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Reduction of Transport Carbon Emissions of India by the Implementation of Strategies Based on IoT-Enabled Intelligent Transportation System: A System Dynamics Approach

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ABSTRACT

India is the third-largest carbon emitter in the world. In this paper, a Synergistic System Dynamics Simulation (SSDS) model is developed to reduce the Total Transport Carbon Emissions (TTCE) and Total Transport Energy Consumptions (TTEC) in million-plus cities of India by the implementation of strategies based on Internet of Things-enabled Intelligent Transportation System (IoT-ITS). Intelligent Transportation System (ITS) refers to the interconnection of an adaptive and intelligent integration of vehicles, drivers, and the transportation system. The SSDS model consists of four subsystems: total population, Gross Domestic Product (GDP), carbon emission, and four sub-models enabled IoT-ITS-based road transportation subsystem and provides the interrelation between parameters, which plays an important role in altering the TTCE and TTEC of the road transportation network. The model is validated, and a sensitivity test is used for the optimum management of the system. Six strategies based on IoT-enabled ITS: Traffic and transportation demand management (TTDM), Bus transport (BT), Rules and regulations management (RRM), Technology upgradation (TU), No implementation (No-IMP), and All integrated (AIN), are also formulated based on derived crucial parameters. The simulation of the model indicates that, despite the high cost of IoT-enabled ITS

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implementation, AIN is best suited, while RRM is the fastest for reducing TTCE. TTDM is highly useful in a short span, while TU gives a very high reduction of TTCE.

Keywords: Internet of Things, Intelligent Transportation System, strategies analysis, system dynamics, Total Transport Carbon Emissions, Total Transport Energy Consumptions

INTRODUCTION

India is the third highest emitter of carbon dioxide (CO_2) in the world (Timperley, 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 (Welle, 2020). India also announced a carbon neutrality commitment by 2070 at the 26th Conference of the Parties (COP26) (World Economic Forum, 2021). In order to fulfil such an ambitious climate target, stricter policies and longer-term decarbonization strategies are needed for carbon-intensive transportation sector. Road transportation is main culprit for the major global transportation pollution due to high vehicular carbon emissions and is the main driving force for the economic development and creation of the well beings of the modern societies. The Indian road traffic and transportation system, which is governed by different modes of mobility- public transport, tempo and auto-rickshaws, taxis and jeeps, motorcycles-scooters-scooty, cars, and bicycles, is a critical life support system of our major population but is a substantial CO_2 emitter source. The dominance of internal combustion engines based four and two wheelers is leading to surge in CO_2 emissions. Due to change in buying habits and high living standard of majority of Indians living in million plus cities of India, the CO_2 emissions of road transportation sector will reach to danger 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 decarbonation of transportation system to achieve net zero emissions will play a negative effect on roads. Roads are the backbone for the survival of society. Hence the main goal shift is now to develop a different line of action for the utilization of roads to strengthen the mobility as well as to achieve net zero emissions. Thus, this research work is an innovative step in this direction to implement strategies based on IoT-enabled ITS for Indian road traffic and transportation system.

ITS can easily create this opportunity by revolutionizing the Indian road network, reducing traffic congestion and emissions of greenhouse gases, making smooth flow of traffic, encouraging green safer mobility, and finally zooming to main goal of achieving net zero emissions. ITS is a holistic system using synergistic approach of people, processes, places, data, technology, and vehicles and will lead to regular carbon reduction role in the Indian transportation system. ITS is a technological platform that offers hi-tech systems to meet future demands of transportation decision makers, traffic policy makers, and commuters, attains other technology outcomes based on different applications that monitor, manage, and improve the quality and efficiency of transportation system.

The IoT is the network of interconnected web based smart devices which uses embedded technology (smart sensors, processors, actuators, software, communication hardware), connectivity technologies (LoRaWan, Zigbee, message queuing telemetry transport [MQTT], cellular, wi-fi, bluetooth), data processing, data security, big data analytics, security and privacy technologies, cameras, and network that enable them to collect, exchange and act on data. The goal of IoT is to create a smart, connected world where devices can communicate and interact with each other to make intelligent decisions and improve efficiency.

System dynamics (SD) modelling technique is an innovative interdisciplinary effective research tool based on feedback of system information to study the dynamic systems and to solve real world very complex social and technical system integrated problems. SD cross fertilizes three background threads, the elements of traditional management, feedback control theory, and the technique of computer simulation, which allows one to determine the time varying behavior implicit in the complex structure of a system. SD focuses on dynamic approach and generates scenarios for real world problems by employing synergistic approach of qualitative and quantitative technique and integrated system reasoning.

In this paper, a SSDS model is designed and developed to reduce the TTCE and TTEC of the road transportation system in Million-plus Cities of India (MCI) by the implementation of strategies based on IoT-ITS. The model generates six critical strategies based on IoT-ITS and policy implementation recommendations on the basis of model simulation, validation, and sensitivity analysis and also delivers a wide range of additional paybacks. The work's architecture is depicted in Figure 1. The contribution of the proposed work is to offer a synergistic SD-based framework, which can study key influencing sub-systems, sub-models, and predict the impact of implementations of critical strategies based on IoT-ITS to reduce the TTCE and TTEC in MCI. The implementation of strategies based on IoT-ITS in Indian road traffic and transportation system, transport infrastructure as well as in green transport solutions like electrification of road traffic and transportation system including e-vehicles and e-public transport buses will definitely reduce TTCE and TTEC by approximately 33-35% upto 2030 and 70-75% upto 2050 and this road map of aggressive and high ambition implementation of strategies based on IoT-ITS finally zoom to main goal of achieving net zero emissions. The model guides the future low carbon transition and serves as an open platform which can be easily adjusted according to the requirements of transportation system decision makers and can be easily applied to any part of world.

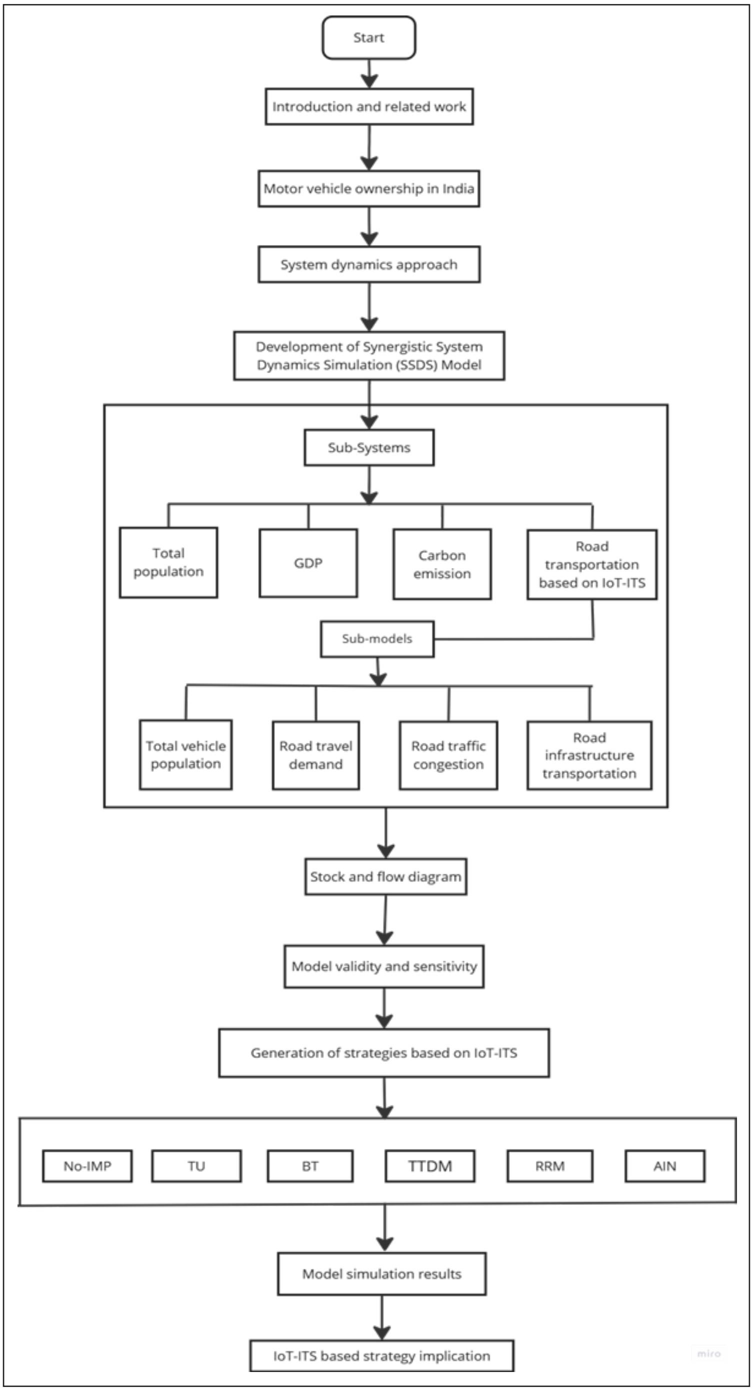


Figure 1. Work's architecture
Note. GDP = Gross Domestic Product; IoT-ITS = Internet of Things-enabled Intelligent Transportation System; No-IMP = No implementation; TU = Technology upgradation; BT = Bus transport; TTDM = Traffic and transportation demand management; RRM = Rules and regulations management; AIN = All integrated

RELATED WORK

Dong and Ullah (2023) provided empirical evidence for the positive effect of IoT, environmental regulations, and related factors on green growth. Bautista and Mester (2023) discussed the impact of IoT on the development of self-driving cars to focus on the broader implications for the development of intelligent cities. Upadhyay et al. (2024) proposed a comprehensive multi-layered framework for V-IoT systems, addressing challenges related to security, scalability, and efficient communication. Al-Mayouf et al. (2018) developed an accident management system that utilized vehicular ad hoc networks in conjunction with cellular technology for public transport. Mahdi et al. (2024) developed an IoT emergency services system based on a real-time node rank index algorithm to determine the optimal route with the dynamic traffic conditions for ambulance to reach the patient quickly and deliver necessary medical services during emergencies. Mahdi et al. (2021) proposed an innovative strategy void-hole aware and reliable data forwarding strategy. This strategy was used to help each cluster head node to know its neighbor's performance ranking index to conduct a reliable packet transmission to the sink via the most energy-efficient route.

