Integration of on-board diagnostics with system dynamics to study road transport pollution

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ABSTRACT

Pollution caused by road transport is the major source affecting human health and adversely affects global warming. The main causes of transport pollution are the increase in the number of motor vehicles, inadequate public transport and inefficient transport management. Transport pollution is due to poor combustion of vehicular fuels, improper air/fuel mix ratio, harmful emissions of Hydrocarbon (HC), Carbon monoxide (CO) and Oxides of Nitrogen (NOX). In order to control the level of air pollutants, a number of policies have been activated in India. This paper proposes a system dynamics approach to evaluate and compare various scenarios of road transport system using On Board Diagnostic system integrated model in controlling CO level in air, including vehicle to population ratio variation, impact of law enforcement effectiveness, and conducting awareness campaign to use public transport. Based on the results, it was found that implementation of On-Board Diagnostics (OBD) in all private vehicles intervention in terms of law enforcement effectiveness and reducing the number of private vehicles by the implementation of transist incentive policy to adopt public transport proved to be efficient in reducing the CO level in air to a great extent.

Keywords: On-board diagnostics, carbon monoxide, system dynamics, vehicular pollution, transport policies.

1. Introduction

In India, there are many control measures and transport policies in practice for mitigating vehicular pollution. But they are found to be inadequate and ineffective due to the tremendous increase in the number of motor vehicles. The increase in vehicular congestion due to increase in the number of vehicles, has become the main source of air pollution in urban India. The vehicular emissions have damaging impacts on both human health and ecology. Therefore, the objective of this paper is too forecast the CO level in air due to vehicular emission represented interms of g/km² unit. In addition, this study also evaluate the proposed policy scenarios that can minimize the CO level in air.

As highlighted by (Faiz & Sturm 2000), the major environmental problems are urban air pollution and road traffic. (Sturm, 2000) has indicated that transport is one of the main source of air pollution. According to (Fenger, 1999), air pollutant concentrations are dominated by the exhaust emissions of carbon monoxide, oxides of nitrogen and suspended particles from the usage of vehicles in mega cities. The author estimated that the contribution of transport
sector as 72% towards the increase of vehicular pollution (Goyal et al 2005). The discharge of motor vehicular carbon monoxide in Lahore is due to mass transit system which is because of frequent stoppages, entering and exit in flow of traffic (Amer 2007 and Ojo 2012). Traffic exhaust emission is one of the most important air pollution sources in urban areas (Xia & Leslie 2004). The previous studies by (Vizayakumar & Mohapatra 1993), (Mashayekhi,1993) and (Karavezyris et al 2002) have reported that the System Dynamics (SD) approach has also been applied to many of the studies related to the environment, environmental impact assessment analysis and solid waste management.

(Naill et al 1992) have stated that the system dynamic methodology is used for analysis of greenhouse gas emissions and global warming. (Stepp et al 2009) have considered both the direct responses associated with policy actions, and the indirect responses that occur through complex relationships within socioeconomic systems. The authors have utilized system dynamics tools (in particular causal loop diagrams) to identify and understand the role of feedback effects on transportation-related Green Houses Gases (GHG) reduction policies.

(Azhaginiyal & Umadevi 2014) have built a system dynamic model that would address transport, energy and emission interactions and test the same for various policy and scenario options. (Kongbootinam & Udomsri 2011) have used system dynamics model to forecast the energy consumption and pollutant emission from the road transportation and to evaluate the policies in transportation management. (Shalini Anand et al 2005) have adopted the system dynamics methodologies for assessment and mitigation of CO₂ emissions from the cement industry in India. The projections of cement production are considered to be mainly influenced by the population growth, the gross domestic product increment rate and technologies employed in the cement industry. (Verma, 2004) has stated that to curtail the emission levels in Delhi’s urban transport system, a system dynamics model was used.

(Ford, 2007) has stated that Global warming has emerged as the dominant environmental problem of our time. The next fifty years will be a period of growing accumulation of greenhouse gases (GHG) in the atmosphere and in rising temperatures. It could also be a period in which all the nations of the world adopt more stringent policies to control the emissions of carbon dioxide (CO₂) and other GHG. If emissions are cut sufficiently, it is possible to stabilize GHG within the first half of this century. The risks of global warming could be reduced but not eliminated.

