System Dynamics Simulation Model to Reduce the Traffic Congestion of Metropolitan Cities of India by Implementing Intelligent Transportation System

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Abstract. Poor traffic condition and severe road traffic congestion are an everlasting problem in metropolitan cities of India. With the rapid increase in vehicles, metropolitan cities of India are indispensably facing traffic congestion, which results in economic and environmental losses. This paper presents a system dynamics simulation model to reduce the traffic congestion by implementing an Intelligent Transportation System (ITS) in metropolitan cities of India. ITS refers to the interconnection of an adaptive and intelligent integration of vehicles, drivers, and the transportation system. The system dynamics simulation model aims to predict the impact of innovative and intelligent transportation strategies and their implementation in metropolitan cities of India. The developed system dynamics simulation model helps in improving the transportation system of metropolitan cities of India and also identifies crucial factors to relieve traffic congestion. It is found that implementation of developed system dynamics simulation model not only helps in reducing traffic congestion but also enhances safety and mobility. The innovative scientific contributions of this research study include system dynamics simulation model development and scenarios generation for reducing traffic congestion by improving reliability, safety and mobility.

Keywords: Intelligent Transportation System · System Dynamics · Metropolitan Cities · Traffic Congestion · Scenario Simulation

1 Introduction

Transportation is an essential requirement for nourishment and rapid progress of a country and is a potential driving factor behind each and every development. The demand of a solid transportation system of metropolitan cities of India, which is now becoming a backbone for the survival and development of a modern society, is increasing due to drastic changes in travel patterns, high population growth, poor and inadequate maintenance of roads and infrastructure, rising cost of petrol and diesel, heavy transport taxes, tremendous rise in shuttling of delivery boys' motorbikes, severe traffic congestion, stop-and-go

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traffic and frequent accidents, industrialization, education infrastructure and desire to travel. The resulting burdens on the transport infrastructure of metropolitan cities, which is already seriously stretched, are multiplying tremendously. It is totally impossible now to modify the metropolitan cities' traffic handling guidelines on a regular basis due to poor road traffic conditions and severe traffic congestion and stop-and-go traffic. The serious consequences of the increase in vehicle amount are not only the increasingly serious traffic congestion, but also the severe urban air pollution due to vehicle exhaust emissions [7]. Past environment and gains in metropolitan cities' road infrastructure safety are now decreasing drastically and in spite of heavy expenditures on existing and totally new road infrastructure, road traffic congestion is continuously rising and rising. It is looking totally impossible that these severe problems can still be solved by depending on our old approaches or by constructing new road infrastructures or by building more and more new roads. Hence it is necessary to generate the hi-tech intelligent base for the next generation roads, highways and vehicles using the innovative concept and the practice of Intelligent Transportation System [4] which will open up new doors of attaining sustainable traffic mobility in the metropolitan cities of India.

Intelligent Transportation System (ITS) is a platform that offers hi-tech alternatives to meet future demands of policy makers, decision makers and commuters, attains other technology outcomes based on different applications that manage and regulate all traffic problems, monitor and improve the quality of transportation system. ITS refers to the interconnection of an intelligent and adaptive integration of the transportation system, drivers and vehicles. Implementing ITS into metropolitan cities of India will improve transportation safety, mobility, efficiency, energy, and the environment. The measurement and evaluation models have been developed for intelligent transportation system products to provide technological means [5]. A novel ITS was proposed using the cellular network, GPS probes, and limited ITS infrastructure [1]. A survey was conducted to explore behavior, Intelligent Transportation System needs, level of service expectations for student parking at a university campus [6]. A detailed presentation of the traffic prediction methods for intelligent cities has been provided [4]. The distribution of standstill distance and time headway was investigated and incorporated this distribution into freeway car-following models [9]. An IoT-based method was proposed to determine the real-time traffic flow in a road section [11]. A survey was provided to discuss machine learning for next generation ITS [12]. A resilient and secure cooperative ITS was proposed using sensor technologies [13].

System dynamics scenario generation technique is an interdisciplinary field of researching on feedback of system information and solving the complex real-life problems integrated in the system and is an innovative and very effective research tool to study the very complex dynamic systems. It is based on fundamental assumption that the main characteristics of any system and its behavior outlines are mainly dependent on the control mechanism of any system's core dynamic feedback infrastructure. System dynamics scenario generation technique highlights dynamic research and real-life problems that should always be developed using integrated system reasoning and the synergistic approach of quantitative and qualitative technique to simulate the dynamic development of real-life systems and its present and prognostic trend for futuristic dynamic long term strategic and tactical quantitative analysis. It is very interesting to note that there is very little literature on generating the scenarios and policy recommendations of the traffic and transportation problems of India using system dynamics. The system dynamics models were developed to determine the energy requirement and emission levels, analysis of traffic safety policy, traffic congestion charging fee management and the impact of regulatory policies for sustainable transport planning [3, 7]. A new framework was proposed by applying a combination of a system dynamics approach and a data envelopment analysis technique [14]. A vehicle emission reduction management model using system dynamics and gray model theory was established to validate the model [2]. The smart city concept was created by using modern technologies to discover solutions to maintain the environment [8]. A perimeter control method was established for a congested urban road network with dynamic and variable ranges [10]. In this paper, a System Dynamics Simulation (SyDyS) model is designed and developed to reduce the traffic congestion by implementing Intelligent Transportation System (ITS) strategies in the metropolitan cities of India. The SyDyS model also generates scenarios and policy recommendations on the basis of simulation and analysis to reduce the traffic congestion and stop-and-go traffic and improve the existing transportation system of metropolitan cities of India.

