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Urban transport emissions under current and alternative mitigation policy scenarios for the Mumbai Metropolitan region

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ABSTRACT

This paper first estimates the emission inventory for Mumbai Metropolitan Region's (MMR) urban transport under business-as-usual (BAU) scenario. The inventory includes five major pollutants, viz. CO_2, CO, NOx, PM, and HC. We used a bottom-up approach based on a traditional four-step travel demand model for the base year (2005) and horizon years (2031 & 2050) to obtain vehicle kilometer traveled (VKT) and vehicular emission factors adopted from the existing literature. The paper then proposes five emission mitigation scenarios for horizon years, including improvement of public transit infrastructure, increase in vehicle operating costs and inclusion of electric vehicles (EVs), to evaluate their impact on the urban transport of MMR. A combination of multiple policies- including the combined effect of land use, increase in vehicle operating cost and transit infrastructure- will reduce private vehicle mode share, VKT, and CO_2 emission by ~21%, ~19%, and ~4% compared to the BAU scenario in 2050.

1. Introduction

Due to rapid urbanization, the urban transportation system could lead to substantial adverse impacts on ambient air quality, society, and health because they are the primary source of air pollution in cities and a major contributor to global climate change. Globally the transport sector depends heavily on fossil fuels, contributing ~25% to total CO_2 emissions (IEA, 2021).

Furthermore, urban cities across developing countries have continuously become embryonic sites because, by 2050, such cities will be home to 66% of the world's population (United Nations, 2014). Such a population might foster a further increase in the air pollution levels due to the shifting of travelers/passengers from non-motorized and other less energy-intensive modes to automobiles. This can be attributed to the attributes being primary reasons for increasing air pollution at the macro (global or regional) and micro (local) levels (Jain et al., 2016; Kumar et al., 2013). Urban transport will significantly contribute to global climate change if such a trend continues because of a five-fold increase in energy demand and carbon emissions (Singh, 2006).

Being a developing country, India's cities are also experiencing rapid growth in population, economy, and urbanization over the last three decades. Such growth contributes to increased vehicle ownership resulting in higher energy consumption and pollution from the road transport sector. This consumption would further increase the oil demand, contributing to local issues like congestion and air pollution (Pathak and Shukla, 2016). For instance, Indian road transport carried about 92% of the total motorized traffic volume of 130,000 billion passenger-km and was responsible for ~13% of national greenhouse gas (GHG) emissions in 2014 (MoEFCC, 2018). Since India is the third-largest contributor to GHG emissions, reducing the emissions from energy consumption poses a big challenge (Timperley, 2019). Urban areas are responsible for ~75 % of the national economy (CBRE, 2019) and contribute to a considerable share in transport demand and energy consumption. Therefore, there is a growing need to emphasize India's urban transport sector concerning climate change and mitigate GHG emissions.

Mumbai Metropolitan Region (MMR) in Maharashtra, India, is rapidly growing and faces several challenges in urban transport management. In the last decade, the mode share of the public transport share of MMR, the highest among all other Indian cities, has decreased from 88% in 1992 to 78% in 2005 (MMRDA, 2008). Furthermore, the total registered vehicles in Greater Mumbai (within MMR) have increased by 275% (1.03 million in 2001 to 2.82 million in 2016) as per MCGM (2016). Such a decrease in the public transportation's mode share and

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an increase in vehicular registrations in MMR is likely to increase health impacts and environmental degradation through energy consumption, traffic congestion, GHG emissions, and air pollution (Tiwari, 2011).

The growing complexities of urban travel demand patterns make it difficult to estimate the emissions from the urban transport sector. Emission inventories are estimated as the product of vehicles' emission factors and their activity level (i.e., vehicle km traveled) over a given time through a top-down or bottom-up approach. The vehicle emission factors are believed to epitome their average long-standing class-wise count in the top-down estimation approach. Vehicle activity is estimated through investigative/statistical methods for each vehicle fleet because of complications in collecting accurate data for large areas. Such estimates result in inaccurate emission estimates (Cook et al., 2006; Hao et al., 2000). Conversely, the bottom-up approach utilizes travel demand models for the vehicle activity data with an in-depth analysis of the spatial dispersal of the transport network and road characteristics, etc. (Gately et al., 2013).

To the best of our knowledge, the existing literature is limited in estimating emission inventory from MMR's urban transport sector especially using a bottom-up approach. This paper aims to contribute to existing literature to comprehend the urban transport situation in MMR while utilizing the bottom-up approach for estimating vehicle emission inventory of five major pollutants, viz. carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxide (NOx), particulate matter (PM), and hydrocarbons (HC). The paper then proposes the appropriate alternative policies and their combinations to mitigate the emissions from MMR's urban transport. The policies include population redistribution, employment redistribution, improvement in transport infrastructure, travel demand management, and improvement in technology. The second section reviews existing literature on emission inventory and mitigation strategies.

2. Literature review

2.1. Emission inventory

In India, some studies utilized a bottom-up approach based on vehicle mileage, fleet, and utilization factors to estimate a national level exhaust emission inventory (Baidya and Borken-Kleefeld, 2009; Pandey and Venkataraman, 2014; Prakash et al., 2020; Ramachandra and Shwetmala, 2009; Sahu et al., 2014; Singh et al., 2017). These studies adopted emission factors estimated from various laboratory measurements (ARAI, 2008; CPCB, 2007). Singh et al. (2019) provided a comprehensive review of all studies estimating greenhouse gas emissions from India's transport sector and concluded that refinement in data inputs, emission factors, and vehicle activity methodology would reduce the uncertainty associated with estimating these emissions.

Sahu et al. (2014) developed an emission inventory for India's road transport sector based on vehicle fleets, average trip length, and emission factors estimated per ARAI (2008). Singh et al. (2017) prepared an emission inventory of different trace gases for India's transport sector using secondary data available on vehicle activity (Ramachandra and Shwetmala, 2009) and emission factors (CPCB, 2007; Mittal and Sharma, 2003). Results indicated Maharashtra being among the principal states contributing to national-level emissions. Prakash et al. (2020) developed the nationwide emission inventory utilizing mass-based emission factors, fuel economy, fuel density, average vehicle trip length, and vehicle fleet. The authors conducted a road experiment on a 10-km stretch to estimate tailpipe emissions.

Several studies estimated emission inventory exclusively for Indian metro cities (Bose, 1998) like Ahmedabad (Rayle and Pai, 2009), Chandigarh (Bhargava et al., 2018), Chennai (Nesamani, 2010), Delhi (Aggarwal and Jain, 2016; Das and Parikh, 2004; Goel and Guttikunda, 2015; Mishra and Goyal, 2014; Nagpure and Gurjar, 2012; Singh and Sharma, 2012) and Mumbai (Das and Parikh, 2004; Rayle and Pai, 2009). Bose (1998) and Das and Parikh (2004) estimated exhaust emission inventory for Delhi and Mumbai using a fusion of long-range energy alternatives planning (LEAP) with an environmental database (EDB) based on vehicle mileage and fleet. Mishra and Goyal (2014) and Nesamani (2010) used an international vehicle emissions (IVE) model to provide emission inventory for Chennai and Delhi based on the vehicle fleet data. Nagpure and Gurjar (2012) also estimated exhaust emission inventory for Delhi while utilizing secondary emission factors (ARAI, 2008) in a vehicle air pollution inventory (VAPI). Furthermore, Goel and Guttikunda (2015) provided emission inventory for Delhi based on secondary emission factors (CPCB, 2007), vehicle mileage, and vehicle fleet data.

