July, 2023

Final report on the project

Reducing Emissions by Mass Transport

Submitted to:

Tamil Nadu Pollution Control Board (TNPCB)

Chennai

Submitted by:

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EXECUTIVE SUMMARY

Air pollution is the contamination of the atmosphere by physical, chemical, or biological agents which are highly detrimental to the environment as well as living organisms, including humans. The effects of air pollution include global climate changes and toxicity to living organisms. The gases which contribute to global climate change are known as Green House Gases (GHGs). Road transport is a significant contributor to these gases, accounting for 24% globally and 14% in India. To reduce the quantity of emissions from the transport sector and their impacts, it is essential to have a thorough understanding of the emissions from individual vehicles and aggregated emissions at a city level. This report can be segmented into three parts. The first part contains tailpipe emission estimations for Chennai Metropolitan Area (CMA) for the base year (2018) and future year (2030) by considering various scenarios. In the second part, Life Cycle Analysis (LCA) was conducted considering the electrification of vehicles, and their results were used for assessing the environmental performances of the different modes in the base year as well as for the chosen future year. The analysis in these two parts is based on data collated from the published literature. In the third part, ambient emission and traffic data were collected from a site in the CMA to study the effect of traffic on ambient emission levels.

Tailpipe emission estimations were done for the base year to be used as a base for comparing with different scenarios created for the chosen future year. The quantification of emissions under these scenarios can be used as a tool for reducing the environmental impacts from the transport sector in the future. The scenarios created are: 1). Business-As-Usual (BAU), 2). 70% of all the trips are made on sustainable modes (public transport, walk, cycle), and 3). All the additional trips generated in the future will be made using sustainable modes. In the BAU scenarios, the total number of trips will increase as the population increases, but the mode share remains the same as the base year. Chennai city will benefit from shifting the passengers from personal vehicles to public transport. The Comprehensive Mobility Plan of Chennai, 2019, targets 70% of the total travel to be made on sustainable modes by 2030. If this target is achieved, there will be a reduction in overall emissions at the city level of nearly 26%. However, if the all-new additional trips are attracted towards sustainable modes only, the reduction in emissions is even greater (~33%).

If all the vehicles are electrified in the future, comparisons based on tailpipe emissions will indicate a 100% reduction from the use of EVs! However, the emissions from production of electricity and EV including batteries can be significant. Hence, Life Cycle Analyses were conducted, which will account for emissions at all stages of the vehicle cycle (manufacturing to End-of-Life) and fuel cycle (exploration and extraction to utilization in vehicles). There is a reduction in emissions from all road vehicles if they are shifted to battery electric vehicles from the current internal combustion engines. Even here, the use of public transport results in significantly lower emissions as opposed to using private vehicles, particularly cars.

From the analysis of the locally collected ambient pollutant and traffic data, a high correlation between the two was observed i.e., as the volume of vehicles increases, there is an increase in the level of ambient pollutant. Hence, programs and policies aiming at discouraging people from driving personal vehicles and at the same time attracting trips to sustainable (public transport and non-motorized) modes are needed to improve the sustainability of transportation sector.

Contents

List of Figures

List of Tables

Introduction:

Air pollution is the contamination of the indoor or outdoor environment by any physical, chemical, or biological agent that alters the natural characteristics of the atmosphere. Motor vehicles, household combustion devices, forest fires, and industrial facilities are common sources of air pollution. Many drivers of air pollution are sources of greenhouse gas emissions. The pollutants causing major public health concerns include carbon dioxide, particulate matter, ozone, carbon monoxide, nitrogen oxides, and sulphur dioxide. Outdoor and indoor air pollution cause respiratory ailments and other diseases and are major causes of morbidity and mortality. World Health Organisation (WHO) data shows that almost all of the global population (99%) breathe air that exceeds WHO guideline limits and contains high levels of pollutants, with low-income and middle-income countries suffering from the highest exposure to these pollutants. The quality of air in the atmosphere is closely linked to the Earth's ecosystems and climate globally. When put in place, policies to reduce air pollution offer a win-win strategy for both climate and health, lowering the burden of disease attributable to air pollution and contributing to the near- and long-term climate change mitigation.

Types of pollution:

Air Pollution develops in two contexts.

a. Indoor (household) air pollution, and
b. Outdoor (ambient) air pollution.

a. Indoor/Household Air Pollution:

Indoor air pollution is caused by burning solid fuel sources like firewood, dung, and crop waste. These are mainly done for domestic cooking and as heat sources. The burning of such fuels especially occurs in poor households, resulting in air pollution leading to respiratory diseases, which can result in premature death. The WHO calls indoor air pollution "The world's largest single environmental health risk."

b. Outdoor/Ambient Air Pollution:

Outdoor air pollution is the presence of one or more pollutant substances at a concentration for duration above their natural levels in the air. These pollutants have the potential to produce an adverse effect on the environment. Outdoor air pollution is one of the world's most significant health and environmental problems. Outdoor air pollution is the one that tends to aggravate for low-income countries as they industrialize and transition to middle incomes. In this study, the main point of concentration is outdoor air pollution.

The major pollutants contributing to pollution include Carbon Dioxide (CO_2), Carbon Monoxide (CO), Nitrogen Oxides (NO_2 and NO_3), Hydrocarbons (HCs), and Particulate Matters (PMs).

Carbon Dioxide:

Carbon Dioxide is a colourless gas having a faint sharp odour and a sour taste. It is one of the most critical greenhouse gases linked to global warming. Still, its presence in the Earth's atmosphere is in a very minor component (about 3 volumes in 10,000), formed in the combustion of carbon-containing materials, in fermentation, and in the respiration of animals, and carbon dioxide is utilized by plants in the photosynthesis of carbohydrates. The presence of this gas in the atmosphere keeps some of the radiant energy received by Earth from being returned to space, which produces an effect called the greenhouse effect. Figure 1 shows the annual CO_2 emissions from each country for the year 2021.

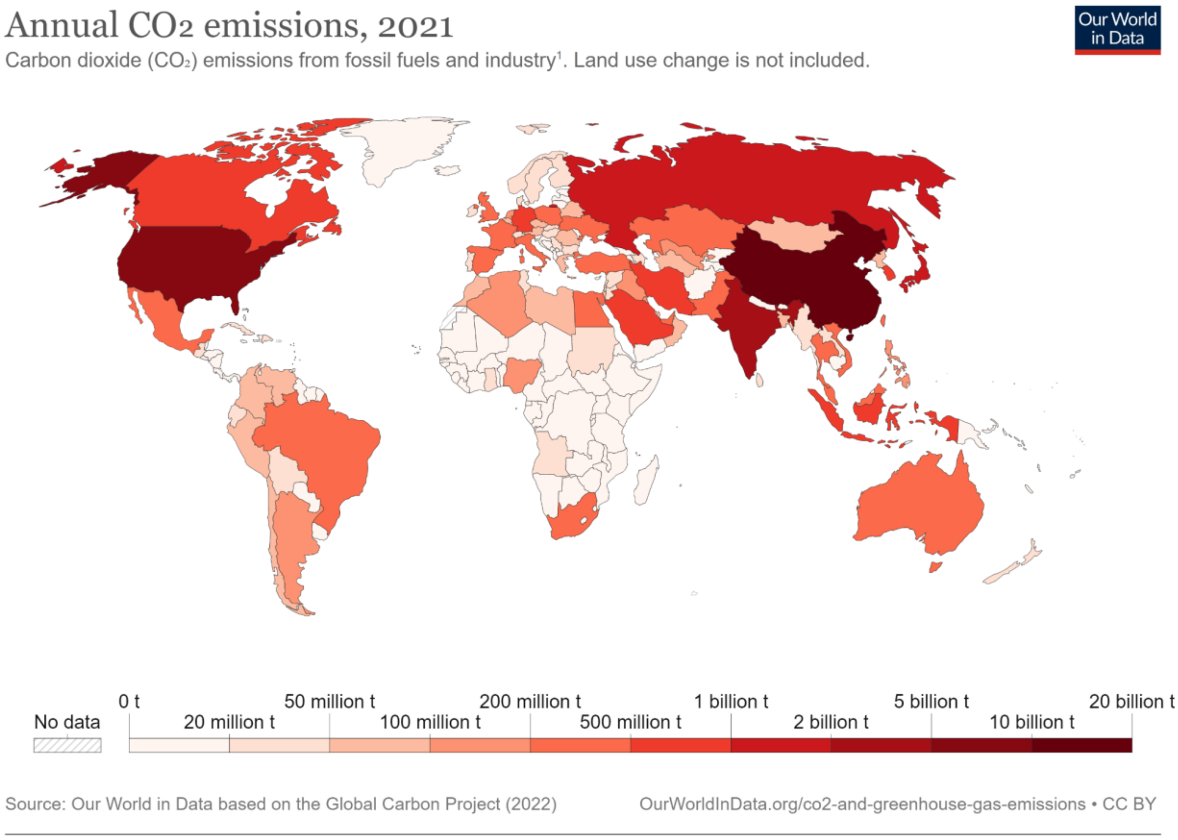
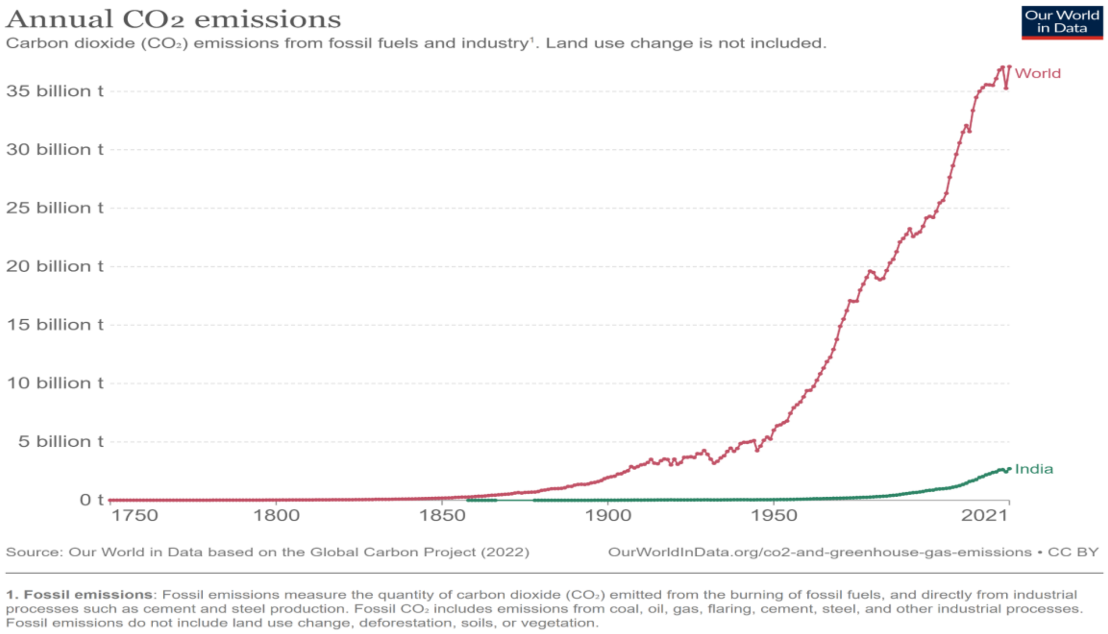


Figure 1: CO_2 emissions from each country in the year 2021 [1]

Figure 2 depicts the growth of global CO_2 emissions from the mid-18th century to today. It can be observed that before the Industrial Revolution, the emissions were very low. The increase in emissions observed was still relatively slow until the mid-20th century. In the year 1950, the world emitted 6 billion tonnes of CO_2. By 1990 this amount had almost risen four times, reaching more than 22 billion tonnes. CO_2 emissions have continued to grow rapidly. At present, the world emits over 37 billion tonnes each year.



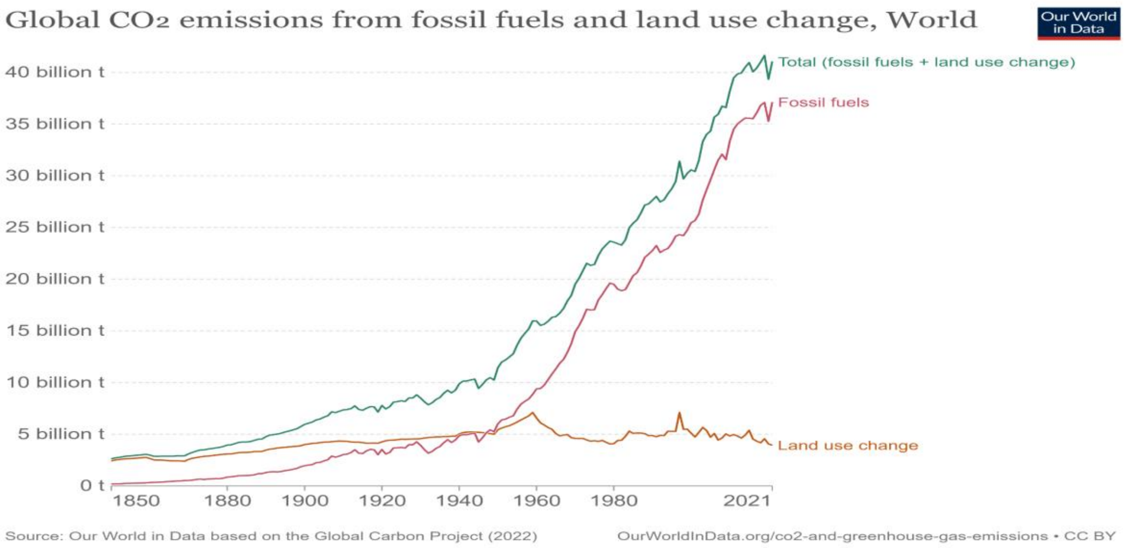
Annual CO2 emissions

Carbon dioxide (CO_2) emissions from fossil fuels and industry[1]. Land use change is not included.

Source: Our World in Data based on the Global Carbon Project (2022) OurWorldInData.org/co2-and-greenhouse-gas-emissions • CC BY

1. Fossil emissions: Fossil emissions measure the quantity of carbon dioxide (CO_2) emitted from the burning of fossil fuels, and directly from industrial processes such as cement and steel production. Fossil CO_2 includes emissions from coal, oil, gas, flaring, cement, steel, and other industrial processes. Fossil emissions do not include land use change, deforestation, soils, or vegetation.

