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System Dynamics Simulation Modeling of Transport, Energy and Emissions Interactions

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Abstract The Transport Sector of India is largely dependent on the Energy resources accounting to nearly 11% of its total primary energy use which is predicted to reach 20% by 2030. Fuel usage in transportation sector is bound to increase by 87% in 20 years with a decrease in the available diesel stock and an alarming increase in the demand. Also the growing vehicle population has increased the contribution of Vehicular Pollution to the Urban Air Pollution from 60% in the year 1990 to 90% in 2010. In order to eliminate these risks the interaction between these sectors should be studied in detail. Since there was a lack of interdisciplinary works involving the sectors of Transport, Energy and Emissions interaction based on a Systems Approach this study is focused on carrying out an in depth study of the same based on Systems Dynamics principles. The major objective of the work is to study and appreciate the existing Transport demand and supply in Chennai city, to procure data through inventory on energy requirement and emissions from transportation sector and to build a System Dynamics (SD) model using STELLA to determine the Energy requirement and Emission levels from the transport sector in the year 2026. When the existing growth trend was assumed to be continued over the horizon year it was found that the Public Transport sector contributed to only 18% of the total trips whereas the personalised modes contributed to about 80% of the trips with about 300% increase in Fuel demand. A scenario of augmenting the Public Transportation and simultaneously restricting the growth of personalized vehicles showed a substantial decrease of nearly 65% in Energy consumption and nearly 50% reduction in Emission levels from the personalised modes of travel.

Keywords Systems Approach, System Dynamics, Simulation Modeling, Transport and Energy Interaction, Transport-Environment/Emission Interaction

1. Introduction

India is the sixth largest energy consumer in the world. The transport sector of the country accounts to nearly 19% of global energy use which is projected to reach 50% by 2030. Studies reveal the fact that at the present rate of economic growth, energy needs may increase by 16% and more with respect to the present scenario. This increase in energy use leads to an increase in Carbon di-oxide emissions also. It has been projected that the greenhouse gases emission will increase at a rate of 7% per annum (Zhou et al., 2007). Hence proper planning measures should be adopted to reduce the increasing energy demand and concomitant reductions in emissions.

2. Need for the Study

In 2005, India's transport sector consumed 11% of its total primary energy demand (16.9 % of commercial energy supply). 78 % of this demand was consumed by Road Transport, 11% by Aviation, 10% by rail transport and 1 % by Inland water. The transport sector is set to grow at over 6% per annum on the back of rising economic activity and a rapid surge in the vehicle stock. By 2030, the share of transport sector is likely to double to about 20% of the primary energy demand. Globally, the share of the Indian transport sector is likely to triple from its low of 2% in 2005 to about 6% in 2030. The growth of transport sector, primarily driven by road transport will remain heavily dependent on the availability and affordability of oil. For the energy requirement of the country as a whole, coal will however remain a dominant fuel with its share of 48% of total energy needs in 2030, followed by oil at 25%. The total demand of primary energy is likely to go up from 566Mtoe in 2006 to 1280Mtoe in 2030, which is about 3.5%. This demand is higher than the World average of 1.6% (K.P.Singh, 2009). As a result, India will become more dependent on imports and hence will be exposed to global supply risks and external price shocks casting a shadow on the long term sustainability, economy and security of its energy requirements. Hence a collective effort and unified policy direction is the need of the hour to face the challenges.

3. Objectives of the Study

- To study and appreciate the existing transport demand and supply in Chennai city.
- To procure data through inventory on energy requirement and the level of emissions in transportation sector.
- To build a System Dynamics model that would address transport, energy and emissions interactions and test the same for various policy and scenario options.
- To suggest appropriate measures that would ensure developments towards achieving sustainability in Transportation Planning

4. Scope of the Study

In this study, a System Dynamics model relating Transport, Energy and Emission sectors has been built. Data relating to Transport Energy usage in the present scenario has been collected and simulated to find the future Energy demand in the Transport sector. The level of emissions from the present and future simulated levels of traffic has also been identified. The model has been subjected to various scenario analysis aimed at studying the interaction between Transport, Energy and Emissions of the study area under various conditions. The impacts of the policies framed by the government to achieve sustainability in Transportation with respect to economic development have been analyzed at a macro level. A comparison of the results under various scenario options has been carried out to determine the advantages of the policy measures to be adopted. Based on the results, suitable recommendations of policies have been provided. The impact of Transport, Energy and Emission on the Economy of the nation can also be studied in detail based on the results obtained. Also further research could be carried out to determine the advantages of using Alternate fuels instead of Petrol and Diesel and the advantages of adopting EURO VI emission norms in the near future. The impact of these scenarios on the economy of the nation can also be analyzed.

5. System Dynamics Model Development

Generally the model building process can be divided into two phases namely the Conceptual phase and the Technical phase. It is the process of defining a problem out of a situation, developing various relationships quantitatively, testing the model with several policy options and analyzing the behaviour of the model. The various phases in model building process are as shown in Figure 1 and each phase with its characteristics is presented here.

The first phase of problem definition involves recognizing and defining a problem. System Conceptualization is to commit to paper the important influences believed to be operating within the system mostly in the form of causal-loop diagram. In the next phase, models are represented in the form of computer code that can be fed into the computer in the form of computer programming languages. In the Model Behaviour phase, computer simulation is used to determine how all the variables within the system behave over a period of time. Numerous tests must be performed on the model in the Model Evaluation phase to evaluate its quality and validity. In the final phase, the model is used to test alternative policies that might be implemented in the system under study. Furthermore, the analyst might be able to investigate the possible impacts of government policies.

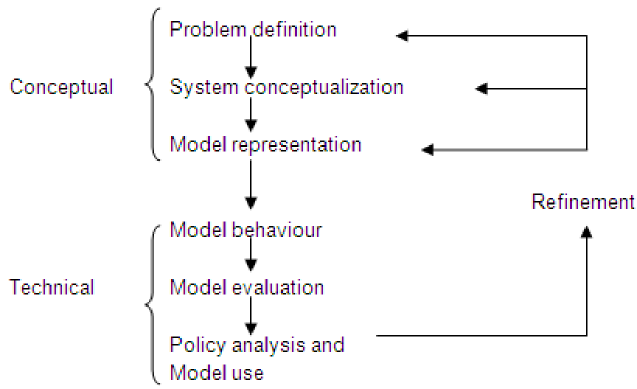


Figure 1. Phases in Model Building Process

The System Dynamics tool used in this study has four basic building blocks namely Stock, Flow, Connector and Converter. Stocks or levels are used to represent anything that accumulates. Flows or rates represent activities that increase and decrease stocks. Connectors are used to establish the relationship among variables in the model represented graphically as arrows. Converters transform input to output which can accept input in the form of algebraic relationships, graphs and Tables. For ease of presentation, the symbols used for flow diagramming of System Dynamics are presented in the Figure 2.

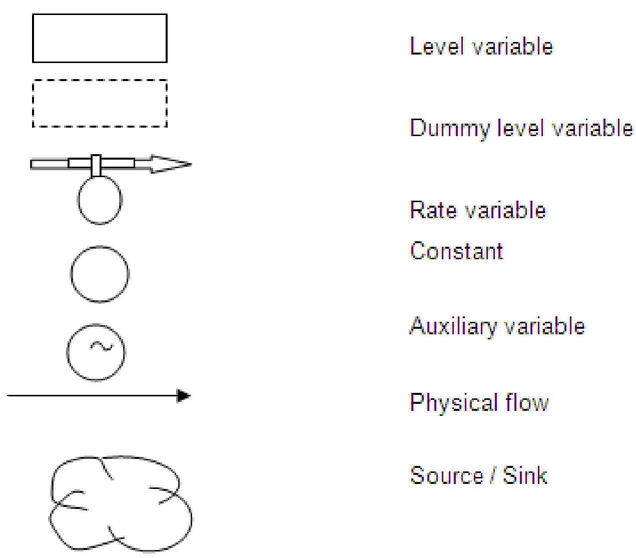


Figure 2. Flow Diagramming Symbols

The concept of the stocks and flows in System Dynamics is very appropriate to deal with a transport energy economy interaction modeling. The System Dynamics approach is based on theory of feedback processes. A feedback system is influenced by its own past behaviour. This system has a closed loop structure that brings result from past interactions of the system. Negative feedback seeks a goal and responds as a consequence of failing to achieve the goal. It is a negative feedback or goal-seeking structure of the system that causes balances and stability.