The scope of the work involved:

1. Taking into account the population growth and growth of private vehicles and predicting the CO level in air in the city of Chennai (India) for 60 months.
2. Evaluating different control options and identifying the most sensitive option which would give a drastic reduction in the concentration levels of CO in air.
3. Facilitating the policy makers to formulate a policy to allow feasible growth without compromising on air quality.

2. System dynamics methodology

The system dynamic approach is used here to model the road transport system to capture the dynamics involved in vehicle to population ratio variation, impact of law enforcement effectiveness, number of campaign programmes to use public transport, time to adopt, time to infect, CO level in air, Private vehicles with controlled pollution and cases of respiratory diseases and other related problems. The steps involved are given as follows

1. Process description
Integration of on-board diagnostics with system dynamics to study road transport pollution

2. Identifying the variables and their interaction
3. Develop causal loop diagram
4. Construct the stock and flow diagram using a Vensim software
5. Simulate the model
6. Validation
7. Conclusion

2.1 System dynamics process description

With the increase in complexity of our environment, there is an increase in the un-intended and unexpected responses from system due to narrow decision making and other interventions. Transport system is a nonlinear complex system with numerous components and interconnections,

The road transport system model is developed with respect to private vehicles and its various dynamics and inter actions are captured here. The increase in population is influenced by the birth and death rate. Increase in population leads to increase in number of private vehicles and its increasing rate. But the rate of increase of private vehicles can be reduced by creating more awareness about vehicular pollution. The awareness about the impact of vehicular pollution leading to health hazards will alert the people and hence they will shift from using the private vehicles to public transport. Subsequently the rate of increase of private vehicles is decreased. For easy online measurement of vehicular emissions, an advanced onboard diagnostic system has been utilized.

This utilizes the Radio Frequency Identification tag (RFID) and ZIGBEE to identify and acquire vehicle data. This online vehicular emissions information alerts the owners to go for proper maintenance of their vehicles. This could be used to curb the transport pollution. When the number of vehicles on road are increased, automatically the volume of vehicular emission increases. This would prevent the exhaust emission of harmful gases which in turn mitigate the vehicular pollution. This will make a proportional increase of carbon monoxide level in air. This will definitely affect the public health leading to respiratory and other related problems. This dangerous situation forces the Government to conduct more awareness campaigns.

The key variables of interest in the system dynamics modelling are stock variables CO level in air, cases of respiratory and other related problems, Number of awareness campaign to use public transport and private vehicles with controlled pollution and flow variables infection rate, campaign rate, adoption rate, OBD adoption rate and regular check rate. The above variables are listed in the (Table 1).

<table>
<thead>
<tr>
<th>S.No</th>
<th>Level variables</th>
<th>Flow variables</th>
<th>Auxillary variables</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vehicles emission</td>
<td>Private vehicle increase rate</td>
<td>Population density</td>
<td>Time to adopt</td>
</tr>
<tr>
<td>2</td>
<td>Stock of public vehicles</td>
<td>Public vehicle increase rate</td>
<td>Time to dropout</td>
<td>Law enforcement effectiveness</td>
</tr>
<tr>
<td>3</td>
<td>Stock of private vehicles</td>
<td>OBD adoption rate</td>
<td>Ratio of CO level to exposure span</td>
<td>Contact Frequency</td>
</tr>
</tbody>
</table>

Table 1 Important variables and parameters used in the model
### Table 1: Variables and Parameters