Figure 2: Annual CO_2 emissions from the World and India [1]



Global CO2 emissions from fossil fuels and land use change, World

Source: Our World in Data based on the Global Carbon Project (2022) OurWorldInData.org/co2-and-greenhouse-gas-emissions • CC BY

Figure 3: Annual CO_2 emissions from each country, considering land use change [1]

Figure 3 shows the annual CO_2 emissions from each country considering land use change. While the emissions from fossil fuels have increased, the emissions from land use change have declined slightly in recent years. Overall, it can be said that total emissions have roughly stabilized over the past few years.

The major effect that CO_2 causes is global warming; an increase in the CO_2 levels in the atmosphere leads to supercharging of the natural greenhouse effect, causing the global temperature to rise. Exposure to CO_2 tends to produce a variety of health effects. These may include headaches, restlessness, dizziness, difficulty breathing, a tingling or pins or needles feeling, sweating, tiredness, coma, asphyxia, increased heart rate, elevated blood pressure, and convulsions.

Carbon Monoxide

Carbon Monoxide (CO) is an odourless and colourless gas that has harmful effects when inhaled in substantial amounts. CO gets released into the atmosphere when something is burned. The major contributors of CO to outdoor air pollution are trucks, cars, and other vehicles or machinery that burn fossil fuels. A variety of home items, such as leaking chimneys and furnaces, unvented kerosene and gas space heaters, and gas stoves, also contribute to CO release and can affect indoor air quality.

The annual CO emission from the world population in the year 1750 was 6,76,47,748t, whereas, in the year 2019, it has risen to 52,72,66,938t. The contribution from India was 83,65,132t in 1750 and 5,33,92,564t in 2019. Figure 4 shows the CO emissions for the year 2019.

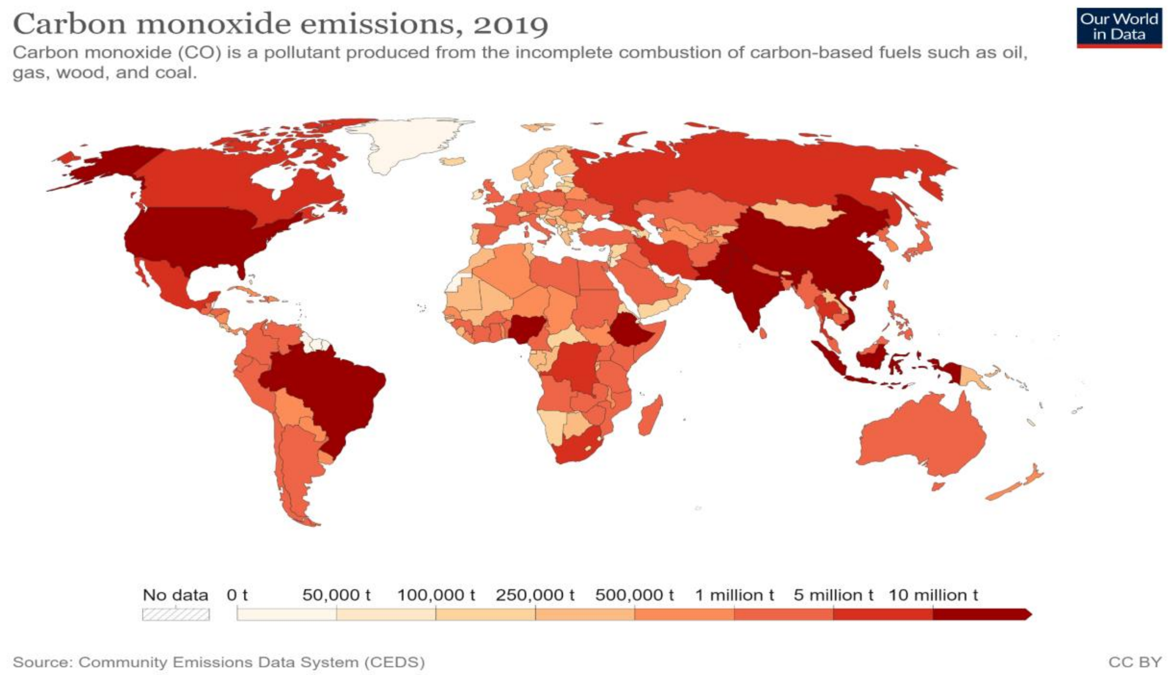


Figure 4: CO emissions for 2019 [2]

Breathing air with a high CO concentration reduces the amount of oxygen that can be transported in the bloodstream to critical organs like the heart and brain. At extremely prominent levels, which can be found indoors or in other enclosed environments, CO has effects that can cause dizziness, confusion, unconsciousness, and even death in some cases. Remarkably elevated levels of CO are rare to occur outdoors. However, when CO levels are found at a higher-level outdoors, they can be of special concern for people with ailments relating to heart disease. These people will be already having a reduced ability to get oxygenated blood to their hearts in situations where the heart needs more oxygen than usual. These people are especially vulnerable to the effects of CO when they are exercising or under an increased amount of stress. In situations like these, short-term exposure to higher CO may result in reduced oxygen to the heart accompanied by chest pain, known as angina.

Nitrogen Oxides

Nitrogen Oxides are a family of highly reactive poisonous gases. These gases are formed when the fuel is burned at high temperatures. NO_x pollution is emitted by trucks, automobiles, and various non-road vehicles (e.g., construction equipment, boats, etc.). These pollutants are also found in industrial sources such as power plants, cement kilns, industrial boilers, and turbines. NO_x often appears as a brownish gas. It is a strong oxidizing agent and plays a major role in atmospheric reactions with volatile organic compounds (VOC) that produce ozone (smog) on scorching summer days. Nitrogen Dioxide (NO_2) is one among the group of these highly reactive gases. Other nitrogen oxides include nitrous acid and nitric acid. NO_2 is used as the indicator for the larger group of nitrogen oxides.

The annual NO_x emission from the world population in the year 1750 was 1,84,937t, whereas, in the year 2019, it has risen to 9,72,07,281t. The contribution from India was 30,553t in 1750 and 94,76,940t for the year 2019. Figure 5 shows the NO_x emissions for the year 2019.

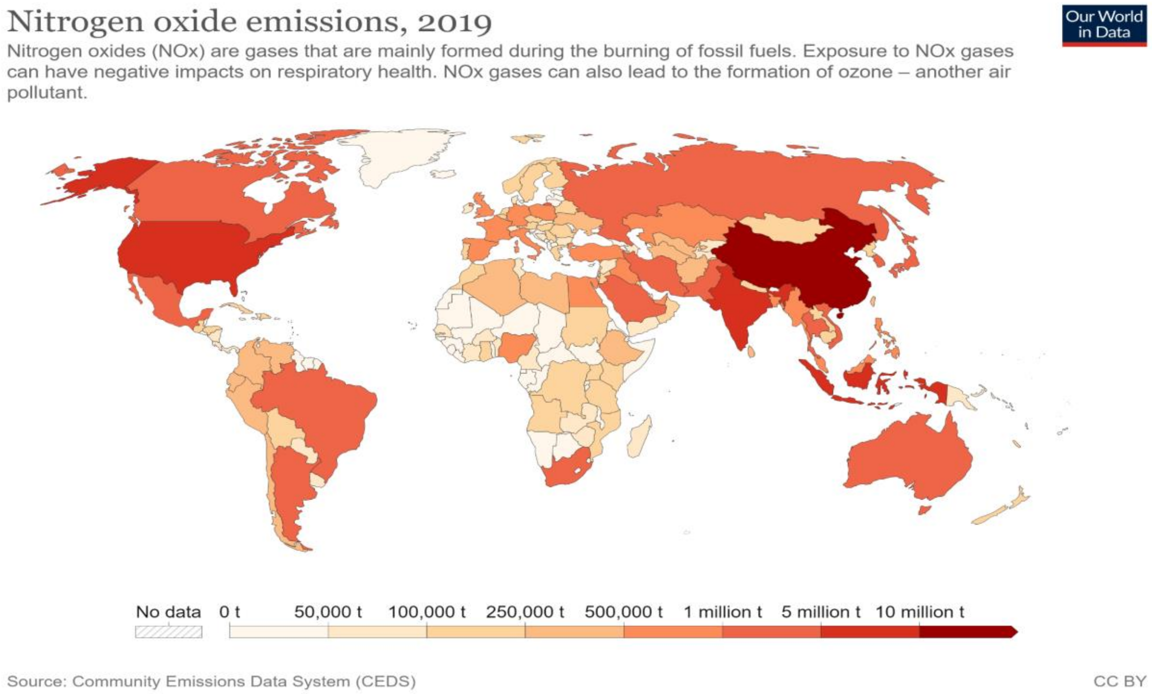


Figure 5: Annual NOx emissions [3]

Breathing air with a high concentration of NO_2 irritates the airways in the human respiratory system. Such exposures over short periods can aggravate respiratory diseases, particularly asthma, leading to respiratory symptoms (such as coughing, wheezing, or difficulty breathing), hospital admissions, and visits to emergency wards. Longer exposures to high concentrations of NO_2 may contribute to the development of asthma and can potentially increase susceptibility to respiratory infections. People with asthma, children, and the elderly, are at greater risk for the health effects of NO_2. NO_2 and other NO_x gases react with other chemicals in the air to form particulate matter and ozone. Both pollutants are harmful when inhaled and cause effects on the respiratory system.

NO_2 and other NO_x pollutants interact with water, oxygen, and various chemicals present in the atmosphere to form acid rain. Acid rain has harmful effects on sensitive ecosystems such as lakes and forests. The nitrate particles that result from NO_x make the air hazy and difficult to see. NO_x in the atmosphere leads to nutrient pollution in coastal waters.

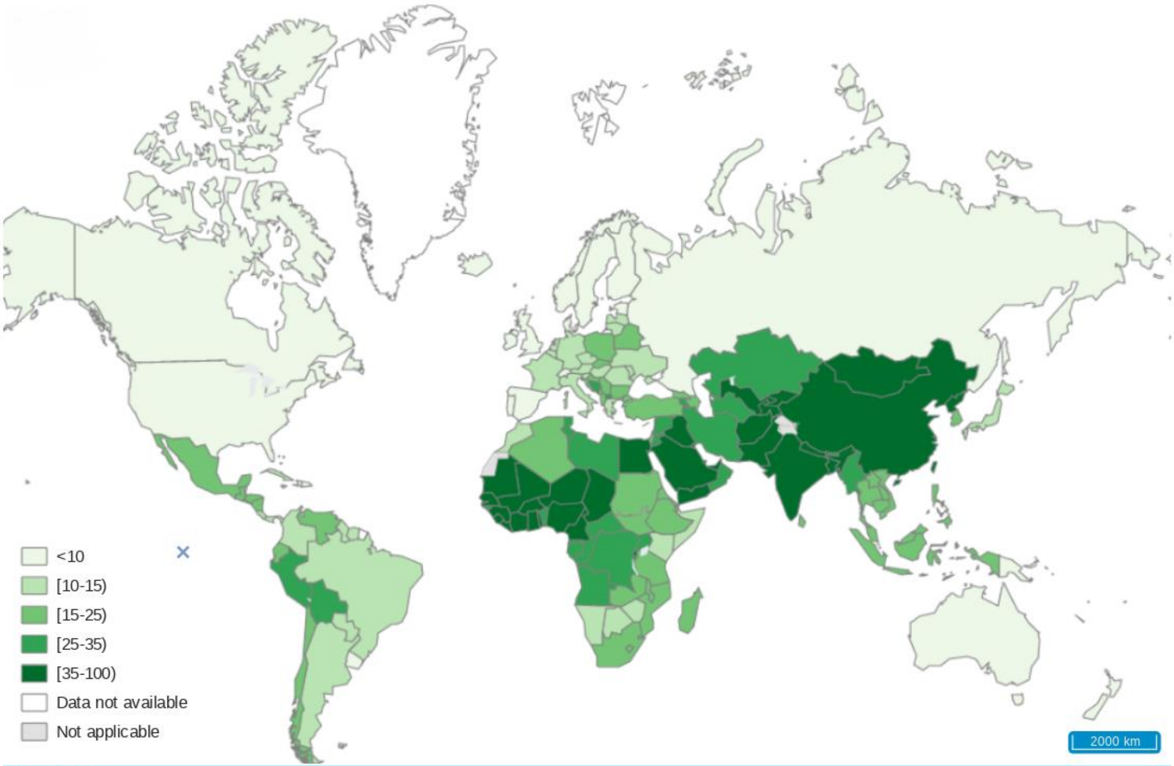
Hydrocarbons

Hydrocarbon refers to the chemical composition of a compound on a molecular level. Hydrocarbons are carbon/hydrogen isomers, meaning hydrocarbons are made of two - and only two – elements, that are carbon and hydrogen. Hydrocarbon emissions are a product of one of the two combustion processes; they are - complete combustion and incomplete combustion. The complete combustion of fossil fuels produces only two emissions, which are carbon dioxide and water. While both are greenhouse gases that have a high global warming potential, neither are toxic. But the complete combustion of a fuel is currently impossible to achieve. Limitations of technology and the nature of fossil fuels make a complete burning of fuel possible only in theory. As a result, to one degree or another, all the combustions are incomplete. Incomplete combustion churns out many both high global-warming potential greenhouse gases and gases that are toxic to flora, fauna, and people. Just a few of the dangerous gases that result from incomplete combustion include cancer-causing volatile organics like benzene, acetone, xylene, and toluene, as well as carbon monoxide (CO), nitrous oxide (NO), and sodium dioxide (SO_2). Incomplete combustion not only includes the generation of toxic and greenhouse gases but it also leads to the release of hydrocarbons into the atmosphere completely unburned. In some cases, hydrocarbons moving through a combustion system without burning are not an issue because the hydrocarbons are inert. But some hydrocarbon fuels are themselves greenhouse gases.

Hydrocarbons are a major contributor to smog, which can be a major problem in urban areas. Prolonged exposure to hydrocarbons contributes to asthma, liver disease, lung disease, and cancer.

Particulate Matter (PM):

Particulate matter (PM) (also called particle pollution) is the term for a mixture of solid particles and liquid droplets that are found in the air. Some particles, such as soot, dust, dirt, or smoke, are large or dark enough to be seen by the naked eye. Others are so small that they can only be detected using an electron microscope and other specialized sensors. Figure 6 shows the concentration of particulate matter in the world.