2 Intelligent Transportation System

Intelligent Transportation (ITS) is a platform technology that offers hi-tech alternative to meet Intelligent Transportation System (ITS) is a platform technology that offers hi-tech alternatives to meet future demands of policy makers, decision makers and commuters, attains other technology outcomes based on different applications that manage, monitor and improve the quality of transportation system. ITS depends heavily on input of different types of data collected from infrastructure, road, highway, vehicles, environmental surroundings and conditions using various radio frequency identification scanners, sensors, global positioning system, and intelligent video cameras, and after real-time and rapid transmission to traffic management centers, this data is filtered, synthesized and logically analyzed and the output in the form of intelligent information (road accidents, traffic diversions, traffic flow, change in route, travel speed and time, delay, conditions of work zone etc.) is again disseminated in real-time and rapid transmission mode, from the traffic management centers and operation centers to the users (commuters, travelers, infrastructures) through wide range of wireless networks with cloud platforms, electronic devices for better strategic, tactical and operational planning, decision making, managing and controlling the transportation system. ITS has the potential to save human lives, money and time. ITS applications are capable in the following:

- Improving safety by installing advance warning systems; improving air quality by reducing levels of pollution; improving flow of traffic by reducing recurring congestion, for example infrastructure-related and non-recurring congestion e.g. human related, mechanical failing related and environment related; improving travel safety and efficiency, mobility of freight transport and handicapped, senior citizens, rural and remote areas commuters, security, reliability, operational performance, travel convenience, travel comfort and planning, productivity, global competitiveness.
- Minimizing travel cost and travel time, injuries and deaths due to traffic, delays and uncertainty in travel, fuel consumption.

- Reducing road accidents due to human factors, highway related factors and environmental factors.

The central nervous system of ITS is made up of twin technologies - information technologies, and infrastructure-based and vehicle-based control technologies. The following are the basic categories of the ITS: Traffic Management Systems, Commuter Information Systems, Intelligent Vehicle Control Systems, Arterial Management System, Transit Management System, Electronic Payment System, and Crash Prevention and Safety System. ITS is a system of systems integrating leading-edge broad range of systems to improve transportation sustainability, enhance productivity of the traffic management systems and driver's skills. ITS offers comfort and reliability for the individual user; optimal decision making and additional effective operations for the transportation system operator user; using flexible real-time approach to address general traffic and transportation problems. The jump-start implementation of ITS strategies in the metropolitan cities of India, can play an important role in making transport system more effective and efficient by managing and optimizing the movement of freight, vehicles and people.

3 System Dynamics Simulation Model

System Dynamics Simulation (SyDyS) model is designed and developed to reduce the traffic congestion in the metropolitan cities of India by implementing ITS strategies. The SyDyS model also generates scenarios and policy recommendations on the basis of simulation and analysis to reduce the traffic congestion and stop-and-go traffic and improve the existing transportation system of metropolitan cities of India. The SyDyS model is designed and developed in four phases: phase I: qualitative phase, phase II: quantitative phase, phase III: testing phase, and phase IV: experimentation phase. Causal loop diagrams of various sub-systems are generated in phase I while stock and flow diagrams are created in phase II using system dynamics Vensim software. The developed model is tested with the real-life data in phase III, and after successful testing the designed and developed, model is used to generate scenarios in the phase IV. The SyDyS model is mainly based on four main sub-models: Total Population sub-model, Habitat sub-model, GDP sub-model and Total Vehicle Population sub-model and three sub-systems: Road Traffic Congestion sub-system, Road Travel Demand sub-system and Transportation Infrastructure sub-system. Road Traffic Congestion sub-system feedbacks to GDP sub-model and is basically an interface between Road Travel Demand sub-system and Transportation Infrastructure sub-system. Total Vehicle Population sub-model, GDP sub-model and Total Population sub-model are fundamental sub-models for quantitative analysis and plays an important role for the metropolitan cities' transport system and its environment. The Habitat sub-model acts as a main hurdle in the development of metropolitan cities' transport system and directly affects the Total Population sub-model and GDP sub-model. Figure 1 shows the relationship between Total Population sub-model, Habitat sub-model, GDP sub-model and Total Vehicle Population sub-model and three sub-systems: Road Traffic Congestion sub-system, Road Travel Demand sub-system and Transportation Infrastructure sub-system of the SyDyS model. The Causal Loop Diagram of the System Dynamics Simulation (SyDyS) Model is shown in Fig. 2.