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>CO level in air</td>
<td>CO increase rate</td>
<td>OBD-CO emission per vehicle</td>
<td>Adoption fraction</td>
</tr>
<tr>
<td>5</td>
<td>Cases of respiratory and other related problems</td>
<td>Infection rate</td>
<td>Checking due to Legal pressure</td>
<td>Probability of contact with adopters</td>
</tr>
<tr>
<td>6</td>
<td>Population</td>
<td>Death rate</td>
<td>Social Contact</td>
<td>Time to dissipate</td>
</tr>
<tr>
<td>7</td>
<td>Number of awareness campaigns to use public transport</td>
<td>Birth rate</td>
<td>Contact with adopters</td>
<td>Time of contact with environment</td>
</tr>
<tr>
<td>8</td>
<td>Private vehicles with OBD</td>
<td>Campaign rate</td>
<td>Voluntary adoption</td>
<td>Total area coverage</td>
</tr>
<tr>
<td>9</td>
<td>Private vehicles with controlled pollution</td>
<td>Check and maintenance rate</td>
<td>CO in tonnes per sq kilometer</td>
<td>Frequency of exposure</td>
</tr>
<tr>
<td>10</td>
<td>Private vehicles with no OBD</td>
<td>Normal cure rate</td>
<td>Probability of infection</td>
<td>Time to infect</td>
</tr>
<tr>
<td>11</td>
<td>Passive owners</td>
<td>Adoption rate</td>
<td>Vehicle density</td>
<td>Dropout fraction</td>
</tr>
<tr>
<td>12</td>
<td>Active owners</td>
<td>Vehicles addition rate</td>
<td>Vehicle to population ratio</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Stock of auto rickshaws</td>
<td>CO decline rate</td>
<td>Time to acquire</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Stock of public and private buses</td>
<td>Regular check rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Stock of taxis</td>
<td>Dropout rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Stock of taxis</td>
<td>CO emission rate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 2.2 Development of causal loop diagram

There are many variables in the road transport system occupying important positions in the system. In (Figure 1), the causal loop diagram for the road transport system with various incentive factors and other influencing factors are presented. This is a part of the system dynamic model of the road transport system. The arrows represent the relations between each pair of variables. The arrows also show the direction of the relationship with sign. There are five causal feedbacks in the causal loop diagram presented in (Figure 1) in which one is reinforcing and the other four are self correcting types.

Feedback loop 1 (Private vehicle population → CO Pollution level → CO exposure → cases of respiratory diseases → Cured case → Population → Private vehicle population)

The increase in private vehicle population will increase CO pollution level. This leads to more CO exposure which in turn leads to increase in the number of cases of respiratory diseases and other related problems. If the number of cases of respiratory diseases increases, there will be an increase in the number of cured cases also. This will make a proportional increase in the population which will result in increase of private vehicles population. Hence this loop is reinforcing type.
Figure 1: Causal loop diagram for road transport system

Feedback loop 2 (Private vehicle population \(\rightarrow\) CO Pollution level \(\rightarrow\) CO exposure \(\rightarrow\) cases of respiratory diseases \(\rightarrow\) Campaign against Private transport \(\rightarrow\) Transit to Public Transportation \(\rightarrow\) Private vehicle population)

Increase in private vehicles’ population will increase the CO pollution level which result in greater CO exposure. This will result in more stock with cases of respiratory diseases and other related problems and this will increase the number of campaigns to use public transport. This will induce more number of people to shift to public transport. This will result in decrease in private vehicle population and hence it is a self correcting loop.

Feedback loop 3 (Private vehicle population \(\rightarrow\) CO Pollution level \(\rightarrow\) CO exposure \(\rightarrow\) cases of respiratory diseases \(\rightarrow\) Drop outs from Private transport \(\rightarrow\) Private vehicle population)

An increase in private vehicle population will increase the CO pollution level. This will result in more number of people to be exposed to carbon monoxide (CO). This will in turn increase the number of cases of respiratory diseases and other related problems. This will result in increasing the drop out from private vehicles which would lead to reduction of private vehicle population.

Feedback loop 4 (Private vehicle population \(\rightarrow\) Passive Owners \(\rightarrow\) OBD adoption \(\rightarrow\) Active Owners \(\rightarrow\) Private vehicles with controlled pollution \(\rightarrow\) Private vehicle population)

Increase in private vehicle population without controlled pollution will increase passive owners. With more passive owners and with influence of law enforcement of OBD will result in more OBD adoption. This will increase the number of active owners. This will result in increase of private vehicles with controlled pollution. This will in turn decrease the private vehicle population without controlled pollution.

Feedback loop 5 (Private vehicle population \(\rightarrow\) Passive Owners \(\rightarrow\) Voluntary adoption \(\rightarrow\) Active Owners \(\rightarrow\) Private vehicles with controlled pollution \(\rightarrow\) Private vehicle population)
Increase in private vehicle population would lead to proportional increase of passive owners. If the passive owners are more, then it would increase voluntary adoption of OBD. This will make proportional increase of active owners which would make more number of vehicles to run with controlled pollution. This would make a corresponding reduction of private vehicle population. Hence it is a self correcting loop.