Rayle and Pai (2009) utilized data available on vehicle energy demand (Mittal and Sharma, 2003), mode share, and trip rate to estimate CO_2 emission inventory, until 2041, for three cities, i.e., Ahmedabad, Surat, and Mumbai. Singh and Sharma (2012) utilized the top-down approach based on fuel consumption and emission factors data to estimate emission inventory for Delhi. Bhargava et al. (2018) estimated CO, N_2O, and CO_2 emissions from Chandigarh's road transport sector using VAPI and obtained vehicle activity from the vehicle fleet and average daily trip length. To the best of our knowledge, the existing literature is limited in estimating emission inventory from MMR's urban transport sector (Das et al., 2021; Kumar, 2009). Kumar (2009) utilized secondary data available on vehicle travel activity (MMRDA, 2008) and emission factors (ARAI, 2008) to estimate the emission inventory for MMR. Das et al. (2021) estimated CO_2 emissions from MMR's public transport system and explored the potential of electric vehicles (EVs) in mitigating these emissions.

2.2. Emission reduction strategies

In India, few studies exist on exploring the reduction of city-level CO_2 and other emissions (Aggarwal and Jain, 2016; Bhargava et al., 2018; Jain et al., 2016, 2014; Li, 2011; Pathak and Shukla, 2016; Yedla et al., 2005). The majority of such studies considered the impact of particular transport infrastructure or policies on emissions, ridership, and travel time rather than the entire transport infrastructure of a city or region (Doll and Balaban, 2013; Khanna et al., 2011; Sharma et al., 2014; Singh et al., 2021; Soni and Chandel, 2018). Bhargava et al. (2018) developed two policy scenarios viz. business as usual (BAU) and the best estimate scenario (BES) for sustainable urban transportation to assess the reduction in GHG pollution load for Chandigarh city. However, to the best of our knowledge, only limited studies exist on covering the impact of various emission reduction scenarios for the urban transport sector of the Mumbai Metropolitan Region (MMR). Yedla et al. (2005) compared the greenhouse mitigation strategies (GEMS) with local emission mitigation strategies (LEMS) for Mumbai. This was achieved by considering three strategies targeted at CO_2, total suspended particles (TSP), and HC emissions. These strategies included the different proportions of vehicle fleets in terms of their technology and fuel. The results showed that LEMS performed better than GEMS in reducing CO_2 emissions. TSP and CO_2 targeted strategies successfully reduced emissions, whereas HC targeted strategy underperformed in reducing the other emissions except for targeted pollutant, HC. (Yedla et al., 2005).

In addition to scholarly literature, there are some governmental initiatives through shifting to a fuel-efficient engine technology, alternate fuels, and stringent emission norms to reduce vehicular emissions from road transport in India (Lathia and Dadhaniya, 2019; Singh et al., 2021). Under fuel-efficient engine technology, policies included converting two-stroke engines to four-stroke engines in two-wheelers and three-wheelers and excluding diesel-powered vehicles older than 15 years from the fleet. Compressed natural gas and biofuel-powered vehicles were introduced in major Indian cities (starting with New Delhi) as part of adopting alternate fuels (Singh et al., 2021). Recently, the government introduced the National Electric Mobility Mission Plan to encourage the adoption of electric and hybrid vehicles (MHI, 2023). Under stringent emission norms, in 1999, the Government of India

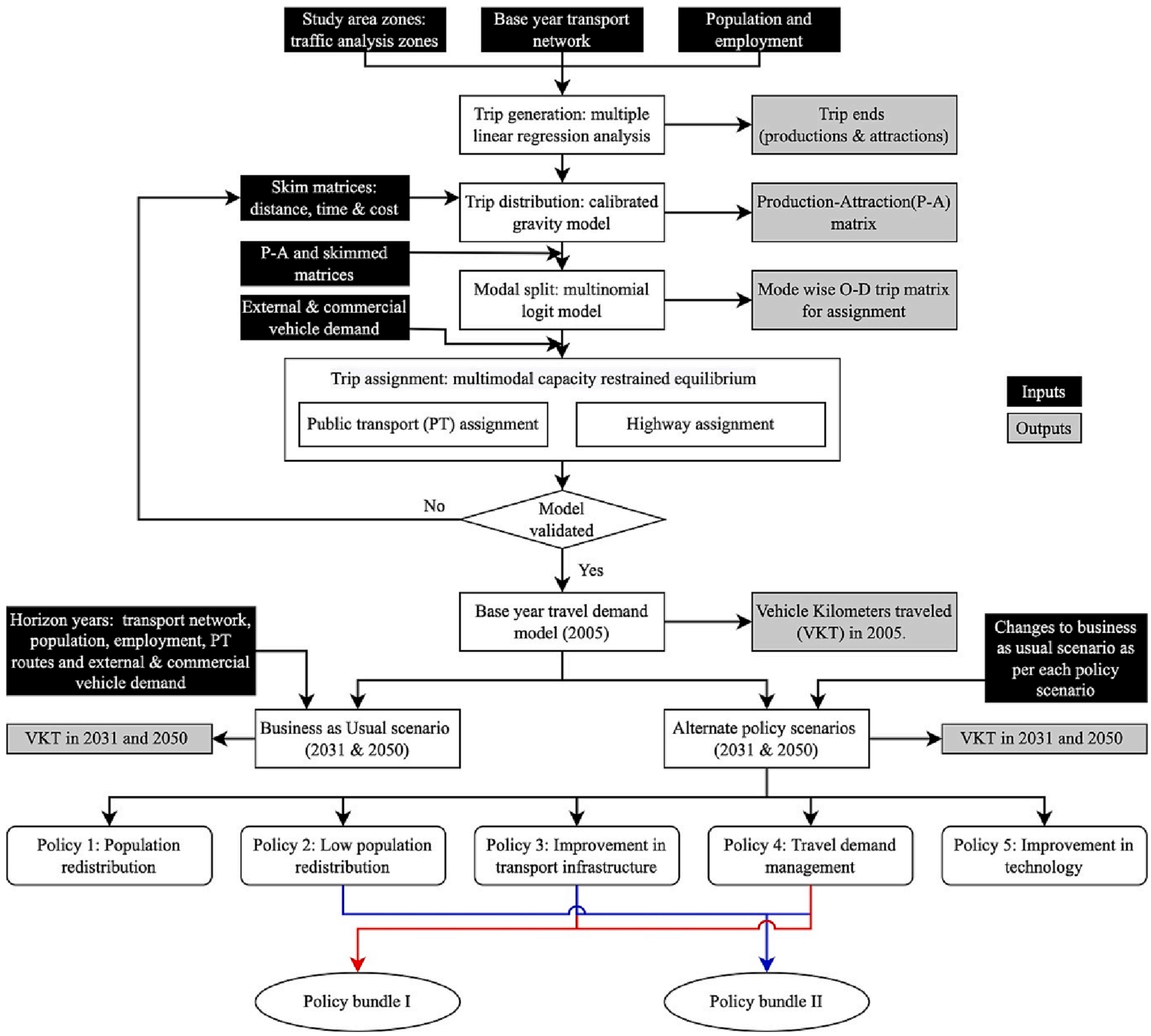

Fig. 1. Methodology of scenario generation for MMR's urban transport sector.

