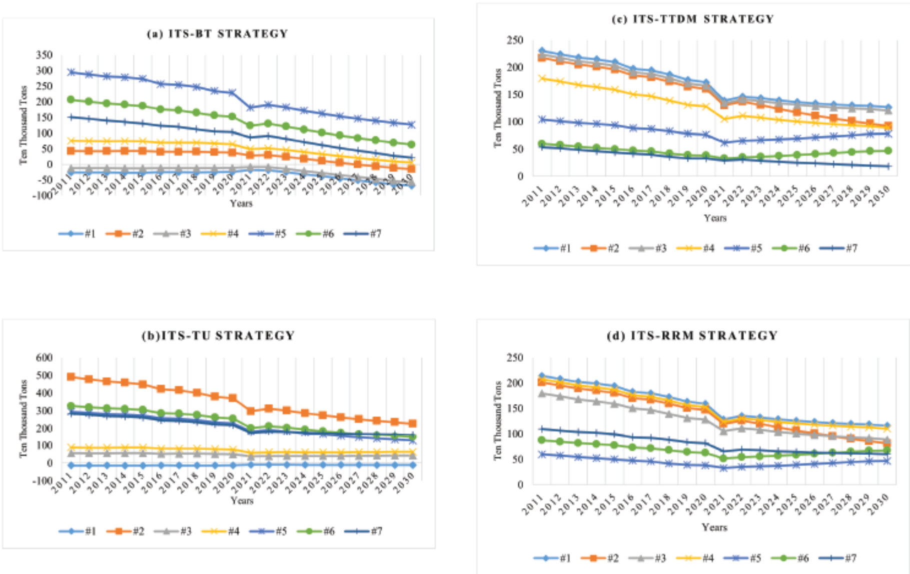


Figure 8. Outcome changing pattern in reduction of TTCE due to implementation of (a) ITS-BT strategy, (b) ITS-TU strategy, (c) ITS-TTDM strategy and (d) ITS-RRM strategy

Now **Figure 8(b)** shows the outcome changing pattern in the reduction of TTCE due to the implementation of the ITS-TU strategy under different strategy combinations #1, #2, #3, #4, #5, #6, and #7 shown in **Table 4**. Now the outcome pattern of #5: (ITS-TU) — [(ITS-BT) +(ITS-TTDM)] is prominent in all and recommends that (ITS-TU) should be implemented first, and then (ITS-RRM) should be implemented to give us the most effective results. Now, comparison of three pairs #2: (ITS-TU) — (ITS-BT); #3: (ITS-TU) — (ITS-TTDM); and #4: (ITS-TU) — (ITS-RRM), clearly shows the best order of implementation: (ITS-BT) followed by (ITS-TTDM) and then in the last (ITS-RRM). So now to capitalize the maximum effect of (ITS-TU), the best sequence is (ITS-BT) → (ITS-TTDM) → (ITS-TU) → (ITS-RRM).

Now **Figure 8(c)** depicts the outcome changing pattern in the reduction of TTCE due to the implementation of the ITS-TTDM strategy under different strategy combinations #1, #2, #3, #4, #5, #6, and #7 shown in **Table 4**. Now the outcome pattern of #5 (ITS-TTDM) — [(ITS-BT) + (ITS-TU)] is best in all and indicates that the outcome pattern of (ITS-TTDM) is most realistic when this is implemented after the implementation of (ITS-BT) and (ITS-TU). Now, comparison of three pairs #2 (ITS-TTDM) — (ITS-BT); #3 (ITS-TTDM) — (ITS-TU); and #4 (ITS-TTDM) — (ITS-RRM), shows that the outcome pattern of (ITS-TTDM) is weak after the implementation of (ITS-RRM) but is strong after the implementation of (ITS-TU). Now the outcome pattern of #8 (ITS-TTDM) — [(ITS-BT) + (ITS-TU) + (ITS-RRM)] is noticeable, which indicates that (ITS-TTDM) always gives a realistic pattern to reso

lve the problems at any stage of time, and hence it should be used continuously. Therefore, the optimal order to maximise the effect of (ITS-TTDM) is (ITS-TU) → (ITS-BT) → (ITS-TTDM) → (ITS-RRM).