The System Dynamics model development process is summarised in the schematic diagram of a model life cycle in Figure 3. The modeling process starts with defining the purpose/goal of the system. Then boundaries of the system to be modelled are specified. This is followed by identification of key variables in the system that affects the system, the most. Then behaviour of the key variable is described, the stocks and flows are identified, and their structure is mapped in the modeling tool using basic building blocks. Quantitative information, i.e., equations and data, is included in the model structure. The model is run to test the behaviour. The model is then evaluated and adjustments are made. Once the model is replicating system behaviour, it is ready for simulation modeling.

- Model Verification

The purpose of model verification is to assure that the conceptual model is reflected accurately in the computerized representation. The conceptual model quite often involves some degree of abstraction about system operations, or some amount of simplifications of actual operations. It provides answers to the questions like Is the conceptual model (assumptions on system components and system structure parameter values, abstractions and simplification) accurately represented by the operational model (i.e., by the computerized representation). Verification and Validation although conceptually distinct are conducted simultaneously by the modeler.

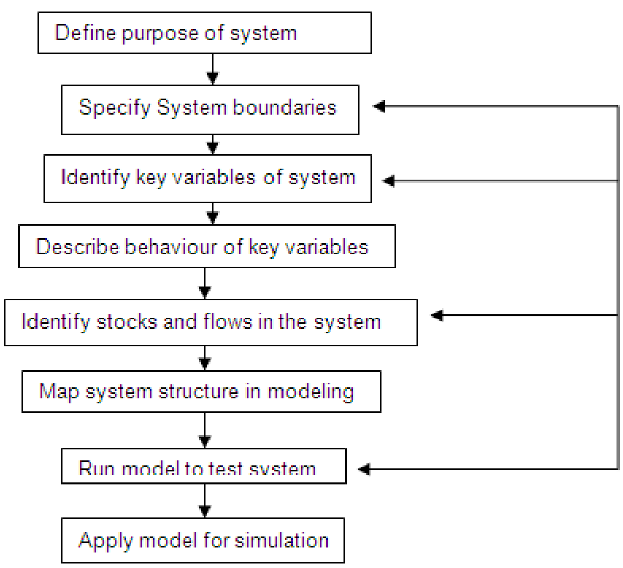


Figure 3. System Dynamics Model Development Life Cycle

- Model Calibration

Calibration is the iterative process of comparing the model to the real system, making adjustments (or) manipulations (or even major) changes to the model, comparing the revised model to reality, making additional adjustments comparing again and so on. The model calibration process can be pictorially represented as in Figure 4.

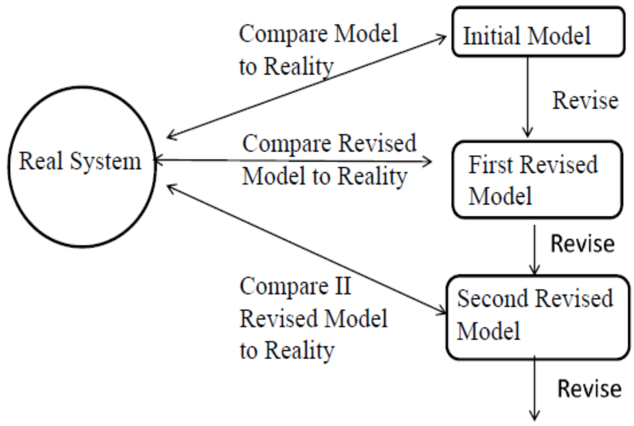


Figure 4. Iterative Process of Calibration of a Model

- Model Validation

Validation is the overall process of comparing the model and its behaviour to the real system and its behaviour. After the model has been calibrated using the original system data set, a "final" validation is conducted using the second system of data set. If unacceptable discrepancies between the model and the real system are discovered in the "final" validation effort, the modeler must return to the calibration phase and modify the model until it becomes acceptable. Validation is not an 'either/or proposition'. No model is ever totally representative of the system under study. (Banks and Carson 1996)

6. Methodology

The methodology for the model development and analysis of the same has been provided in the form of a flow chart in Figure 5. Carrying out a review of various literatures in the study area is the initial work required. Based on the review, a methodology to analyze the work to be carried out has been figured. The need for study and the primary objectives to be fulfilled have been established as given in the earlier chapters. The analysis starts with the data collection required for the study. As far as this study is concerned, the data required is only secondary data which has been collected from various journals and reports pertaining to the data. After the model conceptualization has been carried out, model building, analysis and testing the model for various scenario options has been carried out. Based on the results obtained suitable recommendations for policy options have been given.