Iliopoulou and Kepaptsoglou (2019) discussed the potential of using ITS data to optimize public transportation planning and operations. Gao et al. (2022) proposed an ITS-based vehicle consensus scheme for management of traffic and selection of infrastructure for users. Dasgupta et al. (2022) proposed a fusion model to detect pedestrian in dim light driving during night hours. Alkinani et al. (2022) developed a neural network-based model to make intelligent decisions for public transportation. Ramesh et al. (2022) developed a model to enhance safety on road and to reduce accidents due to traffic jams. Lin et al. (2019) developed measurement and evaluation models for ITS products to provide technological means. Yuan et al. (2022) discussed about machine learning for next generation of ITS.

Chen et al. (2022) developed a system dynamics model for urban pollution to evaluate the impact of various policies and benefits of synergistic approach for addressing environmental problems and traffic congestion. Gupta et al. (2019) used a system dynamics approach to measure the effectiveness of carbon tax on Indian road passenger transport. Wang et al. (2021) developed a system dynamics model to capture feedback processes and to interact between different sectors and various population, water quality, and resources factors. Shahsavari-Pour et al. (2022) developed a simulated model using system dynamics technique to analyze the pollution level taking into consideration its sources and outcomes. Norouzian-Maleki et al. (2022) presented a new framework as a combination of system dynamics approach and data envelopment analysis technique. Nunes et al. (2021) developed a system dynamics approach-based smart city using modern technologies. Ding et al. (2022) developed a perimeter control method for a congested urban road network with dynamic and variable ranges.

It is very interesting to note that very limited literature is available on the reduction of the carbon emissions and energy consumptions of Indian road transportation system using SD modelling 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 system in million plus cities of India by the implementation of six strategies based on IoT-ITS 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.

MOTOR VEHICLE OWNERSHIP IN INDIA

The Indian road transportation system is home to a dynamic blend of everything from luxury petrol cars, sport utility vehicles (SUVs), electric vehicles (EVs), diesel taxis, to the humble two-wheelers, e-bikes, e-autos, and bicycles. There is tremendous change in motor vehicle ownership in India as the auto industry is transitioning from vehicle manufacturing to providing mobility solutions. The advanced technologies—electrification, vehicle intelligence, autonomous driving, and connected features are gaining traction at a very fast pace. The adoption of environment-friendly vehicles is slated to make significant strides. The motor vehicle ownership is gearing up to foray into the battery EVs segment and EVs will be at the sweet spot and forefront of the journey towards sustainable mobility, but its penetration in the freight sector is not gaining traction in India. Table 1 shows the number of EVs from 2019 to 2023 having all types of e-vehicles (AutoInsurance.com, 2025). There is no EV data from 2011 to 2018. The passenger vehicles segment of auto industry is observing louder calls for backing other advanced technologies—biofuels, biogas, strong hybrids besides compressed natural gas (CNG). Table 2 shows the number of traditional internal combustion engine vehicles from 2011 to 2019.

Table 1
Number of electric vehicles (EVs)

Year	EVs
2019	687
2020	3,143
2021	12,050
2022	48,023
2023	82,270

Table 2
Number of traditional internal combustion engine vehicles

Year	Two wheelers (thousand)	Cars, jeeps and taxis (thousand)	Buses (thousand)	Goods vehicles (thousand)
2011	101,865	19,231	1,604	7,064
2012	115,419	21,568	1,677	7,658
2013	127,830	24,056	1,814	8,307
2014	139,410	25,998	1,887	8,698

Table 2 *(continue)*

Year	Two wheelers (thousand)	Cars, jeeps and taxis (thousand)	Buses (thousand)	Goods vehicles (thousand)
2015	154,298	28,611	1,971	9,344
2016	168,975	30,242	1,757	10,516
2017	187,091	33,688	1,864	12,256
2018	202,755	36,453	1,943	12,773
2019	221,270	38,433	2,049	13,766

Source: Ministry of Road Transport and Highways (MoRTH) (2023)

ITS are revolutionizing India's road transportation landscape by integrating advanced ITS technologies to enhance road traffic management, public transit, transportation efficiency, road safety and sustainability. Here is a brief look at the following key ITS technologies being implemented across the country:

Advanced Public Transport Systems (APTS)

Implementation. Indian cities are adopting Global Positioning System (GPS)-based bus tracking, electronic ticketing, and real-time passenger information systems to improve public transportation efficiency.

Examples:

1. Bengaluru Metropolitan Transport Corporation (BMTC): Launched the "Namma BMTC" app, offering real-time bus tracking, route planning, and fare calculation. The app also includes a Save Our Soul (SOS) feature for emergencies.
2. Delhi Integrated Multi-Modal Transit System (DIMTS): Operates the "My Bus" app, providing real-time bus tracking and electronic ticketing.

Advanced Traveller Information Systems (ATIS)

Implementation. Deployment of digital signage, mobile applications, and websites to deliver real-time traffic updates, public transport schedules, and route optimization information.

Examples:

1. Delhi traffic police app: Offers live traffic updates, route planning, and alerts on road closures.
2. Google Maps and other navigation services: Integrated with real-time traffic data to assist commuters in route planning.

Automated Vehicle Control Systems (AVCS)

Implementation. Utilization of AI-driven traffic signal automation, automatic number plate recognition (ANPR), and red-light violation detection to enhance traffic flow and safety.

Examples:

1. AI-based traffic management: Cities like Mumbai, Bengaluru, and Hyderabad have implemented AI-driven traffic management systems to optimize signal timings and reduce congestion.
2. Automatic speed enforcement: Installation of speed cameras on highways to monitor and enforce speed limits.

Electric Vehicle Systems (EVS)

Implementation. Government initiatives such as the Faster Adoption and Manufacturing of (Hybrid) and Electric Vehicles (FAME) India scheme promote EV adoption through incentives and infrastructure development.

Examples:

1. Ola Electric and Tata EVs: Companies like Ola Electric and Tata Motors are expanding the EV market with a wide range of electric vehicles.
2. Charging Infrastructure: Installation of charging stations by entities like Energy Efficiency Services Limited (EESL) and Tata Power across major cities.

There are some major challenges like infrastructure constraints, public awareness, 5^{th} Generation (5G) integration, use of AI and machine learning, expansion of tier-2 and tier-3 cities, and financial limitations in implementing ITS in India. While challenges remain, ongoing efforts and future technological advancements hold promise for a more intelligent and connected transportation ecosystem. ITS offers great opportunity to revolutionize Indian road network system by using transformative approach and can easily provide a better solution to the problems of traffic congestion and total carbon emissions caused by the rapid increase in the motor vehicle ownership/number of vehicles and paves the way for greener mobility, leading to attainment of global net zero ambitions. Table 3 shows the trend for total carbon emissions from the transport sector from 2011 to 2023 (Statista, 2025).

Table 3
Trend for total carbon emissions from transportation sector from 2011 to 2023

Year	Total carbon emissions from transportation sector (million metric tons)
2011	209
2012	222
2013	226

Table 3 *(continue)*

Year	Total carbon emissions from transportation sector (million metric tons)
2014	236
2015	258
2016	269
2017	291
2018	306
2019	308
2020	269
2021	295
2022	324
2023	340

Note. Source = Statista (2025)

MATERIALS AND METHODS

SSDS Model

SSDS model is developed to reduce the total transport carbon emissions and total transport energy consumptions of the road traffic and transportation system in MCI by the implementation of strategies based on IoT-ITS. The model also generates six critical strategies based on IoT-ITS and policy implementation recommendations on the basis of validation and sensitivity analysis to reduce the TTCE and TTEC, and also delivers a wide range of additional paybacks. Figure 2 shows the flowchart of the SSDS model. In this model, the relationship of critical variables affecting the TTCE and TTEC of the road traffic and transportation system in MCI is depicted in the designed and developed SSDS model.