introduced auto-fuel norms, delineating a roadmap for changes in passenger vehicle technology and fuel quality. As per these norms, all vehicles were mandated to follow stringent emission standards, regarded as *Bharat Stage (BS)*, similar to European Euro norms. In this direction, the 2003 Auto-Fuel Policy synchronized Indian vehicular emission standards with Europe, resulting in lesser $PM_{2.5}$ and NO_X emissions (Bansal and Bandivadekar, 2013). Under this initiative, BS-IV norms were implemented entirely in India. In 2016, the Government of India mandated and implemented BS-VI norms (from BS-IV leapfrogging BS-V) for vehicles manufactured after April 2020 from BS-IV (Lathia and Dadhaniya, 2019; Singh et al., 2021). BS-VI included more stringent standards for PM emissions.

2.3. Contribution

Based on the existing literature, it may be concluded that most studies utilized vehicle fleet data to estimate urban transport emissions. Nevertheless, vehicle fleet data includes limitations in terms of biased and partial information on vehicle fleet characteristics (like mileage, speed, vintage), driving behavior, and vehicular traffic counts (Sturm et al., 1996). Aggarwal and Jain (2016) partially rectified these limitations. The authors carried out primary surveys in Delhi's 200 locations to obtain vehicle technology, fuel technology, mileage, vintage, and occupancy-related information from vehicle users. The authors then used the collected information to derive city-specific emission factors based on ARAI's emission factors. To emulate vehicle activity, the authors utilized vehicle kilometers traveled (VKT) from a four-stage travel demand model (TDM) (RITES, 2010). Past efforts are limited (Kumar, 2009) in estimating emission inventory for MMR's urban transport sector, especially using the bottom-up approach or travel demand modeling. In addition to GHG's current situation and other emissions in MMR, the literature also lacks its future projections.

This paper aims to contribute to existing literature to comprehend the urban transport situation in MMR while utilizing the bottom-up approach for estimating vehicle emission inventory. The objectives of this study are fourfold: (i) to estimate the impact of the growth of urban transport infrastructure on vehicle activity; (ii) to estimate the emission from the urban transport sector of MMR with the increase in vehicle activity; and (iii) to prepare an emission inventory for MMR including forecasts of the vehicle activity and emission levels year 2050 (iv) to evaluate the mitigation potential of different policies in the future (2031 and 2050) for emissions from the urban transport sector of MMR.

3. Methodology

Methodology for determination of VKT and emissions for the Business as Usual (BAU) and alternate policy scenarios in 2031 and 2050 consists of three stages, namely, (1) formulation of the travel demand model for BAU and alternate policy scenarios (2) emission factor generation, (3) estimation of emission inventory.

3.1. Data

We selected Mumbai Metropolitan Region (MMR), India, as the case study area. MMR is spread over 4,355 km^2 with nine municipal corporations, 15 smaller municipal councils, and 1,000 villages and houses with over 20.7 million population as of the 2011 census. Globally, it is one of the largest agglomerations, with 31,700 people living per km^2 (United Nations, 2018). MMR is set to experience an increase in emissions from its urban transport sector. For instance, in the last decade, the public transport mode share in MMR has decreased from 88% in 1992 to 78% in 2005 (MMRDA, 2008). Furthermore, the total registered vehicles in Greater Mumbai (within MMR) have increased by 275% (1.03 million in 2001 to 2.82 million in 2016) (MCGM, 2016).

3.1.1. Travel demand model

The principal inputs for the MMR's TDM are based on most recent household travel survey conducted in comprehensive transport study for MMR as provided in MMRDA (2008). The data included zonal employment and population, traffic analysis zones (TAZ), road and transit network, travel demand including external and commercial vehicles, demand modeling related parameters and equations, vehicle occupancy rates, and passenger car unit (PCU) factors (MMRDA, 2008). We utilized the secondary data to complete all three modeling stages. MMR's travel demand modeling exercise is based on the existing literature (MMRDA, 2008; Sharma and Chandel, 2020a).

3.1.2. Emission factors

We obtained emission factors for conventional and electric vehicles from the existing literature (Sharma and Chandel, 2020b). For estimating emission factors for conventional vehicles, Sharma and Chandel (2020b) revised emission factors of five pollutants (CO, HC, NO_x, CO_2, and $PM_{2.5}$) obtained from secondary sources (ARAI, 2008; CPCB, 2015) based on assumptions related to emission standards, vehicles (vintage and distribution of 2-stroke and 4-stroke technology) and the ratio of the share of vehicles running on the older emission standard to the new standards. For EVs, Sharma and Chandel (2020b) estimated electricity emissions (g/kWh) and utilized electricity consumption (kWh/km) of different vehicle classes from the existing literature. More details regarding these emission factors are provided in Section 3.3.

3.2. Travel demand model formulation: BAU and alternate policy scenarios

VKTs for the MMR's urban transport sector were estimated using TDM developed by Sharma and Chandel (2020b). Based on the secondary data from MMRDA (2008), the study's base year is 2005. After validating the base year model, a BAU scenario for MMR for the horizon years 2031 and 2050 was considered. Hence, first, TDM was formulated and validated for the base year 2005 and then was utilized to emulate the BAU scenarios. Similarly, five alternate policy scenarios are also considered for MMR's urban transport sector for the horizon years 2031 and 2050 (Fig. 1). The principal distinctions between the base year model and the BAU scenario model are discussed in the forthcoming sections.

3.2.1. Travel demand model: Base year (2005)

A traditional four-stage TDM was formulated, constituting trip generation, trip distribution, modal split, and traffic assignment. 'Cube Voyager' software was used to formulate the model (Citilabs, 2018). For modeling purposes, MMR was divided into internal and external TAZs (MMRDA, 2008). MMR's 6,266 km long road network, including primary, secondary, and other highways, was coded as highway links and their attributes (MMRDA, 2008). MMR's 400 km long transit network, suburban rail, was coded as public transport links.