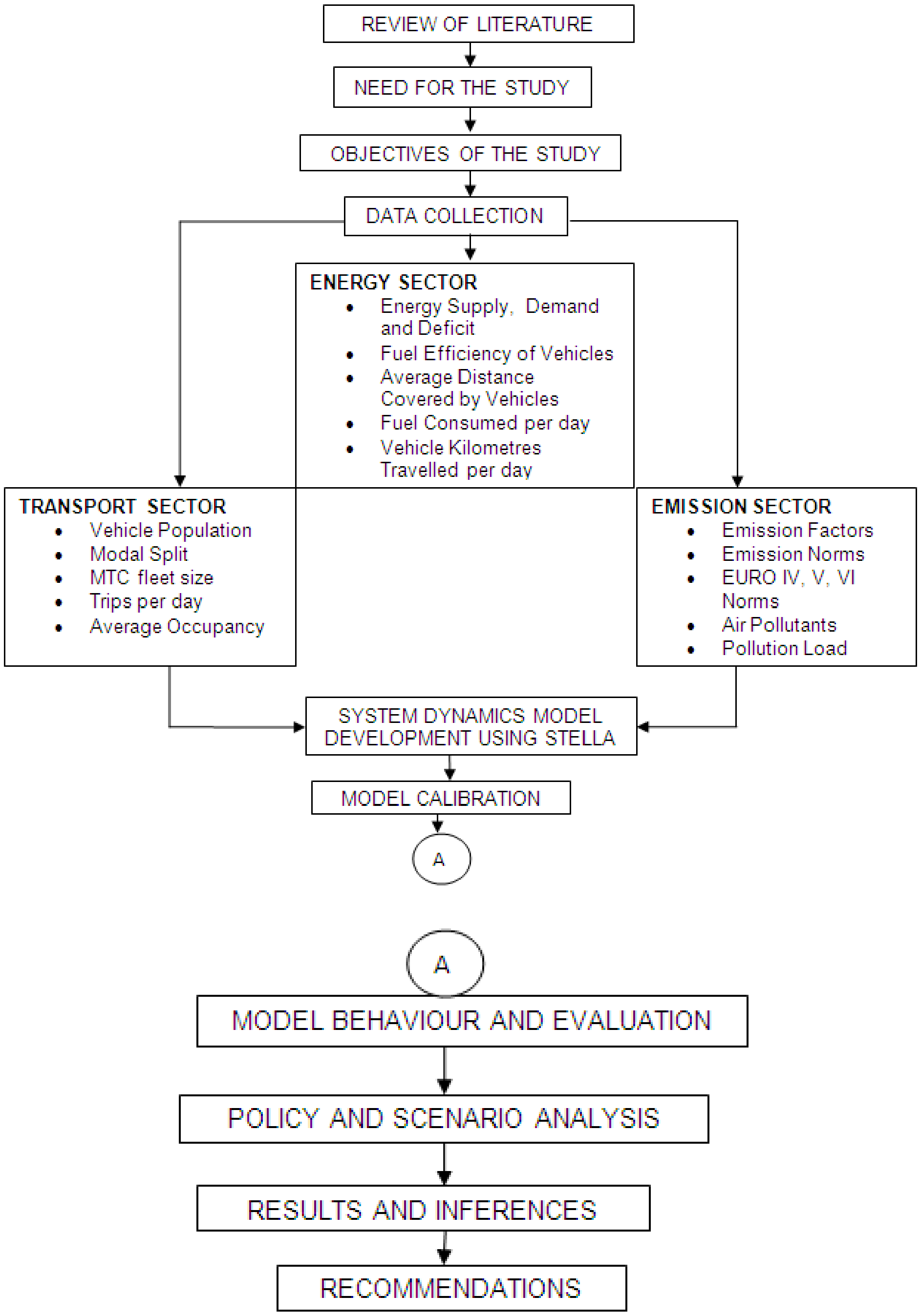


Figure 5. Study Methodology for SD Model Development

7. Description of Study Area

The area selected for study is Chennai city as shown in Figure 6. Chennai is the fourth most populous metropolitan area and the sixth most populous city in India. The Chennai Metropolitan Area (CMA) is spread over an area of 1,189 km^2 (459 sq mi) which consists of Chennai city (174 km^2) and parts of Thiruvallur and Kanchipuram districts. Chennai city is governed by the Chennai Corporation which was established in 1688 and is the oldest municipal corporation in India. In 2011, the jurisdiction of the Chennai Corporation was expanded from 174 km^2 (67 sq mi) to an area of 426 km^2 (164 sq mi).

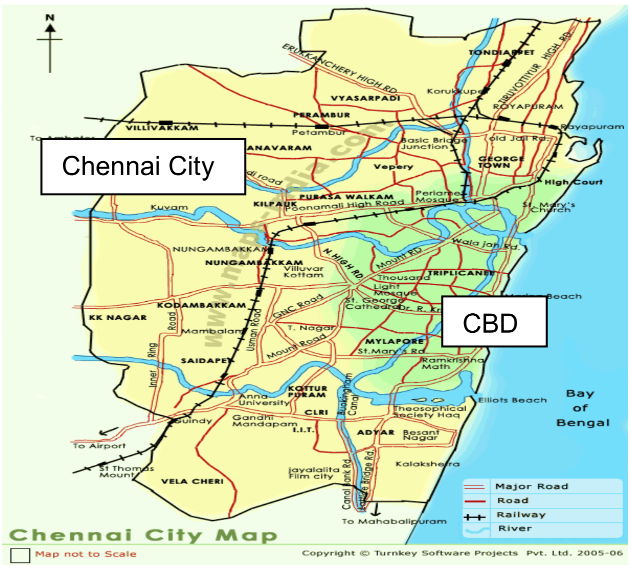


Figure 6. Map of the Study Area – Chennai City

The sectors under consideration for this study are Population, Transport (Trips), Energy and Emission (Vehicular emissions). In spite of the recent expansion of the city, the revised data for the above sectors are not yet available for the new jurisdiction. All the data pertaining to this study were available only for the old city and hence this study is limited to the older Chennai city with an area of 174km^2.

As of 2011, Chennai Metropolitan Area (CMA) had a population of 7.34 million and Chennai city had a population of 4.68 million within the area administered by the Chennai Corporation. According to the Transport Department's official report, the city's total vehicle population had zoomed to 32 lakhs from a mere 8 lakhs barely 12 years ago. Car and two-wheeler ownership in Chennai per 1000 population is 45 and 181 respectively. The two-wheeler population of the city shot up to 2.58 million in 2011 from 0.93 million in 2001 while the number of four-wheelers jumped to 0.56 million in 2011 from 0.21 million in 2001.

The alarming rise in the vehicular population has a greater impact on the Petrol and Diesel consumption of the city. Chennai city's total fuel requirement per day is 4,600 kilolitres per day with 2,100 kilolitres of petrol and 2,500 litres of diesel. This increase in vehicular population and its fuel consumption have resulted in increased emissions into the air making Air pollution as a matter of major concern in Chennai. Tamil Nadu Pollution Control Board (TNPCB) has identified the major contribution to air pollution load in Chennai as Vehicular sector (71.28%) followed by Industrial sector (19.70%). City's pollution level is thrice that of what the World Health Organisation permits and has serious health impacts on the resident population. Hence it is imperative to analyze the impact of the increase in population and transport sector on the energy usage and vehicular air pollution of the city through a System Dynamics approach.

8. Data Collection and Analysis

8.1. Population Sector

In this sector, population of the base year, birth rate, death rate, in migration and out migration is the variables which have been considered. Birth and death rates are the factors useful to estimate the future population in the area. Total birth and death rates are increasing from decade to decade but their rates decreasing. The registered birth rate in Chennai City segment was 24.06 in 1991 and reduced to 22.62 in the year 2003. The death rate also declined from 9.20 in 1981 to 8.01 in 2003. However, net natural increase in population had been decreasing from year to year from 22.00 in 1981 to 14.61 in 2003.

The long-term demographic goal as laid down in the 'National Health Policy- 1983' is to achieve a reproduction rate of unity i.e. Net Reproduction Rate (NRR) equal to one by the year 2000 A.D. this corresponds to achieving a birth rate of 21 per 1000 population, death rate of 9 per 1000 population and annual natural population growth rate of 1.2 percent. But the Eighth Five-year plan envisaged that NRR of one would be achievable only during the period 2011 to 2016 A.D. for the whole nation. Surprisingly, the state of Tamil Nadu achieved this target by the year 1991 itself i.e. 10 year ahead of the projected period. This is mainly due to dynamism in demographic situation revealed by the 1991 census rather than stagnation. The 1991 census data confirm that the dramatic fall in birth rates in Kerala and Tamil Nadu and stagnation in Maharashtra. The primary factors for such a dramatic fall are the age structure of the population, the average age at marriage, incidence of family planning and the psychological feeling of socio-economic security. The average age of marriage in Tamil Nadu is 25.4 years for males and 16.2 years for females. The observed reasons for the higher age of marriage are higher literacy rate and better socio-economic conditions in Tamil Nadu than in most parts of India.

Tamil Nadu has also achieved a low level of Total Fertility Rate (TFR) as 2.2. Part of the reason can be traced to the strong political will for small family, success of family planning programme and efficiency of the official bureaucracy of the state. The state Family Planning Council for Tamil Nadu projects that the Crude Birth Rate (CBR) of Tamil Nadu is likely to decline from the current level of 21 to 15 per 1000 population by the year 2000 and 10 per 1000 population by 2010.

According to 2001 census, migrants to Chennai city from other parts of Tamil Nadu State constitute 74.5 percent. The growth of immigrant population shows a declining trend from 36.80 percent in 1961 to 21.57 percent in 2001. Migrants from other parts of India constitute 23.8 percent and the remaining 1.71 percent of the migrants is from other countries. The migration detail for the Chennai city segment has been presented in Table 1.

The Composition of Population Growth for the Chennai city segment has been presented in Table 2.

8.2. Transport Sector

With respect to the transport sector, the data which are of prime concern are vehicle population and the existing Modal Split in the city which have been obtained from the Second Master Plan for Chennai, CMDA report. The modal split between public and private transport trips in the city was 35:65 in the year 2004 which has been projected to reach 55:45 in 2011, 60:40 in 2016 and 70:30 in 2026. The vehicle population in Chennai city as on the month of April between the years 2006 to 2011 were collected from the Statistics of Transport Department, Chennai which gives the data regarding the total number of commercial and non-commercial vehicles in the city and the data considered for this study have been given in Table 3. Data pertaining to the total no. of trips per day made by the public transportation system comprising the Bus and the Rail system were also obtained from the Second Master Plan for Chennai. The MTC buses with a fleet size of around 3500 buses cater to 36 lakhs trips/day and the train services comprising of three Sub-Urban routes and MRTS route cater to 3 lakh commuter trips per day. The sub modal split between bus and rail was 91:9 in the year 2005 which has been projected to reach 75:25 in 2011, 70:30 in 2016, 65:35 in 2021 and 60:40 in 2026. These projected values have been considered for various scenario analyses.