2.3 Construction of stock and flow diagram

The other part of the system dynamic model is the stock and flow diagram. The model is built under the following general configuration. Modelling equations for all the stock variables, rate variables and parameters are shown in the (Appendix 1). Some of the sample equations are shown below

1. Time horizon; 60 months
2. Time unit; month
3. Time step; 1 month

1. CO level in AIR=INTEG(CO emission rate+Rate of pollution from Pvt. vehicles-CO decline rate,100), units: gm.
2. “Pvt. vehicles with OBD”=INTEG(OBD adoption rate-Check and Maintenance rate, 100), units: vehicles.
3. Pvt. vehicles with controlled pollution=INTEG( Check and Maintenance,100), units: vehicles.
4. Pvt. vehicles with no OBD=INTEG (vehicles addition rate-adoption rate), 1.5e+006, units: vehicles

The Stock and flow diagram of road transport system without OBD and with OBD integration are shown in (Figure 2 and 3).

**Figure 2:** Stock and flow diagram of road transport system without OBD integration
Figure 3: Stock and flow diagram of road transport system with OBD integration

The model features the following dynamics

1. The model provides the variation of CO level in air against the variation of vehicle to population ratio (VTPR) over time.
2. The model also describes how the variation of VTPR affects the problems of respiratory and other related issues of population.
3. The impact of implementing LEFE and its effect upon variation in number of private vehicle with control led pollution is modeled.
4. The effect of LEFE on CO level in air is also captured in the model.
5. The variation in time to adopt (TTA) and its impact on variation in the number of private vehicles with controlled pollution is incorporated in the model.
6. The impact of variation in time to infect (TTI) which leads to vary the number of cases of respiratory and other related problem is modeled.

2.4 Model description

In this section, the stock and flow diagram is explained with some details. Due to variation of carbon monoxide emission from private vehicles and public transport, CO level in air is shown as a stock variable. The case of respiratory and other related problems of population is modeled as the stock variable and is modified by the infection rate and normal cure rate. The cases of respiratory diseases and other related problems are influenced by ratio of CO level to exposure span, population and frequency of exposure.

Similarly private vehicles with controlled pollution is also modeled as stock variable which is modified by OBD adaption rate, regular check rate, check and maintenance rate. The private vehicles with controlled pollution is influenced by the number of awareness campaigns to use the public transport, total private vehicles, voluntary adaption and probability of contact with adapters. The model equations for all stock, rate and other variables are given in Appendix 1.
2.5 Simulation of the model

To simulate the dynamics of the road transport system the vensim software is used. It facilitates the multiple scenario and analysis of stock and flow diagram of road transport system without OBD integration (Figure 2) and with OBD integration (Figure 3). It is supported by graphical and tabular output. The actual data for population, birth rate, death rate, population of two wheelers, three wheelers, four wheelers and their CO emissions are tabulated in Appendices 2.1 to 2.5. These data are used in stock and flow diagram for simulating the road transport model. The major input to the simulation model is VTPR. Since the CO level in air is directly proportional to VTPR, the model is developed by considering actual VTPR for the entire simulation period. The simulation result obtained for various VTPR is compared with the simulation results of constant VTPR as 0.015 as the input for the entire simulation period. The major output variables are CO level in air, cases of respiratory diseases and other related problems, private vehicles with controlled pollution. Simulation is conducted for 60 months and results are analyzed.

Figure 4: CO level in air against VTPR without OBD integration

Figure 5: CO level in air against VTPR with OBD integration
The rate of increase in CO level in air, without OBD, is very high period of 16months, and after that, the rate increase moderately. But in the case with OBD, The rate of increase is moderate throughout the simulation period.

![Graph for Cases of respiratory and other related problems](image1.png)

**Figure 6:** Cases of respiratory and other related problems against VTPR without OBD integration

![Graph for Cases of respiratory and other related problems](image2.png)

**Figure 7:** Cases of respiratory and other related problems against VTPR with OBD integration

**Table 2:** Comparison of impact of implementing OBD

<table>
<thead>
<tr>
<th>Variables Studied</th>
<th>Without OBD g/km²</th>
<th>With OBD g/km²</th>
<th>Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO level in AIR (end of 60 months)</td>
<td>8.78513</td>
<td>7.892772</td>
<td>10.2%</td>
</tr>
<tr>
<td>Unit: People</td>
<td></td>
<td>Unit: People</td>
<td></td>
</tr>
<tr>
<td>Cases of respiratory and other related problems (end of 16 months)</td>
<td>413331</td>
<td>266494</td>
<td>35.5%</td>
</tr>
</tbody>
</table>

