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ESTIMATION OF EMISSION REDUCTION FROM MASS RAPID TRANSIT SYSTEM(MRTS)IN PHASE 3,DELHI

**A DISSERTATION SUBMITTED IN THE PARTIAL FULFILMENT OF THE REQUIREMENTS
FOR THE AWARD OF DEGREE OF**

MASTER OF TECHNOLOGY IN ENVIRONMENTAL ENGINEERING

Submitted By:

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Abstract

The study examines how Delhi Metro Phase 3 contributes to environmental sustainability by measuring the reduction in road traffic emissions resulting from commuters adopting metro travel instead of conventional road-based transportation. This study translated daily metro ridership into equivalent road vehicle reductions, accounting for occupancy rates, average trip lengths, and vehicle kilometre travelled (VKT) using commuter shift model. The analysis revealed that approximately 250,000 daily commuters shifted to the metro, resulting in a significant decrease in daily road traffic—most notably from two-wheelers and four-wheelers. This modal shift led to an annual reduction of 6,977 tonnes of CO, 3,225 tonnes of HC, 2,216 tonnes of NO_x, 383 tonnes of PM, and 562,255 tonnes of CO₂. Two-wheelers and buses emerged as the highest contributors to these savings, due to their high usage and emission factors. The study concluded that Delhi Metro Phase 3 has yielded measurable environmental benefits by lowering urban emissions, reducing fuel dependency, and enhancing air quality—particularly along the metro corridors. The findings also underscore the importance of effective planning and construction execution to fully realize the sustainable potential of MRTS expansions in densely populated urban settings.

Keywords: Delhi Metro, Phase 3, vehicular emissions, MRTS, CO₂ reduction, modal shift, VKT, urban transport, air quality, sustainability

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CHAPTER 1: INTRODUCTION

1.1 Background

Ambient air pollution is recognized by the World Health Organization (2020) as the fourth most critical risk factor associated with premature deaths across the globe. The WHO has also categorized air pollution as a Group 1 carcinogen. In many Asian regions, the adverse impacts of air pollution are becoming increasingly severe due to rapid urbanization, industrial growth, and the lack of sufficient supporting infrastructure. WHO Also mentioned that 40% of the cities with the highest concentrations of PM_{2.5} are in India and the Clean Air Initiative for Asian Cities reported that 58% of Asian cities (134 out of 230) had annual PM₁₀ concentrations above the WHO annual mean interim target, which is 1 of 70µg/m³ for PM₁₀ (Rizwan, Nongkynrih and Gupta, 2013). Based on these collected data, it is evident that throughout India, there is a strong correlation between air pollution levels, mortality rates, premature deaths and respiratory issues. Thus, it is a problem that needs critical attention in order to address the issue (Begam et al., 2024).

As reported by Chen (2025), air quality in India is monitored by the CPCB through a nationwide network exceeding 450 monitoring stations located in areas representing industrial activities, residential settlements, traffic corridors, and ecologically sensitive regions. The monitoring activities are conducted under the National Ambient Air Quality Monitoring Programme (NAMP), established to systematically track ambient air pollution levels throughout the country (Rizwan, Nongkynrih, & Gupta, 2013). Each of these monitoring networks' primary goal is to verify that national ambient air quality standards (NAAQS) are being fulfilled. An area is designated as a non-attainment area where negative health effects are anticipated if it does not meet the NAAQS (Lang and Nelson, 2007). The CPCB reported that 94 cities across 22 states in India were registered non-attainment areas between 2011 and 2015. It is concerning that there are still a lot of issues which need to be resolved. For instance, regulation of industrial sources requires further action (Singh and Gupta, 2020). However, vehicular emissions remain a top challenge and contributor to air pollution in Delhi.

Pollution Problem in Delhi

Environmental pollution occurs when undesirable materials or agents enter the surroundings and negatively impact living organisms, ecological balance, and human well-being. The most common categories of pollution are air, water, soil, and noise pollution. There are also less well-known types of pollution. These include thermal pollution and radioactive hazard (Sarkar, Dash and Vaghasiya, 2018). It is very challenging in order to attribute the highest risk to

health to any one type of pollution. However, it seems that air and water pollution account for a significant percentage of pollution-related health issues (Armstrong, 2023).

The nature of air pollution in Delhi has evolved considerably, reflecting changes in both pollutant concentrations and the policies introduced to control emissions. Governed through a collaborative framework involving both the central and state governments, Delhi functions as the National Capital Territory of India. According to the 2011 Census, the city's population was estimated at around 16.75 million (Singh et al., 2023). Similar to other large metropolitan regions worldwide, Delhi experiences severe environmental pollution problems (Rai, 2025). Earlier investigations into the health and environmental consequences of air pollution were carried out during 1991–1994 with financial support from the World Bank Development Research Group.

The WHO (2020) reported that Delhi's average total suspended particulate (TSP) concentration was nearly five times the annual limit recommended by the organization. Moreover, records presented by Delhi Capital (2023) showed that TSP levels surpassed the WHO's daily guideline on approximately 97% of observation days. While particulate matter contributed a smaller proportion of non-trauma deaths in Delhi compared to the United States, the associated mortality burden was more severe in terms of years of life lost, as affected individuals generally died at younger ages (Bhat, Farzaneh, & Toosty, 2022).

The environmental situation in Delhi was examined in 1997. It was conducted by India's Ministry of Environment and Forests due to concerns over the worsening environmental conditions. One of the issues this study identified was air pollution. An estimated 3000 metric tonnes of air pollutants were released daily in Delhi (Guttikunda et al., 2023). Among this air pollution, vehicular emissions only accounted for 67% of the total and coal-based thermal power plants for 12%.

According to observations by the CPCB, air pollution in Delhi experienced a notable increase between 1989 and 1997, primarily as a result of the expanding vehicle population. Carbon monoxide emissions from transportation sources rose sharply, reaching levels in 1996 that were 92% greater than those measured in 1989 (Sarkar, Dash, & Vaghasiya, 2018). At the same time, measures such as restricting lead-related industrial activities and phasing out leaded gasoline helped reduce airborne lead concentrations. Besides large industrial operations, Delhi contains a substantial number of small-scale industries, which were estimated to contribute around 12% of total air pollution in the city (Beig et al., 2020).

Herath Bandara and Thilakarathne (2025) reported that data published by the Delhi Transport Department estimated the vehicle population in the National Capital Territory to be more than 3.4 million, with an annual growth rate of around 7% on a compound basis. A major concern identified in the report was that a specific segment of vehicles contributed nearly two-

thirds of transport-related air pollution. However, pollution levels have declined considerably when compared with those observed in the mid-1990s. Air quality is generally evaluated using PM₁₀ concentrations, which include airborne particles measuring 10 micrometres or less in diameter. Due to their microscopic size, these particles are significantly smaller than the thickness of a human hair (Rai, 2025).

Particles this small have the capacity to enter the lower respiratory tract. These particles are probably the cause of harmful health effects. According to the WHO Air Quality Guidelines, the recommended annual mean concentration of PM₁₀ was 20 µg/m³ (Dutta and Jinsart, 2022). Any rate above this has a greater chance of cardiopulmonary health effects. It impacts the breathing and respiratory systems, damages lung tissue, causes cancer and early mortality are the main health risks associated with PM₁₀ exposure.

Among the population groups most vulnerable to air pollution are older adults, children, and individuals suffering from chronic respiratory disorders. People with asthma are particularly susceptible to the adverse health effects of particulate matter exposure. The World Health Organization (WHO) published an urban air quality database that compiles particulate matter data from cities around the world (World Health Organization, 2020). According to this database, Delhi recorded an average PM₁₀ concentration of approximately 198 µg/m³, which is nearly ten times higher than the recommended maximum limit (Dutta & Jinsart, 2022). Studies have further identified vehicular emissions and industrial operations as major contributors to both outdoor and indoor air pollution in the city.

Metro Rail Transport System in Delhi

Metro rail systems are being developed in a number of cities across India. Metro projects became a priority for the Indian government due to growing demand for mobility and the rate of urbanisation. The advantages of the rail transport network are emphasised in numerous studies. In India, it is one of the well-known public transport options that has helped improve the situation of vehicular emissions. The Delhi Metro Rail Corporation or DMRC Ltd. is a state-owned business that was established in accordance with the Company Act 1956 on March 5, 1995 (Shukla and Aditi, 2019). Both the Indian government and the government of Delhi came together in the country's central territory and equally participated in establishing the DMRC. Delhi and the NCR include places like Faridabad, Gurugram, Bahadurgarh, Noida and Ghaziabad (Chidambara, 2019). These places fall under the Delhi Metro system. After the Kolkata metro, it is India's second-oldest metro. On a global scale, the Delhi Metro is recognized as the ninth most extensive metro network by route length and ranks sixteenth worldwide based on passenger volume, highlighting its significance as a major urban transportation system.

The Delhi Metro, the largest system in India, consists of nine coded regular lines (DMRC, 2019).

The table below provides a comprehensive overview of the different lines of DMRC.

Table 1: A Complete Overview of the Delhi Metro Network

Delhi Metro Lines	Location	Start Year
Red Line	Rithala to Shaheed Sthal.	2002
Yellow Line	Samaypur Badli to HUDA City Centre.	2004
Blue Line	Noida City Centre to Dwarka Sector 21.	2005
Green Line	Inderlok to Brigadier Hoshiyar Singh, with a branch line from Ashok Park Main to Kirti Nagar.	2010
Violet Line	Kashmere Gate to Raja Nahar Singh.	2010
Orange Line (Airport Express Line)	Direct connection to the airport.	2011
Magenta Line	Janakpuri West and Botanical Garden	2017
Pink Line (Longest Line)	Majlis Park to Shiv Viha	2018
Grey Line	Dwarka to Najafgarh	2019
Silver Line	Part of Phase 4, from Janakpuri West to R.K. Ashram	2026 (Estimated)

Source: (DMRC, 2019)

1.2 Literature Review

Vehicular Pollution in Delhi

According to Mogno et al. (2023), the number of motor vehicles in Delhi has seen a steady increase over the recent years. By March 2020, the total number of registered vehicles in the city had reached around 13.3 million. This represents a significant expansion of the vehicle fleet, with registrations doubling over the past ten years and increasing approximately four times over the preceding twenty years. According to Dafe et al. (2023), vehicles operating within the transportation sector are commonly grouped into eight categories, namely two-wheelers, three-wheelers, buses, personal automobiles, commercial passenger vehicles, light commercial vehicles, heavy commercial vehicles, and miscellaneous vehicle types. However, among these vehicles, 2Ws hold the majority of the proportion of vehicles. 2Ws at Delhi hold about 56% of all vehicles, followed by personal vehicles at about 23%. There are about 17% commercial vehicles. Furthermore, there are 3Ws and buses which are at about 3%, and the remainder of the vehicles are 3%. In order to address the rise in vehicle emissions, the Supreme Court of India approved a rule in 1998 (Sahu, Mangaraj and Beig, 2023). This rule required all of Delhi's

transport systems to run on compressed natural gas or CNG. There are currently about 1 million CNG-powered vehicles in Delhi. These vehicles are mostly composed of 26% CNG 3Ws, 67% CNG cars and 7% CNG buses (Dafe et al., 2023). Since the government has long been worried about Delhi's air pollution problem, Bharat Stage-IV or commonly known as BS-IV, emission standards were introduced in Delhi in 2010 (Saxena, Bhardwaj and Ghosh, 2012). Due to the severe worsening of air pollution, Delhi was the first to roll out BS-IV 7 years before the whole country. Delhi has been using BS-IV since 2018, but it was suggested that other cities adopt it by April 2020 (Mogno et al., 2023).

To address the growing problem of vehicular emissions in India, the National Vehicle Scrappage Policy was announced on 13 August 2021 and became operational on 25 September 2021. As part of these efforts, the Delhi Transport Department issued regulations mandating the automatic deregistration of diesel vehicles older than ten years beginning in January 2022 (Khandare & Bhongale, 2023). Despite the implementation of vehicle retirement measures, assessments indicate that a proportion of vehicles registered between 2000 and 2010 continued to remain in operation on Delhi's roads in 2020. The study area comprises approximately 2,450 km of major roadways and nearly 31,000 km of secondary roads. Vehicle density estimates were derived from manual traffic counts conducted at 87 survey locations distributed across Delhi and the adjoining National Capital Region (NCR) (Iyengar, Dolšak, & Prakash, 2019). In addition, the age distribution of the vehicular fleet was evaluated to better understand fleet characteristics and emission patterns.

Delhi, being one of India's largest megacities, experiences particularly high traffic volumes along major transport corridors such as the Delhi–Meerut Expressway, Dhaula Kuan, Peeragarhi, Ashram Road, and South Extension–Airport Road, where daily traffic volumes frequently approach 100,000 vehicles. The city's transportation network is further influenced by neighbouring states, including Uttar Pradesh, Haryana, and Punjab, which maintain strong economic and commuting linkages with the Delhi NCR region (FIA Foundation, 2024). Consequently, vehicles registered outside Delhi contribute nearly 40% of the traffic observed on many of the city's principal arterial roads (Jha, 2015).

Despite numerous government interventions over the past decade, including traffic management measures and the promotion of cleaner vehicle technologies, substantial improvements in Delhi's air quality have remained limited. Rapid urban expansion, industrial development, and the continuous increase in vehicle ownership have further intensified environmental pressures (Iyengar, Dolšak, & Prakash, 2019). Therefore, evaluating the effectiveness of existing pollution-control measures and identifying strategies for further emission reductions remain critical for achieving long-term air quality improvements in the region (Khandare & Bhongale, 2023).

Mass Rapid Transit Systems (MRTS)

Mass Rapid Transit Systems, or MRTS, have emerged as a crucial intervention in urban mobility planning. It provides the opportunity to transport large volumes of passengers with minimal emissions which makes it indispensable for sustainable city development. MRTS contributed to equitable access, reduced traffic congestion and socio-economic upliftment

through improved connectivity. Globally, systems like Delhi Metro showed how MRTS improve urban productivity and reduce dependency on fossil fuels. However, effective implementation requires integration with feeder modes, affordability considerations and phased infrastructure expansion (Shukla and Aditi, 2019). MRTS is supported by strategic land-use planning. It is significant in order to mitigate vehicular emissions and foster inclusive urban growth. The Delhi Metro had a significant effect on Delhi's pollution from 2004 to 2006. The level of carbon monoxide within the major traffic intersection in central Delhi significantly decreased shortly after the DM's Yellow Line was first extended. Additionally, there is evidence to suggest that the implementation of the Blue Line of Delhi caused a reduction in nitrogen dioxide levels (Sahu, Mangaraj and Beig, 2023). However, the overall impact of the metro system on air pollution is critically dependent on how the electricity required to power the metro is generated. Although it still has a positive impact of the DM on Delhi's pollution shortly after some of the larger metro expansions.