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 Road Transportation Sub-System (RoTr-SS) based on IoT-ITS. RoTr-SS based on IoT-ITS consists of four sub-models: total vehicle population sub-model, road travel demand sub-model, road traffic congestion sub-model, and road transportation infrastructure sub-model and all these four sub-models of RoTr-SS are totally linked with GDP-SS, ToPoP-SS, and CaEm-SS. The relation between four sub systems: GDP-SS, ToPoP-SS, CaEm-SS, and four sub-models based RoTr-SS of SSDS model are shown in Figure 3. Figure 4 depicts stock flow diagram of SSDS model.

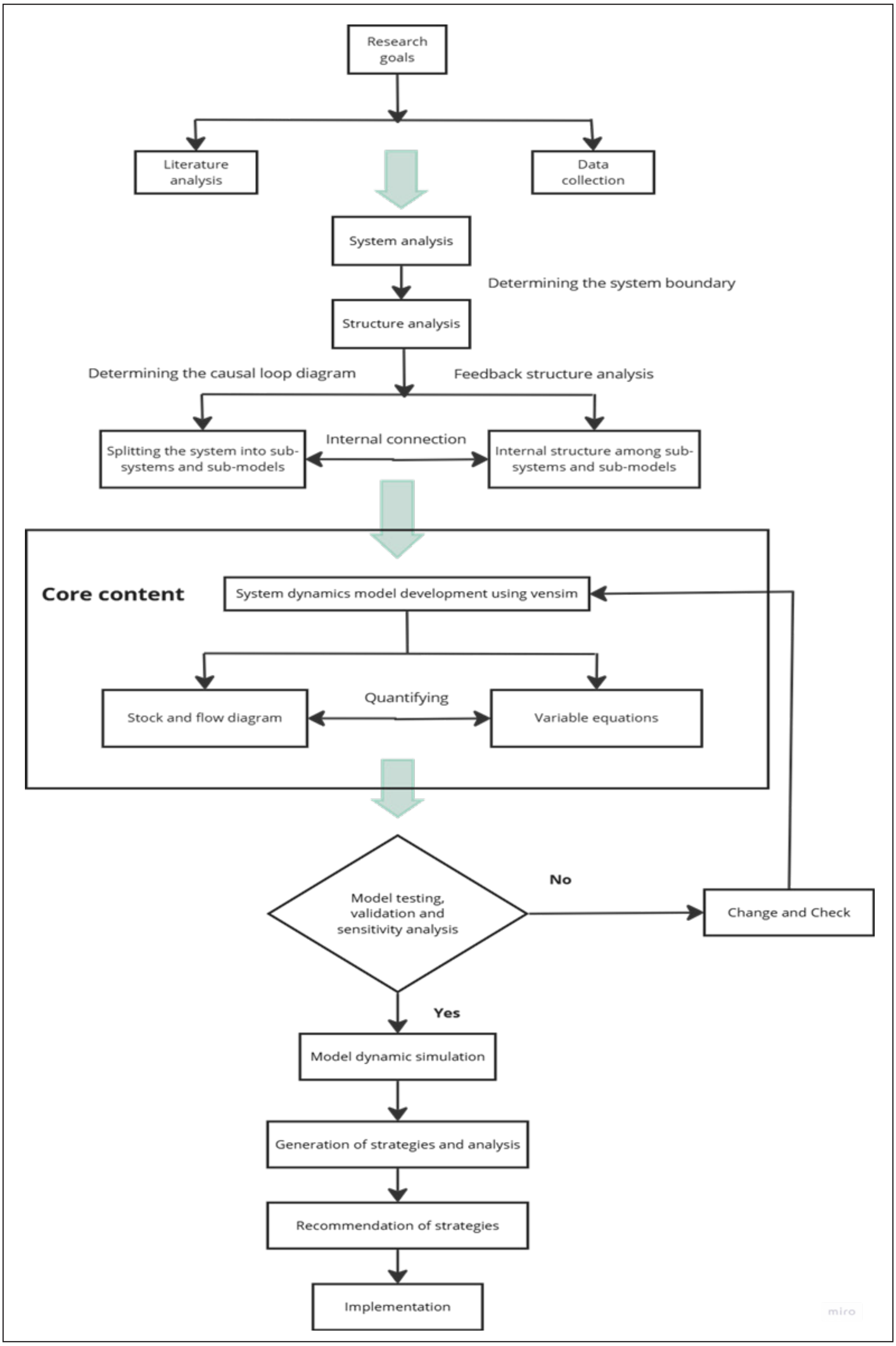


Figure 2. Flow chart of the Synergistic System Dynamics Simulation (SSDS) model

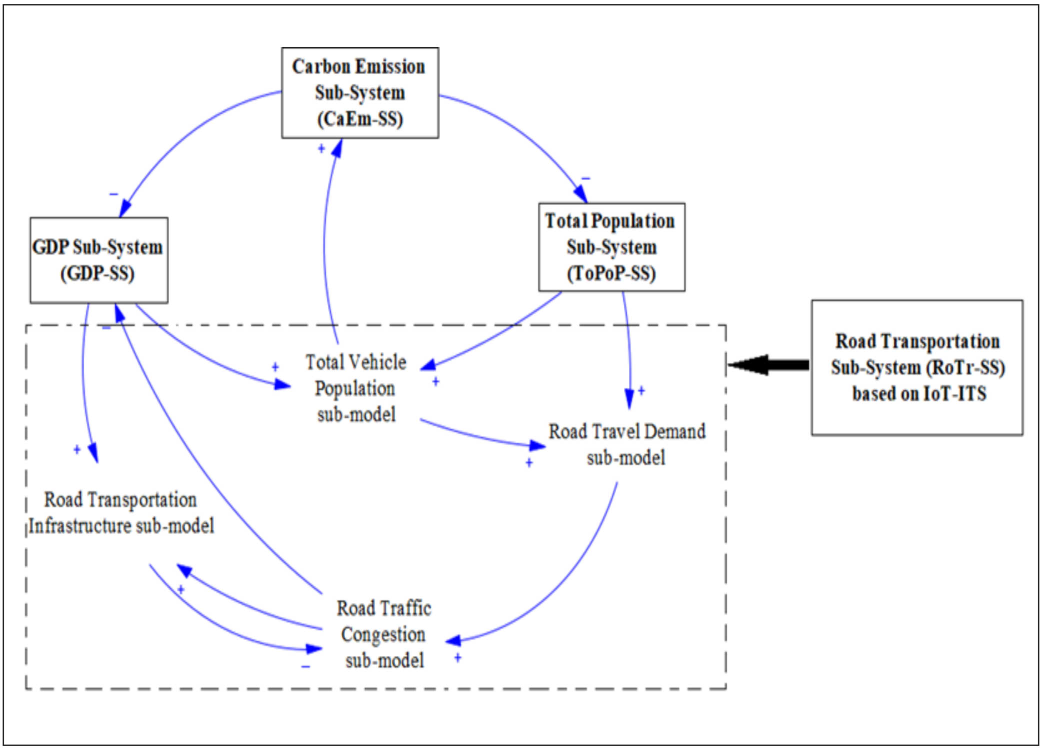


Figure 3. Relation between sub-systems of the Synergistic System Dynamics Simulation (SSDS) model
Note. GDP-SS = GDP Sub-System; CaEm-SS = Carbon Emission Sub-System; ToPoP-SS = Total Population Sub-System; RoTr-SS = Road Transportation Sub-System; IoT-ITS = Internet of Things-enabled Intelligent Transportation System

ToPoP-SS

The road transportation sector of MCI is mainly affected by the structural pattern and magnitude of the total population. Due to expansion in cities of India, the total floating population phenomenon plays an important role in the total population and is slightly different from the 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 in a different place, thus affecting both the origin cities as well as destination cities, and is one of the major problems in the road transportation system of MCI. The rise in this total floating population is bound to drastically affect the road transportation system 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.