8.3. Energy Sector

With respect to the Energy sector the fuels which were of prime concern were Petrol and Diesel. Hence data pertaining to the fuel consumption per day by Petrol and Diesel driven vehicles have been collected from earlier studies and presented in the Table 4 and the respective Fuel Efficiency values have been used in the model analysis.

8.4. Emissions Sector

An inventory regarding the GHGs and Other Urban Pollutants from Transport Sector were collected from earlier studies. Emission factors for trace gas emissions viz. CO, CO_2, NOx, Hydrocarbon (HC), Particulate matter (PM) from various classes of vehicles have been identified and presented in Table 5.

Table 1. Migration to Chennai City (in lakhs)

Year	Total Population	Total Migration in the City from							Percent of Total Migrants in the Total Population
		Other Parts of Tamil Nadu		Other Parts of India		Other Countries		Total	
		No.	Percent	No.	Percent	No.	Percent		
1961	17.49	4.47	69.45	1.71	26.6	0.25	3.90	6.44	36.80
1971	26.42	5.51	70.61	2.00	25.63	0.29	3.76	7.80	29.52
1981	32.84	7.19	71.28	2.55	25.31	0.34	3.41	10.08	30.70
1991	38.43	6.44	70.51	2.42	26.47	0.28	3.01	9.18	23.90
2001	43.43	6.98	74.49	2.23	23.80	0.16	1.71	9.37	21.57

Source: www.cmdachennai.gov.in

Table 2. Composition of Growth in Chennai City

1	Population in the reference year	32,84,622 (in 1981)	38,43,195 (in 1991)
2	Natural increase	6,40,370 (1981-91)	5,82,745 (1991-01)
3	Immigration	9,18,298 (1981-91)	9,37,111 (1991-01)
4	Jurisdiction change	-(1981-91)	-(1991-01)
5	Sum of (1) to (4) above	48,43,290	53,63,051
6	Population in the next reference year	38,43,195 (1991)	43,43,645 (2001)
7	Net increase in population	5,58,573 (1981-91)	5,00,450 (1991-01)
8	Outmigration (Arrived)	10,00,085 (1981-91)	10,19,406 (1991-01)

Source: www.cmdachennai.gov.in

Table 3. Vehicle Population in Chennai City in the years 2006-2011

VEHICLES/ YEAR	2006	2007	2008	2009	2010	2011	% Comp
Public Transport							
Buses	2803	3084	3260	3280	3421	3464	0.11
IPT Vehicles							
Auto Rickshaw	41316	39330	51113	44973	49062	63640	2.00
Taxi	283	284	1165	1252	1259	1268	
Other Vehicles							
Private Bus	883	926	2376	874	2702	2906	0.16
Mini Bus	902	961	1709	1129	2095	2217	
Personal Modes (in lakhs)							
Motor cycles	6.72	7.86	8.96	10.41	13.71	15.63	97.73
Scooters	2.86	2.98	3.12	3.20	3.33	4.03	
Mopeds	4.69	4.76	4.82	4.90	4.97	6.15	
Two Wheelers	14.27	15.60	16.90	18.51	22.01	25.81	
Cars	3.35	3.66	4.00	4.41	4.82	5.80	
Total (in lakhs)	18.08	19.71	21.5	23.43	27.41	32.34	100

Source : www.tn.gov.in

Table 4. Average Fuel Consumption By Different Classes of Vehicles

Type of Vehicle	Average Distance Covered (km/day)	Fuel Efficiency (km/l)	Fuel Consumed (Litres/veh/year)
Two Wheelers	18	53	124
Three Wheelers	96	21 (Petrol)	1669
Cars	22	13.5 (Petrol) 14.0 (Diesel)	593 571
Mini Bus (Diesel)	22	8.7	897
Bus	151	4.1(Diesel)	13415

Source: Report of the Expert Group, Government of India Report, February 2010

Table 5. Emission Factors for Trace Gas Emissions from Vehicles (g/km)

Pollutant/ Vehicle Type	Bus	Omni Bus	Two Wheelers	Auto Rickshaw	Cars	Taxi
CO_2	515.2	515.2	26.6	60.3	223.6	208.3
CO	3.6	3.6	2.2	5.1	1.98	0.9
NO_X	12	12	0.19	1.28	0.2	0.5
CH_4	0.09	0.09	0.18	0.18	0.17	0.01
SO_2	1.42	1.42	0.013	0.029	0.053	10.3
PM	0.56	0.56	0.05	0.2	0.03	0.07
HC	0.87	0.87	1.42	0.14	0.25	0.13

Source : Ramachandra and Shwetmala (2009)

Also the data regarding the Bharat Stage (BS) emission norms prevailing in the country have been collected. Bharat Stage Emission Standards are emission standards instituted by Government of India to regulate the output of air pollutants from internal combustion engine equipments including motor vehicles. The standards and the timeline for implementation are set by the Central Pollution Control Board under the Ministry of Environment & Forests. All new vehicles manufactured after the implementation of the norms have to be compliant with the regulations. Since October 2010, Bharat stage III norms have been enforced across the country. Bharat stage IV emission norms are in place in 14 major cities which include Delhi, Mumbai, Kolkata, Chennai, Bangalore, Hyderabad, Secunderabad, Ahmedabad, Pune, Surat, Kanpur, Sholapur, Lucknow and Agra since April 2010. An overview of various emission norms adopted in

India over the years has been presented in the Table 6.

The emission norms applicable to Passenger Cars using both Petrol and Diesel have been presented in the Table 7.

Emission standards applicable for 2- and 3-wheel vehicles running on Petrol and Diesel are listed in the following Table 8.

India may opt for Euro VI emission levels in 2017, skipping Euro V. As of now, Euro IV emission levels are applicable in 13 major cities of India and rest of the country has Euro III norms. The environment ministry has recommended to the Government that India should directly opt for Euro VI norms, which would be applicable in Europe by 2015, instead of Euro V, applicable in Europe since September 2010. There is not much difference between Euro V and Euro VI, except for emission levels for Respirable Suspended Particulate Matter (RSPM). In Euro VI, emission level for RSPM for passenger vehicles is half of that in Euro V norms i.e. the level of RSPM is 0.025 in EURO IV which has reduced to 0.0025g/km in EURO VI.