Now **Figure 8(d)** shows the outcome changing pattern in the reduction of TTCE due to the implementation of the ITS-RRM strategy under different strategy combinations #1, #2, #3, #4, #5, #6, and #7 shown in **Table 4**. The implementation of (ITS-RRM) has a powerful decreasing pattern tendency on the implementation of (ITS-TTDM), (ITS-BT) and (ITS-TU) and should be executed later. Now, to get the best outcome pattern of #1 (ITS-RRM) — (No-ITS-IMP), the (ITS-RRM) should be executed initially. The outcome pattern of #4 (ITS-RRM) — (ITS-TU) is the next noticeable, and therefore, (ITS-TU) should be executed first. The comparison of #3 (ITS-RRM) — (ITS-TTDM) with #2 (ITS-RRM) — (ITS-BT) indicates that in the early stages, the outcome pattern of #2 (ITS-RRM) — (ITS-BT) is more significant than #3 (ITS-RRM) — (ITS-TTDM), but in the post-Covid-19 period, the outcome pattern is worse. The implementation of (ITS-TTDM) needs good conditions of public transportation as an essential requirement, while the implementation of (ITS-BT) needs a particular time lag. Therefore, the optimal order to maximise the effect of (ITS-RRM) is (ITS-TU) → (ITS-BT) → (ITS-TTDM) → (ITS-RRM). Similarly, the best order to capitalize the maximum effect of all separate strategies in (AIN) is (ITS-TU) → (ITS-BT) → (ITS-TTDM) → (ITS-RRM).

6. Conclusions

A System Dynamics Simulation (SDS) model is designed to reduce the TTCE and TTEC of road transport in Million-plus Cities of India (MCOI) through the implementation of ITS based strategies. Six strategies based on ITS have been developed and generated to monitor the TTEC and TTCE in MCOI. The pattern of outcomes is analysed and examined. The implementation of (ITS-BT) shows a positive outcome trend, but the implementation of (ITS-BT) requires a specific time delay, causing the output trend to be effective gradually over time. In contrast, the implementation of (ITS-TTDM) demonstrates a rapid positive outcome trend and is highly effective for a brief period. When both (ITS-BT) and (ITS-TTDM) are deployed together, (ITS-TTDM) can effectively manage the time delay caused by (ITS-BT). The (ITS-TU) significantly contributes to lowering TTCE more than savings from TTEC, while the implementation of (ITS-RRM) can help in achieving targets faster than other strategies. The implementation of AIN is quite costly in reducing the TTCE and TTEC, yet its overall performance pattern is outstanding when compared to the execution of each particular strategy separately.

To create total low carbon emission transportation modes based on ITS in the near future, and to meet the objective of decreasing TTCE and TTEC, (ITS-BT) offers a practical and effective method for managing and reducing road traffic collisions and accidents, road traffic congestion, and fuel consumption. There is a pressing necessity to encourage designated cycling areas, specific e-vehicle lanes, and secure pedestrian pathways by creating ITS-driven routes and advocating for e-vehicles. The complex framework of (ITS-TTDM) can significantly contribute to managing the Indian road transport sector. Transport strategic planners and administrators must thoroughly investigate potential bottlenecks in this strategy, diagnose and anticipate future actions to prevent last-minute crises, and examine in advance the impact of ITS-based infrastructure development on travel patterns due to (ITS-TTDM).

The (ITS-TU) possesses numerous concealed advantages and deserves comprehensive investigation. (ITS-TU) plays a more significant role in decreasing TTCE compared to total transport energy savings. ITS-based research features a lengthy investment return system and presents significant potential for a variety of high-tech inputs from a practical standpoint. Most energy workers and manufacturers of two or four-wheel vehicles typically show less motivation for technological research. Therefore, it is essential for the Government of India to promptly establish and enforce stringent technical regulations to prevent explosive disasters resulting from carbon emissions. The allowance of tax exemptions and other incentives can also significantly contribute to achieving target goals. The (ITS-RRM) relies entirely on the firm discretion of the Government of India. Therefore, the government apparatus needs to enforce the (ITS-RRM) with complete courage and impartiality. Police and RTO officials should frequently distribute and publicise comprehensive information regarding various (ITS-RRM) to the community to regain their complete support and reduce any backlash. A secure exit procedure and managing behavior are key instruments for various (ITS-RRM). The overall impact of various (ITS-RRM) is certainly quite promising. It is quite fascinating to observe that while the implementation of (AIN) is extremely costly, it remains the most effective strategy among all options. Therefore, the best sequence for executing the strategy in (AIN) is (ITS-TU) → (ITS-BT) → (ITS-TTDM) → (ITS-RRM).