World Health Organization

Figure 6: Concentration of Particulate Matter (WHO) [4]

The particulate matter comes in many sizes and shapes and can be made up of hundreds of different chemicals. Some of these PMs are emitted directly from a source such as unpaved roads, fields, construction sites, smokestacks, or fires. Most particles are formed in the atmosphere because of complex reactions of chemicals like nitrogen oxides and sulphur dioxide, which are the pollutants emitted from power plants, industries, and automobiles. Figure 7 shows the share of the population exposed to PM air pollution levels above the WHO guidelines. PM of general interest includes PM_{10} (inhalable particles with diameters that are generally 10 micrometres and smaller) and PM2.5 (fine inhalable particles with diameters that are generally 2.5 micrometres and smaller).

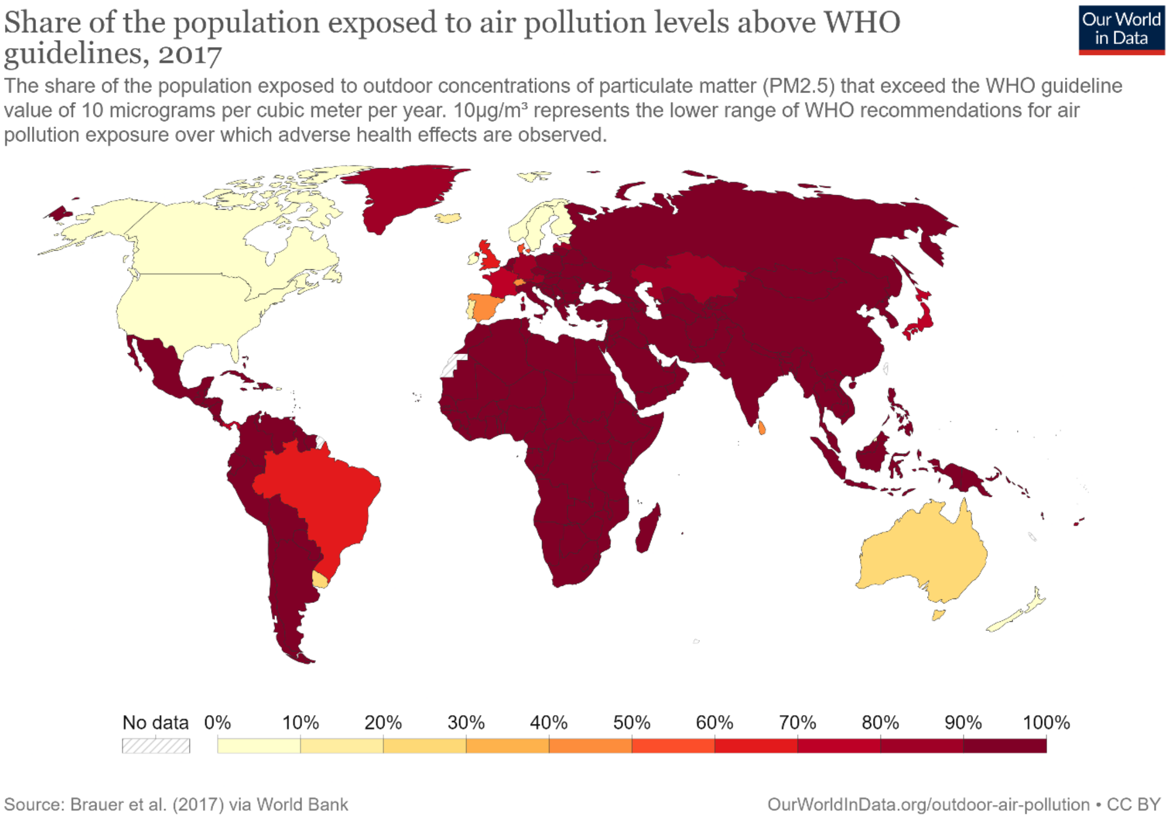


Figure 7: Share of Population exposed to air pollution levels above WHO guidelines [5]

Particulate matter contains microscopic solids or liquid droplets that are so small that they can be inhaled and cause serious health problems. Some particles less than 10 micrometres in diameter can get deep into the lungs and even get into a person's bloodstream. Of these, particles less than 2.5 micrometres in diameter pose the greatest risk to health. Exposure to such particles can affect both lungs and heart of an individual. Numerous scientific studies have linked particle pollution exposure to a variety of problems in humans, consisting of:

- premature death in people with heart or lung disease
- nonfatal heart attacks
- irregular heartbeat
- aggravated asthma
- decreased lung function
- increased respiratory symptoms, such as irritation of the airways, coughing, or difficulty breathing.

People with heart or lung diseases, children, and older adults are the most likely to be affected by particle pollution exposure.

Fine particles (PM2.5) are the main cause of reduced visibility (haze) in many parts of the country. These can be mainly observed in metros of the country like Delhi, Kolkata, Chennai, etc. Particles can be carried over long distances by wind and then settle on the ground or water. Depending on their chemical composition, the effects of this settling may include:

- making lakes and streams acidic

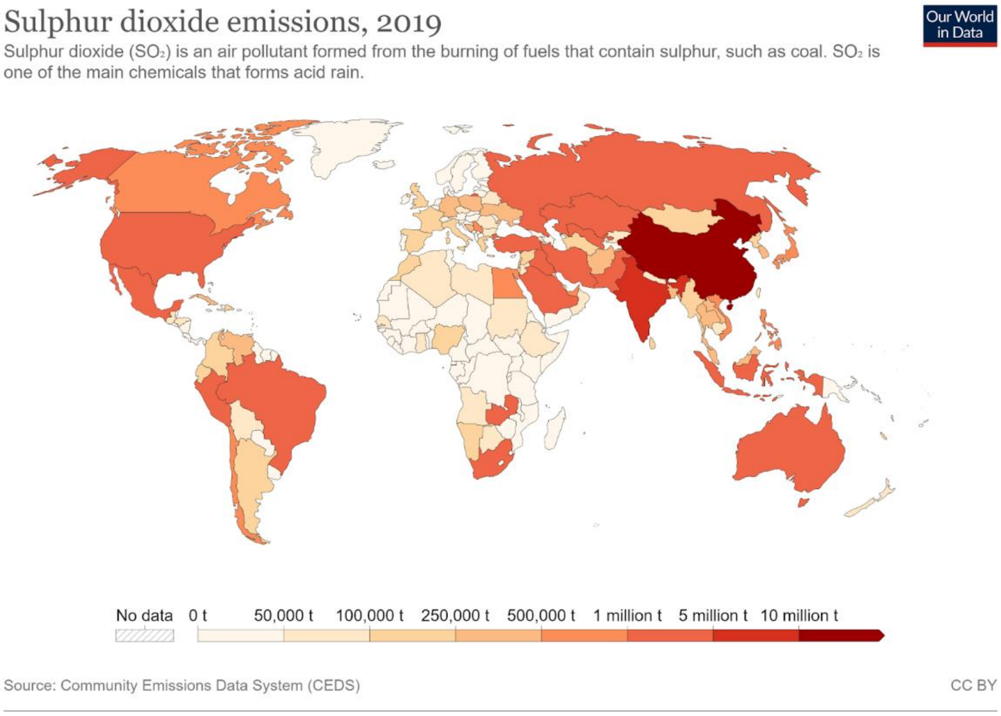
- changing the nutrient balance in coastal waters and large river basins
- depleting the nutrients in the soil
- damaging sensitive forests and farm crops
- affecting the diversity of ecosystems
- contributing to acid rain effects

Exposure is measured in micrograms of PM2.5 per cubic meter (µg/m^3). In the year 1990, the average size of PM2.5 was 44.26µg for the world, and it increased to 45.54µg for the year 2017. For India, the values were 81.29µg and 90.87µg, respectively.

Sulphur Dioxide

Sulphur dioxide (SO_2) is a gaseous air pollutant composed of sulphur and oxygen. SO_2 forms when sulphur-containing fuel such as coal, oil, or diesel is burned. Sulphur dioxide also converts in the atmosphere to sulphates. The largest sources of sulphur dioxide emissions are electricity generation, industrial boilers, and other industrial processes such as petroleum refining and metal processing. Diesel engines are another major source, including old buses and trucks, locomotives, ships, and off-road diesel equipment.

The annual SO_2 emission from the world population in the year 1750 was 3,28,832t, whereas in the year 2019, it has risen to 7,16,57,163t. The contribution from India was 34,838t in 1750 and 96,72,037t for the year 2019. Figure 8 shows the SO_2 emissions for the year 2019.



Sulphur dioxide emissions, 2019

Sulphur dioxide (SO_2) is an air pollutant formed from the burning of fuels that contain sulphur, such as coal. SO_2 is one of the main chemicals that forms acid rain.

Source: Community Emissions Data System (CEDS)

CC BY

Figure 8: Global SO_2 emissions for the year 2019 [6]

Coal-fired power plants remain one of the biggest sources of sulphur dioxide. The plume from a coal-fired power plant touches down at ground level during high wind conditions or gets trapped by inversions in the atmosphere. High levels can happen during start-up, shutdown, upsets, and malfunctions of pollution control equipment. Ports, smelters, and other sources of sulphur dioxide also cause high concentrations of emissions nearby. People who live and work nearby these large sources get the highest exposure to SO_2. After SO_2 gets into the air, it changes chemically into sulphate particles, which can blow hundreds of miles away.

Sulphur dioxide causes a range of harmful effects on the lungs, some of which are listed below:

- Wheezing, shortness of breath, and chest tightness, especially during exercise or physical activity.
- Continued exposure at high levels increases respiratory symptoms and reduces the ability of the lungs to function.
- Short exposure to peak levels of SO_2 in the air can make it difficult for people with asthma to breathe when they are active outdoors.

Contribution of air pollution by the transportation sector:

The transportation sector has been one of the major contributors to emissions. It accounts for 24% of the GHG emissions globally [7] and contributed 5.86 GT CO_2 in 2021 [8]. The major constituents of vehicular emissions mainly include oxides of nitrogen oxides (NO_x), hydrocarbons (HCs), carbon monoxide (CO), particulate matter (PM), etc. These are produced by the burning of fossil fuels used in the vehicles. In addition, the major potential greenhouse gases (GHGs) that are produced by automobiles include carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). Figure 9 represents the global CO_2 emissions from the transportation sector.

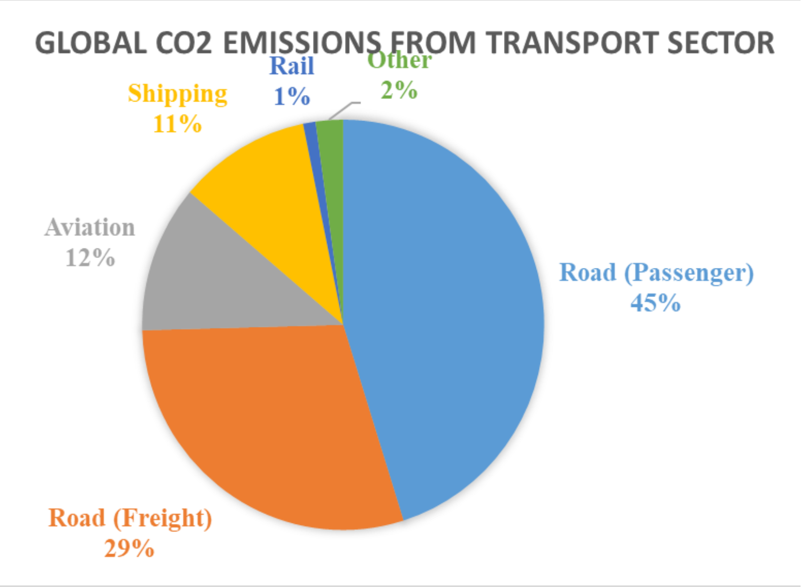


Figure 9: Distribution of CO_2 emissions from the transportation sector globally [9]

The transport sector in India is the third-highest greenhouse gas (GHG) emitting sector and has accounted for nearly 14 percent of our energy-related CO_2 emissions. These emissions have more than tripled since what they were in the year 1990, and with India's urban population expected to double by 2050, they are most likely to increase further. The road sector is the major contributor to these emissions, with 90 percent of the total emissions from the transportation sector. Figure 10 shows the distribution of greenhouse gas emissions from the transportation sector in India in 2014 by type.

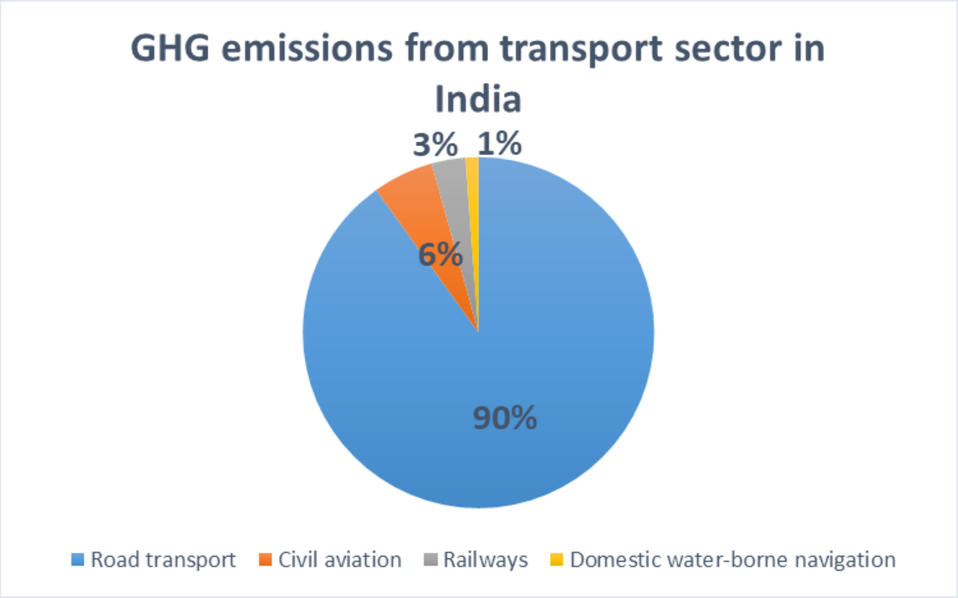


Figure 10: Distribution of greenhouse gas emissions from the transportation sector in India in 2014 by type [10]

With the increasing impact of GHG emissions on the environment, it has become imperative, more than ever, to curb the emissions contributed by the transportation sector. Given the magnitude of emissions from the transport sector and their impact on the environment, it is imperative to collect local data to analyse and monitor the local air quality and the environmental impact. The study area for this project is the jurisdiction of the Chennai Metropolitan Area (CMA). In the city of Chennai, being the major contributor to air pollution, the transportation sector alone accounts for 19.50% [11] of the total GHGs.