Table 6. Indian Emission Standards (4-Wheel Vehicles)

India	Europe	Implementation	
		Year	Region
India 2000	Euro 1	2000	Nationwide
Bharat Stage II	Euro 2	2001	NCR*, Mumbai, Kolkata, Chennai
		2003.04	NCR*, 13Cities†
		2005.04	Nationwide
Bharat Stage III	Euro 3	2005.04	NCR*, 13 Cities†
		2010.04	Nationwide
Bharat Stage IV	Euro 4	2010.04	NCR*, 13 Cities†

* National Capital Region (Delhi)

† Mumbai, Kolkata, Chennai, Bangalore, Hyderabad, Secunderabad, Ahmedabad, Pune, Surat, Kanpur, Sholapur, Lucknow and Agra

Source: http://www.dieselnet.com/standards/in/

Table 7. Emission Standards for Light-Duty Vehicles, g/km

Year	Reference	CO	HC	HC+NO_x	NO_x	PM
Diesel						
1992	-	17.3-32.6	2.7-3.7	-	-	-
1996	-	5.0-9.0	-	2.0-4.0	-	-
2000	Euro 1	2.72-6.90	-	0.97-1.70	-	0.14-0.25
2005†	Euro 2	1.0-1.5	-	0.7-1.2	-	0.08-0.17
2010†	Euro 3	0.64 0.80 0.95	-	0.56 0.72 0.86	0.50 0.65 0.78	0.05 0.07 0.10
2010‡	Euro 4	0.50 0.63 0.74	-	0.30 0.39 0.46	0.25 0.33 0.39	0.025 0.04 0.06
Petrol						
1991	-	14.3-27.1	2.0-2.9	-	-	-
1996	-	8.68-12.4	-	3.00-4.36	-	-
1998*	-	4.34-6.20	-	1.50-2.18	-	-
2000	Euro 1	2.72-6.90	-	0.97-1.70	-	-
2005†	Euro 2	2.2-5.0	-	0.5-0.7	-	-
2010†	Euro 3	2.3 4.17 5.22	0.20 0.25 0.29	-	0.15 0.18 0.21	-
2010‡	Euro 4	1.0 1.81 2.27	0.1 0.13 0.16	-	0.08 0.10 0.11	-

* for catalytic converter fitted vehicles

† earlier introduction in selected regions

‡ only in selected regions

Source: http://www.dieselnet.com/standards/in/

Table 8. Emission Standards for 2- And 3-Wheel Vehicles, g/km

Year	Standard	CO	HC	HC+NOx	PM
2-Wheel Petrol Vehicles					
1991		12-30	8-12	-	-
1996		4.50	-	3.60	-
2000		2.00	-	2.00	-
2005.04	BS II	1.5	-	1.5	-
2010.04	BS III	1.0	-	1.0	-
3-Wheel Petrol Vehicles					
1991		12-30	8-12	-	-
1996		6.75	-	5.40	-
2000		4.00	-	2.00	-
2005.04	BS II	2.25	-	2.00	-
2010.04	BS III	1.25	-	1.25	-
2- And 3-Wheel Diesel Vehicles					
2005.04	BS II	1.00	-	0.85	0.10
2010.04	BS III	0.50	-	0.50	0.05

Source: http://www.dieselnet.com/standards/in/

9. Model Development

9.1. Population Sector

After the identification of key variables, the model for the population sector has been developed based on the causal loop diagram. The System Dynamics model for Chennai City segment population sector is shown in Figure 7. The various parameters considered for building the population sector model are as follows:

POP - Total Population
BR - Birth rate
DR - Death Rate
IMR - In Migration rate
OMR - Out Migration rate
BN - Birth Normal
DN - Death Normal
IMN - In Migration Normal
OMN - Out Migration Normal

In this sector, Population of the Base Year, Birth Rate, Death Rate, In Migration and Outmigration are considered. The size of the population is influenced by both the net birth rate and net migration rate. The net birth rate equals the total number of births per year minus the total number of deaths. Similarly, the net migration rate equals the number of in-migrants minus the number of out migrants. However, the number of births and deaths as well as net in-migrants can be defined as a yearly percentage of the population. Hence, the population model contains one level and four rates as stated below:

$$\text{Population}(t) = \text{Population}(t-dt) + (\text{Birth\_Rate} + \text{Immigration\_Rate} - \text{Death\_Rate} - \text{Out\_Migration\_Rate}) * dt$$

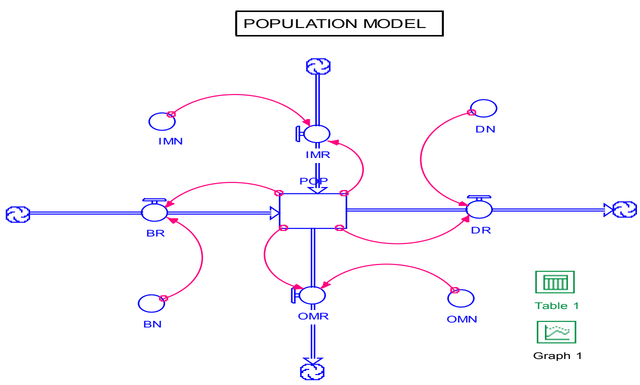


Figure 7. Population Model for Chennai City

Chennai City segment population is the level variable. The level is influenced by the Birth Rate, Death Rate, In-Migration and Out-Migration rate.

Chennai city segment base year population is taken as 43.43 lakhs persons as per 2001 census. The Birth Rate is influenced by the number of births per 1000 Population, Birth Rate Normal and Initial Population. Birth Rate is determined by multiplying the Birth Rate Normal by the population. Birth Rate Normal is expressed in terms of number of births per 1000 of the population. It is taken as 22 per 1000 population as per 2001 census data (CMDA, 2012) and expected to reduce to a value of 10 per 1000 by 2026, based on previous trend and health policy of the government (in 2016). Death rate normal is defined as the number of deaths for every 1000 population. It is considered to be 8 per 1000 population as per 2001 census data (CMDA, 2012) and expected to reduce to a value of 6 per 1000 by 2026.

In Chennai City segment the total migrant population coming from rural and other parts of urban areas was 9.37 lakhs per year during 1991-2001, whereas it was 9.18 lakhs during 1981-1991. This implied that 9.37 lakh people migrated to Chennai city segment every year, accounting for 2.15 percent of the total Chennai city segment population. Similarly Out-migration from Chennai City segment to CMA segment is found to be 1.01 lakh per year during 1991-01, whereas it was 1.00 lakh during 1981-91. Similarly this implied that 1.01 lakh people migrated from Chennai city to its suburbs and other areas within CMA every year, accounting for 2.34 percent of the total Chennai city population.

The graphical output from the Population Sector model has been given in Figure 8 which shows a declining trend in Birth and Death rates in accordance with the health policy of the Government.

9.2. Transport and Energy Sector

Based on the causal loop diagram the System Dynamics model addressing the interactions between transport and energy sector has been developed which is given in Figure 9. The various parameters considered for building of transport sector model are as follows:

TOT - Total Vehicle Population
GR - Vehicle growth rate
ADT - Average distance travelled by the vehicle per day
FE - Fuel efficiency of the vehicle
FC - Total fuel consumed by the vehicle

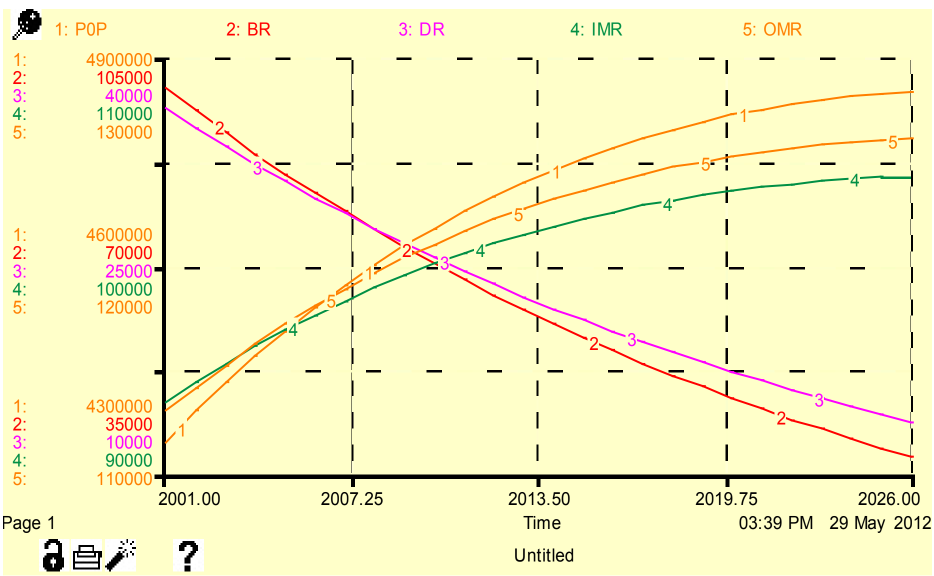
The following vehicles were considered under various sectors for the study. The major sectors taken into account were Public transport vehicles (Bus), IPT vehicles (Auto Rickshaw and Taxi), Personalised vehicles (Two Wheelers and Cars) and Other Vehicles Sector (Private Bus and Mini Bus). The vehicle growth is assumed from the past trend. Using the values of Average Distance travelled per day and Fuel Efficiency in km/litre and the projected values of vehicle population, the final value of Fuel consumption has been determined. In this study, the total trips made by Rail contributing to Public Transport sector have been analyzed. Sub-Urban rail system within the city operates on electricity and hence is devoid of emissions. The demand of electricity by rail sector has not been accounted in this research.