From the above comparative results, (Table. 2) and (Figure 4 to Figure 7) it is clearly indicated that reduction of CO level in AIR is 10.2% and decrease of cases of respiratory and other related problem is 35.5% because of integration of OBD.
3. Validation of the model

The system dynamics literature stresses the importance of the model validity. These checks include dimensional consistency and so on. The model was checked for dimensional consistency and units of variables and parameters were verified. Two extreme conditions were checked by using VTPR. In the first case, the value of VTPR is increased to 0.090 and the anticipated behavior had a extreme high value of CO level in air. The Figure 8 shows the comparison of normal VTPR and maximum extreme value. This shows that the model was able to responded properly with reference to extreme input condition.

**Figure 8:** CO level in air for the maximum value of extreme conditions
Result: Normal VTPR(0.015-red), Maximum VTPR(0.09-blue)

In the second case, the value of VTPR was reduced to zero and the anticipated behavior had extreme low value of CO level in air. The (Figure 9) provides the comparison between normal and minimum extreme value of VTPR. This shows a significant reduction in CO emission, because no private and other vehicles are present and other vehicles are contributing lower vehicle emissions.

**Figure 9:** CO level in air for the minimum value of extreme conditions
Result: Normal VTPR (0.015-red), Minimum VTPR(0.0-blue)
Similarly the VTPR is increased to 0.090 and the anticipated behavior is extreme high number of cases of respiratory and other related problems. The (Figure 10) shows the comparison of normal VTPR and maximum extreme value.

![Graph for Cases of respiratory and other related problems](image)

**Figure 10:** Cases of respiratory and other related problems for the maximum value of extreme conditions

Result: Normal VTPR (0.015-red), Maximum VTPR (0.09-blue)

In the second case the VTPR is reduced to zero and the anticipated behavior had an extreme less number of respiratory and other related problems. The (Figure 11) provides the comparison between normal and minimum extreme value of VTPR. These tests confirmed the validity of the model.

![Graph for Cases of respiratory and other related problems](image)

**Figure 11:** Cases of respiratory and other related problems for the minimum value of extreme conditions

Result: Normal VTPR(0.015-red), Maximum VTPR(0.0-blue)

3. Simulation results

The major outputs that are analyzed are CO level in air, cases of respiratory and other related problems, private vehicles with controlled pollution, and infection rate. The major inputs that are used for experiment are vehicle to population ratio, time to infect, law enforcement
effectiveness, time to adopt and campaign rate. The major outcomes of the model are provided in (Figure 12 to 18).

The first analysis is with respect to the input parameter vehicle to population ratio (VTPR). The vehicle to population ratio indicates how much percentage of population is having private vehicles. If the population is increased, then automatically private vehicles population would also increase. The experiment is conducted by changing the VTPR ratio from minimum of 0.015 to 0.060 with the increment of 0.015. The results are given in (Figure 12 and Figure 13). The increase in VTPR keeps on increasing the CO level in air and is shown in the (Figure 12).

![Figure 12: CO level in air against various VTPR ratio](image)

Results: VTPR1.0.015 (gray), VTPR2.0.030(green), VTPR3.0.045(red), VTPR4.0.060(blue)

Similarly VTPR is a more influential factor in determining the number of respiratory and other related problems. If VTPR increases, then the number of people affected by respiratory and other related problems will increase drastically, this is indicated in the (Figure 13).

![Figure 13: Cases of respiratory and other related problems against VTPR](image)

Result: VTPR1.0.015 (gray), VTPR2.0.030( green), VTPR3.0.045(red), VTPR4.0.060(blue).

The second analysis is with respect to law enforcement effectiveness (LEFE). Law enforcement effectiveness is the time given by the Government for implementing On Board Diagnostics (OBD) unit in all private vehicles. The implementation here means regular checking and maintenance of vehicles. The LEFE is varied from 2 months to 8 months in
steps of 2 months and the results are presented in the (Figure 14). It is observed that a short LEFE period will increase the stock of private vehicles with controlled pollution.