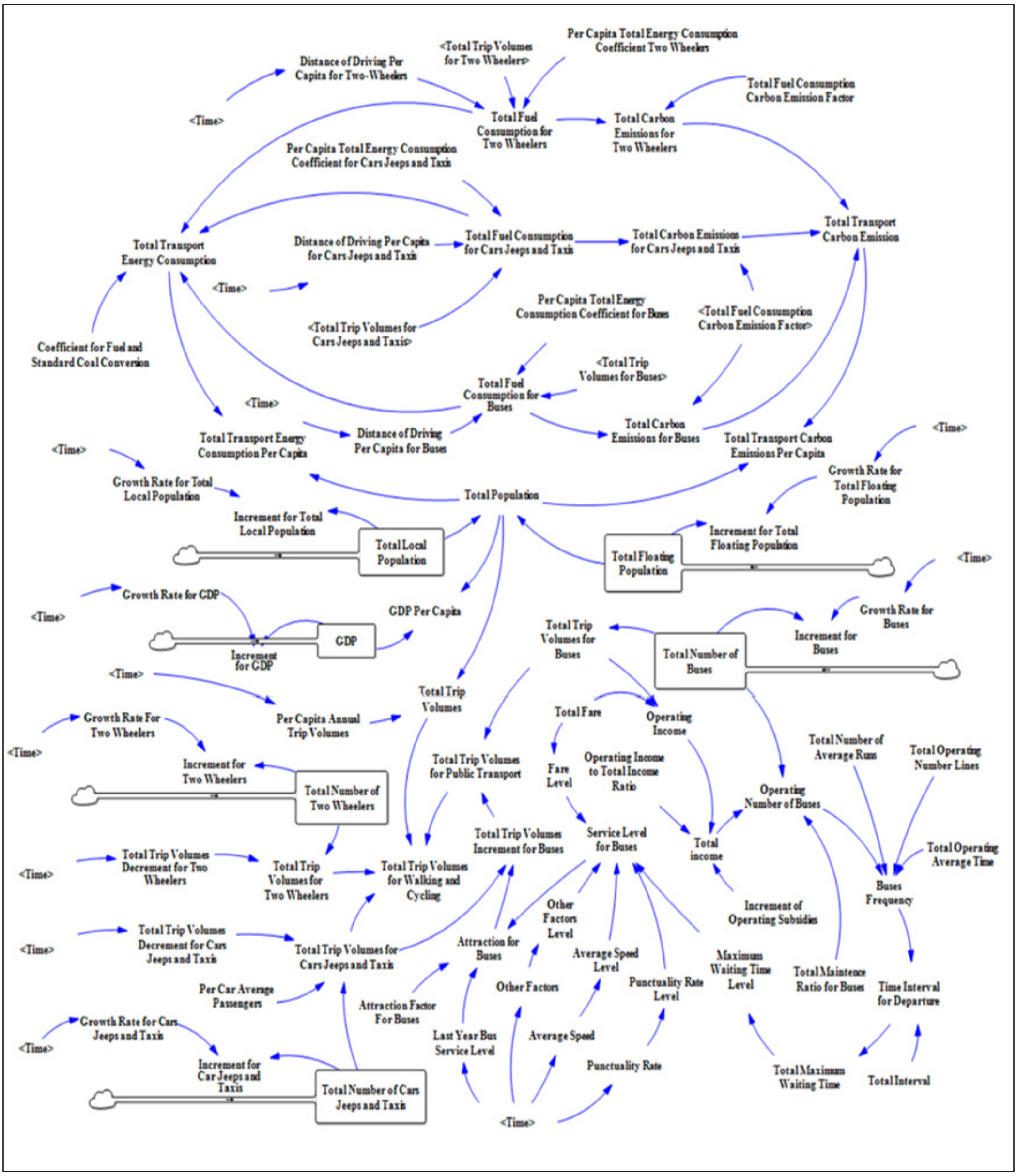


Figure 4. Stock flow diagram of the Synergistic System Dynamics Simulation (SSDS) model

GDP-SS

Due to rise in GDP/capita, the total population of MCI can easily afford to buy motorized vehicles like cars, scooters, and motor bikes, for driving or movement purpose and this will result in 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 MCI.

RoTr-SS Based on IoT-ITS

The RoTr-SS based on IoT-ITS consists of four sub-models: total vehicle population sub-model, road travel demand sub-model, road traffic congestion sub-model, and road transportation infrastructure sub-model. The residents of MCI are changing their mode of road transportation due to their high living standard from non-motorized to motorized and using two wheelers, cars, taxies, jeeps, and public transport. 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, 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 to cars, jeeps and taxies, the majority of commuters are slowly switching over and using the bus transportation system in Indian cities. The important parameters like quantity of vehicles - two wheelers, cars, taxies, jeeps, and buses; vehicles mileage driven, and vehicles energy efficiency are directly affecting the TTEC. The fuel consumption is increasing with a fast pace inspite of price rise and the demand of private jeeps and cars is also continuously growing due to rise in people living standards and growth in economy. The promotion of the usage of IoT-ITS based new energy efficient vehicles and development of IoT-ITS based green bus transport are very strong measures for reduction of TTCE.

CaEm-SS

Reduction of TTEC and TTCE of road traffic and transportation system in MCI is the major goal of SSDS model. Table 4 depicts the notations for equations. The TTEC and TTCE can be calculated from the following equations:

$$\mathrm{TTEC}_{m,n} = \mathrm{TTECC}_{m,n} \times \mathrm{DD}_{m} \times \mathrm{TV}_{m} \quad [1]$$

$$\mathrm{TTCE}_{m,n} = \mathrm{TTECC}_{m,n} \times \mathrm{DD}_{m} \times \mathrm{TV}_{m} \times \mathrm{Ef}_{n} \quad [2]$$

$$\mathrm{TTEC} = \textstyle\sum_{m,n} \mathrm{TTECC}_{m,n} \times \mathrm{DD}_{m} \times \mathrm{TV}_{m} \times \mathrm{ECC}_{n} \quad [3]$$

$$\mathrm{PCTEC} = \frac{\sum_{m,n} \mathrm{TTECC}_{m,n} \times \mathrm{DD}_{m} \times \mathrm{TV}_{m} \times \mathrm{ECC}_{n}}{\mathrm{TP}} \quad [4]$$

$$\mathrm{TTCE} = \textstyle\sum_{m,n} \mathrm{TTECC}_{m,n} \times \mathrm{DD}_{m} \times \mathrm{TV}_{m} \times \mathrm{Ef}_{n} \quad [5]$$

$$\mathrm{PCTCE} = \frac{\sum_{m,n} \mathrm{TTECC}_{m,n} \times \mathrm{DD}_{m} \times \mathrm{TV}_{m} \times \mathrm{Ef}_{n}}{\mathrm{TP}} \quad [6]$$

Table 4
Table of notations

Notations	Description
$TTCE$	Total Transport Carbon Emissions
$TTEC$	Total Transport Energy Consumption
$TTEC_{m,n}$	Total Transport Energy Consumption due to particular modes of transport *m* for different types of total transport energy consumption *n*
$TTECC_{m,n}$	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*
$TTCE_{m,n}$	Total Transport Carbon Emissions due to particular modes of transport *m* for different types of total transport energy consumption *n*
Ef_n	Emission factor from total transport energy consumption *n*
ECC_n	Energy Conservation Coefficient from energy type n
$PCTEC$	Per Capita Transport Energy Consumption
TP	Total Population
$PCTCE$	Per Capita Transport Carbon Emission

SSDS Model Validity and Sensitivity

The parameters of SSDS model are continuously modified and adjusted during the course of development of interrelation between different parameters to reduce the error between actual historical and simulated data, and ultimately to improve the reliability of the model. Table 5 presents the historical data and simulated data for key parameters from 2011 to 2019.

The error rate (ER), error variance (EV), mean absolute percentage error (MAPE), and root mean square percentage error (RMSPE) of the key parameters are calculated using the following equations, respectively:

$$\mathrm{ER} = \frac{|\text{Simulated Value} - \text{Absolute Value}|}{\text{Absolute Value}} \times 100\% \quad [7]$$

$$\mathrm{EV} = \frac{|\text{Average Rate of Simulated Value} - \text{Average Rate ofAbsolute Value}|}{\text{Average Rate of Absolute Value}} \times 100\% \quad [8]$$

$$\mathrm{MAPE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{\text{Simulated Value} - \text{Absolute Value}}{\text{Absolute Value}}\right| \times 100\% \quad [9]$$

$$\mathrm{RMSPE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left|\frac{\text{Simulated Value} - \text{Absolute Value}}{\text{Absolute Value}}\right|^2} \times 100\% \quad [10]$$

Table 5
Comparison between historical data and simulated data of key parameters

Year	Total population			GDP			Total number of two wheelers			Total number of cars jeeps and taxis			Total number of buses		
	Simulated data	**Historical data**	**Error %**	**Simulated data**	**Historical data**	**Error %**	**Simulated data**	**Historical data**	**Error %**	**Simulated data**	**Historical data**	**Error %**	**Simulated data**	**Historical data**	**Error %**
2011	1.25	1.25	0.00	8,736,330	8,736,329	0.00	101,865	101,865	0.00	19,231	19,231	0.00	1,604	1,604	0.00
2012	1.28	1.27	0.01	9,190,620	9,213,017	0.00	113,274	115,419	0.02	21,616.2	21,568	0.00	1,684.89	1,677	0.00
2013	1.31	1.28	0.02	9,686,910	9,801,370	0.01	128,340	127,830	0.00	24,243.1	24,056	0.01	1,761.62	1,814	0.03
2014	1.33	1.32	0.01	10,297,200	10,527,675	0.02	142,072	139,410	0.02	27,039.6	25,998	0.04	1,905.61	1,887	0.01
2015	1.36	1.35	0.01	11,059,200	11,369,493	0.03	154,859	154,298	0.00	29,222.3	28,611	0.02	1,982.33	1,971	0.01
2016	1.39	1.37	0.01	11,932,900	12,308,193	0.03	171,274	168,975	0.01	32,159.3	30,242	0.06	1,737.61	1,757	0.01
2017	1.41	1.43	0.01	12,911,400	13,144,582	0.02	187,545	187,091	0.00	33,992.4	33,688	0.01	1,845.69	1,864	0.01
2018	1.44	1.45	0.01	13,776,400	14,003,316	0.02	207,612	202,755	0.02	37,864.3	36,453	0.04	1,958.15	1,943	0.01
2019	1.46	1.47	0.00	14,671,900	14,569,268	0.01	224,844	221,270	0.02	40,971.9	38,433	0.07	2,041.18	2,049	0.00

Note. GDP = Gross Domestic Product

Table 6 depicts the values of ER, EV, MAPE, and RMSPE for total population; GDP; total number of two wheelers; total number of cars, jeeps and taxis; and total number of buses, respectively.