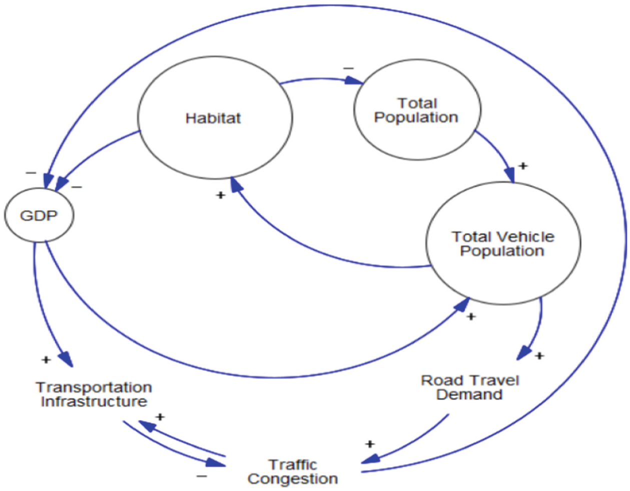

Fig. 1. Relationship between sub-models and sub-systems of the SyDyS Model

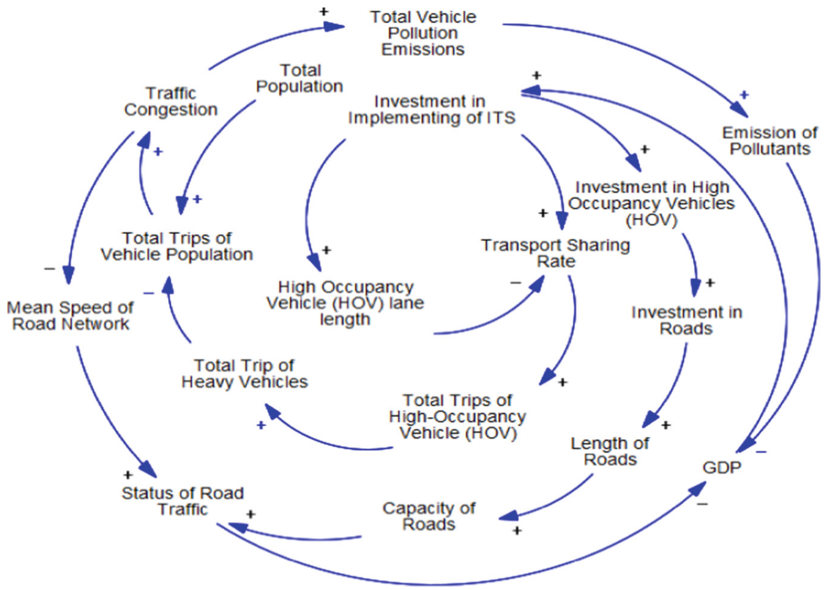

Fig. 2. Causal Loop Diagram of the SyDyS Model

On the basis of change in the variables, the resultant effect in the overall change in the total system and the quantitative relationships between the different variables and system characteristics are shown in the form of Stock and Flow Diagram of SyDyS model Fig. 3.