Factors that influence the amount of emissions from road transport in a macroscopic model for area-wise emissions are the average speed of vehicles, Vehicles Kilometre Traveled (VKT), the modal share of transportation, and vehicular traffic flow rate. Information such as average total daily trips and average daily per capita trips, average trip length, time of the day of the trips, and Origin-Destination (O-D) pattern can be obtained from O-D data. These data will be appended with the other data for emission estimations. Most of these data are available in the CMA Comprehensive Mobility Plan. Other relevant data were collated from the other studies conducted in CMA. These macroscopic models provided an estimate of the area-wide pollution and provided insights into the factors which influence the quantity of emissions. These insights will be helpful in formulating measures at the local level to reduce emissions. Additionally, the Life Cycle Analysis (LCA) of the vehicles is also included in this report. With the introduction of alternative fuel sources such as Electric Vehicles (EVs), the point of emissions shifts from the tailpipe to the upstream stages of energy utilization. Estimation of the tailpipe alone will not provide exact estimates for a future scenario with a high level of EV penetration.

1 Study area:

The CMA comprises Chennai City and 16 Municipalities, 20 Town Panchayats, and 214 village Panchayats from districts of Chennai, Thiruvallur, and Kancheepuram. The area of CMA is 1189 square kilometers (sq. km) after the 2011 expansion. Figure 11 shows the map of CMA, including the expansion areas. The Population of Chennai is 86.54 lakh as of the 2011 census. With a decadal growth rate of 2.08% between 2001-2011, the Population of the CMA is projected to be 126 lakhs by 2026.

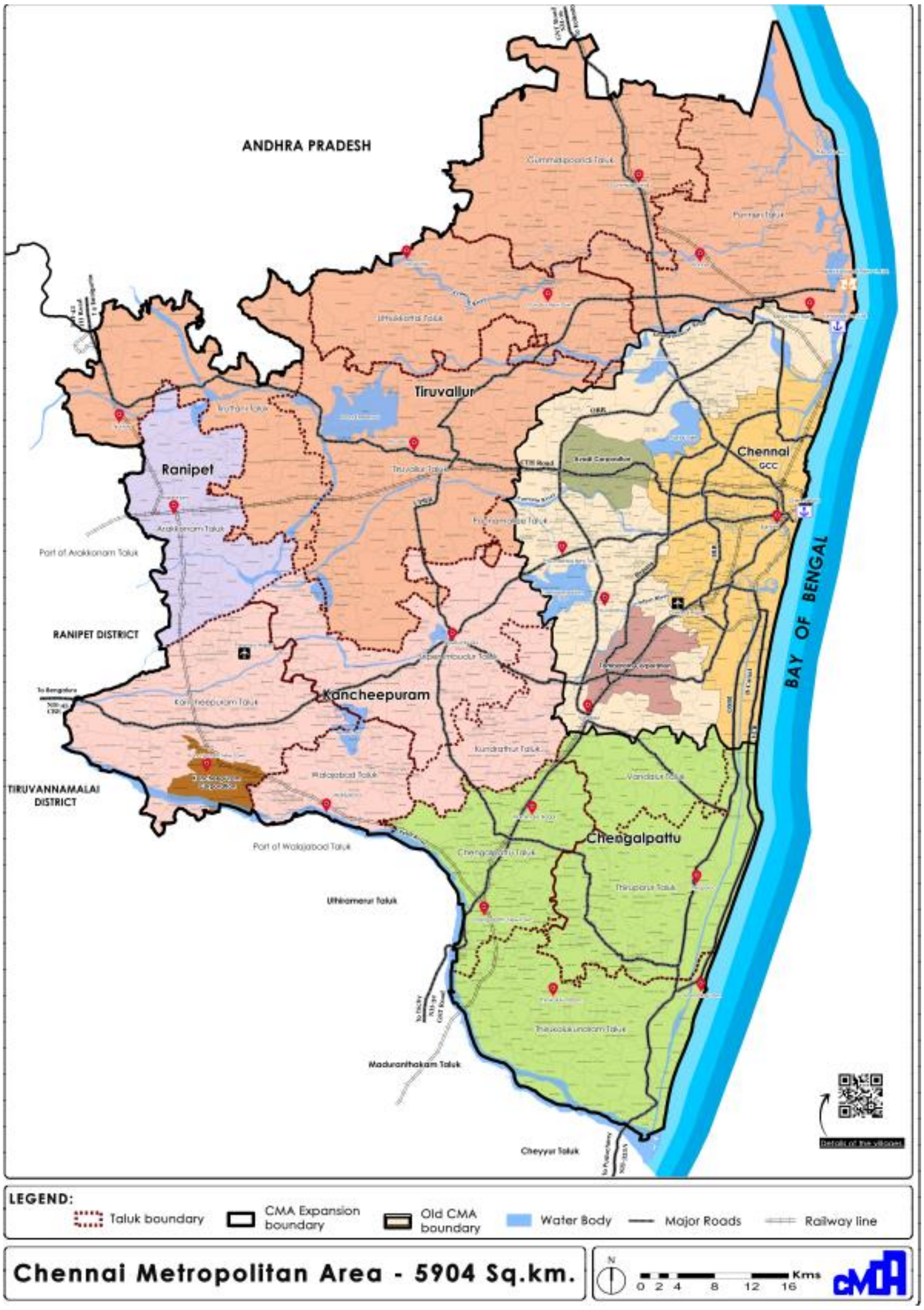


Figure 11: Map of CMA including the expanded area [12]

2 Data collated from inventory:

2.1 CMA mobility plan:

According to the Comprehensive Mobility Plan for CMA, 2019, the people in CMA generate around 157 lakhs daily trips with a per capita trip rate of 1.62 and a motorized trip rate of 1.17. The average trip length of the citizens is 9.9 km. The mode share, average trip lengths, and average occupancy of these trips by different travel modes are listed in Table 1. The average speed of vehicles in CMA is 25.4 kmph. In the rest of the document, the train mode is referred to as ‘metro’ since metro rail will dominate the rail mode in future.

Table 1: Data on mode share, average trip length, and average occupancy

Travel mode	Percentage share (%)	Average trip length (kms)	Average occupancy
Walk	25.10	1.2	-
Cycle	2.90	3.1	-
Two-wheeler	29.60	10	1.2
Auto	7.10	6.9	2
Car	7.10	10.2	2
Bus	22.60	10.3	67
Train	5.60	12.9	-

In the CMA Comprehensive Mobility Plan 2019, traffic volume was collected at 49 spots on the road networks of Chennai. Of these spots, the highest traffic volume was observed at Adyar River - Anna Salai -Maraimalai Adigal Bridge (Saidapet) with 1,46,493 PCUs/day, and the lowest was observed at Perambur Loco Works with 24002 PCUs/day. Journey Speeds were collected along 22 corridors of the road networks. The highest journey speed of 65 kmph along Chennai Bypass from Perungalathur near Tambaram on NH45 to Madhavaram on NH5 via Maduravoyal, and the lowest of 11 kmph on Arcot Road.

2.2 Other literature:

The emission factors of the vehicles were collated from the existing literature. These emission factors are the quantity of emissions produced when the vehicles travel for a kilometer. The emission factors of the different vehicle categories included in the report are presented in Table 2. These emission factors are measured from vehicles confirming BS-IV. Although BS-VI norms are currently in enforcement in India, studies that measured the emission from vehicles confirming this norm are non-existent. The emission factors provided in the norms are measured in ideal conditions using a chassis dynamometer and do not reflect real-world emissions. Additionally, there will be changes in the emission norms for the year 2030, and it is not possible to predict the norms which will be enforced. Hence use of the emission rates as provided in Table 2 simplifies the analysis and eliminates the uncertainties.

Table 2: Emission factors of the vehicles

	Emissions	**Factors**	**unit $CO_{2\ eq.}$**	**Kg $CO_{2\ eq.}$/km**
Motorcycle [13]	CO (g/km)	2.00	3	0.006
	THC (g/km)	0.95	25	0.024
	NOX (g/km)	0.20	298	0.060
	CO_2 (g/km)	33.00	1	0.033
	Total (kg $CO_{2\ eq.}$/km)			**0.155**
3W [14]	CO (g/km)	2.06	3	0.006
	THC (g/km)	1.59	25	0.040
	NOX (g/km)	0.53	298	0.158
	CO_2 (g/km)	64.91	1	0.065
	PM (g/km)	0.026	3000	0.078
	Total (kg $CO_{2\ eq.}$/km)			**0.35**
Petrol car [13]	CO (g/km)	2.72	3	0.008
	NOX (g/km)	0.69	298	0.206
	PM (g/km)	0.06	3000	0.180
	THC (g/km)	0.450	25	0.011
	CO_2 (g/km)	242.000	1	0.242
	Total (kg $CO_{2\ eq.}$/km)			**0.65**
Diesel Bus [15]	CO (g/km)	2.78	3	0.008
	THC (g/km)	0.11	25	0.003
	NOX (g/km)	4.57	298	1.362
	CO2 (g/km)	553.80	1	0.554
	SO2 (g/km)	50.00	0	0.000
	Total (kg $CO_{2\ eq.}$/km)			**1.93**

The generation mix of Tamil Nadu state is listed in Table 3 [16]. The table also contains the emissions in terms of GWP from each source. According to Tamil Nadu Generation and Distribution Corporation Limited (TANGEDCO), the grid system suffers a transmission loss of 12%, resulting in an efficiency of 88% [17].

Table 3: Tamil Nadu electricity grid mix

Grid mix	Internal Generation				Purchase
	RES	Thermal*	Nuclear	Gas	Thermal
Percentage share (%)	50	28	5	3	14
GHG Emissions (gCO2 eq./MJ)	6.2	279	8.2	158	279
GHG Emissions (gCO2 eq./MJ)	3.1	78.12	0.41	4.74	39.06
GHG Emissions (gCO2 eq/MJ)	125.43				
GHG Emissions (kg CO2 eq/MJ)	**0.125**				

The emissions from the metro rail system are estimated by estimating emissions in the production of electricity required to operate the system. There are emissions associated with the production of electricity, which were accounted as the emissions from operating the metro system. The electricity demand of the metro system can be divided into traction demand and auxiliary demand. Traction demand is the electric energy required by the traction motors to propel the vehicles. The auxiliary demand is all other electricity demands, including the operation of ac, lighting, escalators, elevators, etc. A metro train running 400km in a day consumes 6300 kWh of electrical energy a day. These trains are equipped with regenerative braking technology, which regenerates 1900 kWh of electricity [18]. Hence the net energy consumption is 4400 kWh.

3 Emission from the transportation sector:

The inventory data, including emission rates and trip and mode share details, were used for estimating the emission from transportation for the CMA. The emission from every mode considered in this report is quantified in terms of CO_2 equivalent. It is the unit used to express the Global Warming Potential of the emissions over a 100 years time horizon. Expressing the estimated emissions in this unit will make understanding the impact of each pollutant and the comparison of the impact of modes and powertrains easier.

The data obtained from the CMA mobility plan with 2018 as the base year were used in the estimation of the emissions from the transportation sector in CMA. All the estimated values in this section represent the average values. The total daily motorized trips can be obtained from the average daily trip rate and the Population of CMA using Equation 1. It is the total number of person trips made on motorized vehicles per day.

$$T_m = t_m \times P \tag{1}$$

The number of vehicular trips produced by a given mode *i* per day can be calculated using equation 2. In this part of the calculations, person trips had been converted to vehicular trips, which will be helpful in estimating the emissions from the vehicles.

$$T_{m,i} = \frac{p_i \times T_m}{O_i} \tag{2}$$

The total trip length traveled by all the vehicles of a given mode i per day can be estimated using equation 3.

$$L_{m,i} = l_i \times T_{m,i} \tag{3}$$

The average emissions emitted by all the vehicles of a given mode i per day can be estimated using equation 4.

$$GHG_i = L_{m,i} \times GHG_{m,i} \tag{4}$$

Summing up the daily average emissions emitted by all the modes will give the total emissions emitted by all the vehicles in CMA per day (equation 5).

$$GHG_{CMA} = \sum_i GHG_i \tag{5}$$

The total emissions emitted by all the vehicles in CMA in a year can be estimated by multiplying the total daily emission by 365 days (equation 6).

$$GHG_{A,CMA} = GHG_{CMA} \times 365 \tag{6}$$

Where,

T_m = Total motorized trips (trips/day)

t_m = Average per capita motorized trip rate (trips/person/day)

P = Population of Chennai Metropolitan Area

O_i = Average occupancy of a given mode i, i.e., the number of passengers traveling in a vehicle

$T_{m,i}$ = Trips produced by a given mode i.

p_i = mode share of a given mode i, i.e., percentage of trips serviced by mode i (%)

$L_{m,i}$ = Total daily vehicle trip length travelled by all the vehicles of a given mode i.

l_i = Average trip length travelled by a given mode i

GHG_i = GHG emission contributed by a given mode i per day

$GHG_{m,i}$ = GHG emission contributed by a vehicle of a given mode i per day

GHG_{CMA} = Total daily emissions produced by vehicles in CMA

$GHG_{A,CMA}$ = Total annual emissions from vehicles in CMA.

3.1 Results:

At a microscopic level, i.e., at a single vehicular level, the tailpipe emissions in operating a vehicle per km are presented in Table 4. The per capita emission is obtained by dividing the emission by the occupancy of the vehicle.

Table 4: Tailpipe emissions from vehicles

Mode	**kg $CO_{2\,eq.}$/km**	**Per capita kg $CO_{2\,eq.}$/km**
Motorcycle	0.16	0.13
3W	0.35	0.17
Petrol car	0.39	0.20
Diesel Bus	1.93	0.029

The macro-level (CMA) emission estimates calculated using equations 1-6 are shown in Table 5. Walking, cycling, and Metro rail system have no tailpipe emissions. Hence the contribution from these modes in daily emissions is zero. Figure 12 shows the contribution of daily emissions by all the modes. The major contributor of the emissions is the two-wheelers which alone contributes to 57% of the emission. Cars contribute 21% of the total daily emissions.