Table 6
Values of ER, EV, MAPE, and RMSPE in percentage

	ER	**EV**	**MAPE**	**RMSE**
Total population	0.4266	10.3593	0.4635	1.0767
GDP	1.3604	0.8505	1.3409	1.8021
Total number of two wheelers	0.9001	3.9265	0.7141	1.4003
Total number of cars, jeeps and taxis	3.1206	10.6186	2.7628	3.6653
Total number of buses	0.2711	3.3509	0.2826	1.1925

Note. ER = Error rate; EV = Error variance; MAPE = Mean Absolute Percentage Error; RMSPE = Root Mean Square Percentage Error

The developed SSDS model is totally effective, valid, and generating reliable simulated results because the values of ER and EV of 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 SSDS model's prediction ability is best. Using 2011 as the base year, the historical data from 2011 to 2019 (Economic Survey, n.d.; MoRTH, 2023; Office of the Registrar General and Census Commissioner, India & Ministry of Home Affairs, Government of India, n.d.) are utilized to verify the validity of the model. The key parameters fully satisfy the validity for future projections, and Figures 5(a) to 5(e) depict the comparison graph between simulated data and actual data of key parameters.

The sensitivity test of developed SSDS model was also conducted to examine how much sensitive the model is due to alterations in the different values of the selected parameters and due to changes in the basic structure of the developed SSDS model. The results of the sensitivity analysis showed that the total population and per capita annual trip volumes had larger impact on total trip volumes. The total trip volume, per capita total energy consumption coefficient, and distance of driving per capita for cars jeeps and taxis had major impact while total trip volume and per capita total energy consumption coefficient for buses had minor impact on TTCE and TTEC. This clearly proved that the developed SSDS model is totally under control and is totally fit for simulation to generate strategies based on IoT-ITS.

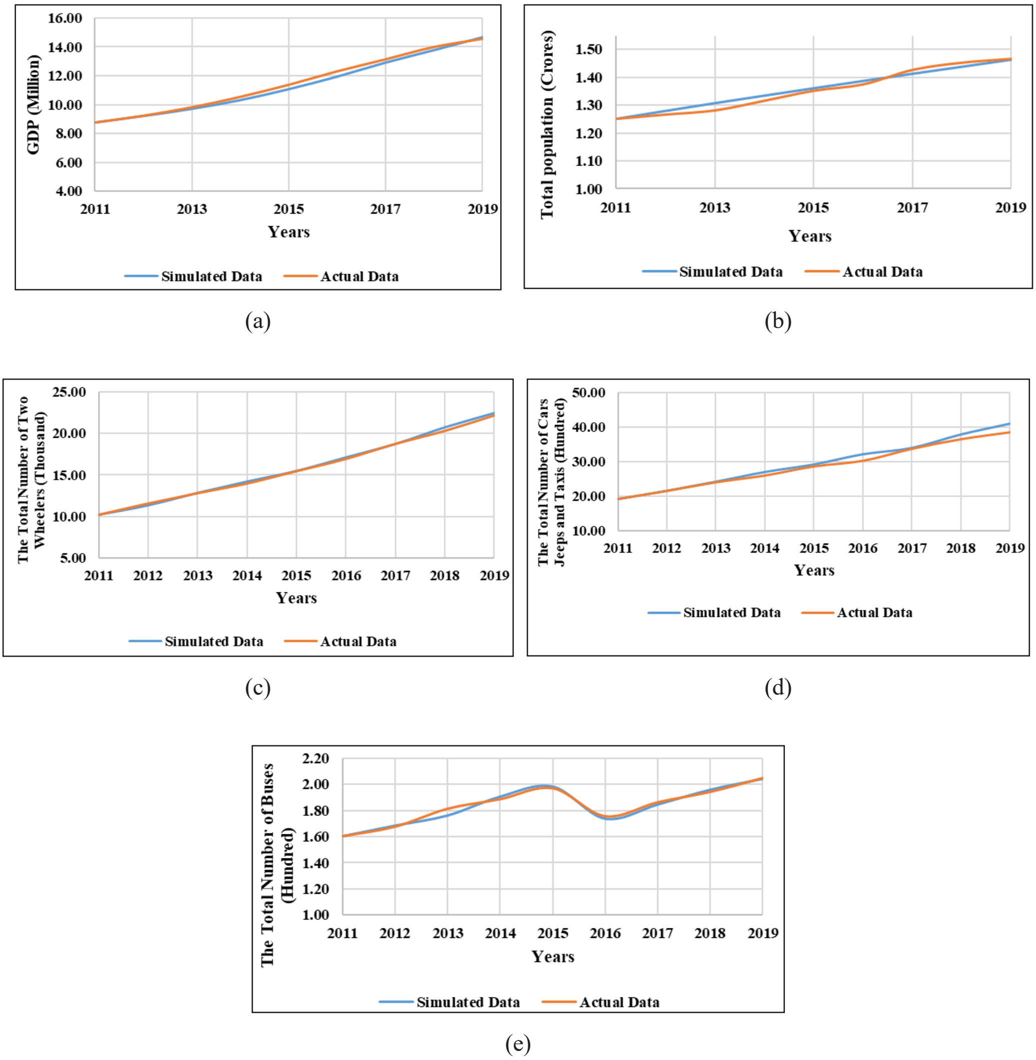


Figure 5. Comparison graph between simulated and actual data of (a) gross domestic product (GDP), (b) total population, (c) total number of two wheelers, (d) total number of cars jeeps and taxis, and (e) total number of buses, respectively

Generation of Strategies Based on IoT-Enabled ITS

The ITS uses integration of information technologies- cloud computing, mobile internet, IoT and big data technology with communication technologies, and by effectively utilizing the present transportation infrastructure can drastically reduce TTCE and TTEC, road accidents, traffic congestions, and improve traffic and transportation services. Thus, ITS reinforces the synergistic relation between environment, vehicles, roads and the commuters, and its demand is increasing day by day and is a future market.

APTS, ATIS, Advanced Traffic Management Systems (ATMS), 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 (networking devices on the bus), smart bus camera (help passenger counting and analysis), driver status monitoring, blind spot detection, ultrasonic sensors and smart card integrated circuit scanners while ATIS is the most extensively used ITS application area that provides real time information to the travelers to enhance their mobility.

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. In contrast, advanced vehicle control systems solution include longitudinal assistance systems preventing rear-end and front-end collisions, dedicated short range communication radios to enable vehicle-to-vehicle, vehicle-to-infrastructure, and infrastructure-to-vehicle to improve safety. Emergency vehicle services solutions include drones and unmanned aerial vehicles, green wave system, visual roadside units, and emergency vehicle lighting and sirens, while commercial vehicle operations application area of ITS deals in regulating and transporting freight in commercial vehicles and includes fleet administration, freight administration, electronic clearance, and commercial vehicle administrative processes.

A total of six strategies based on IoT-ITS: TTDM strategy, BT strategy, RRM strategy, TU strategy, No-IMP strategy and AIN strategy, are formulated and generated to monitor TTCE and TTEC, in MCI using the output of sensitivity test of the key parameters of SSDS model. The developed robust SSDS model is simulated for generated strategies based on IoT-ITS to reduce TTCE and TTEC. The outcome pattern of TTCE and TTEC is analyzed and simulated from 2011-2020 (pre COVID-19 period), during COVID-19 period, and post COVID-19 time period from 2022 to 2030 to observe the effect of generated strategies based on IoT-ITS.

No-IMP Strategy Based on IoT-ITS

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

BT Strategy Based on IoT-ITS

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

TTDM Strategy Based on IoT-ITS

The TTDM strategy aims to establish IoT-ITS-based guidelines for managing road traffic and transportation in MCI to reduce total traffic congestion and emissions. It includes implementing IoT-ITS rules to control vehicle population growth, balancing infrastructure between cities and smaller towns, and supporting scrappage policies for outdated vehicles to achieve net-zero emissions. Additionally, IoT-ITS vehicle fitness testing and automated testing stations are recommended for all vehicles. Policies like an odd-even traffic rule and congestion fees at peak hours would help manage congestion and emissions by tracking vehicle numbers and encouraging eco-friendly vehicle use.

TU Strategy Based on IoT-ITS

The role of TU strategy in MCI will play a very important role in reducing TTCE and TTEC by eliminating the use of very high pollution generation vehicles, and very old two and four wheelers, and introducing IoT-ITS-based hi-tech vehicles. The health of children and adults are slowly coming in danger zone in MCI due to very heavy polluted traffic and transport environment. The only solution to prevent the escalating environmental pollution is the introduction of IoT-ITS-based hi-tech e-vehicles. Road transportation is mainly governed by diesel and petrol-based vehicles. The introduction of IoT-ITS-based hi-tech e-vehicles will improve the quality, efficiency, performance and reduce the fuel consumptions and carbon emissions.