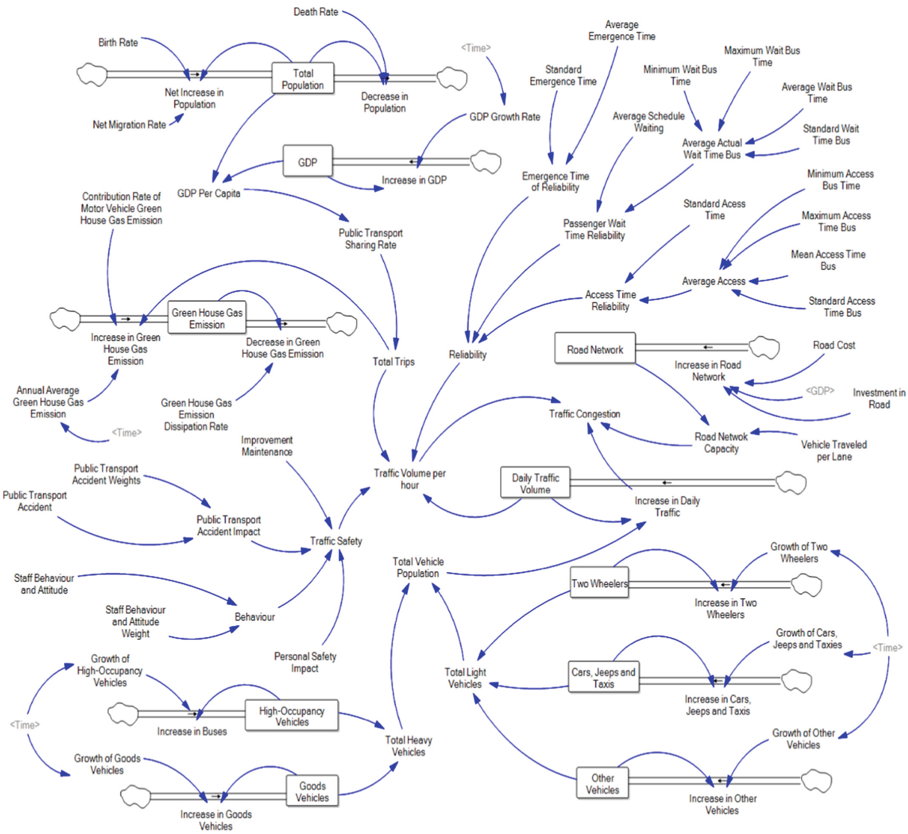

Fig. 3. Stock and Flow Diagram of the SyDyS Model

On the basis of Causal Loop Diagram, the Stock and Flow Diagram of the SyDyS model mainly revolves around GDP sub-model, Total Population sub-model, Habitat sub-model, and Road Travel Demand, Transportation Infrastructure and Road Traffic Congestion sub-system.

3.1 GDP Sub-model

The increase in GDP of metropolitan cities is shown in Fig. 4. Increase in GDP is one of the main competitiveness indicators for metropolitan cities and will also stimulate investment in road construction and implementation of ITS in metropolitan cities. The analysis data pair of the year 2011–2018 and GDP growth rate is shown in Fig. 5.

The GDP stock has just one inflow variable i.e., increase in GDP, in this sub-model and is defined only by the GDP rate. The quantitative relationship between GDP and increase in GDP are shown in "Eq. (1)" where INTEG means the function of integral, GDP_{t0} indicates the starting GDP time and GDP_{tn} indicates the terminating GDP time.

$$GDP_{tn} = INTEG\,(Increase\ in\ GDP, GDP_{t0}) \tag{1}$$

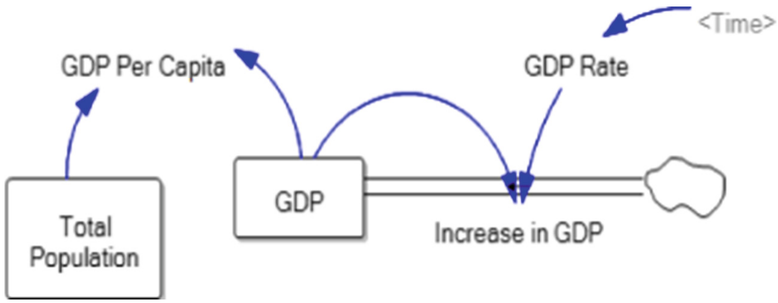

Fig. 4. GDP sub-model

Fig. 5. GDP growth rate

3.2 Total Population Sub-model

Figure 6 depicts the Total Population development status of metropolitan cities in model. The relationship between Total Population, Net Increase in Population and Net Decrease in Population are shown in "Eq. (2)" where $Total\ Population_{t0}$ indicates the population in starting time and Total Population$_{\text{tn}}$ indicates the population in terminating time.

$$Total\ Population_{tn} = INTEG\ (Net\ Increase\ in\ Population - Net\ Decrease\ in\ Population,\ Population_{t0}) \tag{2}$$

3.3 Habitat Sub-model

The Greenhouse Gas requirements in Habitat sub-model are main constraints of metropolitan cities' transport system and Total Trips are directly proportional to high occupancy vehicles sharing rate which is linear function related to GDP per capita. The Stock and Flow Diagram of Habitat sub-model with different rate and level variables is shown in Fig. 7. The increase in Annual Average Greenhouse Gas Emission is shown in Fig. 8.