Table 5: Tailpipe emission for the base year (2018)

Mode	**Total trips**	**Mode-wise total person trips**	**Mode-wise total vehicle trips**	**Mode-wise total vehicular (km)**	**Emissions (kg $CO_{2\,eq.}$)**
Bus	1,40,19,480	9,38,487	47290	4,87,083	9,38,487
Car		19,99,006	4,97,692	50,76,454	19,99,006
3W		11,90,867	4,97,692	34,34,072	11,90,867
2W		53,72,218	34,58,138	3,45,81,384	53,72,218
Cycle		0	0	0	0
Pedestrian		0	0	0	0
Metro		0	7,508	96,857	0
	CMA daily emissions ((kg $CO_{2\,eq.}$)				95,00,578
	CMA annual emissions (tonne $CO_{2\,eq.}$)				34,67,711

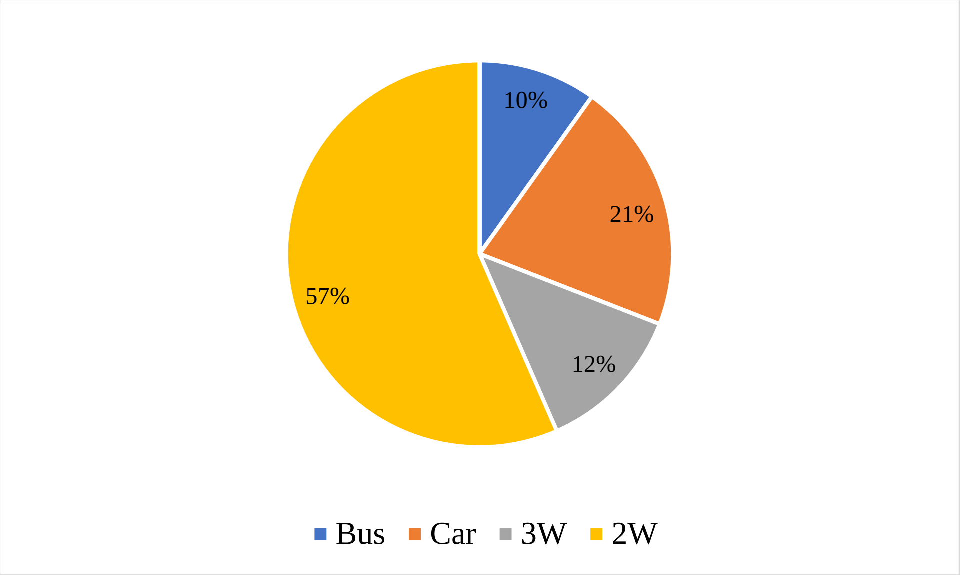
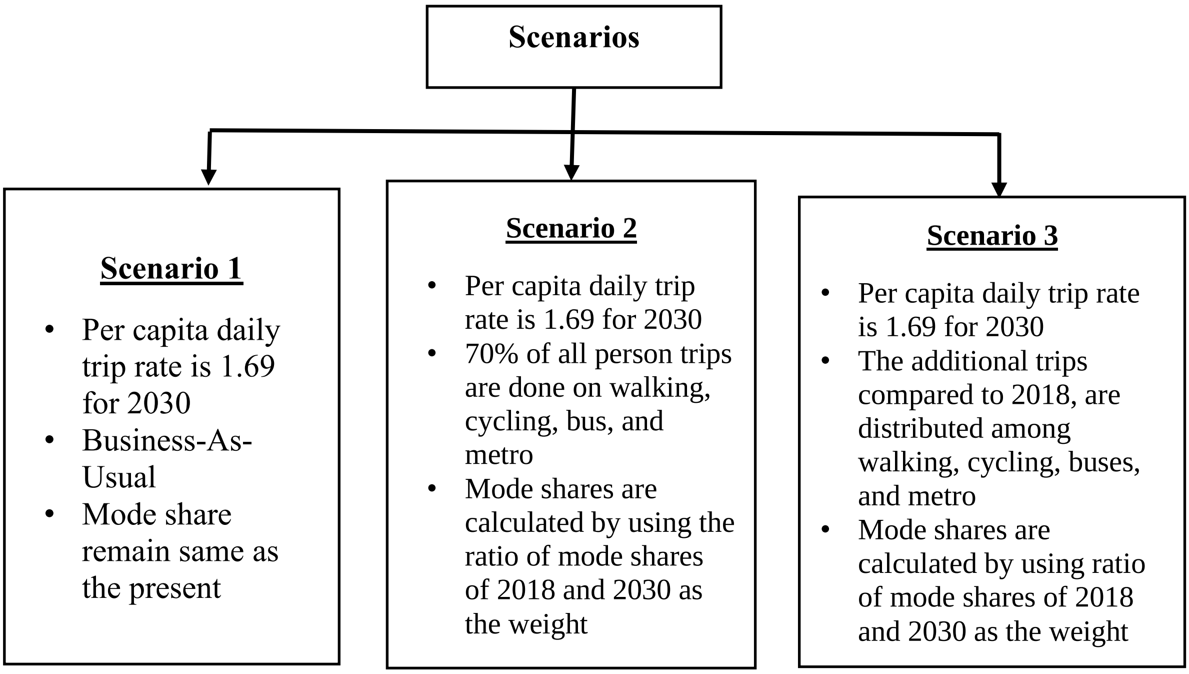


Figure 12: Daily tail pipe emission contribution by modes

3.2 Scenarios:

Based on the results discussed in subsection 4.1, the total as well as per capita emissions contributed by private vehicles are exceedingly high when compared to mass public transport. This subsection will study the emissions for the future and the impact of shifts in mode share on emissions from the transport system. In this report, three scenarios have been created for the year 2030. The scenarios are explained in detail in the rest of the sub-section. Figure 13 is a pictorial representation of the scenarios. In all the scenarios, the average trip length and occupancy are assumed to remain the same.


Scenarios

Scenario 1

- Per capita daily trip rate is 1.69 for 2030
- Business-As-Usual
- Mode share remain same as the present

Scenario 2

- Per capita daily trip rate is 1.69 for 2030
- 70% of all person trips are done on walking, cycling, bus, and metro
- Mode shares are calculated by using the ratio of mode shares of 2018 and 2030 as the weight

Scenario 3

- Per capita daily trip rate is 1.69 for 2030
- The additional trips compared to 2018, are distributed among walking, cycling, buses, and metro
- Mode shares are calculated by using ratio of mode shares of 2018 and 2030 as the weight

Figure 13: Scenarios for the year 2030

Scenario 1:

Scenario 1 is the Business-As-Usual (BAU) scenario, i.e., the mode share of the trips remains constant while the trip rate is updated based on the increase in population. In the Master Plan 2026, the estimation of the population is 125.82 lakh for the year 2026, with a daily trip of 207.60 lakhs. This results in a trip rate of 1.65 per capita daily trip rate. By plotting the population versus trip rate, as shown in Figure 14, it can be observed that the growth of trip rate with respect to population is linear. In other words, there is a constant growth of trip rate with respect to the population.

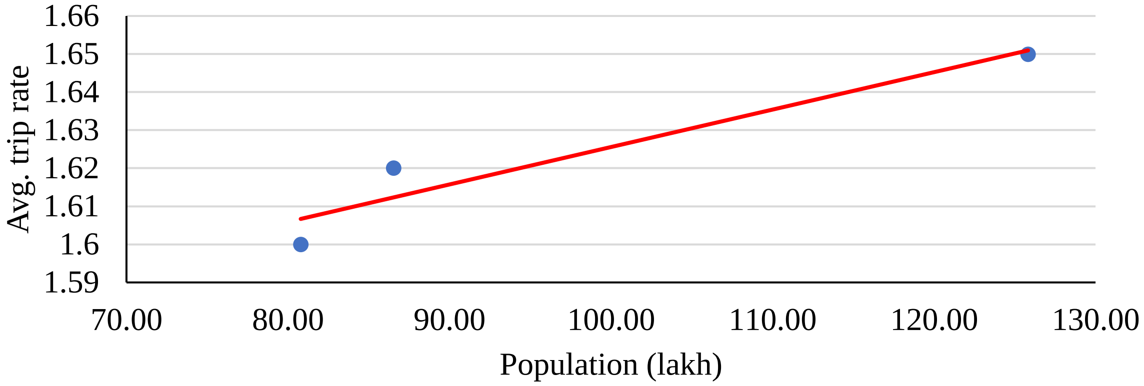


Figure 14: Per Capita trip rate vs population

The trip rate for the year 2030 can be obtained by linear extrapolation from the graph using the equation:

$$y = y_1 + \frac{x - x_1}{x_2 - x_1} \times (y_2 - y_1) \tag{7}$$

Where, y = trip rate for 2030

y_1 = Per capita trip rate per day for the year 2018 (1.16)

y_2 = Per capita trip rate per day for the year 2026 (1.65)

x = Population of Chennai in the year 2030 (138.14 lakh)

x_1= Population of Chennai in the year 2018 (86.54 lakh)

x_2 = Population of Chennai in the year 2026 (125.82 lakh)

A per daily capita trip rate of 1.69 can be calculated after plugging in the values in Equation 7 for the year 2030. This per capita daily trip rate is used in calculating the trip details for future scenarios. The emission estimated for scenario 1 is shown in Table 6.

Table 6: Tailpipe emission for CMA for 2030 – scenario 1

Mode	Mode-wise total person trips	Mode-wise total vehicle trips	Mode-wise total vehicular km	Emissions (kg $CO_{2\ eq.}$)
Bus	52,74,252	78,720	8,10,818	15,62,243
Car	16,56,955	8,28,478	84,50,472	33,27,627
3W	16,56,955	8,28,478	57,16,496	19,82,366
2W	69,07,870	57,56,558	5,75,65,581	89,42,813
Cycle	6,76,785	-	-	0
Pedestrian	58,57,687	-	-	0
Metro	13,06,894	12,499	1,61,233	0
CMA daily emissions (kgs $CO_{2\ eq.}$)				**1,58,15,049**
CMA annual emissions (tonne $CO_{2\ eq.}$)				**57,72,493**

Scenario 2:

Scenario 2 is created by assuming that sustainable modes will cater to 70% of the total person trips in the CMA. The ratio of mode share in 2030 and 2018 were used as the weight to estimate the mode share of the scenario. The emission estimated for scenario 2 is shown in Table 8. This results in a nearly 26% decrease in overall emissions.

Table 7: Tailpipe emission for CMA for 2030 – scenario 2

Mode	Total person trips	Mode-wise total person trips	Mode-wise total vehicle trips	Mode-wise total vehicular km travel	Daily emissions (kg $CO_{2\ eq.}$)
Bus	23337398	6569352	98050	98050	19,45,855
Car		1134900	567450	567450	22,79,196
3W		1134900	567450	567450	13,57,785
2W		4731417	3942848	3942848	61,25,214
Cycle		842970	0	0	0
Pedestrian		7296051	0	0	0
Metro		1627804	15568	15568	0
CMA daily emissions (kg $CO_{2\ eq.}$)					**1,17,08,051**
CMA annual emissions (tonne $CO_{2\ eq.}$)					**42,73,438**

Scenario 3:

In scenario 3, it is assumed that the existing trips will be on their respective modes, i.e., the number of people who travel by their personal vehicles will continue doing so. The additional travel demand due to the increase in trip rate will be met by the sustainable modes of transportation. Here the buses, walking, bicycle, and metro had been classified into the sustainable modes. This assumption can be justified by saying that the upcoming public policies will discourage the use of private vehicles and promote sustainable transportation. The existing personal vehicle users will continue using their current mode of transportation. Like scenario 2, the ratio of mode share in 2030 and 2018 was used as the weight to estimate the mode share of the future scenario. The emissions estimated for scenario 3 is shown in Table 7. This results in a nearly 33% decrease in overall emissions.

Table 8: Tailpipe emission for CMA for 2030 – scenario 3

Mode	New mode share	New person trips increase	Mode-wise total new trips	New Mode-wise total Vehicle trips	New mode-wise total vehicular km travel	Emissions from new trips	Total daily emissions (kg $CO_{2\ eq.}$)
Bus	40.21	93,17,918	37,47,063	55,926	5,76,041	27,99,836	20,48,374
Car	0.00		0	0	0	0	19,99,006
3W	0.00		0	0	0	0	11,90,867
2W	0.00		0	0	0	0	53,72,218
Cycle	5.16		4,80,818	0	0		0.0
Pedestrian	44.66		41,61,561	0	0		0.0
Metro	9.96		9,28,476	8,880	1,14,547	0	0.0
CMA daily emissions (kgs CO2 eq.)							**1,06,10,465**
CMA annual emissions (tonne CO2 eq.)							**38,72,820**

Comparisons across the scenarios:

Comparisons of the daily tailpipe emissions were done for the scenarios discussed earlier. Figure 15 shows the difference in the daily emissions across the scenario as can be seen that the difference with respect to scenario 1 is highest as the daily emission is highest in scenario 1. The target of catering 70% of total trips (represented by scenario 2) by sustainable vehicles reduces emissions by 25.97% compared to the BAU mode share. However, attracting the additional trips generated by sustainable vehicles (represented by scenario 3) is most beneficial in terms of emission reductions as it is 32.91% lower than the BAU mode share and 9.3% lower than scenario 2. The percentage differences are highlighted in Figure 16.