![Graph for Pvt. vehicles with controlled pollution](image)

**Figure 14** Private vehicles with controlled pollution against various law of enforcement effectiveness  
Result: LEFE1.2 months(gray), LEFE2.4months(green), LEFE3.6months (red), LEFE4.8 months (blue).

Similarly if LEFE duration increases, then CO level in air also increases proportionally as shown in (Figure 15).

![Graph for CO level in AIR](image)

**Figure 15**: CO level in air against various LEFE  
Result: LEFE1.2 months(gray), LEFE2.4months(green), LEFE3.6months(red), LEFE4.8months(blue).

3. **Results and discussion**

A system dynamics model is developed to study the impact of VTPR upon CO levels in air. The model is developed to mitigate the vehicular pollution because otherwise the cases of respiratory and other related problems will increase drastically.
From the above comparison results, it is clear that vehicular pollution could be reduced if the private vehicles population is reduced. Also implementing OBD device in all private vehicles will bring down the vehicular pollution and it is shown in the above (Table 3). This model further captured the dynamics and interactions involved between number of awareness campaigns to use public transport, private vehicles with controlled pollution, law enforcement effectiveness, time to adopt, and time to infect. The dynamic model has provided a comprehensive approach to mitigate vehicular pollution from road transport. The model provides the following policy guidelines to mitigate vehicular pollution and appropriate interventions to improve the model shift to public transport.

1. Implementation of OBD in all private vehicles by the manufacturer itself. The OBD system also exerts a lot of pressure on vehicle owners to go for regular maintenance.
2. Periodical awareness campaigns are to be conducted.
3. Intervention in terms of law enforcement effectiveness can enhance the private vehicle with controlled pollution.
4. Public transit incentive schemes should be introduced for minimizing the number of Private vehicles over period of time.

From the results, the OBD system reduces the CO pollution level in Air, which reduces the number of cases of respiratory diseases. This could also prevent greenhouse gases emissions and thus prevent global warming.
4. Conclusions

The summary of predictions after 60 months under different scenarios are analysed.

1. The shift in increase to private vehicles’ with controlled pollution because of reducing the Time to Adapt (TTA) OBD implementation period from 16 months to 4 months is 13.6%.
2. The improvement in mitigating of CO level in air due to decrease in vehicle to population ratio from 0.060 to 0.015 is 53%.
3. The remarkable reduction of CO level in air because of integrating OBD in all private vehicles is 10.2%.
4. Decrease in number of cases of respiratory and other related problems because of installing OBD device in all private vehicles is 35.5%.

From the above results, it is clear that vehicular pollution could be reduced if the private vehicles’ usage is reduced. This could be achieved by installing OBD unit in all private vehicles which would bring down the vehicular pollution.

Based on the analyses of all the results and consideration of local conditions, feasible suggestions are made to mitigate vehicular pollution.

1. Implementation of OBD in all private vehicles by the manufacturer imparts pressure on vehicle owners to go for regular maintenance, hence the CO pollution levels in air would be reduced and the rate of cases of respiratory diseases would decline.
2. Periodical awareness campaigns to promote green travel consciousness should be developed which would focus on the sustainable development of the inhabitable environment. Thus awareness campaign programmes need to be conducted in large numbers to promote the low carbon, safe, comfortable and low pollution Public transport. It is an effective way to introduce the awareness to use public transport consciousness into primary school classroom education which would not only guide the students to establish the right consumption concept, but also to foster their socially responsible manners and have a profound effect on low–carbon transport construction.
3. Intervention in terms of law enforcement effectiveness would help to enhance the private vehicles with controlled pollution. Better enforcement would result in better pollution control.
4. Providing better public transport system would minimize private vehicles over a period of time.