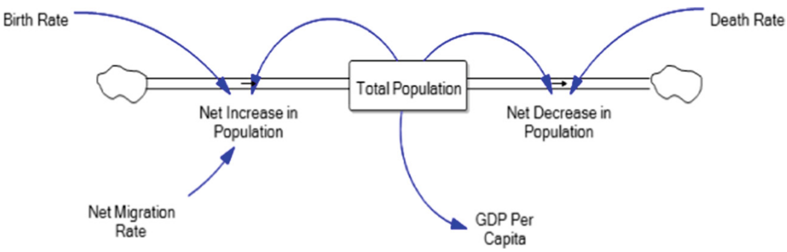

Fig. 6. Total Population sub-model

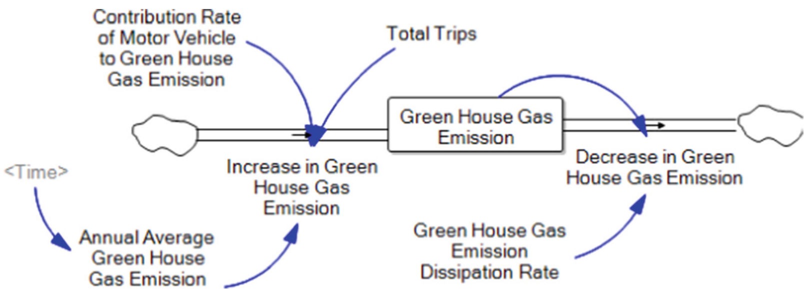

Fig. 7. Habitat (HaT) sub-model

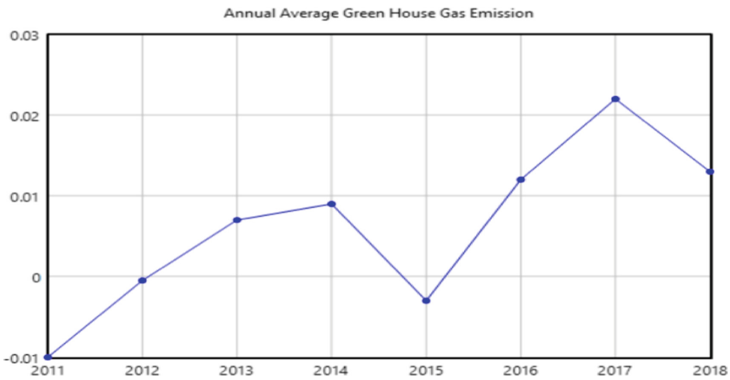

Fig. 8. Increase in Annual Average Greenhouse Gas Emission

The equation for Green House Gas Emission is shown in "Eq. (3)":

$$Green\ House\ Gas\ Emission_{tn} = INTEG\ (Increase\ in\ Green\ House\ Gas\ Emission - Decrease\ in\ Green\ House\ Gas\ Emission, Green\ House\ Gas\ Emission_{t0}) \quad (3)$$

where INTEG means the function of integral, *Green House Gas Emission*$_{t0}$ indicates the Green House Gas Emission in starting time and *Green House Gas Emission*$_{tn}$ indicates the Green House Gas Emission in the terminating time.

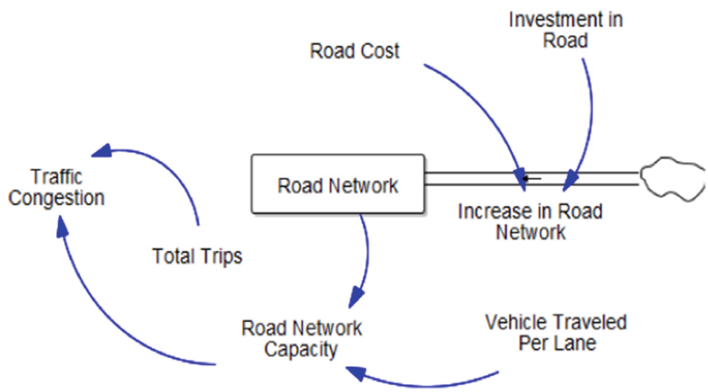

Fig. 9. Road Travel Demand and Transportation Infrastructure sub-system and Road Traffic Congestion sub-system

3.4 Road Travel Demand, Transportation Infrastructure and Road Traffic Congestion Sub-model

The Stock and Flow Diagram of Road Travel Demand, Transportation Infrastructure and Road Traffic Congestion sub-system is shown in Fig. 9. Road Travel Demand is basically a derived needs and mainly depends on Total Population and level of GDP while Transportation Infrastructure depends on investments in implementation of ITS and investments in road construction. Road Traffic Congestion is the major constraints of metropolitan cities' transport system and is the result of interaction between Transportation Infrastructure supply and travel demand.

The equation for Road Network shown in "Eq. (4)".

$$Road\ Network_{tn} = INTEG\ (Increase\ in\ Road\ Network, Road\ Network_{t0}) \quad (4)$$

where INTEG means the function of integral, $Road\ Network_{t0}$ indicates the Road Network in starting time and $Road\ Network_{tn}$ indicates the Road Network in terminating time.

4 Model Simulation and Generated Scenarios

This section presents the generated scenarios and policy recommendations, on the basis of simulation and analysis of the designed and developed SyDyS model, to reduce the traffic congestion and stop-and-go traffic and improve the existing transportation system of metropolitan cities of India by implementing ITS strategies. The system structure of the SyDyS model is modified by the addition of feedback loops and some parameters and then modifying the structure of feedback loops to generate the scenarios. Scenario generation will help in interpreting the futuristic conditions by analyzing the simulated projections. Two main scenarios are generated to articulate and evaluate the impact of implementing ITS strategies for the reduction of the metropolitan cities' traffic congestion and to improve the existing transportation system in near future.

Scenario 1: Scenario of the Total Vehicle Population Volume using "Highly accurate IoT based multi-purpose Sensors with on-board deep learning AI processing", "Surveillance Video Cameras", "IoT based Intelligent Traffic Controller and Monitoring System", "Coordinated Intelligent Traffic Control Signals", "Dynamic Intelligent Control Mechanisms" strategies of ITS.