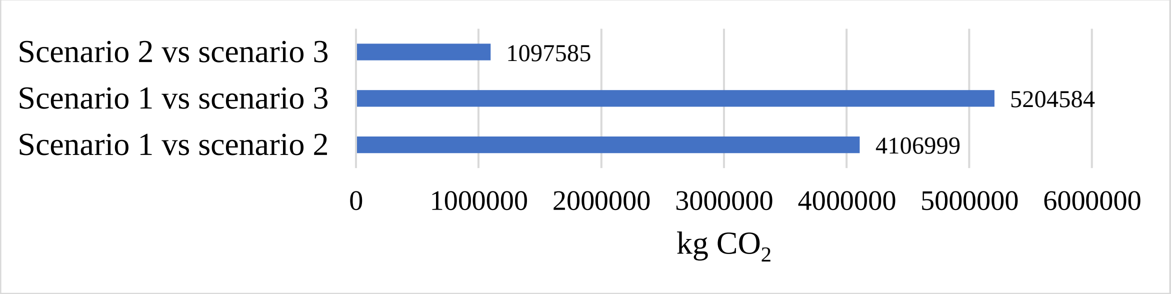


Figure 15: Comparisons of emissions across the scenarios

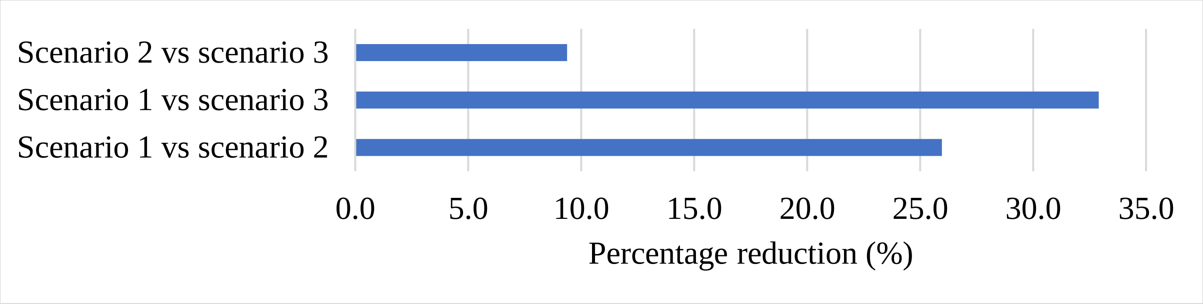


Figure 16: Percentage difference of the scenarios

4 Life Cycle Analysis:

Since 2015, there has been an increase in the number of electric vehicles in India. These electric vehicles are seen as an alternative to conventional petroleum-based fuel-powered vehicles. Exploration and introduction of alternative sources of energy are in their infant stage. These alternative sources are aimed at reductions in reliance on depleting fossil fuels and a reduction in operational emissions. While there are technologies such as hybrid vehicles powering mobility with a cleaner nature, they are still not free from tailpipe emissions. The promising alternative sources for the future include Battery Electric vehicles (BEVs). Vehicles powered by these energy sources are free from tailpipe emissions while operating. These vehicles have powertrains very different from conventional IC-engine-powered vehicles. BEVs have onboard batteries which power the traction motor to power the vehicles for mobility. These onboard batteries are recharged by plugging the vehicles into an external electrical power socket.

Although these powertrains have zero emissions during operations, there are emissions associated with the production of energy. Electricity can be produced from various sources. Each production method and pathway of production have its own share of emissions. Hence claims of zero emissions for these powertrains are often misleading. Additionally, there are emissions in the manufacturing of the vehicles. Vehicle parts such as Li-ion batteries used in the BEVs require enormous amounts of energy and emit a high quantity of emissions. Since there are differences in emissions in different stages of energy production and utilization, comparisons of emissions from these powertrains at any single stage will be misinforming decisions while planning the future of mobility. The method used to compare the emission from the vehicles in section 4 cannot be used for comparisons. A comprehensive comparison encompassing all the stages of a vehicle's production and operation, along with the production and utilization of these energy sources, is required. It can be achieved with the help of the Life Cycle Analysis (LCA) of these powertrains. LCA is the tool used for assessing the impact a product has on the environment throughout its life.

LCA of the mentioned powertrains can be split into vehicle cycle and fuel cycle. The vehicle life cycle will include all the stages of a vehicle's life, starting from the extraction and production of raw materials to the disposal at the end of its life. Hence it is also called Cradle-to-Grave (C2G). The fuel cycle includes all the stages of the fuel, starting from exploration and extraction of the fuel to its consumption in the operational phase. Hence it is also called a Well-to-Wheel (WTW). The impact of these powertrains will be analyzed and quantified based on the impacts from C2G and WTW using LCA. According to ISO 14040 and 14044, LCA should include the following phases.

I. Definition of Goal and Scope.
II. Inventory Analysis.
III. Impact Assessment.
IV. Interpretation.

The four phases of the LCA are covered in the following subsection.

4.1 LCA phases:

I. Definition of goal and scope:

The goal of the study is to assess and quantify the environmental impact of conventional IC-engine, battery electric, and hydrogen fuel cell vehicles. The vehicle classes include motorcycles (2W), autorickshaws (3W), passenger cars, and intracity buses. The impact of each vehicle technology is expressed in terms of Global Warming Potential (GWP) in 100 years horizon. The impact is quantified with the unit $CO_{2\ eq.}$ /km. The system boundaries of the LCA are illustrated in Figures 17 and 18.

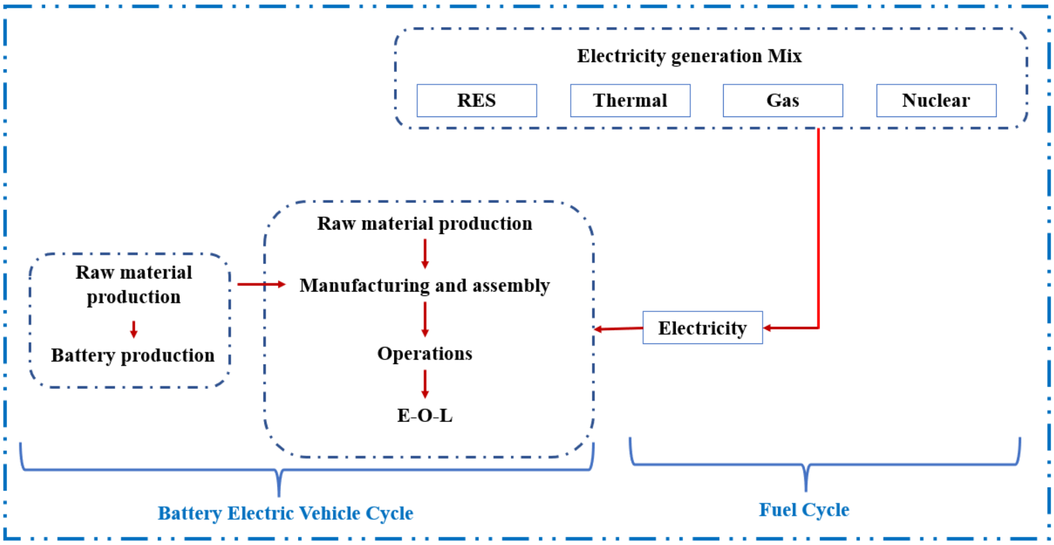


Figure 17: System Boundary for Battery Electric Vehicles

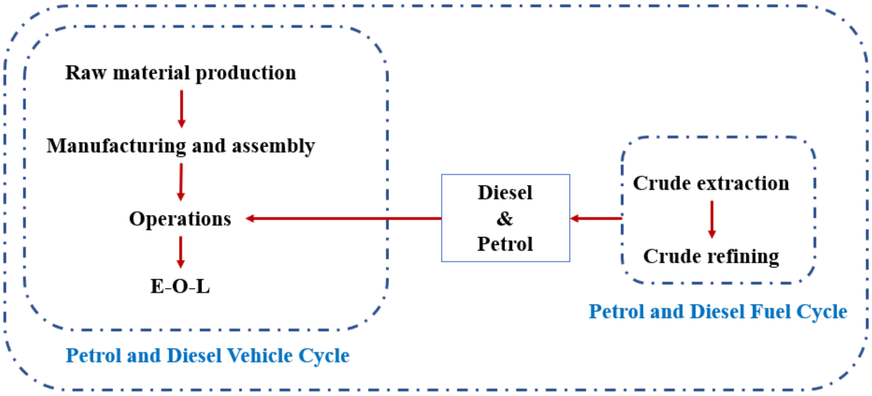


Figure 18: System boundary for petrol and diesel vehicles

II. Inventory analysis:

The inventory data used in this study are collated from existing literature. These collated inventories had been classified into vehicle cycle and fuel cycle.

Vehicle cycle:

In the vehicle cycle, there are emissions associated with the manufacturing of the vehicles as well as other vehicle parts, i.e., battery and charging infrastructure. These associated emissions are accounted for right from obtaining raw materials to the EOL of the vehicles. The unit emissions in the manufacturing of vehicle bodies are 8 kg CO_2eq/kg [19] and battery production is 258 kg CO_2eq /kWh [20], respectively. The unit emission in the manufacturing of Electric Vehicle Supply Equipment (EVSE) is 250 kg $CO_{2\ eq}$. [20]. The unit weight of the onboard battery is 6.4 kg/kWh [21]. The specifications of the representative vehicles for the respective categories are listed in Table 9. These specifications had been collated from manufacturers' websites and catalogs.

Table 9: Vehicle specifications

Vehicle category	Specification	Value
2W – Petrol	Mileage (kmpl)	55
	Kerb weight (kg)	114
2W-BE	Battery capacity (kWh)	3.24
	Range per refill (km)	100
	Mileage (km/kWh)	30.86
	Kerb weight (kg)	108
Car (Petrol)	Mileage (kmpl)	17.5
	Kerb weight (kg)	1230
Car (EV)	Mileage	10.33
	Kerb weight (kg)	1400
	Range per recharge (km)	312
Intracity bus (Diesel)	Mileage (kmpl)	4
	Kerb weight (kg)	5520
Intracity bus (Battery)	Battery capacity (kWh)	186
	Range per refill (km)	150
	Mileage (km/kWh)	0.81
	Kerb weight (kg)	5520

Fuel cycle:

Upstream emissions in the production of electricity for Battery Electric Vehicles (BEVs) will depend on the electricity generation mix. The emission from electricity consumed by BEVs. The Well-to-Tank (WTT) GHG emissions for diesel and petrol are 18175 g CO2eq/million BTU [22]. With an average daily trip length of 400 km and electricity energy consumption of 4400 kWh, the energy efficiency of the metro trains can be estimated at 11 kWh/km (39.6 MJ/km). The embodied emissions (emissions in procuring raw materials, manufacturing, and End-of-Life) of the metro train is 1.61 kg $CO_{2\ eq.}$/km [1].

LCA Formulations:

The average emissions in terms of kg CO_{2eq}/km can be estimated for diesel-powered vehicles using equations 8 and 9.

$$GHG_{D,avg,.i} = GHG_{D,fuel,avg.,i} + GHG_{D,O,avg.,i} + (GHG_{D,M,avg.,i} \times P_{D,i}) \qquad (8)$$

$$= GHG_{D,fuel,avg.,i} + GHG_{D,O,avg.,i} + (\frac{GHG_{D,M.,i}}{VKT_{D,i} \times P_{D,i}} \times P_{D,i}) \qquad (9)$$

The average emissions in terms of kg $CO_{2\ eq}$/km can be estimated for the petrol-powered vehicles using equations 10 and 11.

$$GHG_{P,avg.} = GHG_{P,fuel,avg.,i} + GHG_{P,O,avg.i} + (GHG_{P,M,avg.,i} \times P_{P,i}) \qquad (10)$$

$$= GHG_{P,fuel,avg.,i} + GHG_{P,O,avg.} + (\frac{GHG_{C,M,i}}{VKT_{P,i} \times P_{P,i}} \times P_{P,i}) \qquad (11)$$

The average emissions in terms of kg $CO_{2\ eq}$/km can be estimated for the BEVs using equations 12 and 13.

$$GHG_{E,avg.,i} = \left(GHG_{E,Elect,avg.,i} + GHG_{E,O,avg.,i} + GHG_{E,M,avg.,i}\right) \times P_{E,i} \qquad (12)$$

$$= (\frac{(\Sigma GHG_{E,Elect} \times GM)}{\eta_G \times \eta_{T,i} \times P_{E,i}} + \frac{\Sigma GHG_{E,M,i.}}{VKT_{E,i} \times P_{E,i}} + \frac{GHG_{E,Bat+GHG_{E,EVSE}}}{VKT_{E,i} \times P_{E,i}}) \times P_{E,i} \qquad (13)$$

The average emissions in terms of kg CO2 eq./km can be estimated for the FCEVs using equation 14 and 15.

$$GHG_{Met,avg} = GHG_{Met,Emb.,avg.} + GHG_{Met.,O,avg.} \qquad (14)$$

$$= GHG_{Met,Emb.,avg.} + \frac{GHG_{Met.,E.}}{\eta_G} \qquad (15)$$

Table 10: Notations used in the LCA

Notations	Explanation
$GHG_{D,avg.,i}$	Average emissions for diesel vehicles of class *i* (kg CO_{2eq}/km)
$GHG_{D,fuel,avg.,i}$	Diesel Well-to-Tank (WTT) of diesel vehicle of class *i* (kg CO_{2eq}/km)
$GHG_{D,O,avg.,i}$	Average emissions from the operation of diesel vehicle of class *i* (kg CO_{2eq}/km)
$GHG_{D,M,avg.,i}$	Average emissions from the manufacturing of diesel vehicles of class i (kg CO_{2eq}/km)
$GHG_{D,M.,i}$	Emissions from the manufacturing of diesel vehicles of class i (kg CO_{2eq})

$VKT_{D,i}$	Vehicle Kilometre Travel by diesel vehicle of class i (kms)
$P_{D,i}$	The payload for diesel vehicle of class i (kgs)
$GHG_{P,avg.,i}$	Average emissions from petrol vehicles of class i (kg CO_{2eq}/km)
$GHG_{P,fuel,avg.,i}$	Well-to-Tank (WTT) of petrol vehicle of class i (kg CO_{2eq}/km)
$GHG_{P,O,avg.,i}$	Average emissions from the operation of petrol vehicle of class i (kg CO_{2eq}/km)
$GHG_{P,M,avg.,i}$	Average emissions from the manufacturing of petrol vehicles of class i (kg CO_{2eq}/km)
$GHG_{P,M,i}$	Emissions from the manufacturing of petrol vehicles of class i (kg CO_{2eq})
$VKT_{P,i}$	Vehicle Kilometre Travel by petrol vehicle of class i (kms)
$P_{D,i}$	The payload for petrol vehicle of class i (kgs)
$GHG_{E,avg.,i}$	Average emissions from BEV of class i (kg CO_{2eq}/km)
$GHG_{E,O,avg.,i}$	Average emissions from the operation of BEV of class i (kg CO_{2eq}/km)
$GHG_{E,M,avg.,i}$	Emissions from the manufacturing of BEV of class i (kg CO_{2eq}/km)
$(\Sigma GHG_{E,Elect} \times GM)$	Emissions from the grid (kg CO_{2eq}/KJ)
η_G	The efficiency of transmission of grid
$\eta_{T,i}$	Tank to Wheel (TTW) efficiency of BEV of class i
$P_{E,i}$	The payload for BEV of class i (kgs)
$GHG_{E,EVSE,i}$	Emissions from the manufacturing of EVSE (kg CO_{2eq}/km)
$GHG_{E,Bat}$	Emissions from the manufacturing of battery (kg CO_{2eq}/kWh)
$VKT_{E,i}$	Vehicle Kilometre Travel by BEBs (kms)
$GHG_{Met,avg}$	Average emission in operating a metro train for a km
$GHG_{Met,Emb.,avg.}$	Embedded average emission for metro per km
$GHG_{Met.,O,avg.}$	Operation average emission for metro per km
$GHG_{Met.,E.}$	Average emission in producing electricity required operating a metro for a km

III. Impact assessment:

The impacts estimated from the LCA by the individual vehicles are quantified in this phase of the LCA. The results for the same can be observed in Figure 19. The capacity of a metro train with 4 car is 1276 including seating and standing [23]. While estimating the per capita impact from the use of metro, four cases (25%, 50%, 75%, and 100% occupancy) were considered. The lifetime km for two-wheelers and three-wheelers were assumed to be 80,000 km while for cars it was assumed to be 250,000 km. Buses were assumed to have a lifetime km of 750,000 km.