5. Appendix 1

5.1.1 Modelling of stock variables

1. Active Owners=INTEG(Regular Check rate,100), units: people.
2. Cases of respiratory and other related problems=INTEG(Infection rate-Normal cure rate,100), units: people.
3. CO level in AIR=INTEG(CO emission rate+Rate of pollution from Pvt. vehicles-CO decline rate,100), units: gm.
4. Number of awareness campaign to use public transport=INTEG (campaign rate,100), units: Number of campaign.
5. “POPULATION-T” =INTEG(Birth rate-Death rate, 4.64673e+006), units: people.
6. “Pvt. vehicles with OBD”=INTEG(OBD adoption rate-Check and Maintenance rate, 100), units: vehicles.
7. Passive Owners=INTEG(Adoption rate1-Regular Check rate, 100), units: people.
9. Pvt. vehicles with controlled pollution=INTEG(Check and Maintenance, 100), units: vehicles.
10. Pvt. vehicles with no OBD=INTEG(vehicles addition rate-adoption rate), 1.5e+006, units: vehicles.
11. Stock of Auto Ricksaws=INTEG(Rate of Increase, 63640), units: Auto Ricksaws.
12. Stock of Public & Pvt Buses=INTEG(Rate of addition, 6364), units: Buses.
13. Stock of Taxis=INTEG(Rate of growth, 1300), units: Taxis.
14. “Total Pvt. vehicles-T”=INTEG(increasing rate-Dropout rate-OBD adoption rate-Transit rate to Public Transport, 1.5e+006), units: vehicles.

5.1.2 Modelling of rate variables

1. Adoption rate=Pvt. vehicles with no OBD/Time to adopt
   Units: vehicles per month.
2. Adoption rate 1=OBD adoption rate
   Units: vehicles per month.
3. Birth rate=“POPULATION-T”*Birth fraction
   Units: constant.
4. BR=Population*Birth fraction
   Units: constant.
5. campaign rate=Cases of respiratory and other related problemst/”POPULATION-T”*10000
   Units: Number of campaigns per month.
6. Check and Maintenance rate=Regular Check rate
   Units: vehicles per month.
7. CO decline rate=CO level in AIR/Time to dissipate
   Units: gm/month.
8. CO emission rate=Stock of Auto Ricksaws*5.1*96*25+Stock of Public & Pvt Buses*3.6*151*22+Stock of Taxis*0.9*30*22
   Units: gm/month.
9. Death rate=Death fraction*”POPULATION-T”
   Units: constant.
10. Dropout rate=“Total Pvt. vehicles-T”*Dropout fraction*(Cases of respiratory and other related problemst/”POPULATION-T”)/Time to dropout
    Units: vehicles per month.
11. DR=Population*Death fraction
    Units: constant.
12. Increasing rate=”POPULATION-T”*Vehicle to Population ratio/Time to acquire
    Units: vehicles per month.
13. Infection rate=Population*Ratio of CO level to Exposure span/Time to infect
    Units: People per month.
14. Normal cure rate=Cases of respiratory and other related problemst/2
   Units: people per month.
15. OBD adoption rate="Total Pvt. vehicles-T”/Time to adopt
   Units: vehicles per month.
16. Rate of addition=Stock of Public & Pvt buses*0.0016
   Units: vehicles per month.
17. Rate of growth=Stock of Taxis*0.02
   Units: vehicles per month.
18. Rate of increase=Stock of Auto Ricksaws*0.0016
   Units: vehicles per month.
19. Rate of pollution from Pvt. vehicles="Pvt. vehicles with controlled
   pollution”*2*25*20
   Units: gm per month.
20. Regular Check rate=Checking due to legal pressure+voluntary adoption
   Units: vehicles per month.
21. Transit rate to Public Transport=(Number of awareness campaign to use Public
   Transport/"POPULATION-T”)*"Total Pvt. vehicles-T”/Time to transit
   Units: Vehicles per month.
22. Vehicles addition rate=increasing rate
   Units: vehicles per month.