In the trip generation, base year population and employment were utilized, conforming to the P3E4 distribution scenario of MMRDA (2008), as inputs in multiple linear regression analysis for estimating trip ends, i.e., production and attraction (more details in Sharma and Chandel (2020b)). As per the P3E4 distribution scenario, railway/metro stations, residential & commercial areas, and greenfield lands were assumed to occupy 35%, 32%, and 31% of the population growth between the base year and horizon year (P3). As a result, the population of Greater Mumbai and the rest of MMR would increase from 12.9 million and 7.9 million in the base year to 16 million and 18 million in the horizon year 2031. For employment, as per the E4 scenario, MMR was assumed to have more employment opportunities than the rest of MMR when compared to Greater Mumbai. Consequently, employment in Greater Mumbai and the rest of MMR would decrease and increase from 5.7 million and 2.1 million in the base year to 5.1 million and 10.2 million in the horizon year 2031. The gravity model was used to obtain the trip distribution's production-attraction (P-A) matrix. In modal split, multinomial logit (MNL) framework coupled with captive-choice constraint was used to obtain mode-wise P-A matrices for private (car and two-wheeler) and public transport (suburban rail, bus, and intermediate public transport (IPT): taxi and auto-rickshaw trips). Then directional distribution factors (MMRDA, 2008) were employed to obtain mode-wise origin–destination (O-D) matrices for the morning peak period.

MMR's external and internal commercial vehicle demands were utilized, including light commercial vehicles (LCV) and heavy commercial vehicles (HCV). The total number of internal commercial vehicle trips for the base year was 62,465 per day, LCVs constituting 39.17% (MMRDA, 2008). The external vehicle demand for MMR, i.e., 88,810 vehicles per day, including commercial vehicles (43.37%), buses (7.02%), and personalized vehicles (48.55%: car, two-wheeler, taxi, maxi cab, and three-wheeler) was considered. Due to insufficient data, the average trip length of external vehicles, excluding commercial vehicles, was taken the same as that of the internal vehicles. Finally, all O-D matrices, including mode-wise internal trips (private and public), external vehicles, and internal commercial vehicles, were then converted to peak hour using a peak hour factor. The multimodal capacity restrained equilibrium technique was used in the traffic assignment to assign the O-D matrices to the highway network and public transport links to obtain link flows.

3.2.2. Model validation

Before using the base year model for alternate scenarios in the future, a validation exercise was performed based on the two criteria, i.e., comparing (i) vehicle and passenger flows and counting stations (ii) predicted mode share with observed mode share. For the first criterion, we considered four internal cordons (IC) in the MMR region as per MMRDA (2008) to compare observed traffic/passenger flows with their predicted counterparts. We adopted a percentage difference threshold of $\pm$ 30% from Erhardt et al. (2020). Link and passenger flow at all four ICs satisfy the threshold (Sharma and Chandel, 2020a). Details are provided in Appendix A.1 (Tables A.1 and Table A.2). For the second criterion, we compared the estimated mode share in the base year with observed data obtained from MMRDA (2008). The comparison shows a close match between the estimated share of each mode with their observed counterpart (Figure A.1 in Appendix A). After the validation, a 10% peak hour factor was used to obtain mode-wise VKTs as the final output from the loaded transport network.

3.3. Estimation of emissions

Emissions factors for pollutants (CO, HC, NOx and PM2.5) and CO_2 for all the vehicles (car, two-wheeler, three-wheeler, taxi, bus, suburban rail, metro, and monorail) are estimated and presented in another study: Sharma and Chandel (2020b). For estimating emission factors for

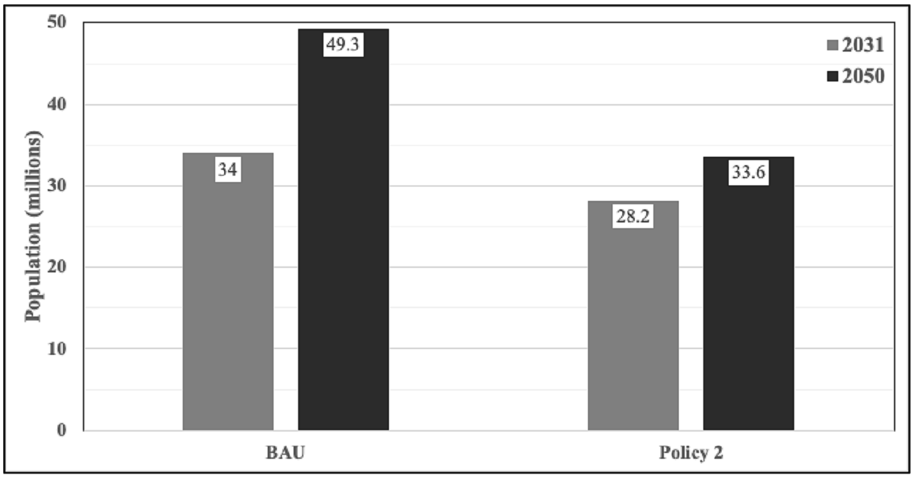

Fig. 2. Population in BAU and Policy 2.

conventional vehicles, Sharma and Chandel (2020b) revised emission factors of five pollutants (CO, HC, NO_x, CO_2, and $PM_{2.5}$) obtained from secondary sources (ARAI, 2008; CPCB, 2015) based on assumptions related to emission standards, vehicles (vintage and distribution of 2-stroke and 4-stroke technology) and the ratio of the share of vehicles running on the older emission standard to the new standards.

For EVs, the emission factors are based on the Indian electricity generation mix scenarios and the mileage of the vehicles, covered in Sharma and Chandel (2020b). The authors estimated electricity emissions (g/kWh) and utilized electricity consumption (kWh/km) of different vehicle classes based upon the existing literature. Authors assumed that all the power plants for non-renewable (coal, heavy fuel oil, natural gas, and nuclear) and renewable sources (hydropower, bioenergy, solar, waste, and wind) of electricity would follow emissions standards. Hence emission standards would serve as the upper bound of the emissions for a particular electricity source. This assumption was then combined with two scenarios for the Indian electricity grid mix. More details regarding both scenarios are provided in Section 3.3.2.5. The detailed methodology and emission factors are shown in Sharma and Chandel (2020b). The emission factors are enumerated in Appendix B. Using these emission factors, we then estimated the emission inventory for all pollutants in all the policies and bundles based on the VKT method:

$$E_{pm} = EF_p \times VKT_m \tag{1}$$

Where, E = total emissions (g), p = pollutant (CO2, CO, HC, NOx and PM2.5), m = mode of travel (car, two-wheeler, taxi, suburban rail etc.), EF = emission factor (g/km) and VKT = vehicle kilometers travelled (km).

For conventional vehicles, the emission factors are delineated in Table B.1 in Appendix B. In BS-VI (Euro-VI equivalent) emission standards, all emission factors (except CO_2) for all vehicle classes of conventional vehicles will reduce significantly. Hence in future years, there will be a significant reduction in such emission factors because of the increase in the proportion of vehicles operating on BS VI standards (Sharma and Chandel, 2020b). For EVs, including suburban rail, metro, and monorail, electricity emission factors under scenario S1 (Table B.2 in Appendix B) are used except for Policy 5 S2, where emission factors for scenario S2 (Table B.3 in Appendix B) are used. A declining trend for all five pollutants can be seen, which can be regarded as a future decrease in the share of electricity produced from non-renewable sources. Sharma and Chandel (2020b) provide a detailed trend analysis of emission factors.