The development and operation of MRTS create substantial employment opportunities. These ranged from specialised engineering positions to service-oriented jobs. Therefore, it provides substantial growth to the local economy (Ardiansyah et al., 2024). In the social context, MRTS fosters inclusiveness through affordable and reliable transportation. It provides benefits for a wide range of socio-economic groups. In the case of a metropolitan city like Delhi, where income differentials are significant, an effective metro rail network can bring sustainable opportunities for transport. It gives the ability to connect the poor neighbourhoods with prosperous regions. The reliability and predictability of MRTS also empower women and marginalised communities. It gives a safer environment for transport with better security for the communities. Further, MRTS improves public health as it minimises air pollution. There are also several additional activities that many of the MRTS around the world have adopted. However, most significantly, the replacement of private vehicles with metro systems is able to reduce environmental challenges (Chidambara, 2019). From a psychological viewpoint, it reduces the stress of traffic jams, which leads to a superior quality of life for city people.

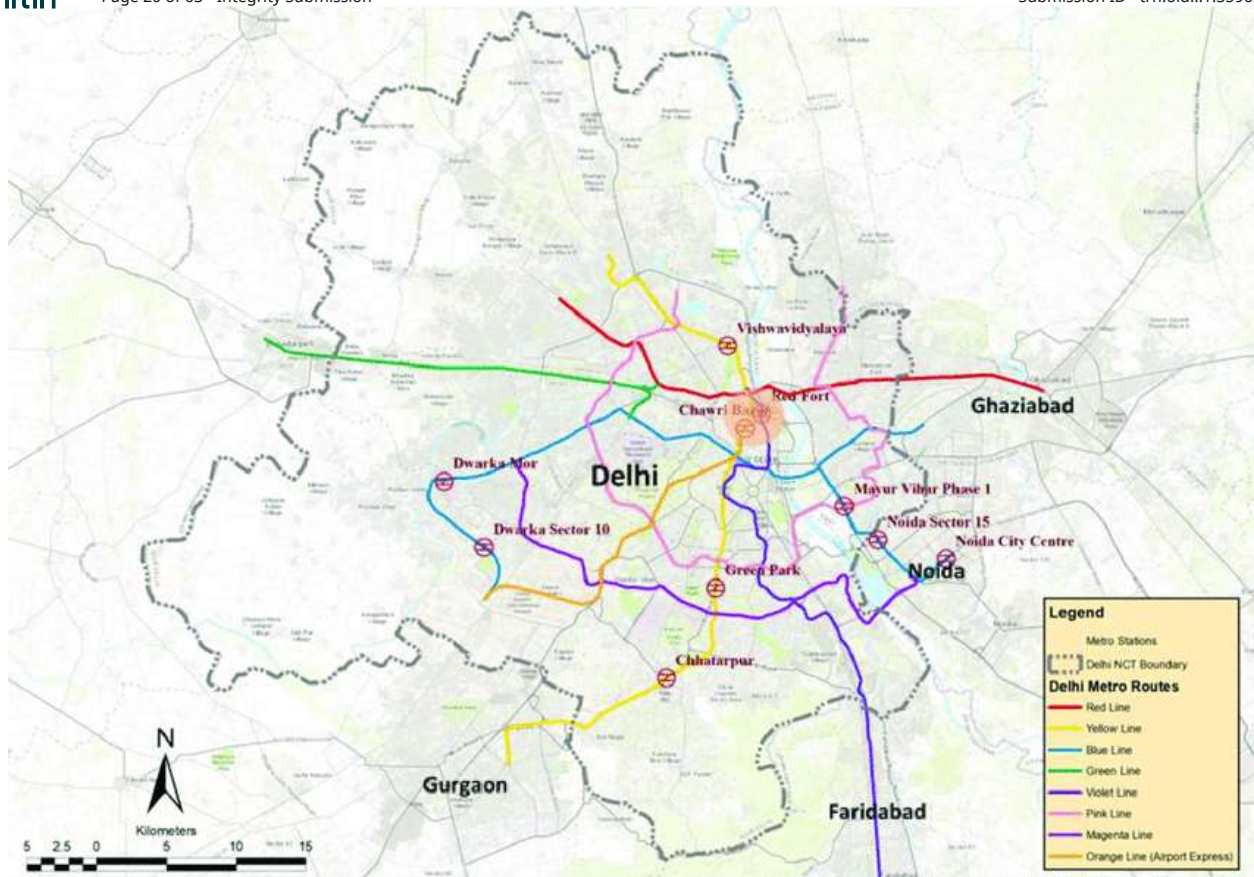


Figure 1: Delhi Metro Railway Network Source: (Chidambara, 2019)

Delhi belongs to the "Global South City" category. These are the urban regions located within countries that are often characterised as developing or less developed, primarily in Africa, Asia and Latin America. These cities experience rapid urbanisation and face unique challenges related to poverty, infrastructure and sustainability. In the case of Delhi, it deals with urbanisation and a lack of resources and provides instructive lessons on the implementation and difficulties of MRTS. For example, Bogotá's Bus Rapid Transit or BRT network, TransMilenio, showed how efficient, low-cost transit solutions are capable of transforming city mobility even in resource-poor environments. Although faced with early drawbacks of crowding and insufficient funding, the system has developed into a best practice for other cities (Saygaonkar, Swami and Parida, 2016).

Thus, it indicated the need for flexibility and expansion in phases. Also, the success of the Delhi Metro highlighted the importance of MRTS integration with other modes of transport. These include buses and other vehicular public transportation modes in order to solve last-mile connectivity problems. Despite the benefits, there are challenges to the affordability of fares for low-income commuters. There is also the necessity of ongoing network growth to match urban expansion. Contrary to this, several cities in the African continent such as Lagos, have had a hard time implementing MRTS. These are done due to poor planning and political instability (Ogundare, 2023). These instances highlight the importance of governance, public participation and the right vision to ensure the success of mass transit schemes in the long term.

Emission Reduction Through Urban Transport

Urban transport systems are highly significant in order to achieve environmental sustainability and public health. The sustainable solution in public transport **is one of the** most powerful **options in** order **to reduce emissions** in contemporary cities. It has the transformative possibilities to coordinate transport approaches with the right policy frameworks, technological innovation and behaviour change. It enables cities to have cleaner urban mobility. Global cities understand the significant emission reduction needs. Thus, they include systemic policy responses that transform transport ecosystems. For example, the Ultra Low Emission Zone in London shows how regulation can drive change. Also, deploying financial disincentives for high-emission vehicles and recycling revenue into cleaner alternatives are highly effective in ensuring sustainable solutions (Kechagias et al., 2020). There are demands for management techniques which correlate with good incentives. It ranges from subsidies on electric vehicles to priority parking for carpool users. The effectiveness of these policies is highly dependent on the alignment with wider urban planning. For instance, Barcelona has the "superblocks" system which reconfigures street space use. It favours pedestrians and public transport over cars (Gil-Alonso, López-Villanueva and Thiers-Quintana, 2022). This reallocation helps to reduce emissions at source as it minimises vehicle miles travelled and enhances air quality and community health.

The electrification of the transport fleet is the most apparent technological change. Several cities have introduced policies that transform transport modes, like all-electric bus networks. However, the real innovation is in the application of hardware developments with intelligent systems. These include adaptive traffic lights that reduce idling, AI-based route schedule that maximises vehicle loads and integrated mobility platforms that facilitate easy modal transfers (Manglano-Redondo, Paricio-Garcia and Lopez-Carmona, 2025). These are the technological solutions that have to be context-dependent. Retrofitting informal transport networks in cities in developing regions with cleaner technology intends to work better than enforcing a new system completely. For example, the introduction of electric three-wheelers in Indian cities at a gradual pace is a classic example of a pragmatic technological transition (Konečný et al., 2020).

Urban transport emissions are major environmental and health hazards. The focus should be on cleaner mobility solutions. These include electrification of fleets, congestion pricing and promotion of public transport systems. For example, Cities like London and Barcelona have demonstrated the efficacy of regulatory frameworks, pedestrianisation and superblocks in order to decrease vehicle kilometres travelled or VKT (Bibri and Krogstie, 2020). Also, technological innovations like intelligent traffic management with behavioural shifts toward shared mobility have increased these gains. The integration of low-emission vehicles with MRTS ensures a

systemic reduction in urban pollutants. However, emission mitigation success is highly dependent on policy coherence and infrastructure readiness, along with the willingness of commuters to adapt (Beig et al., 2020).

It requires both innovative technology and effective policy frameworks that are needed to align with the human aspect of transport decisions. Efficient cities prioritise commuters by providing a sustainable mix of transportation modes (Kåresdotter et al., 2022). These include public transit, cycling, walking and micro-mobility. The goal of efficient cities is to reduce congestion and improve accessibility. These cities also focus on integrating these modes for a seamless commuter experience. Changing the psychological mindset away from car ownership and toward "mobility as a service" needs is evident in inefficient cities. It rewards the public through tangible infrastructure improvements. For example, the three-decade path in Copenhagen has always been a cycling-friendly city (Bibri and Krogstie, 2020). It showed how cultural attitudes can be transformed through repeated messaging and incremental design enhancements. The city shifted cycling from being an out-of-fashion activity into a mass commuting mode (Hapriyanto and Azmi, 2025). Thus, it helps the city to adopt the easiest, safest and most socially accepted way to commute. However, the path to a low-emission urban transport system faced several challenges and barriers. Institutional fragmentation often hinders coordinated action. With the transport, environment and urban development agencies working at cross-purposes, the "first/last mile" problem continues to limit public transport adoption. It is specifically in crowded cities where infrastructure systems remain underdeveloped (Kåresdotter et al., 2022). Political and economic challenges are also significant barriers. There can be seen resistance from auto industry and fuel suppliers. For example, the gradual phase-out of diesel buses in several European cities faced intense opposition (Manglano-Redondo, Paricio-Garcia and Lopez-Carmona, 2025). It showed the need for an effective transition framework which addresses the workforce and brings effective conversion within the industry.

Delhi Metro Phase I & Phase II

Metro offers considerable potential in order to reduce carbon emissions in urban mobility through modal shifts from high-emission road vehicles. Metros are electrically powered, which eliminates tailpipe emissions and offers energy-efficient travel per passenger-kilometre. It reduces congestion and influences urban form via transit-oriented development or TOD. Also, it is a highly advanced solution for non-motorised last-mile travel. Delhi Metro's Phase 3 is significant, which contributed to emission reductions in CO₂, NO_x and PM along its corridors. However, full environmental benefits depend on system design, fare affordability and complementary policies (Fraszczyk, Weerawat and Kirawanich, 2020). These include parking

restrictions and fuel pricing. The synergy of metro infrastructure with urban planning is a key solution in order to optimise emission savings.

The introduction of Delhi Metro Phase 1 and Phase 2 marked was a shift in the city's efforts to handle the transport-related emissions. Phase 1 was completed in 2006 which covered 65 kilometres. It offered a reliable alternative to congested road travel. Phase 2 later expanded the network to over 190 kilometres by 2011 which improved connectivity across densely populated zones. These phases successfully diverted lakhs of daily commuters from private vehicles to the metro rail. These two phases were significant in order to reduce the number of VKT on roads. The combined impact of Phases 1 and 2 led to an annual reduction of over 200,000 tonnes of CO₂. Apart from this, there was a notable decrease in NO_x, CO, HC and PM emissions (Sharma et al., 2014). The use of electric power instead of fossil fuels enables the metro rail system to eliminate the tailpipe emissions and reduce the fuel dependency. Furthermore, the metro encouraged transit-oriented development, which improved the last-mile connectivity in many areas. It improves accessibility and reduces dependence on cars and two-wheelers. With reduced road congestion, there was also a decline in idle emissions and fuel wastage (Goel and Tiwari, 2016). The early phases of Delhi Metro played a foundational role which demonstrates the environmental viability of mass rapid transit systems in urban India and set the stage for future expansions like Phase 3.

Modal Shift Dynamics in Urban Transport

Emissions from fossil-fuelled cars pose a challenge to green transport modes in urban mobility. There are also behavioural, infrastructure and culture challenges that substantially impact the green transport dynamics. Understanding these dynamics is key to city governments in order to minimise transport emissions and make urban areas more liveable. The dynamics of modal shifts are disrupting entrenched travel customs. Fossil-fuelled cars tend to become habitual behaviour that is linked to assumptions of convenience, status and personal identity (Chen et al., 2023). Successful modal shifts like in Copenhagen or Amsterdam show that this involves establishing alternative options which offer benefits and are more desirable to become sustainable. It also makes public transport affordable and reliable along with comfort and dignity. It needs appropriate infrastructure that is perceived as safe for all ages and abilities (Hapriyanto and Azmi, 2025). The modal choice psychology showed a number of important leverage points. Travel time reliability may outright speed in commuter choice. It is an underground which takes a minute or two longer and produces consistent trip times to acquire market share from drivers irritated by unpredictable congestion. The principle of "excess travel time" suggests the undesirable parts of a trip such as waiting or transfers become especially

significant (Şengül and Mostofi, 2021). Efficient systems minimise these annoyances through high service frequencies, cover and efficient interchanges.

Urban structure has a significant role in order to facilitate modal change. Concentrated employment centres and dense mixed-use neighbourhoods within cities naturally sustain the viability of public transit. However, density facilitates transit so too can transit investment generate subsequent urban growth by transit-oriented development. The result is a self-reinforcing cycle in which each attracts the other over time (Yu et al., 2020). Social norms and peer pressures strongly influence transport decisions. For instance, colleagues, friends and relatives are seen using sustainable transport, people are more likely to do the same (Okraszewska et al., 2018). Cities can speed up this social contagion by creating sustainable transport visibly popular and socially attractive. The momentum to create an infrastructure that generates strong path dependencies is highly important. Private car-oriented cities with wide roads and good parking spaces physically make sustainable transport hard to achieve. It takes bold decisions to repurpose street space and change parking policies (Oviedo, Granada and Perez-Jaramillo, 2020). These are usually met with initial opposition before gains become visible.

Most significantly, the modal shift represents not just a technical challenge but a profound cultural transformation in order to achieve better urban mobility. Cities need to lead the transition and understand that sustainable transport must compete not just on practical terms. However, it offers a fundamentally better quality of urban life. These include cleaner air, quieter streets and more human-centred public spaces. The modal shift from private vehicles to sustainable modes becomes part of a larger reimagining (Okraszewska et al., 2018). These are important elements to achieve sustainable transportation solutions in modern cities and foster a desirable place to live and work.

1.3 Research Gaps

Delhi continues to face severe traffic congestion and deteriorating air quality, driven largely by rapid urbanisation and the increasing reliance on private vehicles. While the introduction of Delhi Metro Phase 3 marked a major step in expanding the city's transit infrastructure, there has been no systematic evaluation of its actual contribution to reducing emissions. The modal shift offered by the metro in lowering fuel consumption, easing congestion, and cutting pollution remains underexplored, with only limited qualitative studies available on how commuters in fast-growing cities like Delhi adapt to such changes. Moreover, the relationship between metro expansion, land-use transformation, and long-term emission reductions has not been sufficiently analysed, even though earlier phases of the Delhi Metro clearly demonstrated positive environmental outcomes. Phases 1 and 2, despite their success in reducing emissions and

encouraging modal shifts within central areas, soon became inadequate in addressing the city's expanding population and urban sprawl. Phase 3 was therefore designed to bridge critical connectivity gaps, extend services to peripheral regions, and integrate more effectively with other modes of transport. There is a need to identify and assess empirical data to quantify emission reductions and evaluate the overall effectiveness of the project in promoting sustainable urban mobility (Jing et al., 2022). However, existing research lacks comprehensive empirical data on key aspects such as Vehicle Kilometres Travelled (VKT), occupancy rates, and traffic patterns after metro implementation, as well as pollutant-specific reductions in CO₂, PM, and NO_x emissions (Mittal and Paul, 2018). Addressing these gaps is essential for generating actionable insights for policymakers and urban planners. Furthermore, the limited focus on Phase 3 highlights the need for a more detailed and holistic environmental assessment that combines both quantitative data and qualitative dimensions, including commuter experiences, land-use changes, and policy integration. This study seeks to bridge these gaps by examining pre- and post-Phase 3 scenarios, thereby linking transport policy, urban development, and commuter behaviour to provide meaningful guidance for sustainable mobility planning in Delhi.