5.1.3 Other important equations

1. Adoption fraction=0.3, unit: constant
2. Birth fraction=0.0156/12, unit: constant.
3. Checking due to legal pressure=Passive Owners/Law enforcement effectiveness, unit:
   People per month.
4. CO in tonnes per Sq.km=(CO level in AIR/1e+006)/”Total area coverage-t”, unit:
   tones per Sq.km.
5. Contact frequency=100, unit: times.
6. Contact with adopters=Social contact*Probability of contact with adopters,
   unit: people.
7. Death fraction=0.005/12, unit: constant.
8. Density=”Total Pvt. vehicles-T”/”Total area coverage-t”, units: vehicles per km\(^2\).
9. Dropout fraction=0.033, unit: constant
10. Frequency of exposure=23, unit: times.
11. Law enforcement effectiveness=6, unit: months.
12. Pop density="POPULATION-T”/”Total area coverage-t”, unit: people per km\(^2\).
13. Ratio of CO level to Exposure span=MAX(0.05,((“CO in tonnes per
   Sq.km”*1e+006/(Frequency of exposure*Time of contact with
   environment*Population/48)-0.5))), unit: constant.
14. Social contact=Passive Owners*Contact frequency, unit: times.
15. Time of contact with environment=30, unit: minutes.
16. Time to acquire=2, units: months.
17. Time to adopt=12, unit: months.
18. Time to dissipate=2, units: months.
19. Time to dropout=RANDOM NORMAL(3,4,3.5,1.3,2),
20. Time to infect=6, unit: months.
21. Time to transit=6, unit: months.
22. Total area coverage-t=174, units: km\(^2\).
23. Vehicle to population ratio=0.015, unit: constant.
24. Voluntary adoption=contact with adopters* adoption fraction, unit: People per month.

5.2 Appendix 2

**Table 4:** Vehicles population in Chennai city in the year of 2006-2011

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

Source: www.tn.gov.in

**Table 5:** Emission factors for trace gas emission from vehicles (g/km)

<table>
<thead>
<tr>
<th>Pollutant/ vehicle type</th>
<th>Bus</th>
<th>Omni Bus</th>
<th>Two Wheelers</th>
<th>Auto Rickshaw</th>
<th>Cars</th>
<th>Taxi</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>3.6</td>
<td>3.6</td>
<td>2.2</td>
<td>5.1</td>
<td>1.98</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Source: Ramachandra & Shwetmala (2009)
Table 6: Estimated vehicular emission load in selected metropolitan cities in India

<table>
<thead>
<tr>
<th>Name of the City</th>
<th>Vehicular Pollution Load ( Tons Per Day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Particulates</td>
</tr>
<tr>
<td>Chennai</td>
<td>7.3</td>
</tr>
</tbody>
</table>

Source: Status of the vehicular pollution control programme in India (March 2010), Central Pollution Control Board, Ministry of Environment & Forests, Government of India.

Table 7: Projected population for CMA and Chennai city ( In Lakhs )

<table>
<thead>
<tr>
<th>S.No</th>
<th>Description</th>
<th>Actual</th>
<th>Projection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2001</td>
<td>2006</td>
</tr>
<tr>
<td>1</td>
<td>Chennai city</td>
<td>43.44</td>
<td>46.28</td>
</tr>
</tbody>
</table>

Source: Census of India and CMDA.

Table 8: Statistical data of Chennai

<table>
<thead>
<tr>
<th>Year</th>
<th>Birth rate</th>
<th>Death rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991</td>
<td>25.89</td>
<td>9.67</td>
</tr>
<tr>
<td>1992</td>
<td>24.01</td>
<td>9.50</td>
</tr>
<tr>
<td>1993</td>
<td>23.82</td>
<td>9.14</td>
</tr>
<tr>
<td>1994</td>
<td>23.39</td>
<td>9.07</td>
</tr>
<tr>
<td>1995</td>
<td>23.75</td>
<td>8.49</td>
</tr>
<tr>
<td>1996</td>
<td>22.68</td>
<td>8.54</td>
</tr>
<tr>
<td>1997</td>
<td>22.50</td>
<td>8.20</td>
</tr>
<tr>
<td>1998</td>
<td>23.81</td>
<td>9.00</td>
</tr>
<tr>
<td>1999</td>
<td>25.53</td>
<td>8.92</td>
</tr>
<tr>
<td>2001</td>
<td>24.50</td>
<td>8.92</td>
</tr>
<tr>
<td>2002</td>
<td>23.72</td>
<td>8.27</td>
</tr>
<tr>
<td>2003</td>
<td>22.62</td>
<td>8.01</td>
</tr>
<tr>
<td>2005</td>
<td>23.88</td>
<td>8.36</td>
</tr>
<tr>
<td>2009-2011</td>
<td>15.5</td>
<td>5.1</td>
</tr>
<tr>
<td>2014</td>
<td>19.89</td>
<td>7.35</td>
</tr>
</tbody>
</table>

Source: Census of India and CMDA

6. References


Integration of on-board diagnostics with system dynamics to study road transport pollution

Gunaselvi Manohar et al.,
International Journal of Environmental Sciences Volume 6 No.6 2016