3.3.1. *TDM: Business as usual (BAU) scenario*

The validated base year model was used to evaluate the BAU scenario for 2031 and 2050. The MMR's population and employment compound annual growth rate was taken from MMRDA (2008). For MMR's population, CAGRs were assumed as 1.9%, 2.3%, and 1.9% for 2001–21, 2021–31, and 2031–41 after MMRDA (2008). Similarly for employment growth, MMRDA (2008) provided CAGRs of 1.77%, 3.28%, 2.42%, and 2.19% for 2005–11, 2011–16, 2016–21, and 2021–41. The population and employment CAGR was assumed to be the same as 2031–41 for 2041–50.

In horizon years, based on proposed developments after the base year 2005, transit network and routes of two new public transport modes, i.e., Metro and mono rail, were added along with the proposed extension in the suburban rail line. For the future demand for commercial and external vehicles, MMRDA's (2008) growth rates, i.e., 3%, 2.35%, 10.47%, and 5.48%, for internal commercial vehicles, external commercial vehicles, external personalized vehicles, and external buses, respectively were utilized. The forecasted commercial and external vehicle demands were added to the BAU scenario. Finally, the mode share and VKTs for 2031 and 2050 from the BAU TDM were obtained.

We performed additional validation checks to ensure the robustness of predicted mode shares in the horizon years based on the base year 2005. BAU scenario was formulated for the horizon year 2021, and the predicted mode share in 2021 was compared against the mode share reported by MMRDA (2021). The details are provided in Appendix A (Figure A.2). Results indicated a close match in the mode share of car, two-wheeler, and suburban rail. However, our study's estimates reported mode share buses and taxis 9% and 7% higher than the MMRDA (2021). The mode share of monorail is 20% less than that of MMRDA (2021). Such differences in estimated mode share can be attributed to the non-availability of metro and transportation networking companies in the base year (2005) as compared to MMRDA (2021) and are one of the limitations of this study. However, this difference is not expected to affect VKT forecasts as mode share closely matches among the main contributing modes (private). Furthermore, a mismatch in public transport mode share does not affect their VKTs as the routes and frequency of buses and metro rails are fixed and do not vary with an increase or decrease in ridership.

3.3.2. *TDM: Alternate policy scenarios*

Based on the base year model discussed in section 3.2.1, we considered five alternate policy scenarios for urban transport of MMR. After formulating and evaluating these five alternate scenarios, we also propose two policy bundles by combining various alternate policy scenarios.

3.3.2.1. Policy 1: Population redistribution. The population and

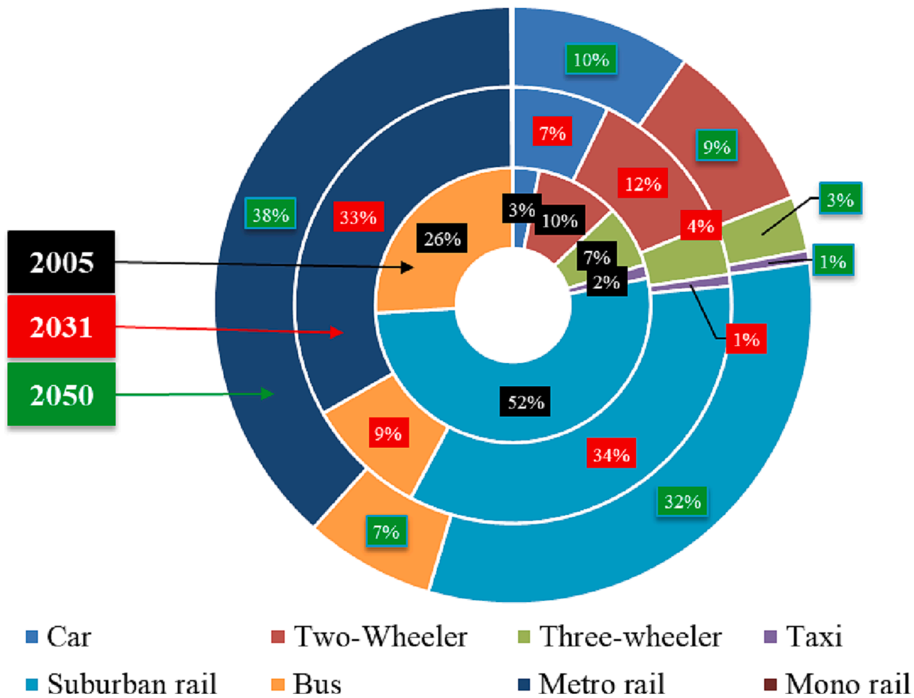

Fig. 3. Mode share of internal vehicles of MMR in the base year and BAU scenario (adopted from Sharma and Chandel (2020b).

employment distribution in the BAU scenario are based on the Comprehensive Transport Study (CTS) carried out for MMR in 2005 (MMRDA, 2008). But MMRDA (2016), a regional plan for MMR published ten years after the CTS, has different regional population growth estimates. MMRDA (2016) predicted that there would be differential growth at an individual corporation level which tends to some municipal corporations like Greater Mumbai, Ulhasnagar and Bhiwandi have already attained high population density which makes them saturated and would exhibit less scope for further densification. Therefore, the population growth rate will be less in these corporations, unlike other less densified corporations like Vasai-Virar and Mira Bhyandar, which will also show higher growth rates because of the land available for further development.

In this policy, we assume that there would be no change in the nature of employment in MMR, and the population will grow at different regional rates as per MMRDA (2016). These assumptions will change the distribution of population and population share of constituent districts and corporations of MMR while keeping the total population projections used in the BAU scenario constant. MMRDA (2016) also highlights some infrastructure development plans for Suburban rail, metro, highway tunnels, and creek bridges (included in Appendix A).

3.3.2.2. Policy 2: Low population redistribution. This policy is based on MMRDA's (2016) draft regional plan for MMR (2016–36), which corresponds to substantially less population growth and distribution in the MMR in the future as compared to MMRDA (2008). The population predicted by MMRDA (2008) was replaced with the population predicted by MMRDA (2016) (Fig. 2). MMRDA (2016) corresponds to this because of the modification and no implementation of special economic zones (SEZ) and other proposals included in MMRDA (2008). The population in this policy will decrease by ~17% and ~32% in 2031 and 2050, respectively, as compared to the BAU scenario. MMRDA (2016) selected trend base method for population projection and to modify the transit network of MMR accordingly. The population of MMR was predicted using the separate growth rates for each constituent (MMRDA, 2016).

MMRDA (2016) also proposes new growth centers and regional industrial areas to facilitate employment creation and decrease the distance between workplace and home of the people living in Vasai-Virar, Bhiwandi, Thane, Kalyan, Dombivali, and Panvel areas (rest of the region of MMR). Growth centers are identified in Vasai, Bhiwandi, Kalyan, and Panvel Tehsils. The employment in this policy was modified because of these growth centers and industrial areas. The distribution of total employment is assumed to shift from the area under the municipal corporation of Greater Mumbai (MCGM) to the rest of the region of MMR. Due to the unpredictability of the exact location and nature of the growth centers and industrial corridors (MMRDA, 2016), the total employment in Greater Mumbai, as estimated for BAU, is reduced by 10% and is distributed in urban areas and rural areas of RoR in 7:3 ratio, respectively. The transit network of MMR was also modified after incorporating the transport infrastructure proposed by MMRDA (2016) (Appendix A).