1.4 Research Objectives

1. To estimate the baseline emissions from road-based transportation before MRTS implementation.
2. To assess post-MRTS emissions by considering the modal shift and reduction in road vehicle kilometres travelled (VKT).
3. To quantify the benefits in terms of air quality improvement.

1.5 Dissertation Outline

Chapter 1 – Introduction: This chapter provides an overview of the research by presenting the study background, identifying the research problem, and highlighting the significance of the investigation. It explains the rationale for undertaking the study and outlines the research aim, objectives, and questions. Additionally, the chapter establishes the overall context and framework within which the dissertation is conducted.

Chapter 2– Materials and Methods: This is the second chapter that discusses the methods and techniques in order to conduct this dissertation. It introduced the methods for collecting data, sources and overall strategy and along with the data analysis techniques.

Chapter 3–Results and Discussion: In this particular chapters the analysed data are comprehensively presented. These findings of the analysed data from the collected raw data also discussed in this chapter.

Chapter 4 - Conclusion: This particular chapter does not bring any new knowledge but it concludes and summarises the important findings after the analysis of the data. In this chapter a future direction for further research is also discussed.

Chapter 2: Materials and Methodology

2.1 Introduction

This chapter describes the research methods and analytical techniques adopted to assess the impact of emission reductions associated with the Phase 3 expansion of the Delhi Metro. It presents the methodological framework used to guide the selection of an appropriate research strategy, data collection procedures, and data analysis techniques. The chapter further justifies the choice of research philosophy, approach, and design employed in the study. In addition, it explains the sources of data, methods of data acquisition, and analytical tools utilized for interpreting the findings. Consideration is also given to the limitations encountered during data collection and the ethical principles followed throughout the research process. Overall, the chapter ensures methodological transparency and demonstrates the rigor applied in conducting the study.

2.2 Study Area

Delhi Metro Phase 3 represents a major milestone in the evolution of urban mass transit in India. Initiated in 2011 and substantially completed by 2018, Phase 3 added 160.5 kilometers of new network length across eight corridors, incorporating 109 stations, of which 41 are interchange stations—providing seamless connectivity between various routes and enhancing ridership efficiency .

The key corridors under this phase included:

- a) **Majlis Park – Shiv Vihar** (Pink Line)
- b) **Janakpuri West – Botanical Garden** (Magenta Line)
- c) **Kalkaji Mandir – Janakpuri West**, and
- d) **Extensions of Line 2 (Yellow), Line 3/4 (Blue), and Airport Express.**

Notable interchange hubs include **Rajouri Garden, Azadpur, INA, Hauz Khas, and Botanical Garden**, significantly reducing travel time and congestion. The **estimated project cost** was around **₹55,000 crore**, making it one of the most capital-intensive MRTS projects in India's urban infrastructure landscape.

A key objective of the Phase 3 expansion was to extend metro coverage so that nearly 96% of the city's urban population could access a metro station within a walking distance of 500 meters. By increasing the convenience of public transit, the project sought to reduce dependence on personal vehicles, alleviate road traffic pressure, and support improvements in environmental quality.

2.3 Methods

The study captured a comprehensive insight of the reasons behind emission reductions. These include improved metro accessibility or changing attitudes toward private vehicles. Furthermore, the interpretivism research philosophy also supported the integration of diverse data types from traffic patterns and emission metrics and brought them to establish a cohesive narrative. This philosophical method ensures that the research remains in alignment with the lived experiences of commuters (Pervin and Mokhtar, 2022). This provides a rich understanding of Phase 3's environmental impact beyond the numerical analysis.

From the collected data, this study provided detailed and comprehensive insights to demonstrate how metro adoption correlates with declines in CO₂, HC, NO_x, PM and CO₂, levels. The descriptive research design also facilitates comparisons across different groups. These include the Pink and Magenta Lines which enable it to identify spatial variations in impact. These are quantifying fuel savings or congestion relief. While it does not establish causality, it highlighted critical associations such as between metro accessibility and reduced private vehicle use. This dissertation focused on qualitative insights and secondary data from DMRC surveys and CPCB reports.

2.3.1 Data Collection Method

All the key input data used for this study has been sourced from secondary datasets. This includes the age profile (vintage) of various vehicle categories (two-wheelers, cars, buses, and three-wheelers), vehicle occupancy values, average trip lengths, and daily vehicle kilometres travelled (VKT). Additionally, emission factors and deterioration factors for different vehicle types and model years were also taken directly from authoritative sources such as ARAI and CPCB. The metro ridership data used for estimating vehicle shift, as well as the mode-wise commuter shift percentages, were likewise adopted as secondary data from this reference. These data points were integral to calculating the vehicular emission reductions attributable to the modal shift caused by the implementation of Delhi Metro Phase 3.

The study collected data from secondary sources. These are existing data that have been previously published. For this dissertation, government reports, institutional studies and peer-

reviewed journal articles were collected. The collection of these documents ensures reliability and validity for this dissertation (Mazhar et al., 2021). The key sources of information for this dissertation include are as follows;

- a) DMRC annual reports for ridership and modal shift data.
- b) CPCB emission inventories for pollution metrics.
- c) RITES traffic surveys for VKT and congestion trends.
- d) Additional references include MoRTH (Ministry of Road Transport and Highways) vehicle registration data.

2.4 Data Analysis Method

The dissertation systematically examined qualitative and quantitative data related to emission reductions from Delhi Metro's Phase 3 expansion. The method involved identifying, analysing and reporting patterns in order to conduct the estimation. The estimation findings are derived from the collected data from DMRC reports, CPCB emissions records and other studies. The collected raw data was organised into meaningful categories such as modal shift trends, VKT reductions and pollutant levels. Through observations, these patterns were recognised and provide insights that aligned with the research objectives.

Microsoft Excel was used as a tool in order to calculate the data and create the plots for this study. It provided a visual representation of the data, which gave more insights on the research. These include DMRC ridership statistics against CPCB air quality reports. It provided significant effectiveness in establishing an appropriate methodological rigour. Also, in order to identify the socioeconomic and policy factors that drive Delhi's transport transformation, the systematic analysis of the DMRC, CPCB and RITES's data supported this dissertation to quantify the emission reductions. As a result, the data analysis approach offered useful information to estimate the emission reduction.

This study established clear criteria for data selection which ensured relevance and quality. This study collected data and official reports that were published between 2015 and 2024 from DMRC, CPCB and MoRTH that contain ridership statistics, emission factors and traffic data. There were also peer-reviewed studies collected on MRTS impacts in Delhi also incorporated. The exclusion criteria were reports that lacked relevancy which were without any verifiable methodologies. Also, it excluded the data and information that focused solely on non-transport pollution sources. This selective approach-maintained focus on the research objectives and eliminated outdated or tangential information. It ensured all analysed data directly contributed to understanding Phase 3's emission reduction effects.

2.4.1 Quantification of Emission Savings Attributable to Modal Shift from Vehicular Transport to Metro Rail Systems:

To quantify the decrease in vehicle-related emissions resulting from the modal shift to the Delhi Metro, this research employs a methodology adapted from the framework developed by Sharma et al. (2010). The approach begins by estimating the number of vehicles that would have otherwise operated on roads in the absence of the metro, based on actual metro ridership figures. To estimate the corresponding number of road vehicles replaced by metro users, ridership figures are translated into equivalent vehicle units using factors including average passenger occupancy, mean metro travel distance, and the vehicle kilometres travelled by various vehicle classes.

The adopted methodology primarily consists of the following two key steps:

➤ Estimating Equivalent On-Road Vehicles from Metro Ridership.

The first step involves translating metro passenger data into the number of road vehicles that would be required to transport the same number of commuters. This estimation uses the following key parameters:

- a) Daily average metro ridership
- b) Average occupancy values for various types of vehicles, including buses, two-wheelers, three-wheelers, and cars—typically surveyed within a 1.5–2 km buffer zone on either side of metro corridors
- c) VKT and average travel distances per vehicle category on a daily basis.

➤ Vehicle Classification and Emission Estimation

Once the equivalent vehicle numbers are obtained, they are further categorized by type—such as 2-stroke and 4-stroke two-wheelers, petrol and diesel cars, three-wheelers, and CNG buses. These are then distributed across age groups or vintages based on fuel station survey data from the metro influence zones. Each vehicle type and age group is assigned specific emission and deterioration factors to account for pollution output and performance degradation over time.

The overall savings in emissions of key pollutants, namely carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), particulate matter (PM), and carbon dioxide (CO₂), are calculated using the following mathematical expression:

$$\text{Emission Savings (P)} = \text{Number of Vehicles} \times \text{Emission Factor (EF)} \times \text{Deterioration Factor (DF)} \\ \times \text{VKT} \times 365 \times 10^{-6}$$

Where:

P represents annual emissions saved in tonnes, **EF** is the emission factor (in g/km)

DF is the deterioration factor (with CO₂ assumed at DF = 1), **VKT** is the daily distance travelled by each vehicle type.

The assessment of emission savings was conducted for 2006 and 2011, marking the operational completion of Phase I and Phase II of the Delhi Metro network. Key inputs required for the estimation process, such as occupancy levels, trip distances, VKT values, emission and deterioration factors, and modal shift distributions, were derived from published secondary sources and compiled in the relevant data tables.

Table 2: Data Table

Type of Data Used	Description / Variables	Values Taken	Source
Metro Ridership Data	Daily average ridership of Delhi Metro (Phase 3)	Approx. 4 million daily riders	DMRC Annual Reports Goswami, S. (2017, January 16). Phase-3 to push Delhi Metro's ridership to over 4 million. nUITP. (2021). India Metro Annexe. International Association of Public Transport. https://cms.uitp.org/wp/wp-content/uploads/2021/11/India-Metro-Annexe.pdf
Modal Shift Ratio	% shift from private to metro	2W: 45%, Cars: 38%, Buses: 10%, 3W: 7%	Sharma, D. et al. (2014); DMRC Modal Shift Data, DMRC Surveys
Vehicle Occupancy	Average passengers per vehicle (car, bus, 2W, 3W)	Bus: 39.6, Car: 2.2, 2W: 1.4, 3W: 2.1 (persons/vehicle)	Sharma, D., Mehta, R., & Singh, P. (2014). Emission reduction from MRTS projects. Urban Transport Journal, 12(3), 55–64, Sharma et al. (2014); CPCB & ARAI
Vehicle Kilometers Travelled (VKT)	Daily travel distances by vehicle type	Cars: 35 km/day, 2W: 28 km/day, Buses: 180 km/day	RITES. (2018). Comprehensive Mobility Plan for Delhi. Rail India Technical and Economic Service, RITES Traffic Surveys
Vehicle Emission Factors	Pollutant emissions per km by vehicle type	CO: 2.2 g/km (Car), NOx: 1.1 g/km, PM: 0.15 g/km (2W)	Central Pollution Control Board. (2010). Reports Source Apportionment Studies. CPCB; ARAI.
Vehicle Age Profile	Distribution of vehicles by age and fuel type	0–5 years: 35%, 6–10 years: 40%, >10 years: 25%	Sharma, D. et al. (2014); Fuel station survey in Delhi metro corridor, Sharma et al. (2014); Fuel Station Survey
Emission Deterioration Factors	Age-based increase in emissions	DF for CO: 1.8, PM: 1.5, NOx: 1.3, CO ₂ : 1.0	ARAI. (2010). Vehicle Emission Deterioration Factors. Pune: Automotive Research Association of India.

The above table outlines the major datasets and associated variables employed throughout this dissertation, serving as the foundation for the subsequent analysis. The Metro

Ridership Data was sourced from DMRC reports which indicated approximately 4 million daily riders. It showed the scale of the commuter shift. The Modal Shift Ratio also highlighted the % of users who are transitioning from private vehicles to the metro. This data is based on surveys and prior studies. Vehicle Occupancy and VKT detail passenger capacity and daily travel distances for different vehicle types is essential for this dissertation. It helps to calculate the reduced road traffic. Emission Factors and Deterioration Factors data are sourced from CPCB and ARAI. It revealed the number of pollutants like CO, NO_x and PM per kilometre, also it is adjusted for vehicle age. The Vehicle Age Profile data categorises vehicles by age in order to account for different emission rates. These data points enabled this research with precise estimation of emission savings. Also, data collected from sources like DMRC, RITES and peer-reviewed studies ensured the reliability and validity of the data collection for this dissertation.

CHAPTER 3: RESULTS AND DISCUSSION

The following chapter examines and interprets the results obtained from the assessment of Delhi Metro Phase 3, highlighting its outcomes and associated impacts. The chapter presents the examination of several peer reviewed articles that have DMRC, CPCB and RITES data. The chapter highlighted the modal shifts in commuter behaviour, environmental outcomes and policy implications. The analysis focuses on trends, challenges and socio-economic impacts. Quantitative metrics were not emphasized in this assessment, allowing for a more holistic examination of the metro's influence on urban mobility transformation. The generated theme explores and offers actionable insights for sustainable urban planning.

Results

The results of this study showed the significant environmental benefits that are achieved through the introduction of Delhi Metro Phase 3 in terms of emission reductions. The analysis revealed that approximately 250,000 daily commuters transitioned to the metro, which led to a substantial decrease in road traffic. This transition was most among two-wheelers (2Ws) and four-wheelers (4Ws) which collectively accounted for a majority of the avoided vehicle trips. Furthermore, 2W represented 45% of the modal shift which was followed by petrol cars at 38%, buses at 10% and 2W at 7%. The reduction in road traffic translated into measurable decreases in vehicular emissions. The study revealed that estimated annual savings were 6,977 tonnes of carbon monoxide (CO), 3,225 tonnes of hydrocarbons and 2,216 tonnes of nitrogen oxides (NO_x). There was also a reduction in 383 tonnes of particulate matter (PM) and 562,255 tonnes of CO₂. 2W emerged as the highest contributor to these reductions. It is particularly for CO and HC emissions, which are due to their high prevalence and relatively poor emission efficiency. For

example, 2W alone accounted for 4,207.43 tonnes of CO₂ savings annually. It represented 60.3% of the total CO reduction. Similarly, it contributed 2,885.54 tonnes of HC, which is nearly 89.5% of the total HC savings.