Figure 10 depicts the generated scenario diagram of the Total Vehicle Population volume using "Highly accurate IoT based multi-purpose Sensors with on-board deep learning AI processing", "Surveillance Video Cameras", "IoT based Intelligent Traffic Controller and Monitoring System" of ITS. The Total Vehicle Population is the sum of Total Heavy Vehicles population and Total Light Vehicles population. The number of Total Light Vehicles and the number of Total Heavy Vehicles passing on the different roads and highways will be detected by the installed ITS based "Surveillance Video Cameras" and their complete data will be detected and collected by "Highly accurate IoT based multi-purpose Sensors with on-board deep learning AI processing". The very high-resolution video data taken by "Surveillance Video Cameras" will also enrich intelligence of Transportation Infrastructure and transportation infrastructure-to-transport vehicle communications due to cloud based advanced transport intelligent solutions to traffic data aggregation use cases and real time traffic events. The installation of "Surveillance Video Cameras" with lidar and radar at road intersection will not only improve the detection of moving vehicle traffic due to poor road light challenge but also provide the best resolution traffic data. This collected data will then be sent online to the main server and "IoT based Intelligent Traffic Controller and Monitoring System" of ITS and will be used as main input to different "Coordinated Intelligent Traffic Control Signals" using "Dynamic Intelligent Control Mechanism" to prioritize the traffic of heavy congested roads/highways by switching green color traffic signal light. The collected data can also be used to manipulate, regulate and adjust the red or green light time of the "Coordinated Intelligent Traffic Control Signals" for the smooth flow of particular heavy/light traffic.

Figure 11 shows the Scenario projections of the car, jeeps and taxies population in blue color and goods vehicles population in red color on the basis of the result of simulation and analysis of SyDyS model. Two wheelers have characteristically made up the largest segment of transport in metropolitan cities. Figure 12 shows the Scenario projections of the two wheelers population in blue color on the basis of the result of simulation and analysis of SyDyS model.

Figure 13 shows the Scenario projections of the High-Occupancy Vehicles population in blue color on the basis of the result of simulation and analysis of SyDyS model. Figure 14 shows the Scenario projections of the Total Heavy Vehicles population in blue color, Total Light Vehicles population in red color and Total Vehicle Population in green color on the basis of the result of simulation and analysis of SyDyS model.

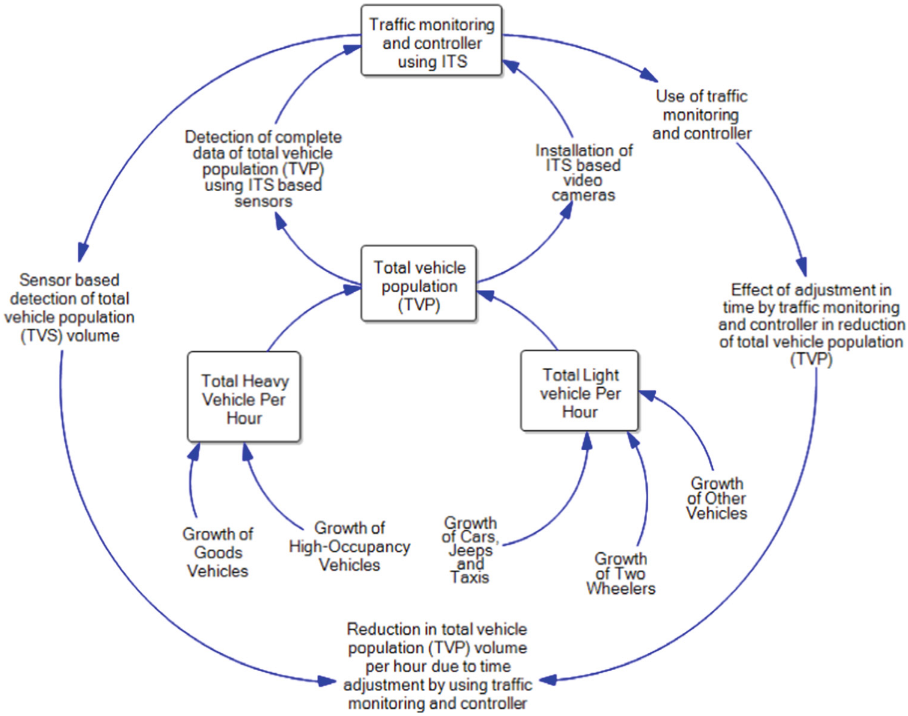

Fig. 10. Generated Scenario Diagram of the Total Vehicle Population

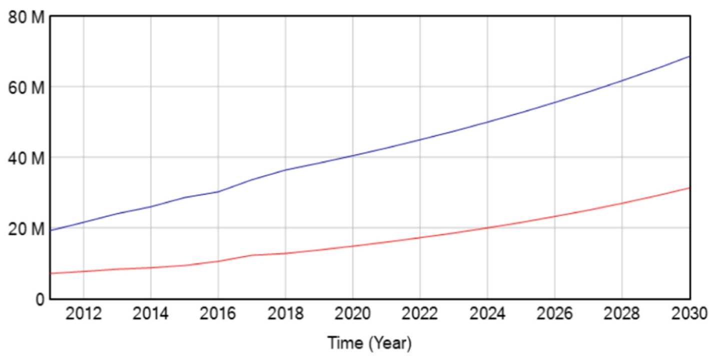

Fig. 11. Scenario projections of the Car, Jeeps and Taxis and Goods Vehicles population

Scenario 2: Scenario of the Road Traffic Congestion using "5G-based edge computing enabled cloud solution", "Highly accurate IoT based multi-purpose Sensors with on-board deep learning AI processing" and "IoT based Intelligent Traffic Controller and Monitoring System" strategies of ITS.