RRM Strategy Based on IoT-ITS

The RRM strategy aims to establish IoT-based guidelines to manage traffic and transportation in MCI, reducing traffic congestion and emissions. Key actions include implementing IoT-driven rules to regulate new vehicle purchases and control population inflow by balancing infrastructure between cities and smaller areas. Government-supported scrappage policies will help phase out old, polluting vehicles, promoting eco-friendly and high-tech e-vehicles. IoT-based vehicle fitness testing stations and odd-even traffic rules will further reduce congestion, while peak-hour congestion fees will manage traffic flow and emissions effectively, moving towards to reduce TTCE and TTEC.

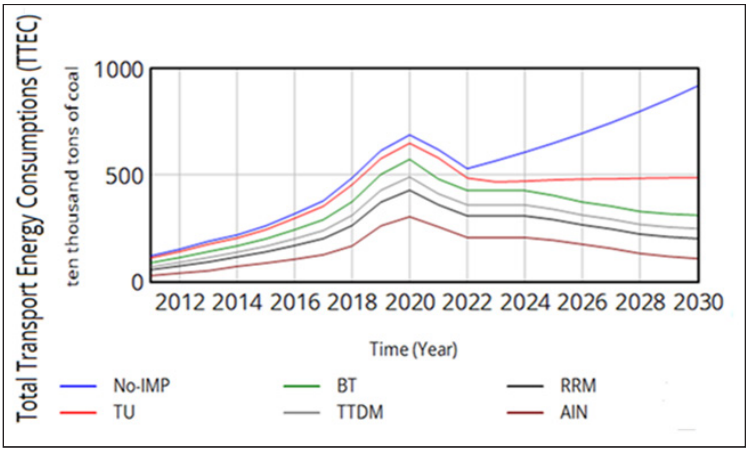
AIN Strategy

AIN strategy is basically a synergistic approach of TTDM, BT, RRM, and TU, with all their restrictions and due to these multiple effects of all these four strategies, an accumulated decreasing pattern of TTCE and TTEC is observed in MCI.

RESULTS AND DISCUSSION

The simulation results of SSDS model for generated strategies based on IoT-ITS to reduce TTCE and TTEC of road traffic and transportation system in MCI are shown in Figures 6 and 7, respectively. Figure 6 (a) depicts TTEC pattern in MCI for different strategies based on IoT-ITS. The value of TTEC under AIN is minimum in base year 2011 and has the lowest rising outcome pattern of all six strategies upto COVID-19 period and after the aggressive implementation of IoT-ITS from the post-COVID-19 time period 2023 to 2030, it has the highest continuous decline pattern of all six strategies. The output pattern of AIN is the most effective strategy pattern among all six strategies in reducing TTEC in both long and short period. In RRM, the value of TTEC has one of the lowest rising patterns of all of five separate strategies upto the COVID-19 period but after the aggressive implementation of RRM from the post-COVID-19 period 2023 to 2030, has the second highest continuous decline pattern and thus very realistic strategy for the short duration reduction of TTEC. In No-IMP, there is minimum decline pattern in comparison to all other strategies and in TU, there is second minimum decline in TTEC before and after the COVID-19 period. Before COVID-19 period, there is less rising pattern in TTEC due to BT and TTDM in comparison of No-IMP and TU but after COVID-19 period there is comparatively further less rising pattern in TTEC due to BT and TTDM. The TTDM looks very realistic strategy for the short duration reduction of TTEC.

Figure 6 (b) depicts the variations in TTEC per capita in MCI for different strategies based on IoT-ITS. There is very minor decline pattern in TTEC per capita under TU primarily due to less short duration progress in energy consumption economy of urban transportation in India mainly due to constraint of advanced technology and finance before COVID-19 period. There is also very slow paced decline pattern in TTEC per capita under TTDM before COVID-19 period. During COVID-19 period, there is a very sharp decline but after COVID-19 period there is a faster decline pattern in TTEC per capita. In BT, the pattern of TTEC per capita depicts a bit sharp decline behavior before COVID-19 period but after COVID-19 period, the decline pattern depicts a gradual slow pace of decline. In RRM, TTEC per capita has the lowermost value of all the specific strategies. In RRM and TTDM before the COVID-19 period in comparison to all other strategies have a tremendous initial decline pattern in TTEC per capita but BT depicts a drastic decline pattern in totality in TTEC per capita not only before COVID-19 period but also in the post-COVID-19 period. The model simulation clearly shows that BT is the best suited strategy for reduction of TTEC from public bus transport. The TTEC per capita depicts the lowest level value in



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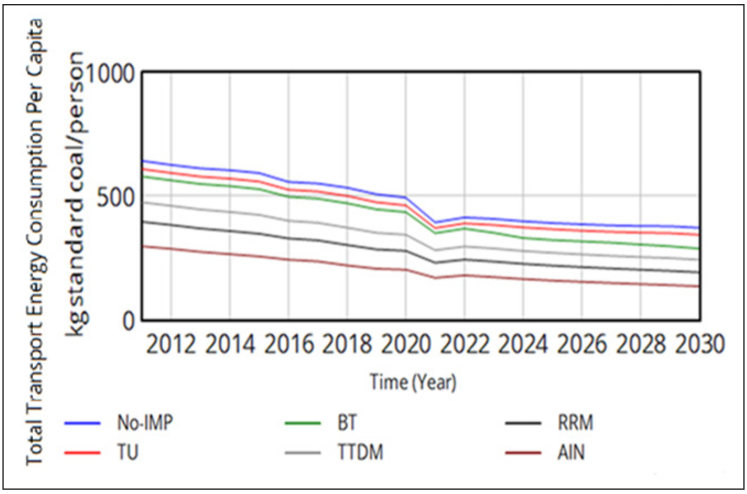
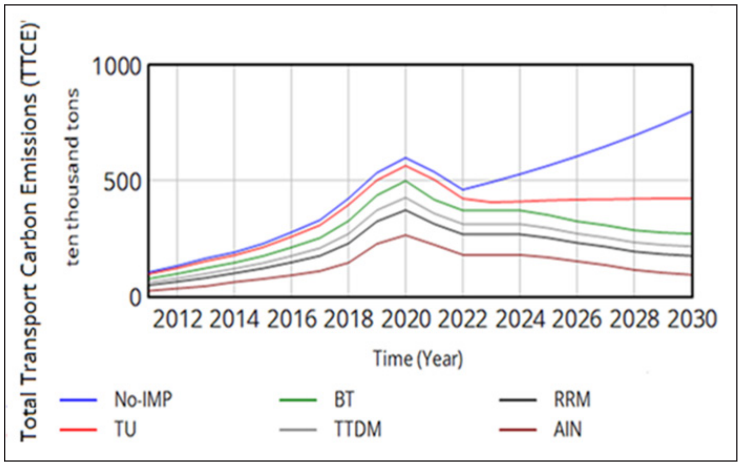


(b)

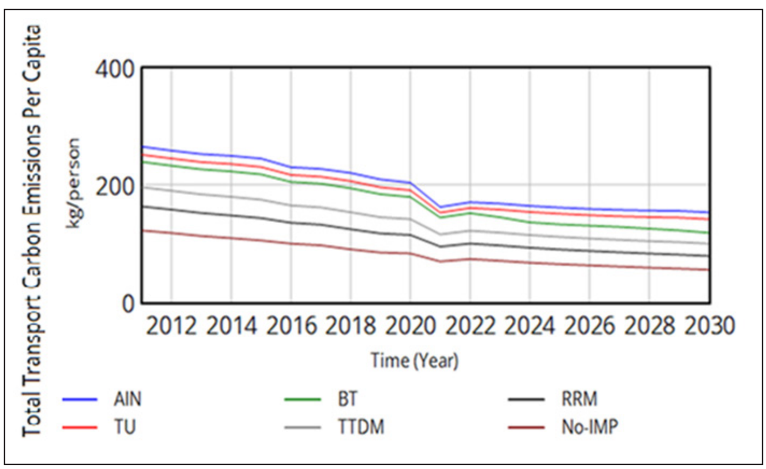
Figure 6. (a) Total Transport Energy Consumptions (TTEC) and (b) TTEC per capita pattern in Million-plus Cities of India (MCI) for different strategies based on Internet of Things-enabled Intelligent Transportation System (IoT-ITS)
Note. No-IMP = No implementation; TU = Technology upgradation; BT = Bus transport; TTDM = Traffic and transportation demand management; RRM = Rules and regulations management; AIN = All integrated

the start for AIN and there is continuous fall in its values before and after the COVID-19 period. It is interesting to note that decline of TTEC per capita under AIN is very fast in the beginning but after a passage of time slows down.