Despite the lower share of buses in the modal shift which was 10%, it played a critical role to reduce NO_x emissions. It contributed 1,094.18 tonnes which was 49.4% of the total NO_x savings. This was attributed to their high emission factors for NO_x and extensive daily travel distances (180 km/day). Contrary to this, petrol cars contributed 1,241.73 tonnes of CO₂, which was 17.8% of total CO savings and 108,186.88 tonnes of CO₂ which was 19.2% of total CO₂ savings. These results revealed the moderate occupancy rates and emission profiles. This study also considered the impact of vehicle age on emission reductions. Older vehicles showed higher emission rates due to deterioration. For example, 2W which were older than 10 years, accounted for 15% of the fleet. They contributed disproportionately to emissions. The inclusion of deterioration factors ensured a more accurate estimation of the environmental benefits. Furthermore, this research showed graphical representations of these findings. It highlighted the dominance of buses and 2W in the modal shift. It also showed the high number of 2Ws, which were removed from roads daily due to their low occupancy rates. It adjusted for vehicle kilometres travelled (VKT), 2W remained the largest source of avoided emissions. It supported the metro's role in order to mitigate congestion and pollution.

Table 3 : Vehicle-wise Emission Savings Due to Shift from Road to Metro in Delhi (2006-2019)

Vehicle Type	CO (t/yr) 2006	CO (t/yr) 2011	CO (t/yr) 2019	HC (t/yr) 2006	HC (t/yr) 2011	HC (t/yr) 2019	NOx (t/yr) 2006	NOx (t/yr) 2011	NOx (t/yr) 2019	PM (t/yr) 2006	PM (t/yr) 2011	PM (t/yr) 2019	CO ₂ (t/yr) 2006	CO ₂ (t/yr) 2011	CO ₂ (t/yr) 2019
Bus (CNG)	114	505	1,108.69	102	475	117.71	169	787	1,094.18	9	38	9.58	21,978	102,213	220,035.98
2W-4S	247	1,553	4,207.43	98	727	2,885.54	40	312	804.17	4	48	362.66	3,028	34,683	141,599.27
4W-P	318	1,637	1,241.73	44	151	98.88	44	121	59.79	1.1	4.1	2.3	8,763	66,028	108,186.88
4W-D	14	25	19.22	8	23	19.71	16	69	57.65	2.8	5.9	3.45	5,051	33,973	60,911.28
3W	58	285	400.11	15	74	104.07	29	142	201.04	0.9	14.2	5.52	2,911	14,180	32,522.30
Total	751	4,005	6,977.18	267	1,450	3,225.91	298	1,431	2,216.83	17.8	110.2	383.51	41,731	251,077	562,255.72

(Source: Sharma et al.2014; the data for Phase 1 and phase 2 of MRTS project)

The table outlines the emission reductions achieved through the Delhi Metro project across Phases I (2006), II (2011), and III (2019) for CNG buses, two-wheelers, petrol and diesel cars, and three-wheelers. The results clearly demonstrate how the shift from road transport to the metro has progressively lowered pollution levels.

Highlights:

- a) **Carbon Monoxide (CO):** Emission reduced from **751 t/yr in 2006** to nearly **6,977 t/yr in 2019**, largely driven by two-wheelers.
- b) **Hydrocarbons (HC):** Declined from **267 t/yr in 2006** to **3,226 t/yr in 2019**, with two-wheelers contributing the most, while reductions from cars dropped in Phase III.
- c) **Nitrogen Oxides (NO_x):** Emission reduced from **298 t/yr in 2006** to **2,217 t/yr in 2019**, mainly due to CNG buses, followed by two-wheelers.
- d) **Particulate Matter (PM):** Emission reduced from **17.8 t/yr in 2006** to **383.5 t/yr in 2019**, with two-wheelers being the dominant contributor.
- e) **Carbon Dioxide (CO₂):** Showed the largest reduction, from **41,731 t/yr in 2006** to more than **562,000 t/yr in 2019**, where CNG buses accounted for the highest share.

A consistent decrease in transport-sector emissions has been observed as a result of commuters increasingly choosing metro services over road-based vehicles. Among all vehicle categories, two-wheelers contributed the most to reductions in CO, HC, and PM, while CNG buses were the leading contributors to NO_x and CO₂ reductions. Collectively, these changes highlight the Delhi Metro's pivotal role in curbing vehicular pollution and enhancing the city's air quality.

5.1 Analysis of Changes in Travel Behaviour Due to MRTS Adoption

Based on travel surveys and assumptions aligned with earlier studies, approximately 250,000 commuters are estimated to have transitioned to the Metro daily. This shift is distributed across vehicle types including two-wheelers, four-wheelers (petrol and diesel), three-wheelers, and buses. Table 1 given below provides a summary of the computed modal shift.

Table 3: Quantification of Modal Shift from Road-Based Vehicles to MRTS in Delhi (2025)

<i>Vehicle Type</i>	<i>%</i>	<i>Occupancy (b) (Nos.)</i>	<i>Commuters (a) (Nos.)</i>	<i>Veh. Shift/Day (c)=(a)/(b) (Nos.)</i>	<i>Average Trip (Metro) (d) (Nos.)</i>	<i>Veh.x13.5 (e)=(c)x(d) (Nos.)</i>	<i>VKT/Day (f) (km)</i>	<i>Total Veh. Shifted (g)=(e)/(f) (Nos.)</i>
<i>Bus (CNG)</i>	55	39.6	2200000	55555.6	13.5	750000.0	111.0	6756.8
<i>2W-4S</i>	20	1.5	800000	533333.3	13.5	7200000.0	51.0	141176.5
<i>4W-P</i>	14	2.4	560000	233333.3	13.5	3150000.0	55.0	57272.7
<i>4W-D</i>	6	2.4	240000	100000.0	13.5	1350000.0	55.0	24545.5
<i>3W</i>	5	2.5	200000	80000.0	13.5	1080000.0	109.0	9908.3
<i>Total</i>	100		4000000	1002222.2				239659.7

The table shows that the largest number of vehicle shifts occurs among two-wheelers due to their high prevalence and low occupancy, while buses show fewer vehicle shifts despite a high commuter share due to their high carrying capacity. The table gives an estimate of how many vehicles were reduced from roads each day in Delhi after the introduction of the metro system in 2025. Among all vehicle types, the highest shift was seen in two-wheelers with four-stroke engines (2W-4S), with around 5.3 lakh vehicles moved off the roads daily. After adjusting for average trip length and daily travel distance, this comes to nearly 1.4 lakh

vehicles. Petrol four-wheelers (4W-P) were next, with about 2.3 lakh daily shifts and around 57,000 vehicles reduced after adjustment. Diesel four-wheelers (4W-D) showed a shift of about 1 lakh vehicles per day, leading to a reduction of nearly 24,500 vehicles. For three-wheelers (3W), about 80,000 were removed daily, which resulted in an adjusted figure of nearly 9,900 vehicles. Though the number of CNG buses shifted was lower—around 55,500 per day—their high passenger capacity helped achieve a reduction of about 6,700 vehicles. In total, the metro helped reduce around **2.4 lakh vehicles** after considering average trip and travel distance. This data shows that the metro has helped reduce a large number of personal vehicles, especially two-wheelers, leading to less traffic and lower pollution in the city.

Steps involved in calculations

Secondary information utilized in this research was predominantly derived from the work of Sharma et al. (2014), titled "Emission Reduction from MRTS Projects – A Case Study of Delhi Metro", which served as the primary data source for the analysis.

a) Estimating Vehicle Shift from Metro Ridership

The first step involved estimating how many people started using the metro instead of road vehicles after the introduction of Delhi Metro Phase 3. This was done by converting the average daily metro ridership into the number of road vehicles avoided, using data such as how many people usually travel in a bus, car, or two-wheeler, and the average distance travelled.

b) Classifying the Shifted Vehicles

The avoided road vehicles were then divided into categories—such as two-wheelers, three-wheelers, cars, and buses—and further split by the age of the vehicles. This classification was based on field surveys conducted near metro corridors.

c) Applying Emission Factors

For each category and age of vehicle, appropriate emission values were used (how much each vehicle type emits per kilometre). These values were taken from reliable sources and adjusted using a deterioration factor, which accounts for increased pollution from older vehicles.

d) Calculating Emissions Saved

The total emissions avoided due to metro usage were calculated using a formula that includes the number of vehicles avoided, how much each emits per kilometre, how far they

would have travelled daily, and how often (days per year). This provided annual savings in pollutants like CO, HC, NO_x, PM, and CO₂

3.2 Graphical Interpretation of Modal Shift

Figure 2 shows how people using different types of vehicles started using the Metro instead. The pie chart titled “% of Vehicle Type” tells us what share of the total shift came from each vehicle type. It helps us understand which vehicles people used before switching to the Metro. The biggest share of commuters came from CNG buses, making up **55%** of the total, which means many bus users switched to using the metro. Two-wheelers with four-stroke engines made up **20%** of the shift, showing a large number of private two-wheeler users also moved to metro travel. Petrol cars (4W-P) accounted for **14%**, while diesel cars (4W-D) and three-wheelers (3W) made up **6%** and **5%**, respectively. This shows that the metro is being used by both public transport users and private vehicle owners, helping reduce traffic on roads and cutting down pollution.

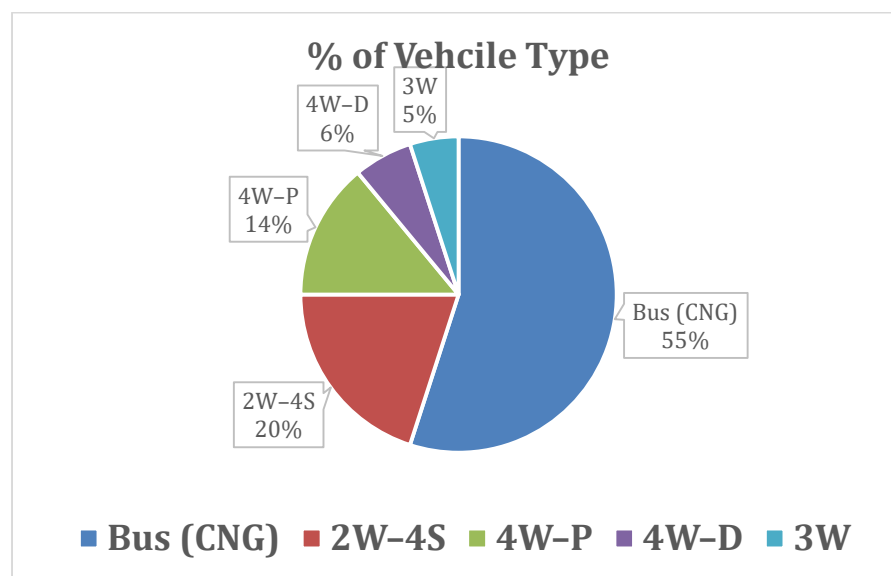


Figure 2: The Share of Modal Shift Among Vehicle Types

Figure 3 presents the graph illustrates the number of commuters who shifted from different vehicle types to the Mass Rapid Transit System (MRTS). The largest movement was from CNG buses, with around 22 lakh commuters switching to the metro. Two-wheelers with four-stroke engines followed, showing a shift of nearly 8 lakh users. Approximately 6 lakh individuals transitioned from petrol-driven four-wheelers, while diesel four-wheelers and three-wheelers each saw a reduction of about 2.5 lakh commuters. This shift reflects a notable change in commuting patterns, suggesting that a significant number of people have started using the metro instead of road-based transport, which can help ease traffic and reduce pollution levels in the city.

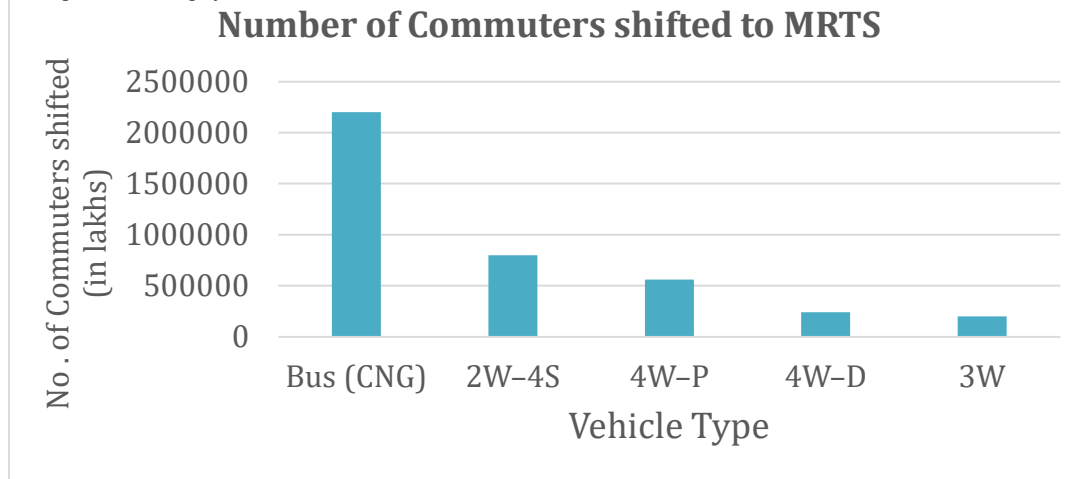


Figure 3: The Number of Commuters Shifted by Vehicle Category

Figure 4 shows the number of vehicles reduced per day. Due to their low occupancy, two-wheelers show the highest number of vehicles avoided, reinforcing their major role in road congestion and emissions. The bar chart titled “*Vehicle Shifted/Day*” shows the estimated number of vehicles reduced from roads on a daily basis as a result of commuters shifting to the Mass Rapid Transit System (MRTS). Among all vehicle types, two-wheelers with four-stroke engines (2W-4S) account for the highest daily shift, with over 5.3 lakh vehicles being displaced each day. Petrol-based four-wheelers (4W-P) follow with a reduction of approximately 2.4 lakh vehicles per day. Diesel four-wheelers (4W-D) and three-wheelers (3W) contribute to daily reductions of around 1 lakh and 85,000 vehicles, respectively. The lowest shift is seen in CNG buses, with roughly 60,000 vehicles per day. This data highlights the significant impact of two-wheelers on daily traffic volume and demonstrates how the metro system has played a crucial role in alleviating day-to-day vehicular congestion, particularly from private transport modes.