9.3. Emissions Sector

Based on the causal loop diagram the System Dynamics model for Chennai City segment Emission Sector has been developed. The model developed for Bus transport sector has been given in Figure 10.

The various parameters considered for building the emission sector model are as follows:

TOT - Total Vehicle Population
ADT - Average distance travelled by the vehicle per day
VKT - Vehicle Kilometres Travelled by the vehicle per day
CO, CO_2, PM, NO_x
SO_2, CH_4, HC - Emissions per km travelled (in g)



POP - Population BR - Birth rate DR - Death rate
IMR - In Migration rate OMR - Out Migration rate

Figure 8. Population Growth Trend (2001-2026)

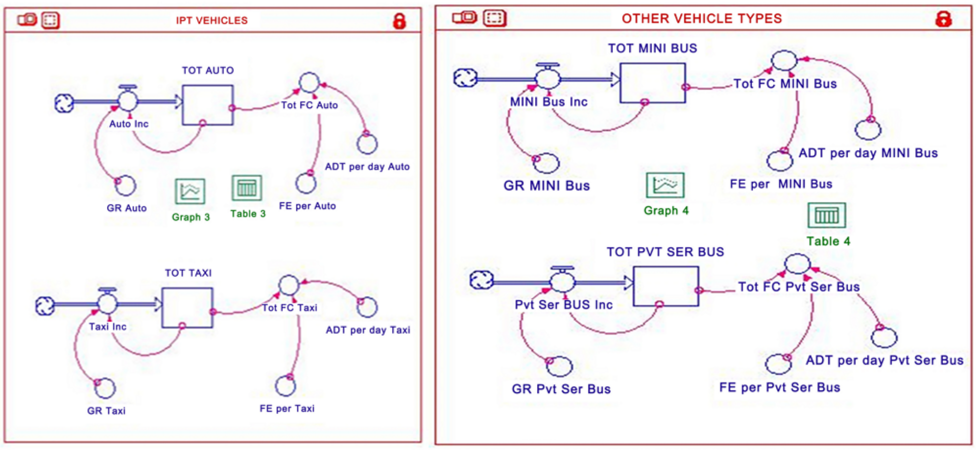


Figure 9. Model Representation for Transport sector

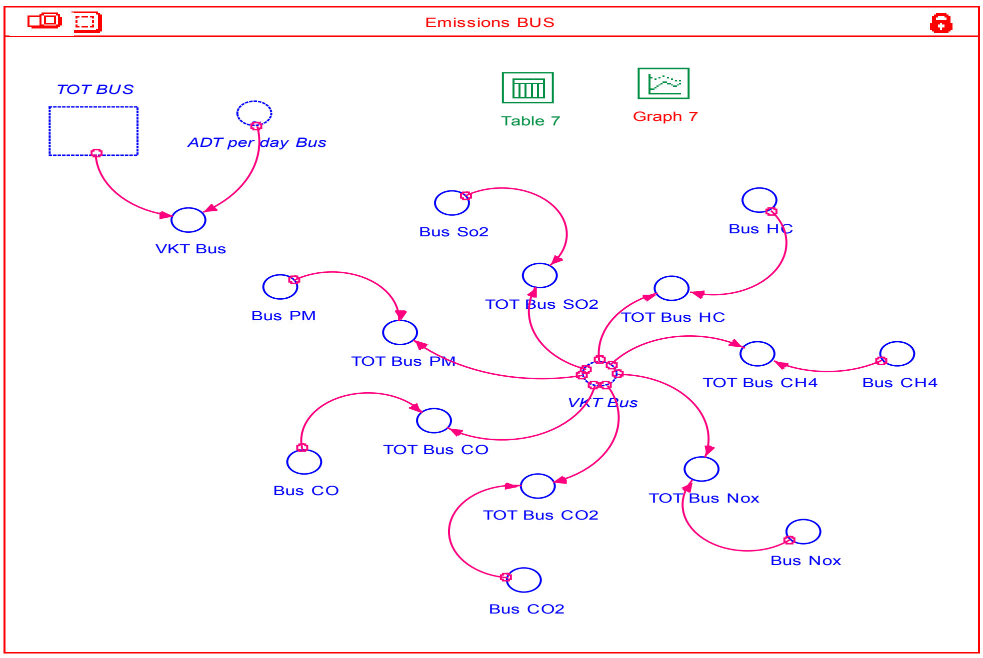


Figure 10. Model Representation for Emissions Sector(Bus Sector)

10. Scenario Analysis and Model Results

In the Do Minimum scenario, the existing trend of growth rates of MTC buses, Two Wheelers, Cars, IPT vehicles and Mini bus has been allowed to continue till the year 2026. Also the Modal Split between Public and Private Transport has been taken as 30:70 and the Sub Modal Split between Road and Rail has been simulated such that it changes from 91:9 to 88:12. Based on the existing growth rate, the amount of fuel consumed by each transport sector and the corresponding emission levels have been simulated. The result showed that the share of Public Transport trips amounts to only 18% whereas the trips by Personalised Vehicles constitute the major share of 80%. This has been shown in the Table 9.

In accordance with the increase in number of vehicles, the fuel consumed by each modes of transport also increases. The demand for petrol and diesel by personalised modes reaches to a maximum of around 35 lakhs litres per day and 12 lakhs litres per day in the year 2026. Similar amount of increase has been observed in other vehicle modes too. The fuel consumed by each vehicle type per day has been given in the following Table 10.

The increase in fuel consumption has concomitant increase in the level of emissions by the vehicles. The quantity of air pollutants in Kilogram per day emitted by each vehicle type in the horizon year (2026) has been given in the following Table 11.

10.1. Results of Scenario II

In the Partial Efforts scenario (Scenario II), simulation has been carried out such that minimal efforts are undertaken by the government to achieve a Modal Split of 50:50 between Public and Private Mode and a Sub-Modal Split of 70:30 between Road and Rail transport. In order to facilitate the above condition, the Public transport has been augmented in a phase wise manner to reach a growth rate of 17% by 2026 and simultaneously the growth rate of Two Wheelers and Cars have been restricted to almost half of the existing value i.e. 3% and 3.5% respectively in 2026. The hypothesis considered is that one bus will replace 19 cars and 38 two wheelers. On comparison with Scenario I, a remarkable decrease of 47% and 41% could be observed in Scenario II with regard to the trips made by cars and two wheelers. This decrease leads to a modal split value of 50:50 between public and private modes of travel as depicted in the Table 12.