TTCE pattern in MCI for six different strategies based on IoT-ITS is shown in Figure 7(a). The value of TTCE under AIN has the lowest rising pattern of all of six strategies upto the COVID-19 period and after the aggressive implementation of IoT-ITS from 2023



(a)



(b)

Figure 7. (a) Total Transport Carbon Emissions (TTCE) and (b) TTCE per capita pattern in Million-plus Cities of India (MCI) for different strategies based on Internet of Things-enabled Intelligent Transportation System (IoT-ITS)
Note. No-IMP = No implementation; TU = Technology upgradation; BT = Bus transport; TTDM = Traffic and transportation demand management; RRM = Rules and regulations management; AIN = All integrated

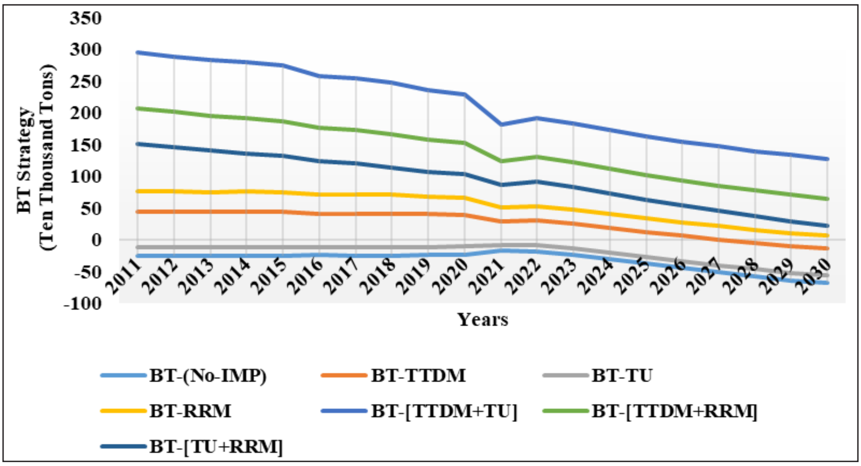
to 2030, again has the highest continuous decline pattern of all six strategies based on IoT-ITS. Under RRM, the TTCE pattern after the aggressive implementation of RRM from the post-COVID-19 period, has the second highest continuous steady decline and thus again highly realistic strategy for the short duration reduction of TTCE. Due to tremendous rise in travel pattern of target population, the value of TTCE is still rising, but not with great pace due to implementation of strategies based on IoT-ITS. Variations in TTCE per capita in MCI for the six different strategies based on IoT-ITS are shown in Figure 7(b). The simulation patterns for TTEC per capita and TTCE per capita are very similar for TTDM, BT, RRM, and AIN. The TTCE per capita due to TU depicts overall greater changes.

Discussion and IoT-ITS Based Strategy Implications

It is interesting to note that RRM has the extreme result in reduction of TTEC and TTCE. Secondly, the role of TU is better in reduction of TTCE to the reduction of TTEC. The implementation of AIN is always most authentic in the reduction of TTEC and TTCE in comparison to the implementation of any particular strategy. Figure 8 (a) depicts the outcome changing pattern in reduction of TTCE due to implementation of BT under different strategy combinations. Now the combinations are: BT– (No-IMP) = ΔBT; BT–TTDM = Δ[BT + TTDM] – ΔTTDM; BT–TU = Δ[BT + TU]– ΔTU; BT– RRM = Δ[BT + RRM] – ΔRRM; BT – [TTDM + TU] = Δ[BT + TTDM + TU] – Δ[TTDM + TU]; BT – [TTDM + RRM] =Δ[BT + TTDM + RRM] – Δ[TTDM + RRM]; BT – [TU + RRM] = Δ[BT + TU + RRM] – Δ[TU + RRM)]; BT– [TTDM + TU + RRM)] = ΔAIN – Δ[TTDM + TU + RRM].

Here BT – [TTDM + TU] represents the outcome pattern in reduction of TTCE due to implementation of BT after the prior implementation of TTDM and TU. Now the outcome pattern BT – [TTDM + TU] is prominent in all and depicts that the outcome pattern of BT is superb but only after the implementation of TTDM and TU. Now comparison of three pairs BT – TU; BT – TTDM; and BT – RRM, clearly shows that BT is most effective after the implementation of TU. Now BT – [TTDM + TU + RRM] has always outcome pattern positive while BT – [TU +RRM] and BT – TU has always outcome pattern negative. These conflicting patterns clearly indicate that RRM has a very strong effect on the implementation behavior of BT. Hence, the correct order is first of all implement BT and then RRM. So now the best order to capitalize the maximum effect of BT is TU > TTDM > BT > RRM.

Figure 8 (b) depicts the outcome changing pattern in reduction of TTCE due to implementation of TU under different strategy combinations. Now the combinations are: TU – (No-IMP) = ΔTU; TU – BT = Δ[BT + TU] – ΔBT; TU – TTDM = Δ[TTDM + TU] – ΔTTDM; TU – RRM = Δ[TU + RRM] – ΔRRM; TU – [BT + TTDM] = Δ[BT + TTDM + TU] – Δ[BT + TTDM]; TU – [BT + RRM] = Δ[BT + TU + RRM] – Δ[BT + RRM]; TU – [TTDM + RRM] = Δ[TTDM + TU + RRM] – Δ[TTDM + RRM]; TU – [BT + TTDM + RRM)] = ΔAIN – Δ[BT + TTDM + RRM]. Now the outcome pattern of TU – [BT + TTDM] is prominent in all and clearly recommends that TU should be implemented first and then RRM should be implemented to give us most effective results. Now comparison of three pairs TU – BT; TU – TTDM; and TU – RRM, clearly shows the best order of implementation: BT followed by TTDM and then in the last RRM. So now to capitalize the maximum effect of TU, the best sequence is BT > TTDM > TU > RRM.



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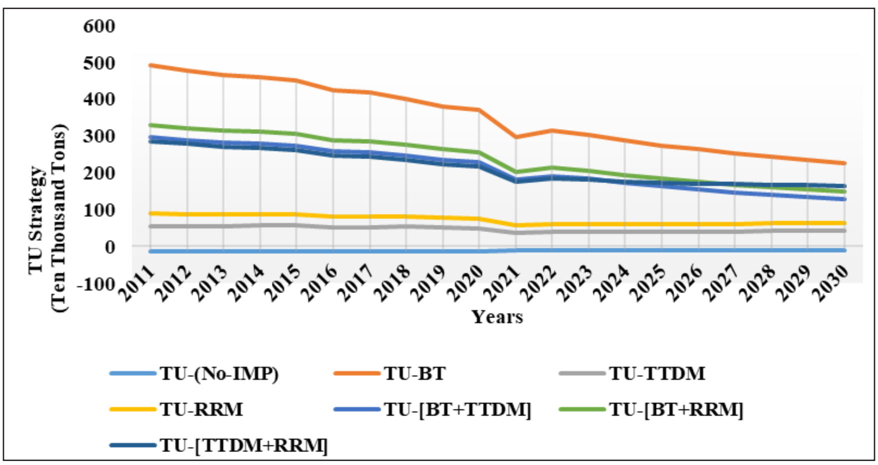
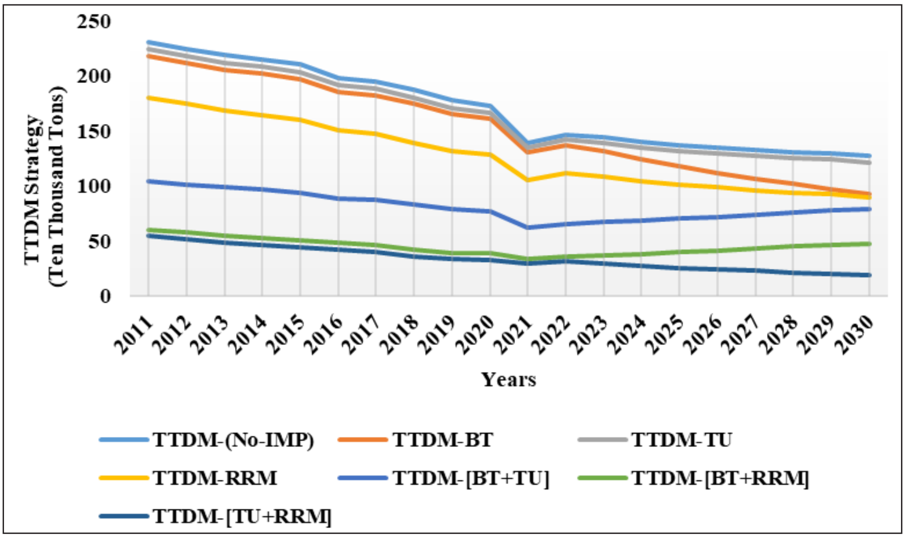


(b)

Figure 8. Outcome changing pattern in reduction of Total Transport Carbon Emissions (TTCE) due to implementation of (a) Bus transport (BT) Strategy and (b) Technology upgradation (TU) Strategy
Note. TU–(No-IMP) = Technology upgradation–(No implementation); TU–BT = Technology upgradation–Bus transport; TU–TTDM = Technology upgradation–Traffic and transportation demand management; TU–RRM = Technology upgradation–Rules and regulations management; TU–[BT+TTDM] = Technology upgradation–[Bus transport + Traffic and transportation demand management]; TU–[BT+RRM] = Technology upgradation–[Bus transport + Rules and regulations management]; TU–[TTDM + RRM] = Technology upgradation–[Traffic and transportation demand management + Rules and regulations management]