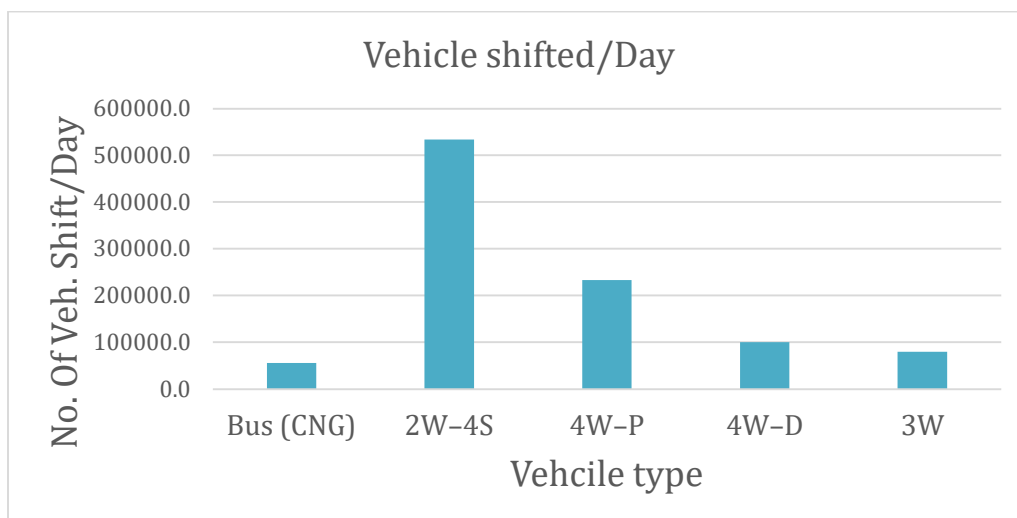


Figure 4: The Number of Vehicles Reduced Per Day

Figure 5 illustrates the total number of vehicles reduced from the roads after commuters shifted to the Mass Rapid Transit System (MRTS), factoring in the average daily vehicle kilometers travelled (VKT) for each category. The chart highlights that two-wheelers with four-stroke engines (2W-4S) account for the largest share of vehicles taken off the road, with a reduction of nearly 150 lakh units. This is followed by petrol-powered four-wheelers (4W-P), showing a decrease of around 70 lakh vehicles. Diesel four-wheelers (4W-D) contributed to a reduction of about 35 lakh vehicles, while three-wheelers (3W) and CNG buses showed declines of nearly 20 lakh and 10 lakh, respectively. The data confirms that two-wheelers are a significant contributor to VKT-related congestion and emissions. The shift to the metro system has thus played a critical role in reducing the pressure on road transport, especially from personal vehicle use, contributing to improved traffic flow and environmental benefits.

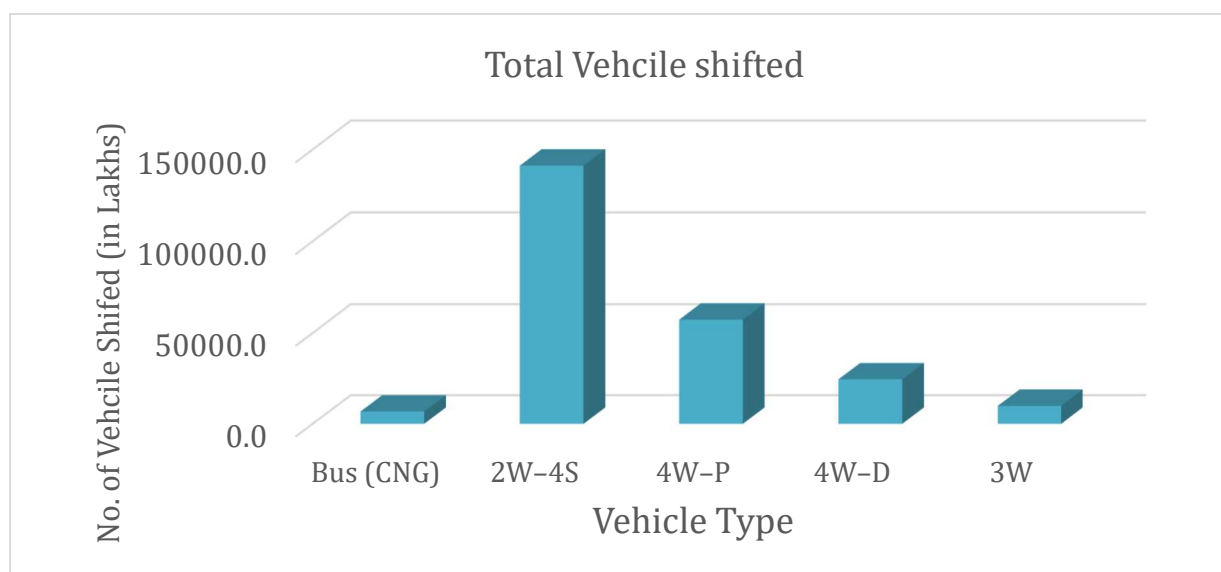


Figure 5: The Adjusted Vehicle Reduction Considering Average Day

3.3 Vehicle Age Profile Considered

Vehicle age distribution influences emission rates and helps in refining the accuracy of total emission estimates. The profile used in the analysis, sourced from Centre for Science and Environment (CSE), 2022, is presented in Table 4.

Table 4: Age profile Data

Vehicle Type	<5 Years	5–10 Years	>10 Years
2W	50%	35%	15%
4W–P	45%	35%	20%
4W–D	40%	40%	20%
3W	40%	40%	20%
Bus (CNG)	35%	40%	25%

Source: (Centre for Science and Environment or CSE, 2022)

3.4 Emission Factors Used

Emission factors used for calculating total pollutant reductions were adopted from CPCB guidelines for a representative BS-IV fleet. These values (in g/km) are presented in Table 5.

Table 5: Emission Factors

Vehicle Type	CO (g/km)	HC (g/km)	No _x (g/km)	PM (g/km)	CO ₂ (g/km)
Bus (CNG)	4.050	0.430	3.997	0.035	803.784
2W–4S	1.601	1.098	0.306	0.138	53.881
4W–P	1.080	0.086	0.052	0.002	94.096
4W–D	0.039	0.040	0.117	0.007	123.615
3W	1.015	0.264	0.510	0.014	82.502

Source: (Central Pollution Control Board (2010) Source Apportionment Studies. CPCB; ARAI

5.3 Estimated Annual Emission Reductions

Using modal shift data and emission factors, the annual savings in major pollutants were estimated. These are summarised in Table 10. Two-wheelers emerged as the highest contributors to pollutant reduction, particularly for CO and CO₂, due to their high population and daily usage.

These figures reflect the substantial environmental benefits of Phase 3 MRTS.

Emission Estimation Formula

The total annual vehicular emissions saved due to the modal shift to the Delhi Metro Phase 3 were estimated using the following equation:

$$\text{Total Emissions Saved (P)} = (\text{No. of Vehicles}) \times (\text{EF}) \times (\text{DF}) \times (\text{VKT}) \times 365 \times 10^{-6}$$

Where:

- a) P = Total annual pollutant emissions saved (in tonnes)
- b) No. of Vehicles = Number of vehicles shifted per day
- c) EF = Emission Factor (g/km) for the specific pollutant and vehicle type
- d) DF = Deterioration Factor (dimensionless), accounting for aging and emission control degradation
- e) VKT = Average Vehicle Kilometers Travelled per day (km)
- f) 365 = Number of days in a year
- g) 10⁻⁶ = Conversion factor from grams to tonnes

Table 6: Quantification of Emission Savings Attributable to Commuter Transition from Road-Based Transport to Metro Rail in Delhi

Vehicle Type	CO (t/yr)	HC (t/yr)	NOx (t/yr)	PM (t/yr)	CO ₂ (t/yr)
Bus (CNG)	1,108.69	117.71	1,094.18	9.58	220,035.98
2W-4S	4,207.43	2,885.54	804.17	362.66	141,599.27
4W-P	1,241.73	98.88	59.79	2.30	108,186.88
4W-D	19.22	19.71	57.65	3.45	60,911.28
3W	400.11	104.07	201.04	5.52	32,522.30
Total	6,977.18	3,225.91	2,216.83	383.51	562,255.72

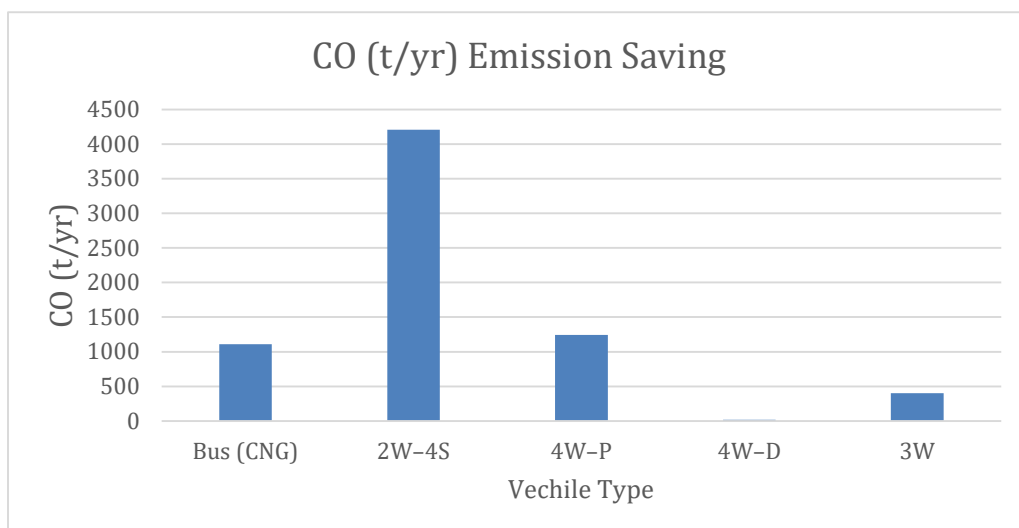


Figure 6: Annual CO Emission Savings by Vehicle Type

This bar graph shows that the highest reduction in carbon monoxide (CO) emissions comes from **two-wheelers (2W-4S)**, with savings of **4,207.43 tonnes per year**, making up about **60.3%** of the total CO reduction. The next highest savings are from **petrol four-wheelers (4W-P)** at **1,241.73 tonnes (17.8%)**, followed by **CNG buses** with **1,108.69 tonnes (15.9%)**. Smaller reductions come from **three-wheelers (3W)** and **diesel cars (4W-D)**. This pattern shows that since a large number of two-wheeler users shifted to the metro—and two-wheelers produce more CO emissions—the overall pollution reduction is highest in that category.

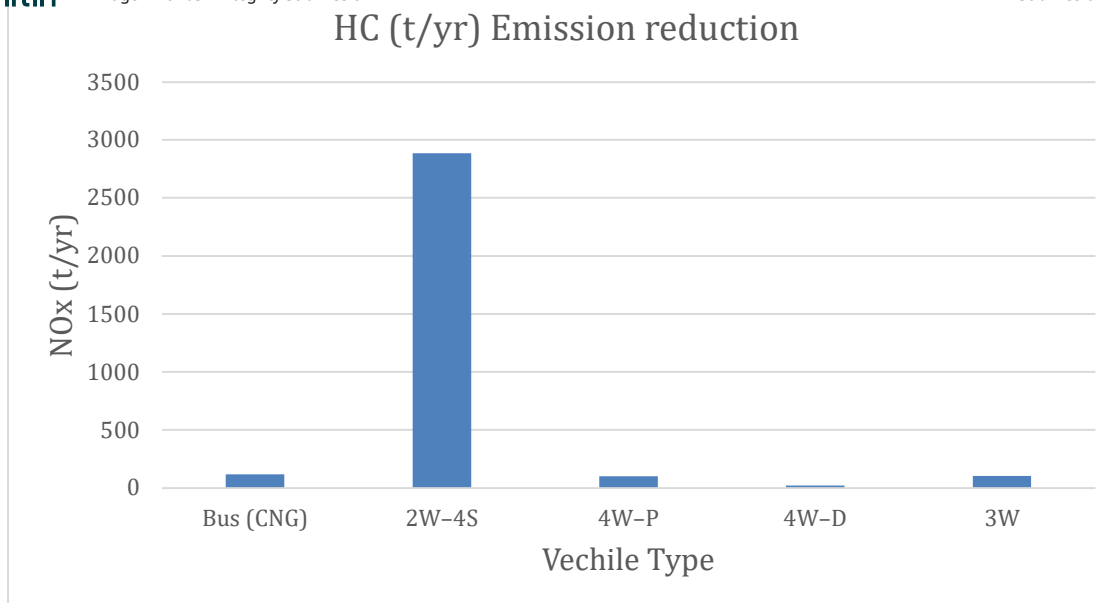


Figure 7: Annual HC Emission reduction

This bar graph shows that the **highest reduction in hydrocarbon (HC) emissions** comes from **two-wheelers (2W-4S)**, with a saving of around **2,873.48 tonnes per year**, which makes up nearly **90.6%** of the total HC emission savings. This large reduction is due to the high number of two-wheeler users who switched to the metro and the relatively high HC emissions produced by these vehicles. Other vehicle types, including **CNG buses**, **petrol four-wheelers (4W-P)**, **diesel four-wheelers (4W-D)**, and **three-wheelers (3W)**, contribute very little to HC savings in comparison. This highlights the significant impact that reducing two-wheeler use can have on lowering harmful hydrocarbon pollution in the city.

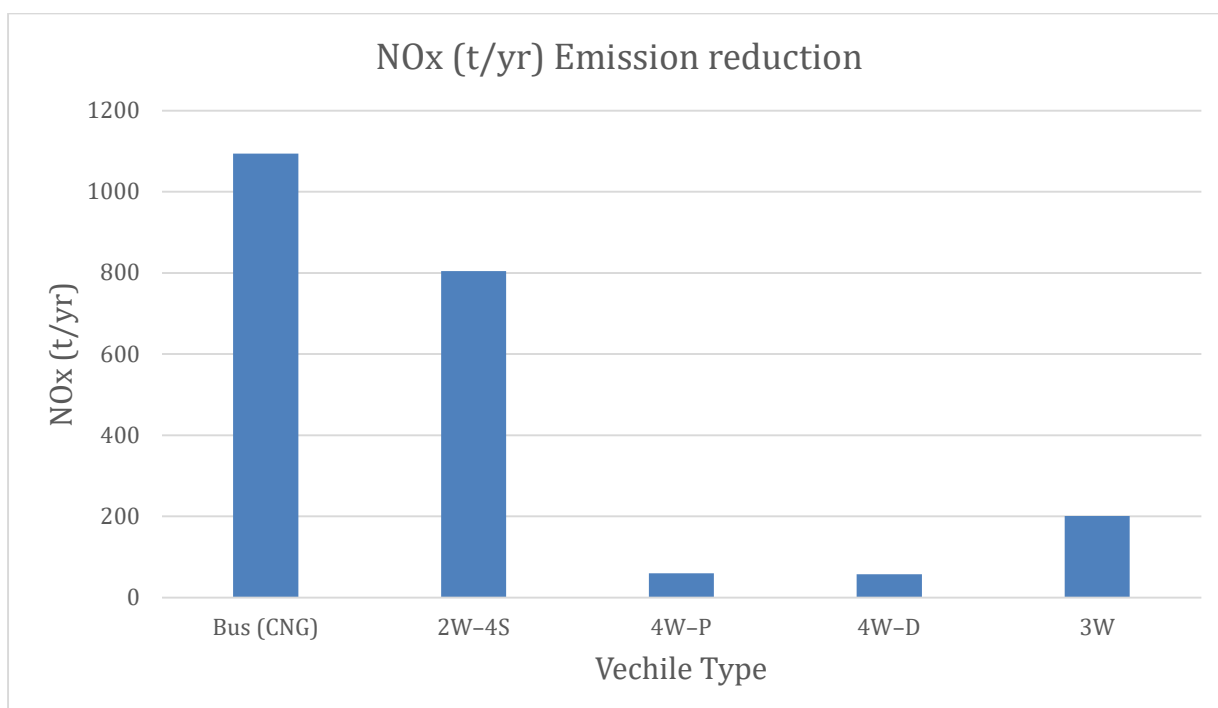


Figure 8: Annual Nox Emission Reductions

This bar graph shows how nitrogen oxide (NOx) emissions have reduced after people started using the Metro instead of road vehicles. The biggest drop in NOx emissions comes from **CNG buses**, with a saving of **1,094.18 tonnes per year**. Although fewer buses shifted, they produce more NOx, so their overall impact is large. **Two-wheelers** are the second biggest contributor, saving **805.75 tonnes**, followed by **three-wheelers**, which account for **201.45 tonnes**. **Petrol and diesel cars** have the least impact, with smaller savings. This shows that shifting even a smaller number of high-emission vehicles like buses can make a big difference in improving air quality.