Table 9. Results of Scenario I – Share of Trips by Modes (%)

Year	Public Transport			Personalised Vehicles Share	Other Trips Share	IPT Share
	Bus Share	Rail share	Total Public Share			
2006	91	09	32	64	1	2
2011	91	09	28	69	1	2
2016	91	09	24	73	1	2
2021	90	10	21	77	1	1
2026	88	12	18	80	1	1

Table 10. Results of Scenario I –Fuel Consumed (litres per day)

Year	Bus	Auto	Taxi	Private Bus	Mini Bus	Diesel Cars	Petrol Cars	TW
	(in lakhs)					(in lakhs)		
2006	2.02	1.88	445	32520	2281	2.90	2.46	4.83
2011	2.28	2.29	467	35905	2518	4.16	3.53	7.27
2016	2.90	2.79	491	39642	2780	5.98	5.07	10.93
2021	3.49	3.40	516	43768	3070	8.59	7.28	16.44
2026	4.20	4.13	543	48323	3389	12.33	10.46	24.72

Table 11. Results of Scenario I – Emissions Sector: Total Emissions in the Horizon Year 2026 (Kg/ day)

Pollutant	CH_4	CO	CO_2 (in lakhs)	HC	NO_x	PM	SO_2
Bus	166	6658	9.52	1609	22,194	1035	2626
Auto	1564	44,323	5.24	1217	11,124	1738	252
Taxi	1	7	0.01	2	4	1	78
Car	5337	62160	70.19	7848	6279	942	1664
TW	23,636	2,88,888	34.92	1,86,464	24,949	6566	1707

Table 12. Results of Scenario II – Share of Trips by Modes (%)

Year	Public Transport			Personalised Vehicles Share	Other Trips share	IPT Share
	Bus Share	Rail share	Total Public Share			
2006	91	9	32	64	2	2
2011	89	11	29	68	1	2
2016	83	17	28	69	1	2
2021	76	24	33	65	1	1
2026	70	30	48	50	1	1

The decrease in total number of Two Wheelers and Cars shows a corresponding decrease in Fuel consumption as shown in Table 13. The total fuel consumed by Two wheelers is 14.63 lakhs litres per day which is 40% lesser than the fuel consumption in Do Minimum scenario. Also, a reduction of 45% and 47% is observed in Fuel consumed by Petrol and Diesel driven cars respectively.

Table 13. Results of Scenario II – Energy sector Fuel Consumed (in lakhs litres per day)

Year	Bus	Diesel Cars	Petrol Cars	TW
2006	2.02	2.90	2.46	4.83
2011	2.28	3.89	3.30	7.14
2016	2.96	4.98	4.23	9.84
2021	4.21	6.01	5.10	12.62
2026	7.84	6.44	5.46	14.63

The decrease in fuel consumption shows a corresponding decrease in the vehicular emissions. Total CO_2 emitted from the two wheelers has reduced to nearly 40% when compared to the Do Minimum condition. The total emissions from all the vehicle modes have been presented in the Table 14.

From the results it could be found that the emission levels from MTC buses have increased. But taking into account the value of emissions per person travelled in Bus with that of a car and two wheeler, emissions from the former is much lesser than that from the latter. A comparison between Scenarios I and II has been provided in Table 15.

10.2. Results of Scenario III

In this scenario, the policy of Government to achieve a modal split of 70:30 between public and private mode and the sub-modal split of 60:40 between Road and Rail has been achieved. Public transport has been augmented in a phase wise manner and simultaneously the growth of two wheelers and cars have been restricted to 0.5% and 2% respectively in 2026. The hypothesis considered is that one bus will replace 19 cars and 38 two wheelers. The growth rate of trips by Rail has been assumed to reach 21% in the year 2026. This increase can be attributed to the introduction of Metro and Mono rail in the city and a maximum utilisation of its services. The trend of change in share of trips between public and personalised modes of travel to the proportion of 70:30 can be observed in the results given in Table 16.

Table 14. Results of Scenario II – Emissions Sector Total Emissions in the Horizon Year 2026 (Kg/ day)

Pollutants	CH4	CO	CO2	HC	NOx	PM	SO2
Bus	310	12421	1777634	30011	41404	1932	4899
Car	2789	32489	3669010	4102	3281	492	869
TW	13989	170984	2067363	110362	14766	3886	1010

Table 15. Comparison of Scenarios I and II – Total vehicles and Fuel Consumed (FC) in 2026

Sector	Scenario I			Scenario II			% Inc/ Dec In FC
	Total Vehicles	FC	Share of Trips %	Total Vehicles	FC	Share of Trips %	
Public (Bus)	5853	4.2	18	2803	7.84	48	(+) 86
Auto	90528	4.13	1	90528	4.13	1	0
Taxi	345	543		345	543		0
Cars* (Petrol)	6.42	10.46	80	3.35	5.46	50	(-) 48
Cars* (Diesel)	7.84	12.33		4.10	6.44		(-) 47
TW*	72.95	24.72		43.17	14.63		(-) 41
Mini bus	1340	3389	1	1340	3389	1	0
Private Bus	1312	48323		1312	48323		0

Note: * in lakhs, Fuel Consumption (FC) values in litres per day

Table 16. Results of Scenario III – Share of Trips by Modes (%)

Year	Public Transport			Personalised Vehicles Share	Other Trips share	IPT Share
	Bus Share	Rail share	Total Public Share			
2006	91	9	32	64	2	2
2011	89	11	29	68	1	2
2016	77	23	30	67	1	2
2021	65	35	43	55	1	1
2026	60	40	68	30	1	1

With the decrease in the vehicle population, the Fuel Consumed by personalised vehicles has been found to decrease as shown in the Table 17.

Table 17. Results of Scenario III – Fuel Consumed (in lakhs litres per day)

Year	Bus	Diesel Cars	Petrol Cars	TW
2006	2.02	2.90	2.46	4.83
2011	2.28	3.89	3.30	7.18
2016	3.00	4.92	4.17	10.05
2021	5.28	5.43	4.61	12.39
2026	13.57	4.25	3.61	12.33

Demand of Petrol by Two wheelers and Cars is 12.33 and 3.61 lakhs litres per day respectively and the Diesel requirement is 4.25 lakh litres per day in Diesel driven cars. This implies a reduction of 34% in the demand for Diesel, 33% in Petrol cars and 12% in Two Wheelers than Scenario II.

The concomitant decrease in emission levels of air pollutants from personalised modes of travel can be observed in Table 18. Emission level of CO_2 from Two wheelers has reduced to about 50% and 40% when compared with Scenario I and Scenario II respectively.

An increase in the emission levels from MTC buses could be observed in this scenario. But taking into account the value of emissions per person travelled in Bus with that of a Car and Two Wheeler, emissions from the former is much lesser than that from the latter.

A comparison between Scenarios I and III has been provided in Table 19.

Thus from the analysis of Desirable Scenario it has been found that achieving a modal split of 70:30 gives very good results in connection with Fuel Consumption and Emission levels. But an important fact to note at this juncture is that the above mentioned scenario is the most desired one and at the same time the most difficult one to be achieved too. On analysing the results of Scenario II (Partial Efforts Scenario) it could be noticed that it gives pragmatic results when compared to both Scenario I (Do- Minimum) and Scenario III (Desirable Scenario). Hence it could be concluded that even if the desired Modal Split of 70:30 could not be achieved by the government it could strive towards achieving Modal Split of 50:50 thus enhancing the Quality of Life of the people and the environment.

Table 18. Results of Scenario III – Total Emissions in the Horizon Year 2026 (Kg/ day)

Pollutants	CH_4	CO	CO_2	HC	NO_x	PM	SO_2
Bus	538	21503	3077358	5197	71678	3345	8482
Car	1843	21469	2424451	2711	2169	325	575
TW	11787	144069	1741927	92990	12442	3274	851

Table 19. Comparison of scenarios I and III – Total vehicles and Fuel Consumed in 2026

Sector	Scenario I			Scenario III			% Inc/ Dec In FC
	Total Vehicles	FC	Share of Trips (%)	Total Vehicles	FC	Share of Trips (%)	
Bus	5853	4.2	18	18,902	13.57	68	(+) 223
Auto	90528	4.13	1	90528	4.13	1	0
Taxi	345	543		345	543		0
Cars* (Petrol)	6.42	10.46	80	2.21	3.61	30	(-) 65
Cars* (Diesel)	7.84	12.33		2.71	4.25		(-) 65
TW*	72.95	24.72		36.38	12.33		(-) 50
Mini bus	1340	3389	1	1340	3389	1	0
Pvt Bus	1312	48323		1312	48323		0

Note: * in lakhs, Fuel Consumption (FC) values in litres per day

11. Results

11.1. Scenario I – Do Minimum (Allowing the Existing Trend to Continue)

- At the present growth rate of vehicles in Chennai, Public transport would share 18% of the total trips whereas Personalised transport would share 80% of the total trips in the year 2026. This implies that the policy set by the government in achieving a Modal Split of 70-30 with respect to Public and Private transport is highly impossible.
- Fuel Consumed by the personal modes of travel viz. Petrol Driven cars, Diesel driven cars and Two Wheelers are 10.46, 12.33 and 24.72 lakhs litres per day respectively in the year 2026.
- This shows an alarming increase of about 300% to 400% in the fuel consumption by personalised modes of travel which would correspondingly increase the demand for Petrol and diesel.
- With respect to the emissions sector, personalised modes of transport contribute to the major share of pollution in the city amounting to 40% roughly.