Figure 9 (a) depicts the outcome changing pattern in reduction of TTCE due to implementation of TTDM under different strategy combinations. Now the combinations are: TTDM – (No-IMP) = ΔTTDM; TTDM –BT = Δ[BT + TTDM] – ΔBT; TTDM – TU = Δ[TTDM + TU] – ΔTU; TTDM –RRM = Δ[TTDM + RRM] – ΔRRM; TTDM – [BT



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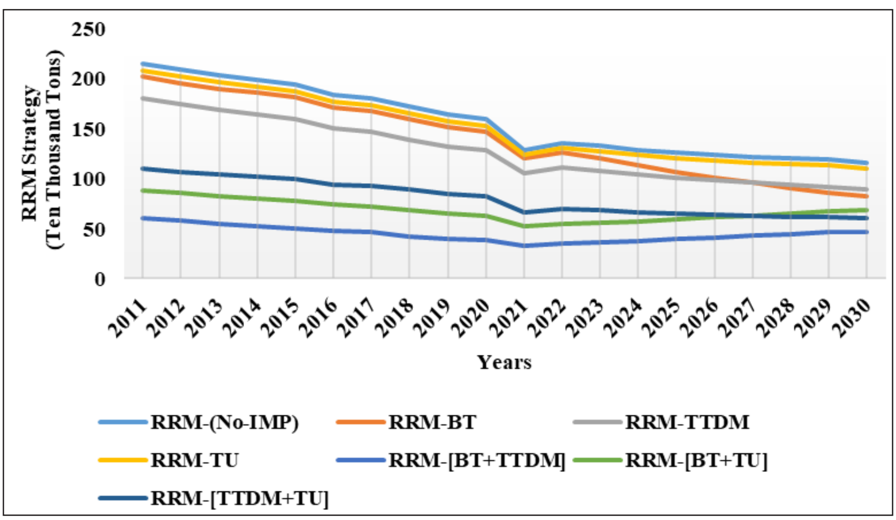

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Figure 9. Outcome changing pattern in reduction of Total Transport Carbon Emissions (TTCE) due to implementation of (a) Traffic and transportation demand management (TTDM) Strategy and (b) Rules and regulations management (RRM) Strategy

Note. RRM–(No-IMP) = Rules and regulations management–(No implementation); RRM–BT = Rules and regulations management–Bus transportation; RRM–TTDM = Rules and regulations management–Traffic and transportation demand management; RRM–TU = Rules and regulations management–Technology upgradation; RRM–[BT+TTDM] = Rules and regulations management–[Bus transportation + Traffic and transportation demand management]; RRM–[BT+TU] = Rules and regulations management–[Bus transportation + Technology upgradation]; RRM–[TTDM+TU] = Rules and regulations management–[Traffic and transportation demand management + Technology upgradation]

+ TU] = Δ[BT + TTDM + TU] – Δ[BT + TU]; TTDM – [BT + RRM] = Δ[BT + TTDM + RRM] – Δ[BT + RRM]; TTDM – [TU + RRM] = Δ[TTDM + TU + RRM] – Δ[TU + RRM); TTDM – [BT + TU + RRM] = Δ AIN – Δ[BT + TU + RRM]. Here the TTDM – [BT + TU] represents the outcome pattern in reduction of TTCE due to TTDM after the prior implementation of BT and TU. Now the outcome pattern of TTDM – [BT + TU] is best in all and indicates that outcome pattern of TTDM is most realistic when this is implemented after the implementation of BT and TU. Now comparison of three pairs TTDM – BT; TTDM – TU; and TTDM – RRM, shows that the outcome pattern of TTDM is weak after the implementation of RRM but is strong after the implementation of TU. Now the outcome pattern of TTDM – [BT + TU + RRM] is noticeable which clearly indicates that TTDM always gives realistic pattern to resolve the problems at any stage of time and hence it should be used continuously. So now the best order to capitalize the maximum effect of TTDM is TU > BT > TTDM > RRM.

Figure 9 (b) depicts the outcome changing pattern in reduction of TTCE due to implementation of RRM under different strategy combinations. Now the combinations are: RRM – (No-IMP) = ΔRRM; RRM – BT = Δ[BT + RRM] – ΔBT; RRM – TTDM = Δ[TTDM + RRM] – ΔTTDM; RRM – TU = Δ[RRM + TU] – ΔTU; RRM – [BT + TTDM] = Δ[BT + TTDM + RRM] – Δ[BT + TTDM]; RRM – [BT + TU] = Δ[BT + TU + RRM] – Δ[BT + TU]; RRM – [TTDM + TU] = Δ[TTDM + TU + RRM] – Δ[TTDM + TU]; RRM – [BT + TTDM + TU] = ΔAIN– Δ[BT + TTDM + TU]. The implementation of RRM has a powerful decreasing pattern tendency on implementation of TTDM, BT and TU and should be executed latter. Now to get the best outcome pattern of RRM – No-IMP, the RRM should be executed initially. The outcome pattern of RRM – TU is the next noticeable and therefore TU should be executed first. The comparison of RRM – TTDM with RRM – BT clearly indicates that in the early stages, the outcome pattern of RRM – BT is more significant than RRM – TTDM but in the post Covid-19 period the outcome pattern is worst. The implementation of TTDM need good condition of public transportation as an essential requirement while implementation of BT need a particular time lag. So now the best order to capitalize the maximum effect of RRM is TU > BT > TTDM > RRM.

Similarly, the best order to capitalize the maximum effect of all separate strategy in AIN is TU > BT > TTDM > RRM.

CONCLUSION

A SSDS model was designed in four stages to reduce TTEC and TTCE of road traffic and transportation system in MCI by the implementation of strategies based on IoT-ITS. Total six strategies based on IoT-ITS were formulated and generated to monitor TTEC and TTCE in MCI. The outcome pattern was analyzed and simulated. The implementation of BT has an optimistic outcome pattern but implementation of BT needs a particular time lag and hence the output pattern will only be effective slowly after a passage of time, whereas the implementation of TTDM has a quick favorable outcome pattern and is very effective for short duration. When both BT and TTDM are implemented jointly, then TTDM can easily take care of time lag due to BT. The TU plays a very important role in reduction of TTCE than savings of TTEC, while implementation of RRM can play an important role in attaining the targets very quickly than others. The implementation of AIN is very expensive in reducing TTCE and TTEC but its overall outcome pattern is excellent in comparison of implementation of each specific strategy individually.

For the generation of IoT-ITS-based total low carbon emission transportation modes in the near future and for achieving the target goal of reducing TTCE and TTEC, BT is a very realistic and sound to manage and reduce the road traffic accidents and collisions, road traffic congestions and consumption of fuels. There is also an urgent need to promote the dedicated cycling zones, dedicated e-vehicle lanes, and safe walking zones by developing IoT-ITS-based driveways and promoting e-vehicles. The sophisticated structure of TTDM can play a very important role in managing the traffic and transportation system. The transport strategic planners and administrators are supposed to carefully examine the possible bottlenecks in this strategy, and should diagnose and predict the future line of action to avoid the eleventh-hour crisis and should study in advance the effect of IoT-ITS-based infrastructure development on the travel pattern due to TTDM.

The TU has a lot of hidden merits and should be thoroughly explored. TU has a better role in reducing TTCE than the savings in total transport energy. IoT-ITS-based research has a very long duration investment remuneration system, and has a good potential for a variety of different high-tech inputs from the practical point of view. The majority of energy workers and two or four-wheelers manufacturers generally have less drive for technology research. Hence, it is necessary for the Government of India to strictly introduce and implement very severe technical guidelines immediately to avoid an explosive disaster due to carbon emissions. The provision of exemption from taxes and such other incentives can also play a significant role in the realization of target goals.

The RRM is totally based on the strong discretion of the Government of India. Hence it is very necessary for the government machinery to strictly impose the RRM with full boldness and fairness. The police and Regional Transport Office (RTO) officials must circulate as well as announce detailed explanations on a regular basis about different RRM to the residents to get back their full cooperation and to minimize the rebound behavior. A safe exit process and controlling behavior are main tools for different RRM. The overall effect of different RRM is definitely very optimistic. It is very interesting to note that though implementation of AIN is highly expensive, but it is the best golden strategy in all the strategies. Hence, the optimal order of strategy implementation in AIN is TU > BT > TTDM > RRM.

The traffic and transportation system at present globally contributes approximately 26% of total energy-based emissions, and this will rise to approximately 55 to 60% in the year 2050. Similarly, the contribution of freight road transportation-based energy emissions will rise to approximately 80% in the year 2050, which is at present around 42%. The aggressive and high ambition implementation of strategies based on IoT-ITS using SSDS model in Indian road traffic and transportation system, total infrastructure as well as in electrification of road traffic and transportation system including electric vehicles and e-public transport buses will definitely reduce TTCE by approximately 33-35% upto 2030 and 70-75% upto 2050 and this road map of aggressive and high ambition implementation of strategies based on IoT-ITS finally zoom to main goal of achieving net zero emissions.

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