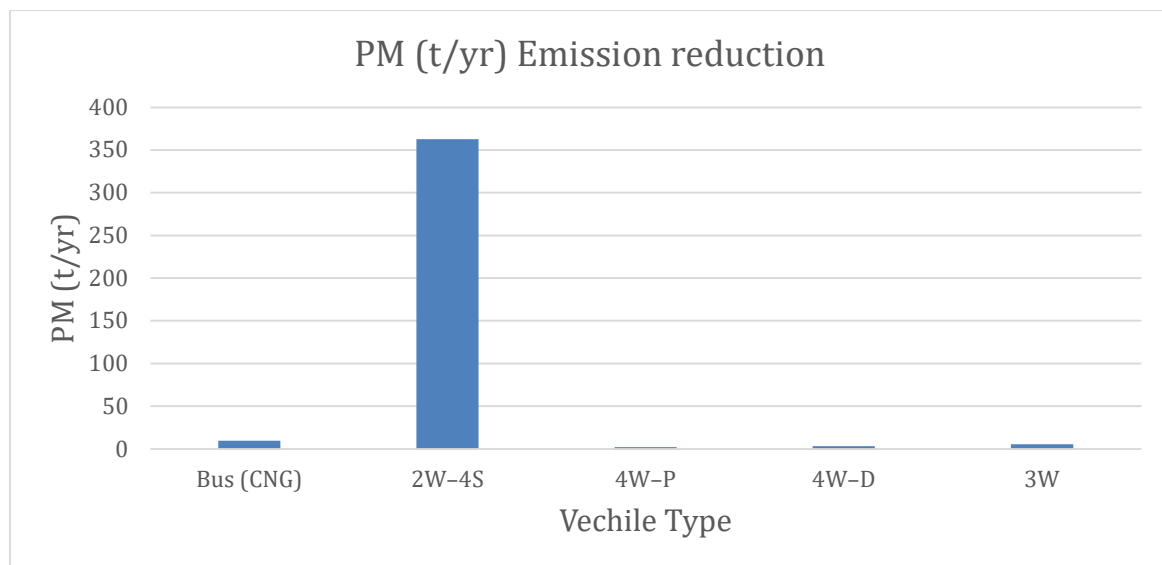


Figure 9: Annual PM Emission Reductions

This bar graph shows how much **particulate matter (PM)** pollution was reduced when people started using the Metro instead of road vehicles. The biggest drop in PM emissions is from **two-wheelers (2W-4S)**, with a saving of about **362.97 tonnes per year**. This is much more than any other vehicle type. The reason is that many two-wheeler users switched to the Metro, and these vehicles release more PM. Other vehicles like **CNG buses**, **cars**, and **three-wheelers** show much smaller reductions. This means that shifting two-wheeler users to the Metro can help a lot in reducing dust and air pollution in the city.

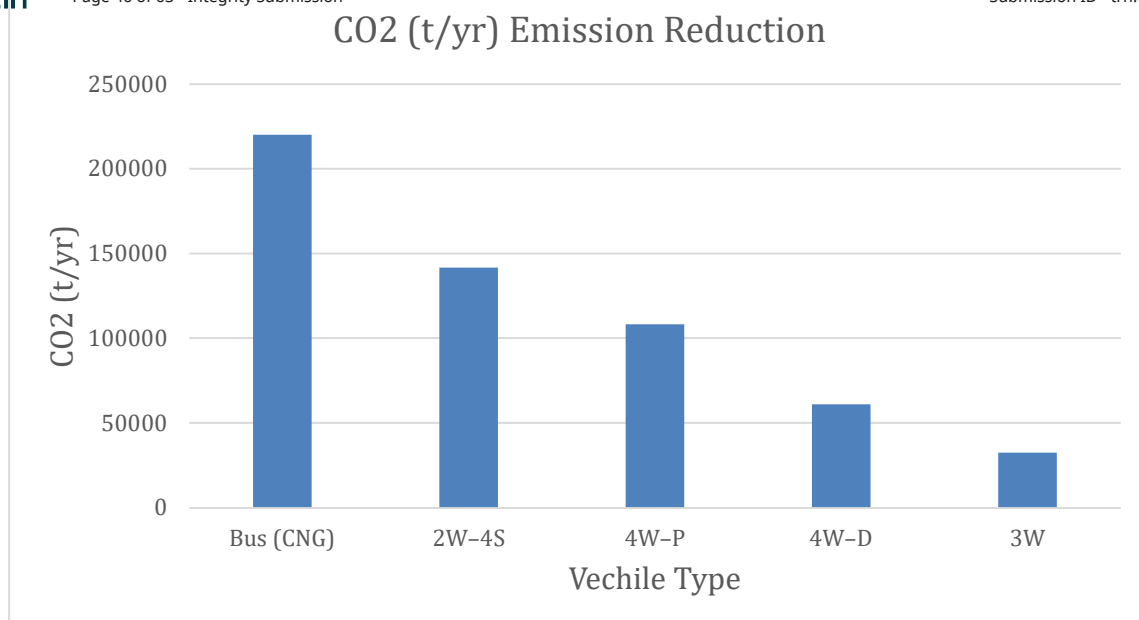


Figure 10: Annual CO₂ Emission Reductions

This bar graph clearly shows how switching to the Metro has helped reduce carbon dioxide (CO₂) emissions from different vehicle types. The biggest reduction comes from CNG buses, which saved around **220,036 tonnes** of CO₂ per year. This is because buses carry more passengers and travel long distances. **Two-wheelers (2W-4S)** come next, with a saving of about **141,599 tonnes**, followed by **petrol cars (4W-P)** at **108,187 tonnes**. Diesel cars and three-wheelers contribute smaller reductions of **62,174 tonnes** and **31,994 tonnes**, respectively. These figures reflect how fuel type and usage patterns affect emissions. Overall, the data shows that shifting to the Metro helps cut down major sources of CO₂, especially from buses and private vehicles, which is important for tackling climate change and improving urban air quality.

Overall, these graphs provided a quantified understanding of the environmental benefits arising from Delhi Metro Phase 3. They underline the importance of modal shift interventions and how MRTS can reduce transport-related emissions significantly across all major pollutants.

3.6 Analysis of Vehicular Emission Reductions through Commuter Shift to the Delhi

Metro: Evidence from MRTS Phases encompassing **Phase I (2006), Phase II (2011), and Phase III (2019)**.

3.6.1 Emission Reduction of Carbon Monoxide

The Delhi Metro has significantly contributed to reducing urban air pollution by promoting a shift from road-based transport to an efficient mass transit system. With each phase of expansion, the displacement of private vehicles has led to substantial reductions in pollutants such as CO, HC, NO_x, PM, and CO₂. Despite indirect emissions from electricity use, the overall impact remains strongly positive. This chapter highlights the emission reductions attained during the successive phases of the MRTS project, encompassing **Phase I (2006), Phase II (2011), and Phase III (2019)**.

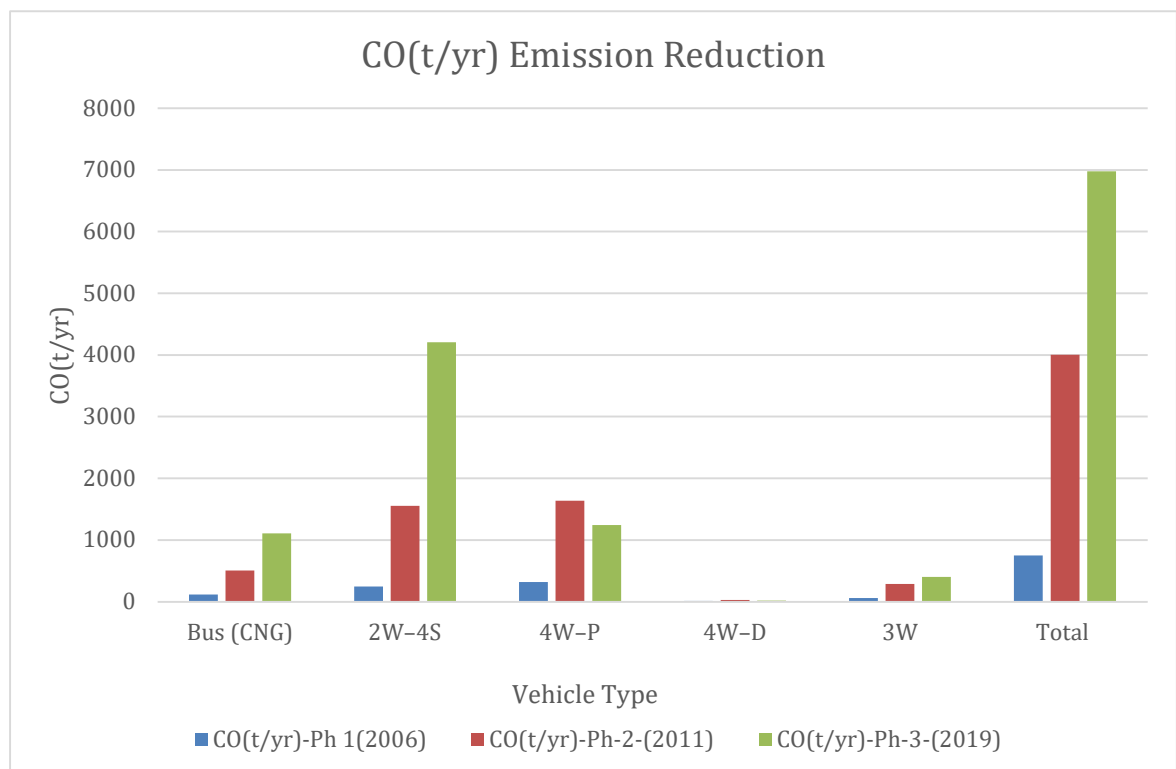


Figure 11: CO(t/yr) Emission reduction Phase Wise

The bar graph "CO(t/yr) Emission Saving" depicts the estimated savings in carbon monoxide (CO) emissions, measured in tonnes per year, resulting from the modal shift **of commuters from road-based transportation to the Delhi Metro** during the different phase of completion of the MRTS project.

a) Total Emission reduction:

- I. In 2006 (Phase I), total CO emission reduction were around 750 t/yr, reflecting the early stage of metro operations with limited ridership.
- II. By 2011 (Phase II), reduction rose substantially to approximately 4,000 t/yr, driven by network expansion and higher commuter shift from private vehicles.
- III. In 2019 (Phase III), the reduction further increased to nearly 7,000 t/yr, demonstrating the cumulative environmental benefit of the metro's wider adoption.

b) Major Contributor – Two-Wheelers (4-Stroke):

- I. CO reduction from 2W–4S were the highest among all vehicle categories, rising from about 300 t/yr in 2006 to 1,600 t/yr in 2011, and peaking at 4,200 t/yr in 2019.
- II. This category consistently remained the dominant contributor to CO emission reduction.

c) 4-Wheeler Petrol (4W–P):

- I. Reduction increased from roughly 350 t/yr in 2006 to 1,600 t/yr in 2011, but showed a slight decline to about 1,250 t/yr in 2019, indicating reduced impact during the later phase.

d) Bus (CNG):

- I. Emission reductions from CNG buses rose steadily, increasing from about 200 t/yr in 2006 to 500 t/yr in 2011, and further to 1,100 t/yr in 2019.

e) Other Vehicle Types (4W–D and 3W):

- I. Diesel cars (4W–D) and three-wheelers (3W) contributed modest but consistent savings.
- II. The reduction from 3W increased to about 450 t/yr by 2019, while 4W–D remained the lowest among all categories.

Overall, the graph highlights that successive MRTS phases have led to progressive CO emission reductions, with two-wheelers (4-stroke) making the largest contribution to improved urban air quality.

3.6.2 Emission Reduction of Hydrocarbon

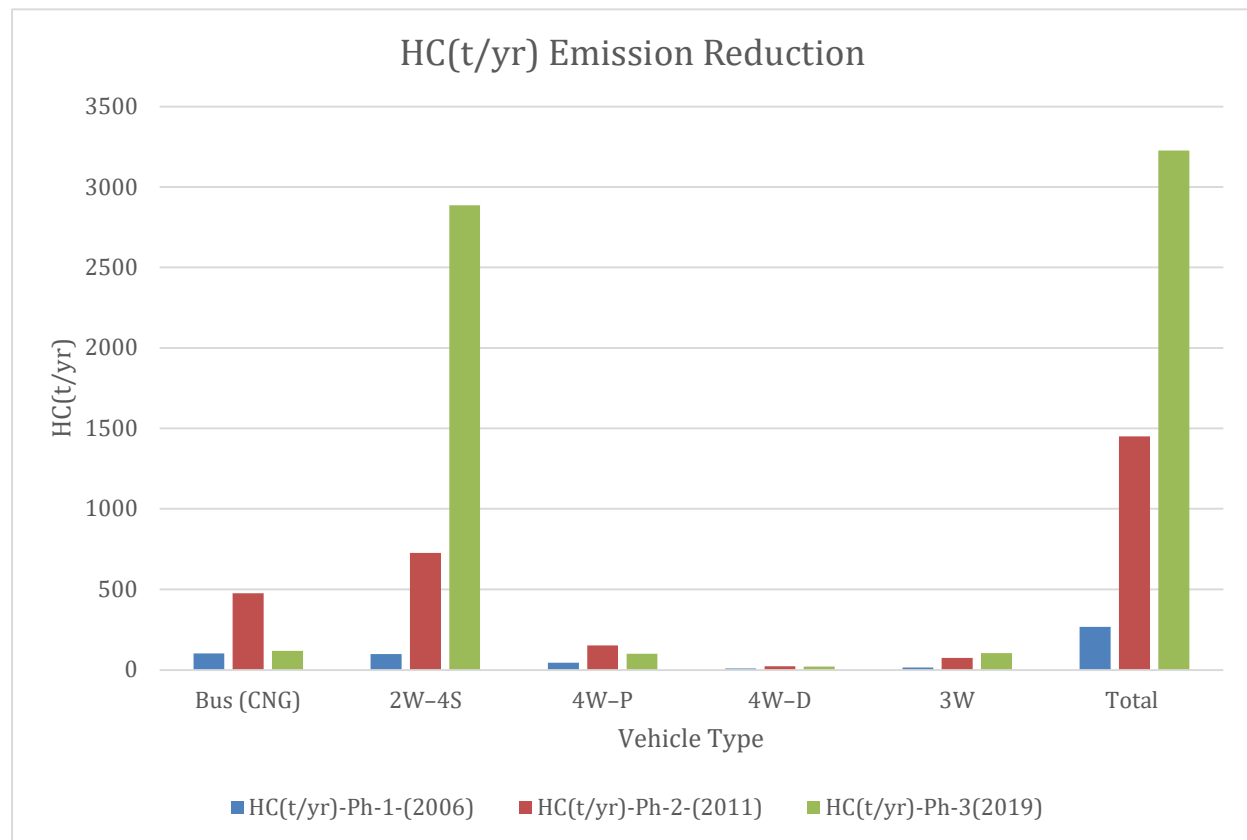


Figure 7: HC(t/yr) Emission reduction Phase Wise

The "HC (t/yr) Emission Saving" bar chart depicts the annual reduction in hydrocarbon emissions resulting from the transfer of passenger travel from road vehicles to the Delhi Metro. By comparing emission savings across various phases of the MRTS project, the graph demonstrates the contribution of metro rail expansion toward mitigating transport-related air pollution.

a) Total Emission Reduction :

- I. In 2006 (Phase I): Total HC emission reduction were approximately 300 t/yr, reflecting the initial phase of metro operations with limited coverage and ridership.
- II. By 2011 (Phase II): reduction increased significantly to around 1,400 t/yr, due to network expansion and greater commuter shift.