11.2. Scenario II – Partial Efforts Scenario (Augmentation of Public Transport and Restricting Growth of Personalised Modes)

- The Modal Split between Public and private modes of travel has been achieved as 50:50 and the sub modal split between Road and the Rail trips has been achieved as 70:30.
- When compared with Do Minimum condition, Fuel consumption in personalised mode of travel is found to reduce by about 48% in the case of Petrol driven cars, 47% in diesel driven cars and by 41% in Two Wheelers.
- A corresponding decrease of about 60% is noted in the Emissions from the personalised vehicles.

11.3. Scenario III – Desirable Scenario (Augmentation of Public Transport and Restricting Growth of Personalised Modes)

- Based on this scenario, the Modal Split between Public and private modes of travel has been achieved as 70:30 and the sub modal split between Road and the Rail trips has been achieved as 60:40.
- This increase in Rail trips can be attributed to the introduction of Metro Rail, Mono Rail and increasing the ridership in MRTS.
- When compared with Do Minimum condition, Fuel consumption in personalised mode of travel is found to reduce by about 65% in the case of Petrol driven cars, 65% in diesel driven cars and by 50% in Two Wheelers. This reduces the load on Petrol and Diesel demand.
- A corresponding decrease of about 60% is noted in the Emissions from the personalised vehicles.
- Though an increase in the emissions from the public transport sector is observed, it is evident that the emission per capita in Public Transport is much lesser than that observed in Personalised vehicles sector.

12. Recommendations

From the study carried out, the following recommendations are given.

- There is an immediate need to restrict the growth of personalised vehicles and augment the public transport. This augmentation can be attributed to increasing the MTC fleet size, introduction of Metro Rail and Mono rail in the city.
- In order to achieve the Modal Split of 70:30, the MTC fleet size should be not lesser than 18,000 with efficient services. Also the Metro rail and Mono Rail services should be implemented on time and operated with maximum efficiency.
- The growth rate of Two Wheelers and Cars should be restricted to 0.05% and 2% respectively implying that the number of vehicles should be contained within 36 lakhs and 4.93 lakhs in the year 2026 to achieve the above mentioned policy of the government.
- This policy leads to a considerable reduction in pollution load of the city making it a place with reduced environmental hazards.
- Since the results of Partial scenario prove to be much better than Do Minimum condition, it is recommended that even if the desired condition of achieving a Modal Split value of 70:30 cannot be done at least the government should strive towards achieving a modal split of 50:50.
- At the same time, since there is no specification for CO_2 emissions from vehicles it is found to be on the rising trend. Hence the government should take needful steps to provide emission standards for CO_2 as well and hence reduce the contribution of CO_2 emissions in the Greenhouse gases.

13. Model Equation / Output (from 'STELLA' Simulation Software)

Scenario I

TOT_AUTO(t) = TOT_AUTO(t - dt) + (Auto_Inc) * dt
INIT TOT_AUTO = 41316
INFLOWS:
Auto_Inc = TOT_AUTO*GR_Auto

TOT_BUS(t) = TOT_BUS(t - dt) + (Bus_Inc) * dt
INIT TOT_BUS = 2803
INFLOWS:
Bus_Inc = TOT_BUS*GR_Bus
TOT_CARS(t) = TOT_CARS(t - dt) + (Car_Inc) * dt
INIT TOT_CARS = 335932
INFLOWS:
Car_Inc = TOT_CARS*GR_Cars
TOT_MINI_BUS(t) = TOT_MINI_BUS(t - dt) + (MINI_Bus_Inc) * dt
INIT TOT_MINI_BUS = 902
INFLOWS:
MINI_Bus_Inc = TOT_MINI_BUS*GR__MINI_Bus
TOT_PVT_SER_BUS(t) = TOT_PVT_SER_BUS(t - dt) + (Pvt_Ser_Bus_Inc) * dt
INIT TOT_PVT_SER_BUS = 883
INFLOWS:
Pvt_Ser_Bus_Inc = TOT_PVT_SER_BUS*GR_Pvt_Ser_Bus
INFLOWS:
TOT_TAXI(t) = TOT_TAXI(t - dt) + (Taxi_Inc) * dt
INIT TOT_TAXI = 283
INFLOWS:
Taxi_Inc = TOT_TAXI*GR_Taxi
ADT_per_day_Auto = 96
ADT_per_day_Bus = 151
ADT_per_day_DC = 22
ADT_per_day_MINI_Bus = 22
ADT_per_day_PC = 22
ADT_per_day_Pvt_Ser_Bus = 151
ADT_per_day_Taxi = 22
ADT_per_day_TW = 18
FE_per_Auto = 34
FE_per_Bus = 4.1
FE_per_DC = 14
FE_per_MINI_Bus = 8.7
FE_per_PC = 13.5
FE_per_Pvt_Ser_Bus = 4.1
FE_per_Taxi = 14
FE_per_TW = 53
GR_Auto = 0.017
GR_Bus = 0.041
GR_Cars = 0.116
GR_Pvt_Ser_Bus = 0.269
GR_Taxi = 0.346
GR__MINI_Bus = 0.2
TOT_DC = 0.55*TOT_CARS
TOT_PC = 0.45*TOT_CARS
TOT_BUS(t) = TOT_BUS(t - dt) + (Bus_Inc) * dt
INIT TOT_BUS = 2803
Bus_Inc = TOT_BUS*GR_Bus
ADT_per_day_Bus = GRAPH(TIME)
(2006, 267), (2008, 267), (2010, 267), (2012, 316), (2014, 316), (2016, 316), (2018, 316), (2020, 316), (2022, 316), (2024, 316), (2026, 316)
FE_per_Bus = GRAPH(TIME)
(2006, 3.70), (2008, 4.00), (2010, 4.20), (2012, 4.40), (2014, 4.40), (2016, 4.40), (2018, 4.40), (2020, 4.40), (2022, 4.40), (2024, 4.40), (2026, 4.40)
Bus_CH4 = 0.09
Bus_CO = 3.6
Bus_CO2 = 515.2
Bus_HC = 0.87
Bus_NOx = 12
Bus_PM = 0.56
Bus_SO2 = 1.42
Auto_CH4 = 0.18
Auto_CO = 5.1
Auto_CO_2 = 60.3
Auto_HC = 0.14
Auto_NOx = 1.28
Auto_SO2 = 0.029
Auto__PM = 0.2
Car_CH4 = 0.17
Car_CO = 1.98
Car_CO_2 = 223.6
Car_HC = 0.25
Car_NOx = 0.2
Car_PM = 0.03
Car_SO2 = 0.053
Mini_Bus_CH4 = 0.09
Mini_Bus_CO = 3.6
Mini_Bus_CO_2 = 515.2
Mini_Bus_HC = 0.87
Mini_Bus_NOx = 12
Mini_Bus_PM = 0.56
Mini_Bus_SO2 = 1.42
Taxi_CH4 = 0.01
Taxi_CO = 0.9
Taxi_CO_2 = 208.3
Taxi_HC = 0.13

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