3.3.2.3. Policy 3: Transport infrastructure development. This policy proposes an improvement in the existing public transport network to boost transit ridership. We propose implementing a bus rapid transit system (BRTS) to increase transit accessibility and ridership (shift of potential private vehicle users to public transport). Following the recommendations of providing dedicated bus lanes on North-South and East-West arterials in Mumbai (MCGM, 2005), we propose to add BRTS corridors on four major highways of MMR in the horizon year travel demand model, i.e., Jogeshwari- Vikhroli Link Road (JVLR), Eastern Expressway (EE), Eastern Freeway (EFW) and Western Expressway (WE).

3.3.2.4. Policy 4: Travel demand management. Travel demand management consists of a wide range of policies that directly or indirectly influence the travel behavior of commuters and proactively affect the travel demand within the city boundaries (Mittal and Biswas, 2019). This policy includes the change in the operating cost of private vehicles. This policy captures the effect of travel demand management strategy including the increase in parking charges and congestion pricing within city boundaries and increase in road taxes (fuel and vehicle registration) in the region. Existing literature is prolific in terms of increasing vehicle operating costs (Mittal and Biswas, 2019) but limited on "by how much it should be increased".

To evaluate the policy, we increased the vehicle operating from 5%

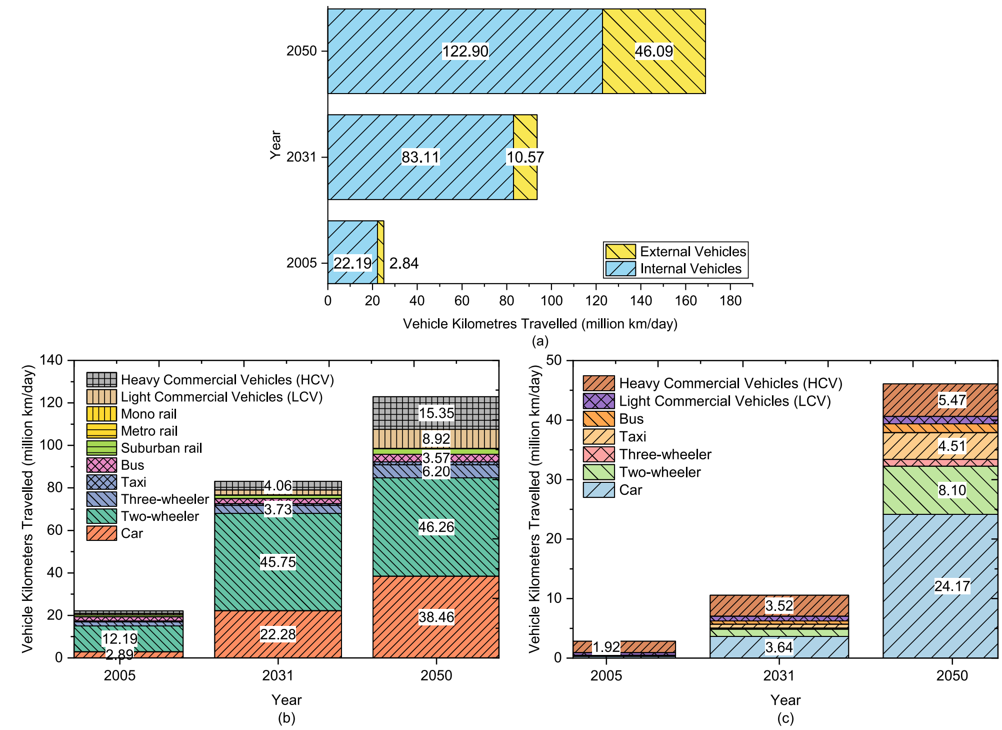

Fig. 4. VKTs (million km/day) obtained from TDM for MMR in base year and BAU scenario (a) total vehicles (internal + external) (b) internal vehicles (c) external vehicles.

to 100% with an equal increment of 5%. For regional level (MMR), the travel demand model showed significant reduction in private vehicle mode share at 10% increase in the travel costs. However, for the city level (Greater Mumbai), the model showed significant reduction at 60% increase in the vehicle travel costs which can be attributed to high reliance of population on private vehicles. Hence, the policy was evaluated in two subparts with the following assumptions:

Policy 4a): A combined effect of congestion pricing and parking policy resulting in a 60% increase in the travel cost of private vehicles in Greater Mumbai.

Policy 4b): A combined effect of an increase in fuel pricing and registration cost of vehicles resulting in a 10% increase in travel cost of private vehicles in the whole area of MMR.

3.3.2.5. Policy 5: Improvement in technology. This policy proposes technology improvement to mitigate vehicular tailpipe emissions. This policy includes the uptake of EVs in the MMR in 2031 and 2050. For the penetration of EVs, it was assumed that the share of the electric car, three-wheelers, taxis, and buses will be 40% in 2031 and will further rise to 100% by 2050. For the electric two-wheelers, 80% and 100% share in 2031 and 2050 respectively was assumed. The cost of ownership of EVs was assumed to be competitive with that of conventional fuel vehicles; hence the mode share and VKTs of the BAU scenario will remain unaffected.

The emissions from EVs are completely indirect or the electricity emissions. These emissions depend upon the source of electricity generation. We considered two different scenarios to account for uncertainty in the electricity grid mix in the horizon years 2031 and 2050, i.e., S1 and S2. Scenario S1 is the electricity generation in business as usual case, adapted from the New Policies Scenario of IEA (2015). Scenario S2 assumes that renewable and non-renewable sources will have an equal share of 50% in the electricity generation mix (Sharma and Chandel, 2020b). We utilized emission factors for EVs in scenarios S1 and S2 from Sharma and Chandel (2020a).

4. Results and discussions

4.1. Business as usual (BAU) scenario

4.1.1. Mode share

Fig. 3 shows the model shares of internal vehicles, including private and public modes, in the base year and horizon year (adopted from Sharma and Chandel (2020b)). In the base year, suburban rail dominated the share (52%), followed by buses (26%) and private mode (13%). However, in 2050, the metro (38%) would have the maximum share, followed by suburban rail (32%), and the private mode share (19%) surpasses buses (7%). The decline in suburban rail share in 2050 from 2005 can be attributed to an increase in the metro's share (38% in 2050). This increase in the metro's share is because of its benefits of greater convenience, lesser congestion, and lesser travel time than suburban rail and private mode. The decrease in suburban rail share may also be attributed to a drastic increase in private vehicle trips. It was observed that although there was a decline in the share of public transport (train and bus) and an increase in private vehicles in the horizon years, the total mode share of MMR's public transport would remain the same (77–78%) due to the implementation of the metro.