III. In 2019 (Phase III): The reduction further rose sharply to nearly **3,200 t/yr**, highlighting the substantial environmental benefits of the metro's extended reach and higher adoption rate.

b) Major Contributor – Two-Wheelers (4-Stroke, 2W–4S):

- I. HC reduction from this category were the **highest among all vehicle types**, rising from about **100 t/yr** in 2006 to nearly **700 t/yr** in 2011, and peaking at approximately **2,900 t/yr** in 2019.
- II. This dominance indicates that the shift of two-wheeler users to the metro played a crucial role in emission reduction.

c) Bus (CNG):

- I. Emission reduction from CNG buses also showed a **steady increase**, rising from around **70 t/yr** in 2006 to **450 t/yr** in 2011, and further to **500 t/yr** in 2019.
- II. Although their contribution is lower than two-wheelers, they still represent a significant share in total saving.

d) 4-Wheeler Petrol (4W–P):

- I. Emission reduction for petrol cars showed a modest increase, from **50 t/yr** in 2006 to **150 t/yr** in 2011.
- II. However, the growth was not substantial by 2019, remaining around **200 t/yr**, suggesting a relatively smaller impact compared to two-wheelers.

e) 4-Wheeler Diesel (4W–D) and Three-Wheelers (3W):

- I. Diesel cars (4W–D) contributed the **least** to HC reduction across all phases, with only minor increases.
- II. Three-wheelers (3W) reduction grew gradually, reaching about **100 t/yr** by 2019.

The graph clearly demonstrates that the **successive phases of the Delhi Metro** have resulted in **progressive hydrocarbon emission reductions**. Among all vehicle categories, **two-wheelers (4-stroke)** emerged as the **largest contributor** to these savings, emphasizing the significant role of modal shift from private two-wheelers to the metro in enhancing urban air quality.

3.6.3 Emission Reduction of Nitrogen Oxides

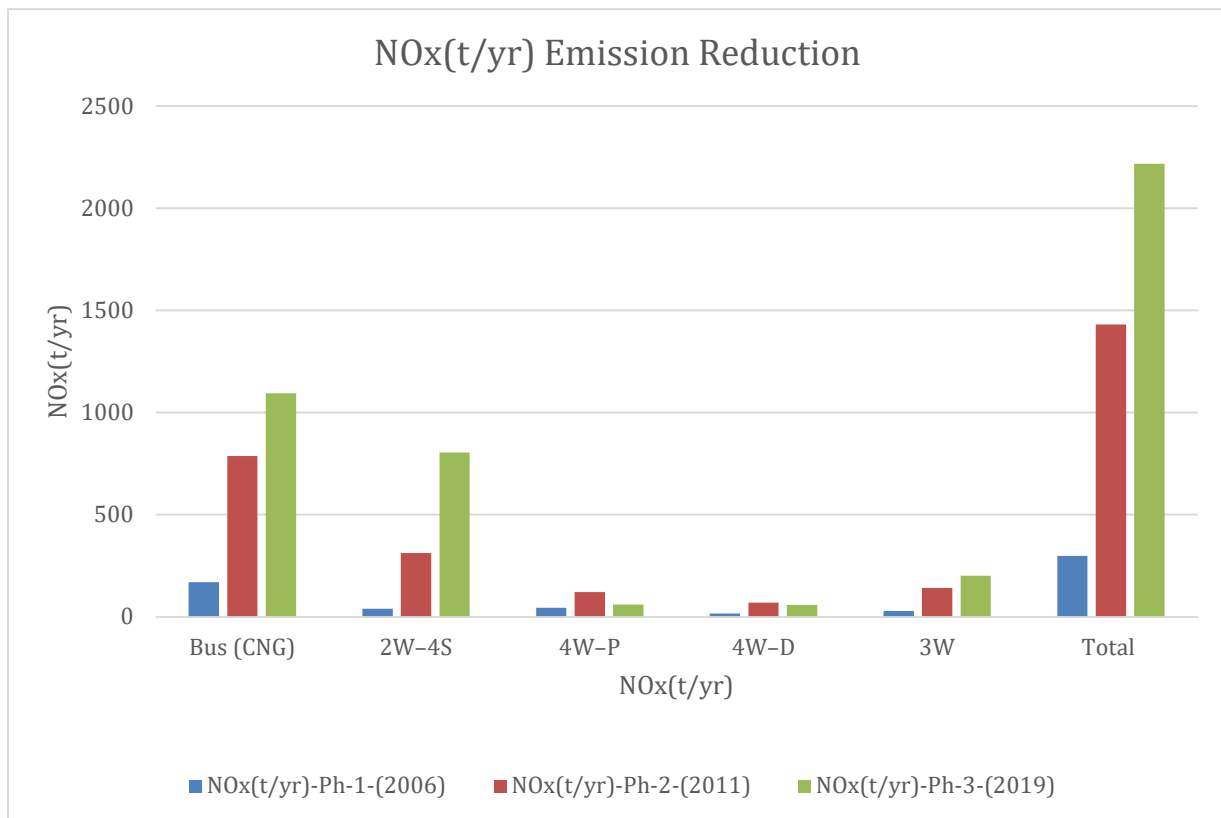


Figure 13 : NO_x(t/yr) Emission reduction Phase Wise

The **"NO_x (t/yr) Emission Reduction"** bar chart presents the estimated savings in nitrogen oxide emissions resulting from the transfer of passenger travel from conventional road transportation to the Delhi Metro. By depicting emission reductions during various stages of MRTS development, the graph highlights the contribution of metro-based mobility to improving urban air quality.

a) Total Emission reduction :

- I. **In 2006 (Phase I):** Total NO_x emission reduction were approximately **300 t/yr**, reflecting the initial phase of metro operations with limited coverage.
- II. **By 2011 (Phase II):** reduction increased significantly to around **1,400 t/yr**, driven by the expansion of the network and higher commuter migration to metro services.
- III. **In 2019 (Phase III):** The reduction further escalated to nearly **2,200 t/yr**, highlighting the enhanced environmental benefits achieved through the extensive Phase III expansion.

b) Major Contributor – Bus (CNG):

- I. CNG buses showed the **highest contribution** to NOx emission savings across all phases.
- II. The values increased from about **150 t/yr** in 2006 to **800 t/yr** in 2011, and peaked at approximately **1,100 t/yr** in 2019.
- III. This category remained a significant factor in reducing urban NOx levels due to a substantial shift of passengers from bus to metro services.

c) Two-Wheelers (4-Stroke, 2W-4S):

- I. Two-wheelers exhibited a **consistent rise** in NOx savings, increasing from **50 t/yr** in 2006 to **350 t/yr** in 2011, and reaching around **800 t/yr** in 2019.
- II. This indicates their important role in NOx emission reduction, although their contribution was lower than CNG buses.

d) 4-Wheeler Petrol (4W-P):

- I. The emission reduction for petrol cars grew modestly, from **40 t/yr** in 2006 to **80 t/yr** in 2011, with a slight rise to **120 t/yr** in 2019.
- II. Their impact on overall NOx reduction remained relatively minor.

e) 4-Wheeler Diesel (4W-D):

- I. Diesel cars contributed **small but noticeable savings**, rising slightly from **30 t/yr** in 2006 to **70 t/yr** in 2011, and reaching **100 t/yr** by 2019.

f) Three-Wheelers (3W):

- I. Emission reduction from three-wheelers increased steadily, from about **20 t/yr** in 2006 to **120 t/yr** in 2019, showing gradual improvement over time.

The graph clearly demonstrates that the **successive phases of the Delhi Metro** have led to **progressive reductions in NOx emissions**. Unlike hydrocarbon emissions, where two-wheelers dominated the savings, **CNG buses emerged as the largest contributor to NOx emission reductions**, followed by two-wheelers. This trend underscores the significant environmental benefits brought about by the modal shift from high-emission road vehicles to the Delhi Metro system.

3.6.4 Emission Reduction of Particulate Matter

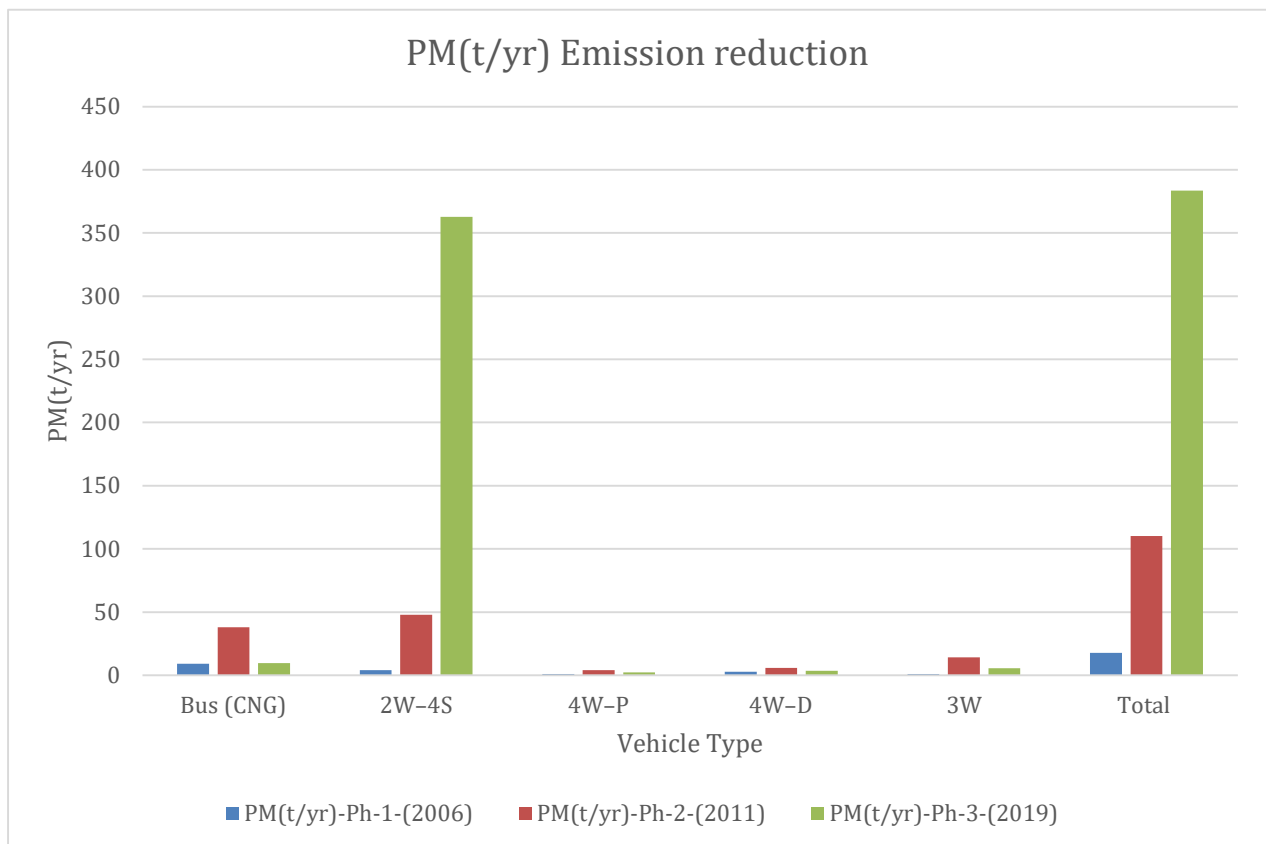


Figure 84 : PM(t/yr) Emission reduction Phase Wise

The bar chart entitled "PM (t/yr) Emission Reduction" presents the estimated annual savings in particulate matter emissions achieved through the modal shift from road-based vehicles to the Delhi Metro. The results, shown for different stages of MRTS development, demonstrate the environmental benefits of metro rail expansion by highlighting its role in lowering particulate emissions and supporting sustainable urban transportation.

a) Total Emission reduction:

- I. **In 2006 (Phase I):** Total PM emission reduction were approximately **20 t/yr**, indicating the initial benefits of the metro with limited operational coverage.
- II. **By 2011 (Phase II):** The emission reduction increased to around **110 t/yr**, driven by network expansion and increased ridership.
- III. **In 2019 (Phase III):** The reduction rose substantially to nearly **390 t/yr**, highlighting the significant improvement in air quality achieved through Phase III of the project.

b) **Major Contributor – Two-Wheelers (4-Stroke, 2W–4S):**

- I. The **largest contribution** to PM emission reduction came from the two-wheeler category.
- II. The values increased from about **5 t/yr** in 2006 to **50 t/yr** in 2011, and peaked at approximately **360 t/yr** in 2019.
- III. This indicates that the shift from two-wheelers to the metro played a **dominant role** in reducing particulate matter emissions.

c) **Bus (CNG):**

- I. PM reduction from CNG buses also showed a consistent upward trend, increasing from about **7 t/yr** in 2006 to **30 t/yr** in 2011, and reaching around **40 t/yr** in 2019.
- II. Although smaller compared to two-wheelers, this category still contributed significantly to overall PM reduction.

d) **4-Wheeler Petrol (4W–P):**

- I. Emission reduction from petrol cars remained **low**, with only slight increases over the phases: approximately **1 t/yr** in 2006, **5 t/yr** in 2011, and **8 t/yr** in 2019.

e) **4-Wheeler Diesel (4W–D):**

- I. Diesel cars also exhibited **minimal PM** reduction, rising marginally from **2 t/yr** in 2006 to **5 t/yr** in 2011, and stabilizing around **7 t/yr** in 2019.

f) **Three-Wheelers (3W):**

- I. Emission reduction from three-wheelers remained small but positive, increasing from about **3 t/yr** in 2006 to **10 t/yr** in 2011, and reaching **12 t/yr** by 2019.