Implementation of ITS-RRM, ITS-BT, ITS-TTDM and ITS-TU strategies in India faces numerous types of challenges, like inadequate transportation infrastructure, inter-agency coordination, technological readiness, limited funding, severe traffic congestion, and resistance to behavioral change among commuters. There is severe public resistance to ITS-RRM and ITS-TTDM measures, such as vehicle scrap page policies and the traffic congestion charging fee rule. Additionally, long-term sustainability and coordinated implementation is severely hindered by inadequate technological capacity and fragmented governance. ITS-RRM involves low capital cost but mainly needs legal and administrative frameworks, ITS-TTDM comprises moderate cost, while ITS-BT and ITS-TU comprise high capital investment of around ₹10,900–18,500 billion by 2030. For implementation of ITS-RRM, ITS-BT, ITS-TTDM and ITS-TU strategies, the Present Value of Benefits (PVB) discount rate @10% per year (₹ cr) is 3349.84, 11628.19, 7433.61, and 5712.52; Present Value of Costs (PVC) @10% (₹ cr) is 892.91, 7563.73, 1626.47, and 2245.76; and Benefit-Cost Ratio (BCR) is 3.75, 1.54, 4.57, and 2.54 respectively. (1 crore = ₹10 million).

ITS-RRM, ITS-BT, ITS-TTDM, and ITS-TU strategies have been actively implemented across selected areas of the USA, UK (London), South Korea (Seoul), Germany, Japan (Tokyo and Osaka), Sweden (Stockholm) and Singapore to reduce transportation carbon emissions and improve mobility. ITS-RRM reduced carbon emissions by 10-14% and traffic by 20% in Stockholm and there was a mode shift to bus transport. In Seoul, there was a reduction in traffic idling and good support in clean air goals, while in the USA, there was a reduction in traffic congestion-related emissions due to ITS-RRM. The eco driving support system guided fuel-efficient driving behavior of ITS-RRM in Tokyo and Osaka reduced CO_2 emissions and fuel consumption. Due to ITS-RRM, there was a substantial drop in usage of high-emission diesel vehicles, and roadside NOx within the Ultra-Low Emission Zone (ULEZ) of London was reduced by 44%. Sweden integrated ITS-BT, ITS-TTDM and ITS-TU strategies as part of its sustainable urban transport planning [European Environment Agency (2020), *Sustainable Transport* –

https://www.eea.europa.eu]. Germany and Japan used advanced public transport systems (ITS-BT) supported by continuous technical innovation [OECD (2021), Decarbonising Urban Mobility – https://www.oecd.org]. Singapore is known for its strong implementation of ITS-RRM and ITS-TTDM, like congestion pricing and vehicle quotas [Land Transport Authority, Singapore – https://www.lta.gov.sg].

Currently, the global traffic and transportation system accounts for roughly 26 percent of total energy-related emissions, with projections indicating an increase to about 55 to 60 percent by the year 2050. Likewise, the share of energy emissions from freight road transportation will increase to about 80 percent by 2050, which is currently around 42 percent. The assertive and highly ambitious implementation of strategies based on ITS using the SDS model throughout the entire infrastructure of the Indian road transportation sector, along with the electrification of road traffic and transport systems—including electric vehicles and e-public transport buses—will significantly lower the TTCE by around 33-35 percent by 2030 and 70-75 percent by 2050. This roadmap featuring assertive and highly ambitious strategies based on ITS ultimately hones in on the primary objective of attaining carbon neutrality.

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