The IPT share would drop by 5% in 2050 from 2005. Compared to the base year, bus and suburban rail mode shares would decrease by 19% in horizon years. The proportion of the metro in the horizon years would increase from 33% in 2031 to 38% in 2050. Further, the two-wheeler's mode share would decrease from 9.7% in 2005 to 12% in 2031 and 9% in 2050. The share of cars would increase from 3% in 2005 to 8% in 2050.

4.1.2. Vehicle kilometers traveled

Estimated VKTs portrayed in Fig. 4 indicate that commercial vehicles, cars, and two-wheelers constituted a significant share of VKTs (88%) in 2050. The total VKTs increased by nearly 4 and 7 times in 2031 and 2050, respectively, compared to the total VKTs in the base year 2005. The VKTs of external and internal vehicles would increase by 16.21 and 5.5 times, respectively, from 2005 to 2050. The share of VKTs

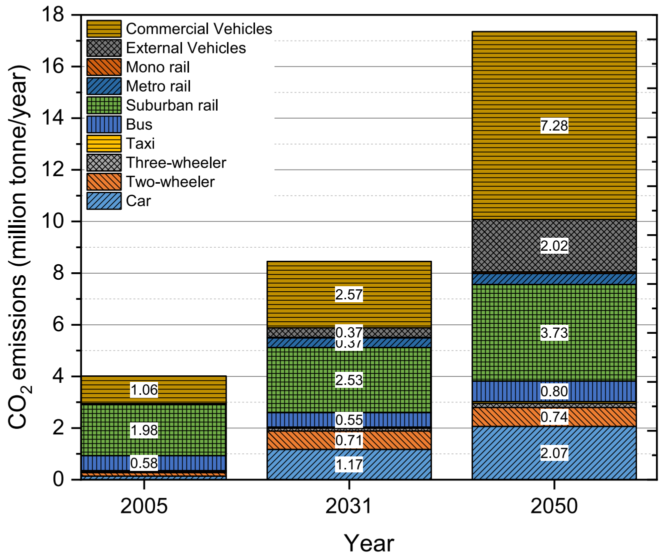

Fig. 5. CO_2 emissions (million tonnes/year) from MMR's transportation system in the base year and BAU scenario.

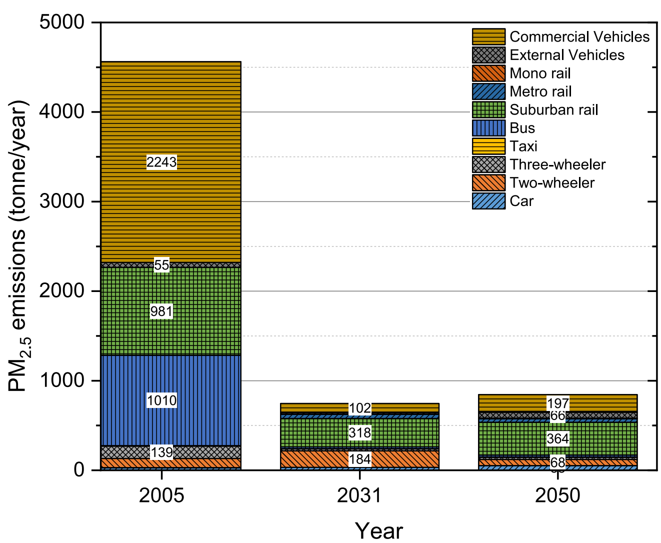

Fig. 6. $PM_{2.5}$ emissions (tonne/year) from MMR's transportation system in the base year and BAU scenario.

by public transport would decrease by 42% in 2050, attaining 12%, from 22% in the base year. The share of VKTs of private mode would increase by 12% in 2050, attaining 69%, from 62% in the base year. Despite their small mode share as compared to public transport, the VKTs were higher because of the associated low vehicle occupancy and high trip lengths.

The VKT by various transport modes like cars, two-wheelers, buses, IPT, trains, metro, and monorail in MMR increased by nearly 675% in 2050 than in 2005. This was due to the increase in the purchasing power of the booming middle class, undiminishing aspirations to own a vehicle, and the disadvantages of using public transport. The increase in VKTs can also be attributed to new road infrastructure and public transport routes in horizon years. It is worth mentioning that the metro and suburban rail have a minuscule share in VKTs despite dominating the mode share because the vehicle kilometers traveled by these are negligible compared to private vehicles. Mode share for public transport represents their ridership and has higher vehicle occupancy values than private modes. Also, public transport services have fixed routes with a fixed number of vehicles irrespective of ridership.

4.1.3. Emissions from MMR's transportation system

4.1.3.1. CO_2 emissions. CO_2 emissions are set to increase in the future as they would be 111% and 333% more in 2031 and 2050, respectively, from 2005 (Fig. 5). External vehicles dominated this increase as these vehicles would contribute to 119% and 456% more CO_2 emissions in 2031 and 2050 than in 2005. The external and commercial vehicles constituted about 35% and 54% of CO_2 emissions in 2031 and 2050. Overall results show that CO_2 emissions would increase by 400% in 2050 from 2005. This increase can be attributed to vehicles operating on fossil fuel in horizon years. Another reason is increased car trips as these modes release most CO_2 emission/pass-km (Sperling and Salon, 2002). The increase in CO_2 levels may also be attributed to the addition of electrical rail (mono, metro, and suburban trains), for which fossil fuel-fired power plants dominate the source of energy. The maximum increase in CO_2 emissions came from the external vehicles, as external vehicles consisted of a significant share of car and commercial vehicles, which exhibited higher emissions.

4.1.3.2. $PM_{2.5}$ emissions. $PM_{2.5}$ emissions from the transportation sector of MMR illustrated in Fig. 6 depict a declining trend. $PM_{2.5}$ emissions were estimated to decrease by 84% and 81% compared to the base year in 2031 and 2050, respectively. The significant decrease was from the bus, alleviating by 98% in 2050 from the base year. $PM_{2.5}$ emissions from commercial vehicles would also reduce by 96% and 91% in 2031 and 2050 from the base year.

4.1.3.3. CO, HC, and NO_x emissions. CO, HC, and NO_x emissions enumerated in Table 1 also depicts cars, two-wheelers, and commercial vehicles as the primary source of these pollutants. CO and HC emissions would increase by 111% and 209% in 2050 from 2005. However, NO_x emissions would decrease drastically by 51% in 2050 from 2005. Commercial vehicles in MMR would contribute to 46% of CO, 40% of HC, and 42% of NO_x in 2050. $PM_{2.5}$ and NO_x would substantially decline

Table 1
Emissions from MMR's transportation system (tonne/year) in BAU scenario.