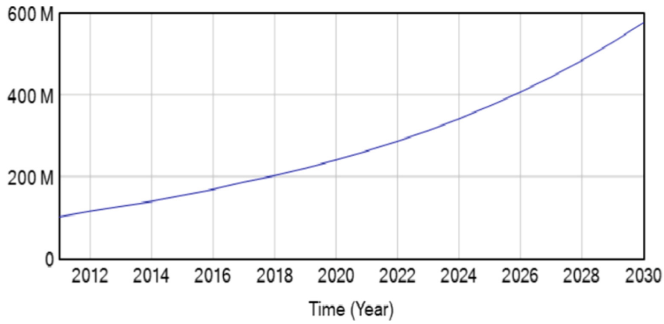

Fig. 12. Scenario projections of the Two Wheelers population

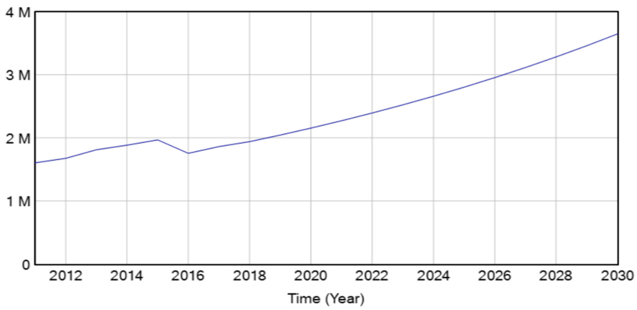

Fig. 13. Scenario projections of the High-Occupancy Vehicles population

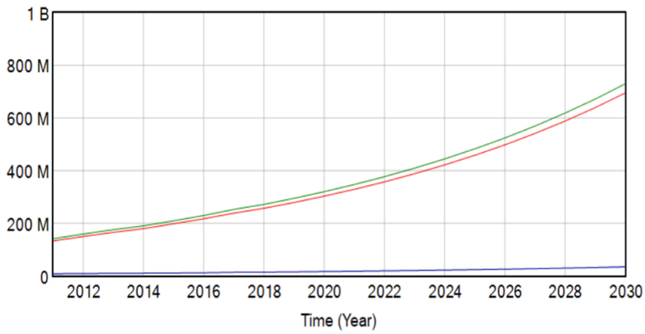

Fig. 14. Scenario projections of the Total Heavy Vehicles, Total Light Vehicles and Total Vehicle Population