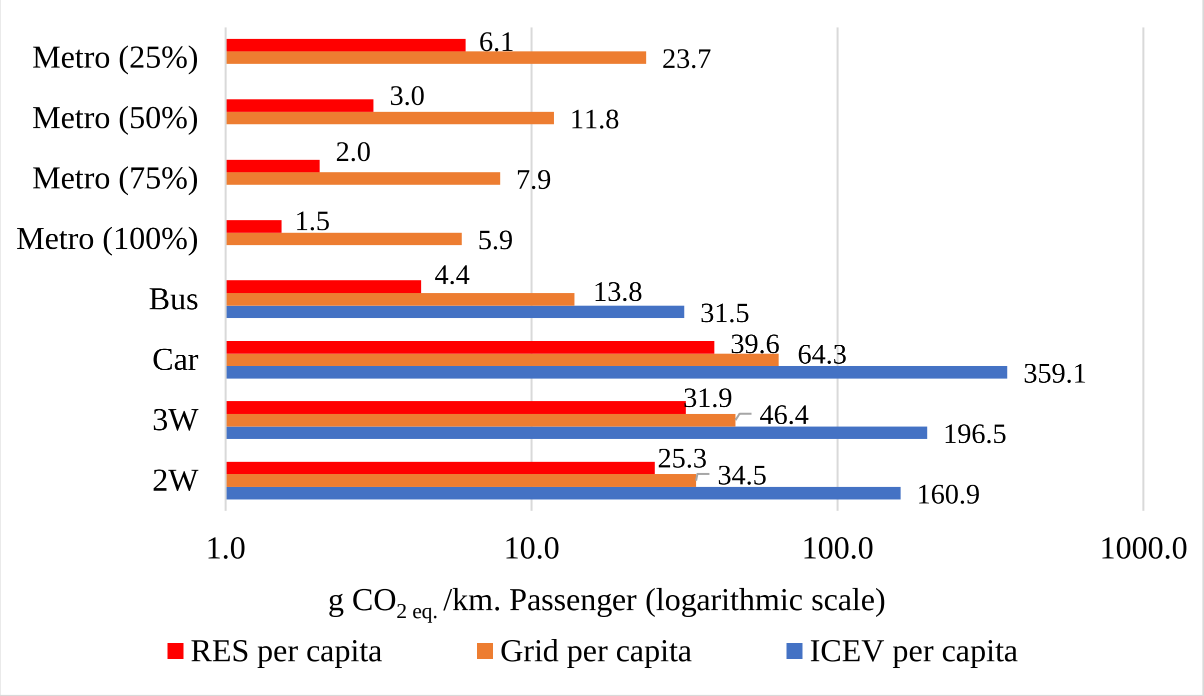


Figure 19: LCA results (kg $CO_{2\text{ eq.}}$ /km. passenger)

The results are also tabulated in Table 11.

Table 11: Tabulated LCA results

Vehicle	**Per capita** (g $CO_{2\text{ eq.}}$ /km. passenger)		
	ICEV	**Existing Grid**	**RES Grid**
2W	160.9	34.5	25.3
3W	196.5	46.4	31.9
Car	359.1	64.3	39.6
Bus	31.5	13.8	4.4
Metro (100%)	-	5.9	1.5
Metro (75%)	-	7.9	2.0
Metro (50%)	-	11.8	3.0
Metro (25%)	-	23.7	6.1

IV. Interpretations of the results:

When the LCA result is quantified in terms of emissions per vehicle per km per person (kg $CO_{2\text{ eq.}}$ /km. passenger), the metro outperforms most of the other modes (except bus) even when it is running at 25% occupancy. Following the metro rail system, buses also outperform all other modes. Cars perform the worst, followed by 3Ws. For all modes, LCA results can be significantly reduced by increasing the percentage of renewable sources of electricity in the current grid mix.

4.2 Scenarios:

The impact assessment is conducted for the future (2030) by creating two scenarios which are explained in detail in the following. In these scenarios, it is assumed that the average trip length and the average vehicle occupancy are the same as the base year, like the assumption done in scenario 1 for the tailpipe emissions. Also, the growth rate in the city population and the trip rate used are as calculated in subsection 4.2.

Scenario 1:

Scenario 1 is created by assuming that all the vehicles will get electrified, and the mode share will be the same as that of the base year. The LCA results for road transport in CMA for 2030 are shown in Table 12.

Table 12: LCA of modes in Scenario 1

Mode	**%age share**	**Mode-wise total person trips**	**Mode-wise total vehicle trips**	**Mode-wise VKT**	**Existing grid**	**100 RES**
Bus	22.6	52,74,252	78,720	8,10,818	7,50,563	2,36,839
Car	7.1	16,56,955	8,28,478	84,50,472	10,87,109	6,69,165
3W	7.1	16,56,955	8,28,478	57,16,496	5,30,781	3,65,189
2W	29.6	69,07,870	57,56,558	5,75,65,581	2383724	17,48,391
Cycle	2.9	6,76,785	-	-	-	-
Pedestrian	25.1	58,57,687	-	-	-	-
Metro	5.6	13,06,894	12,499	1,61,233	12,17,690	3,13,239
CMA daily emissions (kg $CO_{2\text{ eq.}}$)					**59,69,868**	**33,32,822**
CMA annual emissions (tonne $CO_{2\text{ eq.}}$)					**21,79,002**	**12,16,480**

Here the LCA result for bicycles and pedestrians is shown as zero because the impact is contributed by only embodied emission, which is negligible.

Scenario 2:

Scenario 2 is created by assuming that all the vehicles will get electrified and sustainable mode will cater to 70 % of the total person trips in the CMA. The LCA results for road transport in CMA for 2030 are shown in Table 13.

Table 13: LCA of modes in Scenario 2

Mode	**New %age share**	**Mode-wise Total VKT**	**$CO_{2\ eq.}$ - Existing grid**	**$CO_{2\ eq.}$ -100 RES**
Bus	28.15	10,09,915	9,34,865	2,94,995
Car	4.86	57,87,994	7,44,595	4,58,332
3W	4.86	39,15,408	3,63,549	1,25,065
2W	20.26	3,94,28,480	16,32,688	11,97,528
Cycle	3.61	-	-	-
Pedestrian	31.26	-	-	-
Metro	6.98	2,00,824	15,16,696	3,90,155
CMA daily emissions (kg $CO_{2\ eq.}$)			**51,92,393**	**24,66,075**
CMA annual emissions (tonne $CO_{2\ eq.}$)			**18,95,224**	**9,00,117**

When 70% of the daily trips acre catered by sustainable modes, there is a significant reduction in daily $CO_{2\ eq.}$ emission from the passenger transportation system. The difference between the daily emission from scenarios 1 and 2 is 7,77,475 kg $CO_{2eq.}$, resulting in a 13.02% higher emission in scenario 1 compared to scenario 2. This is an indication of the sustainability of mass transport to cater to travel demand.

5 Emission contribution from vehicular traffic:

5.1 Data collection site location:

To study the amount of emission contributed by vehicular traffic, onsite traffic and emission data were collated from a section of Surya Narayana Street, Royapuram. These data will be used for studying the correlations between traffic volume and several types of pollutants measured on the site. The study area location is located near Royapuram loco shed and Chennai Container Terminal Limited's (CCTL) old port. The selected location has a mixture of residential and commercial hubs in the vicinity. It also houses many people from the fishing community. The detailed map of the site location and approach to the site are shown in Figures 20 and 21, respectively. A video camera and pollutant sensors were the equipment used for collecting the onsite data. 24-hour daily traffic data were collected for 20 days from 29/03/2023 to 17/04/2023. The next subsection contains a detailed description of the equipment.

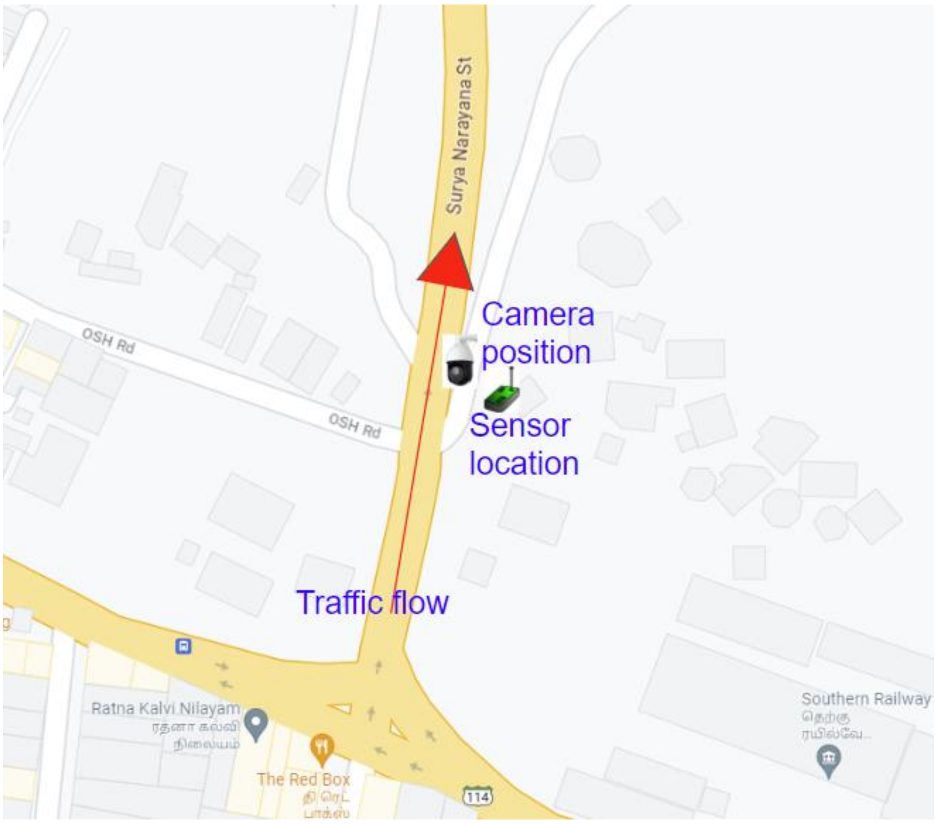


Figure 20: Detailed map of the site location

Figure 21: Approach to the site

5.2 Equipment used in the data collection:

Camera:

The camera was mounted atop an unused light pole on the side of the road section to have an adequate field view for accurate data extraction from the video feed, as shown in Figures 22 and 23.

Figure 22: Camera installation

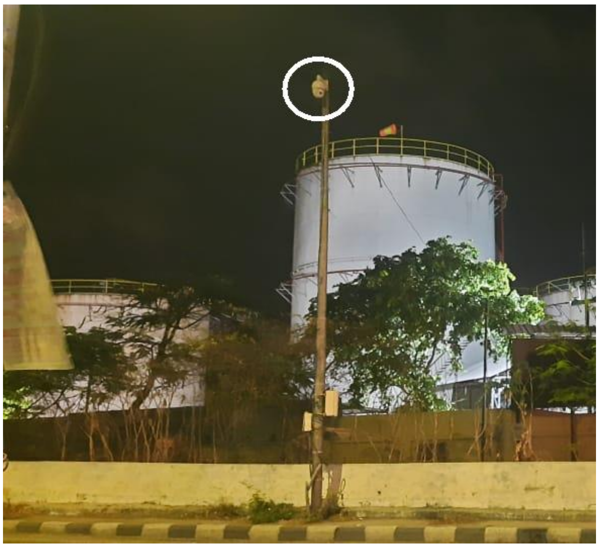


Figure 23: View of the installed camera from the road

The camera used for the data collection was HIKVISION, model number DS-2DE7230IW-AE (B)FC 2MP 30× Network IR Speed Dome camera having the following specifications:

- 1/1.9" Progressive Scan CMOS
- Up to 1920 × 1080 resolution 30× Optical Zoom
- 16× Digital Zoom WDR, Auto Tracking
- EIS Up to 150 m IR distance

- 24 VAC & Hi-PoE power supply
- Support H.265 video compression
- Fibre Optical Transmission, Built-in Fibre Optical slot

Pollutant sensors:

In this report, the ambient pollutants present in the site have been classified into other pollutants and Particulate Matter (PM) based on the source of data collection. The list of pollutants included in the category of other pollutants includes SO_2, NO_2, CO, NH_3, O_3, and Benzene. The data on these pollutants were sourced from the sensors installed in the Air Quality Monitor (AQM) of the Tamil Nadu Pollution Control Board (TNPCB). The station is equipped with Acoem Ecotech Model No: Serinus 50 (SO_2 Analyzer), Acoem Ecotech Model No: Serinus 44 (NO/NH_3 Analyzer), Acoem Ecotech Model No: Serinus 30 (CO Analyzer), and Acoem Ecotech Model No: Serinus 10 (O_3 Analyzer), the same can be seen in figure 24. The PMs were measured on the site with Mini-WRAS, which can be seen in figure 25, which was installed by a team from IIT Madras.