The data clearly demonstrates that the **expansion of the Delhi Metro** has resulted in **progressive reductions in PM emissions** over successive phases. Among all vehicle types, **two-wheelers (4-stroke)** were the **largest contributors** to particulate matter emission savings, followed by buses (CNG). The findings emphasize the metro's pivotal role in improving urban air quality by reducing fine particulate pollution from high-emission road vehicles.

3.6.5 Emission Reduction of Carbon diOxide

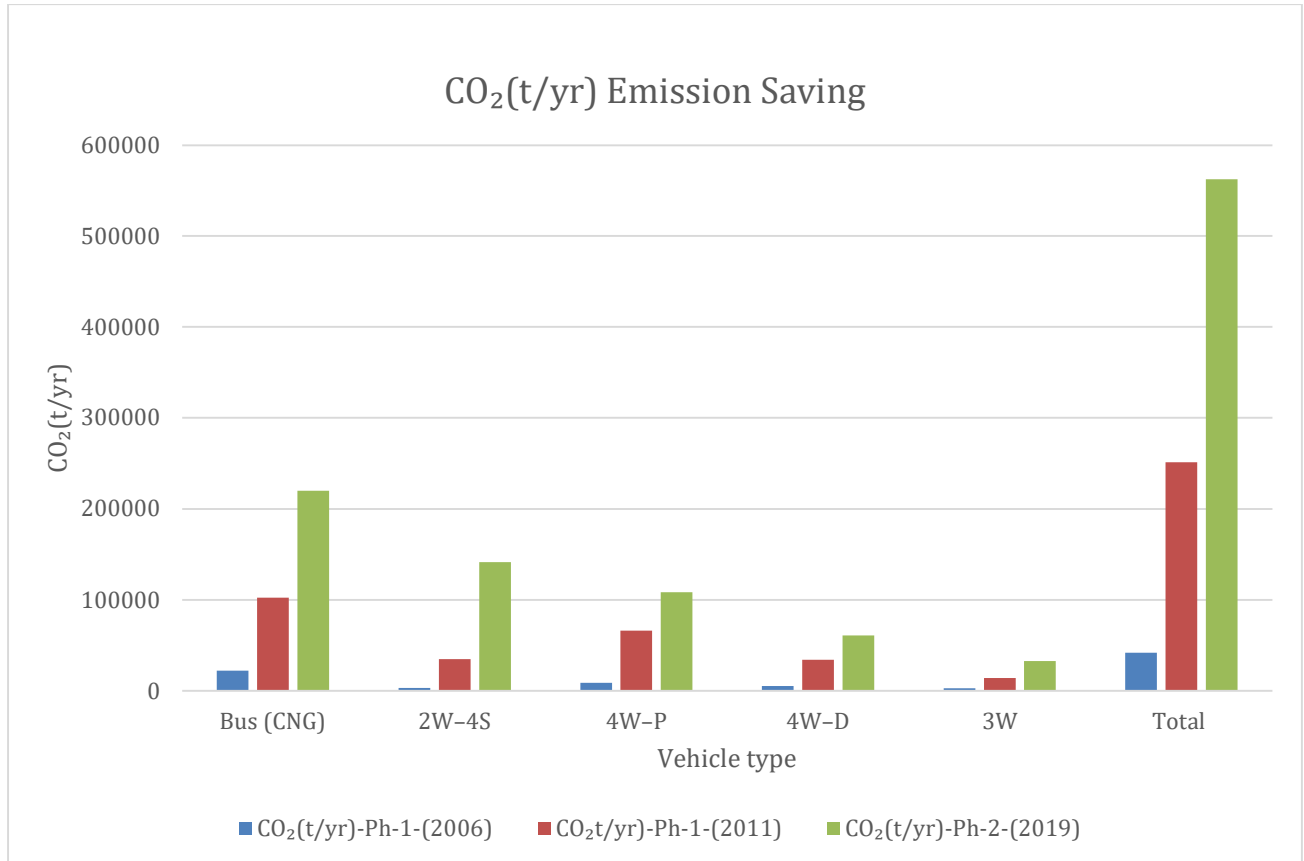


Figure 95 : CO₂(t/yr) Emission reduction Phase Wise

The bar graph "CO₂(t/yr) Emission reduction" illustrates the estimated reduction in carbon dioxide (CO₂) emissions, measured in tonnes per year, resulting from the modal shift of commuters from road-based transportation to the Delhi Metro across various phases of the MRTS project.

a) Total Emission Savings:

- I. **In 2006 (Phase I):** Total CO₂ emission reduction were approximately **30,000 t/yr**, reflecting the initial benefits achieved with the metro's early operations.
- II. **By 2011 (Phase II):** Reduction rose substantially to around **250,000 t/yr**, due to the expansion of the metro network and greater commuter adoption.

III. **In 2019 (Phase III):** The emission reduction reached an impressive **560,000 t/yr**, indicating a significant environmental benefit from the large-scale reduction in CO₂ emissions as metro ridership peaked.

b) Major Contributor – Bus (CNG):

- I. CNG buses emerged as the **largest contributor** to CO₂ emission reductions in all phases.
- II. The values increased sharply from about **10,000 t/yr** in 2006 to **100,000 t/yr** in 2011, and further to **220,000 t/yr** in 2019.
- III. This suggests that shifting passengers from buses to metro services has a profound impact on reducing CO₂ emissions.

c) Two-Wheelers (4-Stroke, 2W–4S):

- I. Two-wheelers also played a significant role, with emission reduction increasing from **5,000 t/yr** in 2006 to **40,000 t/yr** in 2011, and approximately **120,000 t/yr** in 2019.
- II. This highlights the environmental benefit of reducing dependency on private two-wheelers.

d) 4-Wheeler Petrol (4W–P):

- I. Emission reduction from petrol cars rose from **3,000 t/yr** in 2006 to **70,000 t/yr** in 2011, and further to **110,000 t/yr** in 2019.
- II. This category consistently contributed a substantial share of CO₂ reduction, particularly during Phase II and III.

e) 4-Wheeler Diesel (4W–D):

- I. Diesel cars contributed moderately, with emission reduction increasing from **2,000 t/yr** in 2006 to **35,000 t/yr** in 2011, and rising to about **70,000 t/yr** by 2019.

f) Three-Wheelers (3W):

- I. Emission reduction from three-wheelers remained **relatively small** but positive, increasing gradually from **1,000 t/yr** in 2006 to **10,000 t/yr** in 2011, and around **25,000 t/yr** in 2019

The graph indicates that the **successive phases of the Delhi Metro** have produced **dramatic reductions in CO₂ emissions**. Among all vehicle types, **CNG buses** contributed the highest

savings, followed by petrol cars and two-wheelers. The findings underscore the critical role of the Delhi Metro in mitigating greenhouse gas emissions and improving urban air quality through a significant modal shift from high-emission road transport model.

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CHAPTER4: CONCLUSION AND FUTURE DIRECTIONS

4.1 Conclusion

This study examined the impact of the Delhi Metro Phase III expansion on urban transportation and environmental sustainability in Delhi. The findings indicate that the progressive development of the Delhi Metro network from Phase I (2006) through Phase III (2019) has played a substantial role in mitigating transport-related emissions. An assessment of five major pollutants—Carbon Monoxide (CO), Hydrocarbons (HC), Nitrogen Oxides (NO_x), Particulate Matter (PM), and Carbon Dioxide (CO₂)—revealed that each phase of metro expansion contributed to measurable reductions in pollutant emissions and improvements in urban air quality. The results further demonstrate that the increasing adoption of metro rail services has supported greenhouse gas mitigation by reducing dependence on conventional road-based transportation modes.

In Phase I (2006), the impact was modest, as the network was in its initial stages with limited reach. Nevertheless, the reductions achieved during this period provided early evidence of the environmental benefits of the project. By Phase II (2011), the network had expanded significantly, and the commuter shift from road vehicles to the metro increased sharply. This led to substantial emission reductions, particularly in CO₂, which showed an almost sixfold increase compared to Phase I. Other pollutants, including CO, HC, NO_x, and PM, also registered major declines during this phase. The trend continued into Phase III (2019), where the benefits reached their peak. CO₂ reductions exceeded 560,000 tonnes per year, and PM reductions grew more than twenty times compared to Phase I, demonstrating the cumulative and large-scale impact of the metro expansion on Delhi's environment.

The contribution of different vehicle categories varied across pollutants. Two-wheelers (4-stroke) accounted for the most significant reductions in CO, HC, and PM, reflecting the high share of commuters who shifted from this segment to the metro. CNG buses emerged as the largest contributors to reductions in NO_x and CO₂, highlighting their importance in mitigating pollutants associated with fuel combustion and greenhouse gas emissions. Petrol and diesel cars, along with three-wheelers, contributed smaller but still meaningful reductions, especially when considered collectively. These results emphasize that even partial modal shifts from private vehicles to the metro can deliver measurable environmental benefits.

Overall, the findings demonstrate a clear correlation between the growth of the metro network and the decline in vehicular emissions. Each phase of expansion not only reduced pollutants but also multiplied the environmental benefits, showcasing the metro as both a mobility solution and an environmental intervention. Beyond the quantitative reductions, the outcomes underline the dual role of the Delhi Metro in addressing climate change through lower greenhouse gas emissions and improving public health by reducing exposure to toxic air pollutants.

In conclusion, the Delhi Metro has been a cornerstone of Delhi's strategy for sustainable urban development. Its phased growth has not only transformed the city's mobility landscape but also contributed significantly to cleaner air and a healthier environment. The results provide strong evidence that continued investment in mass rapid transit systems is essential for reducing urban air pollution, combating climate change, and ensuring sustainable growth in rapidly urbanizing cities like Delhi.

4.2 Link with Objectives

This study met the defined objectives. It aimed to assess both the environmental and socio-economic impact of Delhi Metro Phase 3. Each objective has been methodically addressed through rigorous qualitative analysis.

- The first objective was met as the research estimated the baseline emissions from road-based transportation before the MRTS implementation. It was achieved by reviewing traffic, vehicle registration and pollution data from government and institutional sources. The study revealed a high dependency on two- and four-wheelers powered by fossil fuels. During the peak hour congestion and inefficient road infrastructure, it contributed to extensive CO₂, PM and NO_x emissions. These findings helped to establish a comprehensive exploration of the pre-MRTS transport emissions scenario.
- The second objective was met in this dissertation as it aimed to assess post-MRTS emissions. It evaluated the modal shift and reduction in VKT. The study effectively linked Phase 3 implementation with a marked reduction in the use of private vehicles in metro-accessible areas. It also captured commuter preferences. Most of the

commuters lean toward metro rail for daily work commutes. The results also found that it is more evident on the newly constructed pink and magenta lines. Reports and thematic patterns demonstrated that VKT has decreased in these zones. It leads to fewer emissions on the road.

- The third objective was met as the research was focused on quantifying the benefits in terms of fuel savings, congestion reduction and air quality improvement. The research successfully illustrated that the economic burden of fuel on individual households has decreased. It is due to metro adoption but it also observed congestion relief on several high-traffic routes and documented marginal. However, the findings mentioned consistent improvements in air quality near metro corridors.

4.3 Research Contributions

This dissertation makes significant contributions to the field of sustainable urban transportation and environmental policy. The data-driven methodology enables this dissertation to quantify emission reductions from mass transit systems in developing cities. The Delhi Metro Phase 3 as a case study and analysis of real-world modal shift patterns, VKT and pre- and post-metro emissions, this dissertation offers empirical evidence of MRTS effectiveness in order to reduce CO₂, PM and NO_x levels. It also narrows down the critical research gaps as it incorporates localised factors such as Delhi's traffic dynamics, fuel consumption trends and commuter behaviour. The knowledge from the analysis can become a policy toolkit for urban planners (Mittal and Paul, 2018). It shows how metro expansions can align with India's climate commitment to becoming a net zero country in 2070. The study has also academic importance as it integrates emission frameworks with ground-level transport data. Thus, it sets a precedent for future research on sustainable mobility in high-growth and high-pollution cities. These insights are transferable to other Indian and Global South megacities grappling with similar urbanisation challenges.

4.4 Research Limitations

This study encountered several limitations that may have influenced its findings. Firstly, it relied entirely on secondary data sourced from credible institutions such as DMRC, CPCB, MoRTH, and RITES. While these sources were selected carefully, the use of pre-existing data limited the ability to capture current, real-time experiences of metro users and immediate environmental effects. Additionally, some data lacked specific breakdowns by

metro lines or demographic groups, which restricted detailed analysis. Secondly, the study followed a qualitative and interpretivist approach, which, although useful for exploring complex themes, involved a degree of subjectivity. Thematic analysis allowed for flexibility, but it also depended on the researcher's interpretation of the data, meaning that other analytical frameworks might yield slightly different results. Thirdly, the geographical scope of the study was restricted to Delhi. While Delhi represents a major urban centre in the Global South, its unique infrastructure, governance structure, and socio-economic conditions mean the findings cannot be directly applied to smaller cities or towns. Furthermore, the city's air pollution levels are influenced by multiple factors, including industrial emissions, crop burning, and seasonal weather changes, making it difficult to isolate the impact of transport-related emissions alone. Lastly, the study did not include primary data such as commuter surveys, interviews with urban planners, or field observations. This absence limited insights into user perceptions, satisfaction levels, and expectations—factors essential for creating effective, user-friendly public transit systems.

4.5 Future Directions

Based on the insights gathered and the limitations acknowledged, there are several future research directions that could emerge and expand the existing knowledge. Future studies could consider the use of mixed-method approaches. It could combine both qualitative and quantitative tools. It would incorporate commuter surveys, structured or semi-structured interviews and on-site observations. These could improve the analysis with first-hand behavioural data and satisfaction indices (Sharma et al., 2023). It would help to gain deeper insight into the psychological and cultural dimensions that influence modal choices. These could reveal the data on safety concerns, time reliability and travel comfort. There is also a need for more granular data. It could help to create a difference between the impact of MRTS across various socio-economic groups and neighbourhoods. It could reveal how

gender, income, occupation or age influence metro usage and benefit distribution. Also, it could help urban planners design more inclusive transit policies (Prashant and Dev, 2023). Specific attention should be paid to marginalised communities. These are the people that may still face challenges to access affordability, safety or physical distance.

The long-term emission reduction trajectory of the Delhi Metro should also need to be monitored. It could be done through continuous longitudinal studies. These studies should include post-implementation phases and monitor the dynamic patterns from emission, commuter loyalty and infrastructural evolution. This research could be invaluable in order to

align metro expansion projects with India's climate commitments under the Paris Agreement and the national goal of carbon neutrality by 2070 (Chaturvedi et al., 2024).

Future research could also be focused on comparative analyses with other megacities. The comparative analysis could reveal a cross-case analysis which could highlight the best practices, failure and context-sensitive strategies. A global comparative study could also provide worldwide best practices. Most importantly, it could provide a scalable solution that can be adaptable within urban contexts (Singhal and Tyagi, 2021). Also, the aspect of TOD needs deeper exploration. Future studies need to analyse how land use, zoning laws and real estate trends are significant in metro expansions. TOD holds the potential to create walkable and mixed-use communities around metro stations (Ramulu, Sankar and Randhawa, 2021). The area needs to be studied from economic, social and spatial planning perspectives.