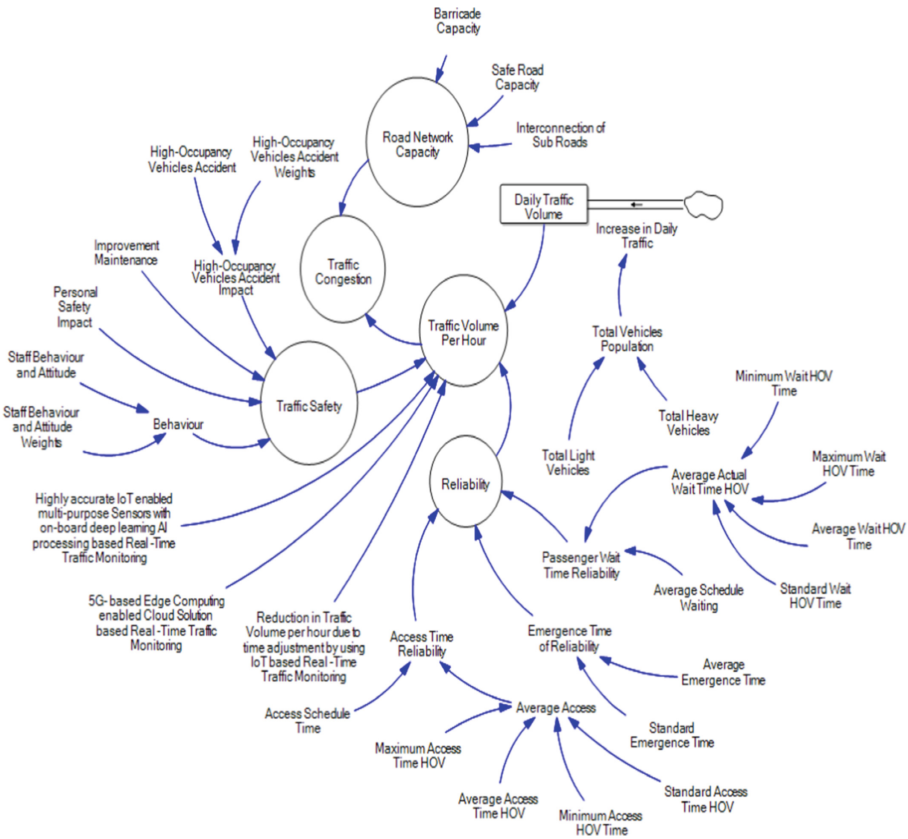

Fig. 15. Generated Scenario Diagram of the Road Traffic Congestion factor

Generated scenario diagram of the Road Traffic Congestion using “IoT based Intelligent Traffic Controller and Monitoring System” of ITS is shown in Fig. 15. Capacity of metropolitan cities’ roads and traffic volume per hour plays an important role on the metropolitan cities’ traffic congestion. Capacity of metropolitan cities’ roads is based on Speed controller restriction, safe road capacity and inter connection of sub roads. Traffic volume per hour is dependent on Daily traffic of metropolitan cities, which in turn is based on Total Vehicle Population, which is basically sum of Total Heavy Vehicles population and Total Light Vehicles population. “5G-based edge computing enabled cloud solution” of ITS will provide real-time Traffic Monitoring and automated traffic management which will help in managing and optimizing Traffic volume per hour. “Highly accurate IoT based multi-purpose Sensors with on-board deep learning AI processing” fitted in the Transportation infrastructure and different varieties of vehicles will help in traffic capacity constricting measures, providing intelligent information to drivers regarding less congested alternative routes and real-time Traffic Monitoring and ultimately will optimize traffic volume per hour. The online vehicle data received by “IoT based Intelligent Traffic Controller and Monitoring System” will be used by different

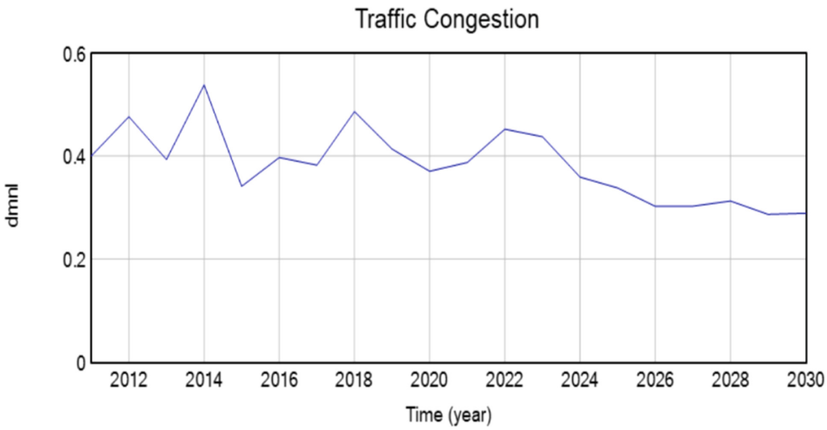

Fig. 16. Scenario projections of the Road Traffic Congestion

"Coordinated Intelligent Traffic Control Signals" to prioritize the traffic of heavy congested highways/roads by converting to green color light. This adjustment of traffic time by "Coordinated Intelligent Traffic Control Signals" will help in reduction of traffic volume per hour. The Vehicle Detection Devices, Dynamic Message Signs and Road Side Units will also play an important role in providing accurate information about poor road and traffic conditions, less congested and fast traffic routes, traffic incidents, major traffic accidents to the different vehicle drivers. Figure 16 depicts the scenario projections of the traffic congestion of metropolitan cities' on the basis of the result of simulation and analysis of SyDyS model. From the last few years, the traffic congestion of metropolitan cities' is increasing with a tremendous fast pace except during Covid-19 duration. The implementation of ITS strategies in metropolitan cities' is bound to have a positive outcome on traffic and transport conditions of metropolitan cities. The implementation of ITS strategies will definitely increase the amount of investment in Transportation infrastructure of metropolitan cities of India, but in the long run will bring metropolitan cities, in a far better condition of almost negligible severe traffic congestion inspite of slow rise in Total Vehicle Population and thus in turn will improve the saturation of metropolitan cities' roads/highways drastically.

5 Conclusion

In this paper, a System Dynamics Simulation (SyDyS) model is designed and developed to reduce the traffic congestion and improve the existing transportation system of metropolitan cities of India by implementing ITS strategies. On the basis of simulation and analysis, the designed and developed SyDyS model generates scenarios and policy recommendations, for addressing the challenges of traffic congestion (to reduce traffic congestion of metropolitan cities of India using 5G-based edge computing enabled cloud solution, Highly accurate IoT based multi-purpose Sensors with on-board deep learning AI processing, Surveillance Video Cameras, Coordinated Intelligent Traffic Control Signals and IoT based Intelligent Traffic Controller and Monitoring System), which in the long run, will effect metropolitan cities' traffic mobility (to reduce traffic delays, time of travel, budgets of travel time), metropolitan cities' traffic safety (to reduce the traffic conflicts and crash rates, traffic accidents and number of road deaths, violation of traffic laws), metropolitan cities' environment (to minimize the undesirable effects of traffic on road environment such as greenhouse gas emissions and consumption of fuels) and reliability of transport system of metropolitan cities. SyDyS model is based on transportation data and information of metropolitan cities of India and can play an important role to integrate, plan and manage transportation on a dynamic system level to reduce traffic congestion, increase traffic safety and traffic efficiency. The developed SyDyS model works as a "Scenario Laboratory" and is more generic and can be used for any particular city of India also by simply altering the indicator values.

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