The salient features of Mini-WRAS include:

- Two analysers in one instrument - Combination of optical (OPC) and electrical (nanosized) particle detection
- One combined data set - PM10, PM2.5, PM1, inhalable, thoracic, and respirable particle number size distribution
- 41 equidistant size channels - from 10 nm to 35 µm
- Intelligent Li-Ion battery - for portable use up to 10 hours
- Flexible data acquisition and communication - with USB flash drive, Bluetooth, and MiniWRAS software
- Particle free rinsing air design - for improving detection and reducing signal noise

Figure 24: Sensors installed in TNPCB AQM

Figure 25: Mini-WRAS

5.3 Data analysis:

Traffic data were extracted from the video recorded from the site using object detection. Object detection is the task of autonomously identifying the objects in an image using deep learning. It is a technique to make computers learn using "artificial neural networks" from the labeled training data. For this project, we take the raw videos from the traffic cameras, then feed them to a tiny object detection model to extract the vehicle detections. Then, we use these detections to extract the vehicle trajectories, and once a vehicle has entirely left the frame, we update the directional counts. All the above steps are executed as Python programs. A visual presentation of the data extraction process is shown in Figure 26.

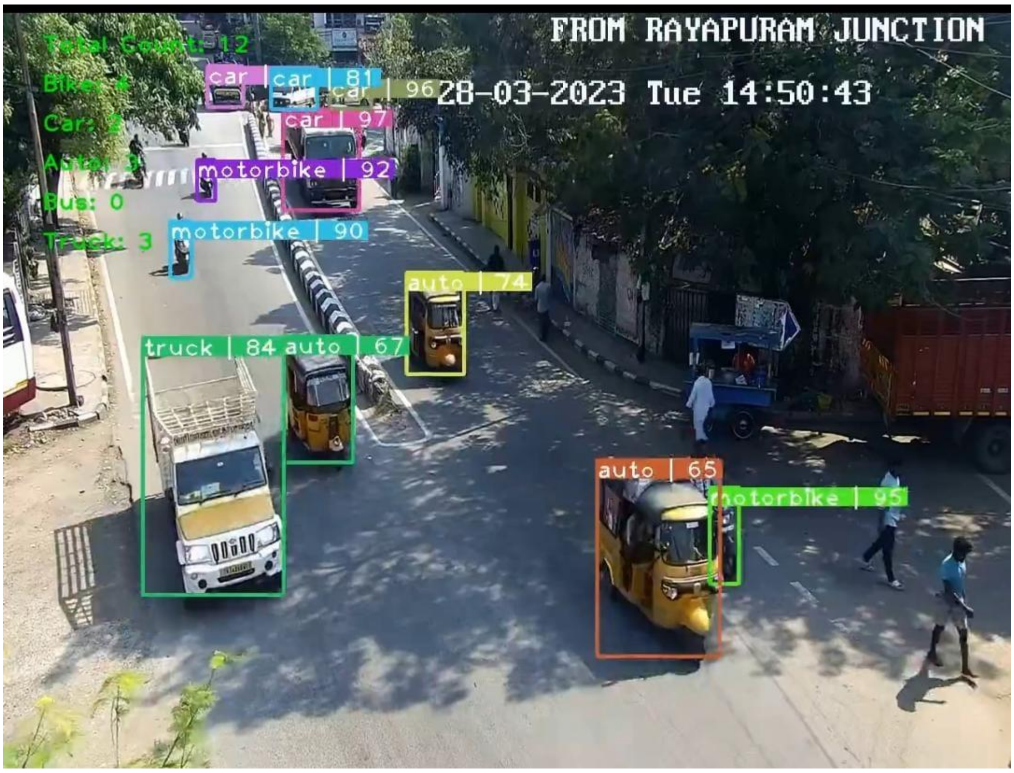


Figure 26: Traffic data extraction from recorded videos

5.4 Data presentation:

This sub-section contains the exploratory data analysis of the pollutant data as well as their correlation with the traffic volume. The correlation study is to observe the change in pollutant concentration with the change in traffic volume. Additionally, changes with respect to the time of the day also had been studied. The traffic volume here had been quantified in terms of Passenger Car Unit (PCU) value. Urban roads are characterized by a mix of various types of vehicles, and the interaction and impact of these vehicles on traffic vary. PCU is a way to quantify the impact imparted by these vehicles on traffic in a unit comparable across all vehicle types. The PCU values for the vehicle types in this study are listed in Table 14.

Table 14: PCU value of vehicle categories [24]

Vehicle type	PCU values
2W	0.75
Car	1
3W	2
Truck/Bus	3.7

PCU values of the traffic volume calculated using the PCU value from Table 14 were used for analyzing the influence of traffic volume on ambient pollution. PM vs PCU values was plotted to find the correlation between the traffic and the PM values. Also, the wind directions provided by the TNPCB AQM, Royapuram, were used to study the impact of wind direction on the concentration of the PM. Here, the wind directions had been classified into: Away and Towards. Wind directions between 45°-135° were classified as away, and 135°-360+45° as towards since the wind from the sea (45°-135°) will be blowing the PM particles away from the sensor. The data point corresponding to these wind directions were colour-coded blue (towards the sensor) and red (away from the sensor) while plotting. The plotted data corresponds to a total of 18.5 hours.

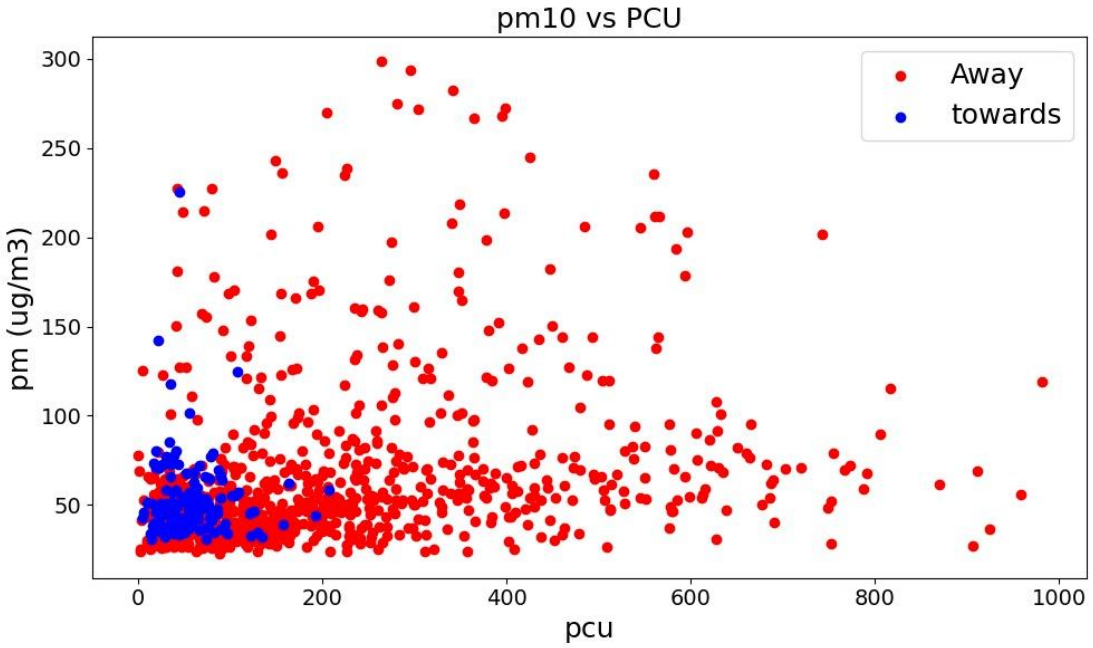


Figure 27: PM10 vs PCU

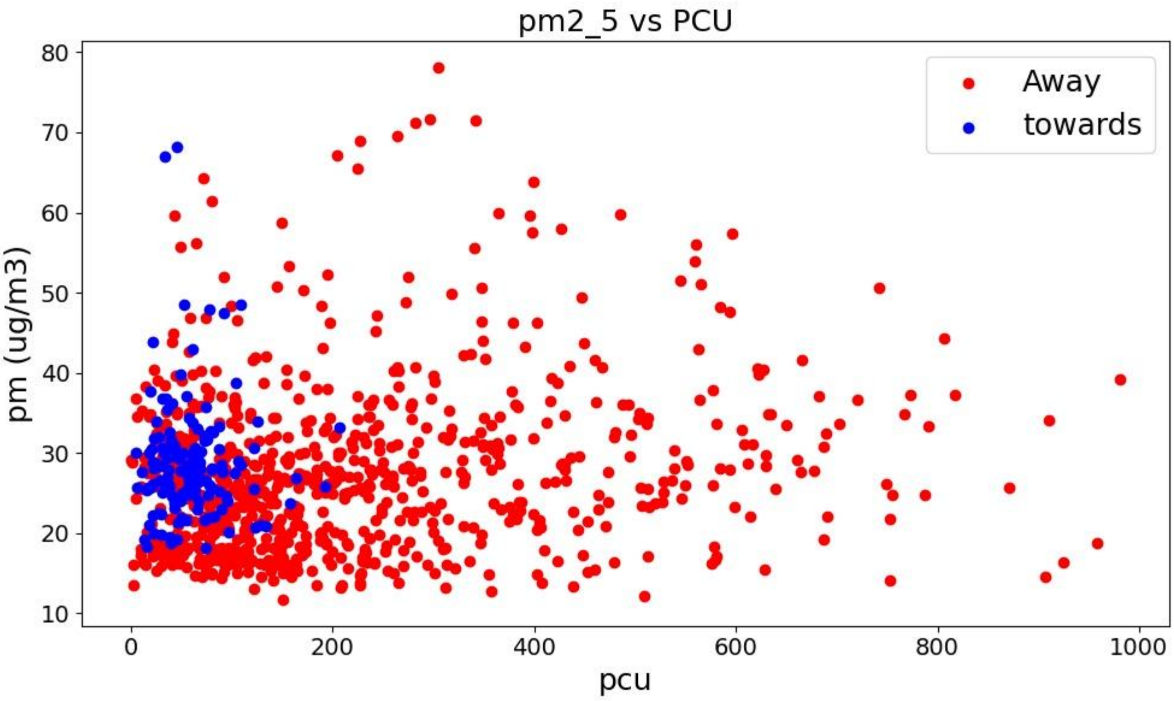


Figure 28: PM2.5 vs PCU

From Figures 28 and 29, it can be observed the changes in PM pollutants have high sensitivity to the changes in traffic volume (PCU values). The concentration of PM particulates can be seen increasing with an increase in the PCU values and decreasing with the decrease in PCU value. This provides insights into the contribution of vehicular traffic to the environment.

The scatter plot also shows that the PM concentration measured by the sensor when the wind direction is away from the sensor is lower, and the same is higher when the wind direction is towards the sensor. The PM concentrations measured when the wind direction is away from the sensor may be under-observed values. Nevertheless, the values exceed the standards specified nationally and internationally. There is an urgent need to reduce the impact of vehicular emissions to improve air quality in the city.

6 Conclusions and policy recommendations:

Air pollution is a critical concern considering the health and environmental impact it causes. The steep increase in air pollution makes the matter even more concerning. There is a need to introduce measures to reduce emissions in the sectors that significantly contribute to emissions. Such actions can be initiated for the transportation sector, which is one of the significant contributors to emissions. These measures can be in regulating tailpipe emissions, reducing the use of personal vehicles, shifting to a cleaner source of energy for mobility, etc. And for effective use of these measures, there is a need to quantify and understand the emissions from the existing fleets of vehicles at a micro-level (vehicle level) as well as at a macro-level (city level).

Hence, tailpipe emissions from 2-W, 3-W, cars, and buses were considered in this report. Tailpipe emission estimations were done for the transportation sectors in CMA using emission rates of the vehicles available in the published literature as well as localized data. These localized data were obtained from reports including the mobility plan, CMRL, and CMDA master plan. These localized data included population, per capita trip rate, mode share of the vehicles, and average trip length per mode. For the present scenario, the emission is minimum for buses when the per capita emission is considered. When the emission at the city level is considered, the maximum emission is contributed from 2-Ws followed by the buses. Using past and present data from reports published by public agencies of the city, population and trip rates were projected for a future year (2030), and the tailpipe emissions were estimated for that year. Three scenarios were created for 2030: business-as-usual (BAU), all new trips choosing to use sustainable mode, and 70% of the total trips being done on sustainable modes. The scenario with BAU produced the maximum emissions, followed by the scenario with 70% of the total trips being done on sustainable modes (26% reduction), and the scenario all new trips choosing to use sustainable mode have the minimum total emissions (33% reduction).

Considering that electrification of mobility is underway and electric vehicles gaining significant market penetration, an LCA study was also conducted in this report. Considering only tailpipe emissions in the methodology for quantifying emissions will lack credibility. Hence, LCA was used to estimate and quantify the impacts on human health as well as on the environment. Using the data available in the existing literature as well as from the localized data, LCA was conducted for vehicles in the city at micro and macro levels. When per capita LCA values are calculated, metro have the least impact even when operated at 25% occupancy. The other public transport system, the buses, also had lower per capita impact than other modes. For any mode, electrification reduces the impact in terms of LCA emissions even while considering the existing TANGEDCO grid. We can see a significant reduction in the impact if fossil-based sources are eliminated from the grid. The usage of personalized vehicles has lower impacts than the mass modes of transportation from the LCA point of view. Two scenarios were created for the future year 2030 to study this. However, in this study we have not considered the impact of improvement in emission standards as well as future technologies that can improve battery chemistry and recycling. These along with other impacts on traffic, such as the increase in the number of vehicles and congestion, also need to be considered to obtain more exact estimates.

Ambient pollution data were collected from a site at Royapuram. These data were used for studying the contribution of vehicular traffic to ambient pollution. The plots from the data reveal that the pollutant concentration increases with an increase in traffic volume. With the limited data collected a quantifiable relation was not obtained however the trends were observed using graphical plots. Also, the inclusion of the wind direction in the plots reveals that pollutant concentration measured when the wind is blowing away from the sensor may lead to under-observed values.

To summarize, Chennai can gain significant reduction in the GHG emissions by electrifying the vehicles. The BEVs outperformed their IC-based counterparts for all the modes. However, as expected, the most significant reduction in environmental impact from transportation can be achieved by shifting more trips to public transport modes that are electrically operated. While the plans of shifting 70% of all trips to mass transport and non-motorized modes reduce the emission, the maximum reduction in emission is observed if all the future additional trips generated are attracted to these sustainable modes. Policies and planning which will discourage the passengers from using personal vehicles and attract them to the mass transport will help reduce emissions at the city level significantly.

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