Vehicle Class	CO			HC			NO_x		
	2005	**2031**	**2050**	**2005**	**2031**	**2050**	**2005**	**2031**	**2050**
Car	2,574	4,294	7,412	281	1,082	1,867	362	1,057	281
Two-wheeler	5,129	15,579	16,785	3,515	3,356	1,672	498	952	1,013
Three-wheeler	3,070	662	683	1,298	430	466	383	200	190
Taxi	369	158	262	40	40	66	52	39	10
Bus	5,852	2,598	3,750	1,172	183	249	8,749	1,191	1,009
Suburban rail	878	1,164	1,758	0	0	0	5,944	4,476	4,968
Metro rail	0	172	200	0	0	0	0	660	565
Mono rail	0	7	32	0	0	0	0	29	89
External Vehicles	602	1,837	10,125	113	358	1,871	480	495	834
Commercial Vehicles	17,973	13,074	35,329	2,806	1,373	4,078	14,936	4,632	6,423
Total	**36,447**	**39,545**	**76,335**	**9,225**	**6,821**	**10,269**	**31,405**	**13,730**	**15,383**

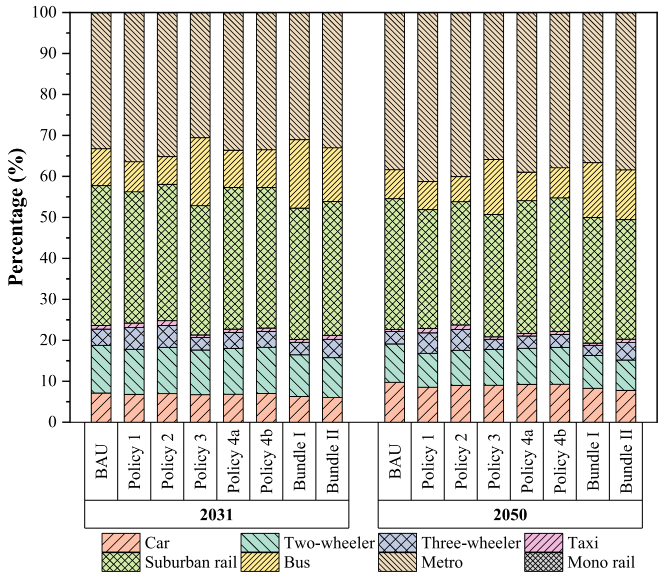

Fig. 7. Mode share of internal vehicles of MMR in BAU and policy scenarios.

by 81% and 51% in 2050 from 2005 levels. NO_x emissions from commercial vehicles would be alleviated by 85% in 2050 from 2005 levels. This reduction in NOx and $PM_{2.5}$ emissions was due to the introduction of stringent emission standards and fossil fuel-fired power plant emission standards in the future.

Kumar (2009) reported the CO_2, $PM_{2.5,}$ and NO_x emissions as 3.67 million tonnes/year, 4,295 tonnes/year, and 26,782 tonnes/year, respectively in 2009; 9%, 15%, and 6% less than the results reported in this study for 2005. This dispute corroborates to different methodologies employed to estimate VKTs and emission factors. Kumar (2009) used extrapolated VKTs obtained from MMRDA (2008) and obtained emission factors from ARAI (2008) against our methods of obtaining VKTs from TDM and derived emission factors based on vintage and technology.

4.2. Alternate policy scenarios

After evaluating all the five policies explained in section 3.3.2, we combined them to form two bundles. The main objective of these bundles was to capture the combined mitigation effect of the policies recognizing the impact of promoting public transport and discouraging the use of private vehicles, simultaneously. Policies with the most reduction in emissions as compared to BAU scenarios were considered in both bundles. Hence, Policy 1 was excluded from bundle formation as it included an increase in VKTs as compared to the BAU scenario. Therefore, Policy 3 and 4 are coalesced to form Bundle I, whereas Policy 2, 3, and 4 are fused to get Bundle II.

4.2.1. Mode share

The share of cars and two-wheelers decreased in all policies as compared to BAU in 2031 and 2050 (Fig. 7). The maximum decrease of ~12% would be in Policy 1 in 2050 and a minimum decrease of ~5% in Policy 4a and 4b. The share of three-wheelers and taxis would increase in all the policies except Policy 3 in 2050, recording a maximum increase of ~70% in Policy 2. The bus share would witness a maximum increase of ~91% in Policy 3 compared to BAU in 2050. Suburban rail's share is almost the same as the BAU scenario, recording only ~2–3% increase in Policy 4a and 4b in 2050. The share of the metro would increase maximum in Policy 1 by ~8% and will record a maximum decrease of ~7% in Policy 3. The minuscule share of monorail (0.13% in 2050) will also record a maximum decrease in Policy 3 and a maximum increase in Policy 4b in 2050.

In the case of policy bundles, Bundle I and Bundle II would record a decrease in private mode share (car and two-wheeler) by ~15% and 21%, respectively in 2050, as compared to the BAU scenario. The share of IPT, i.e., three-wheeler and taxis, would decrease in the Bundle I by ~14% and increase in Bundle II by 42% in 2050 as compared to the BAU scenario. The share of buses increases by 89% and 72% in Bundle I and II, respectively, as compared to the BAU scenario in 2050. Suburban

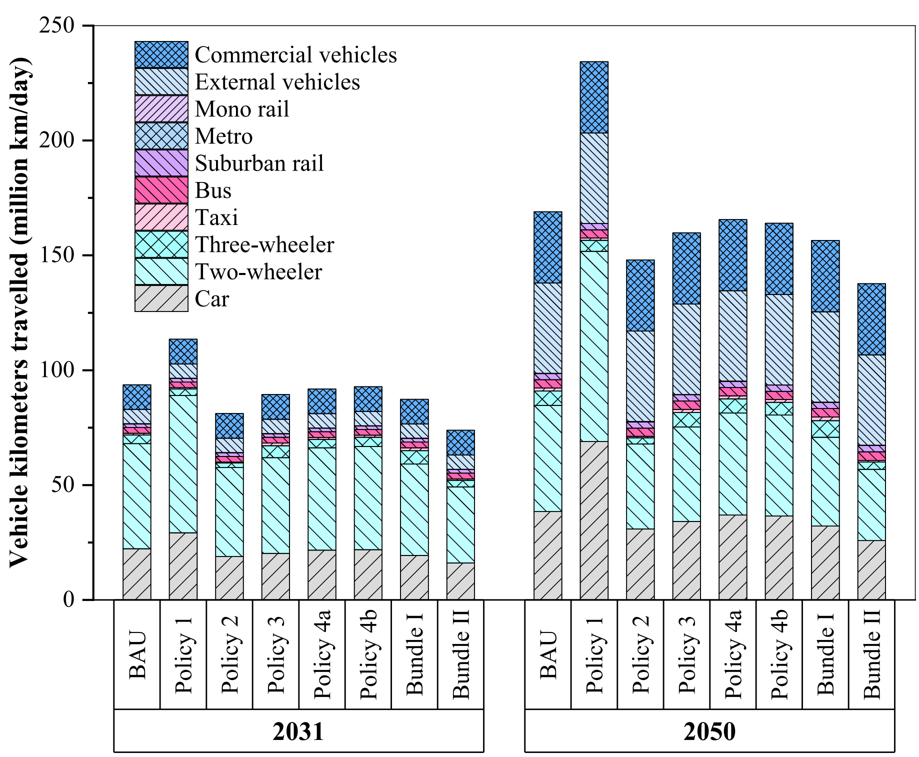

Fig. 8. VKTs (million km/day) obtained from TDM for MMR in BAU, policies and bundles.

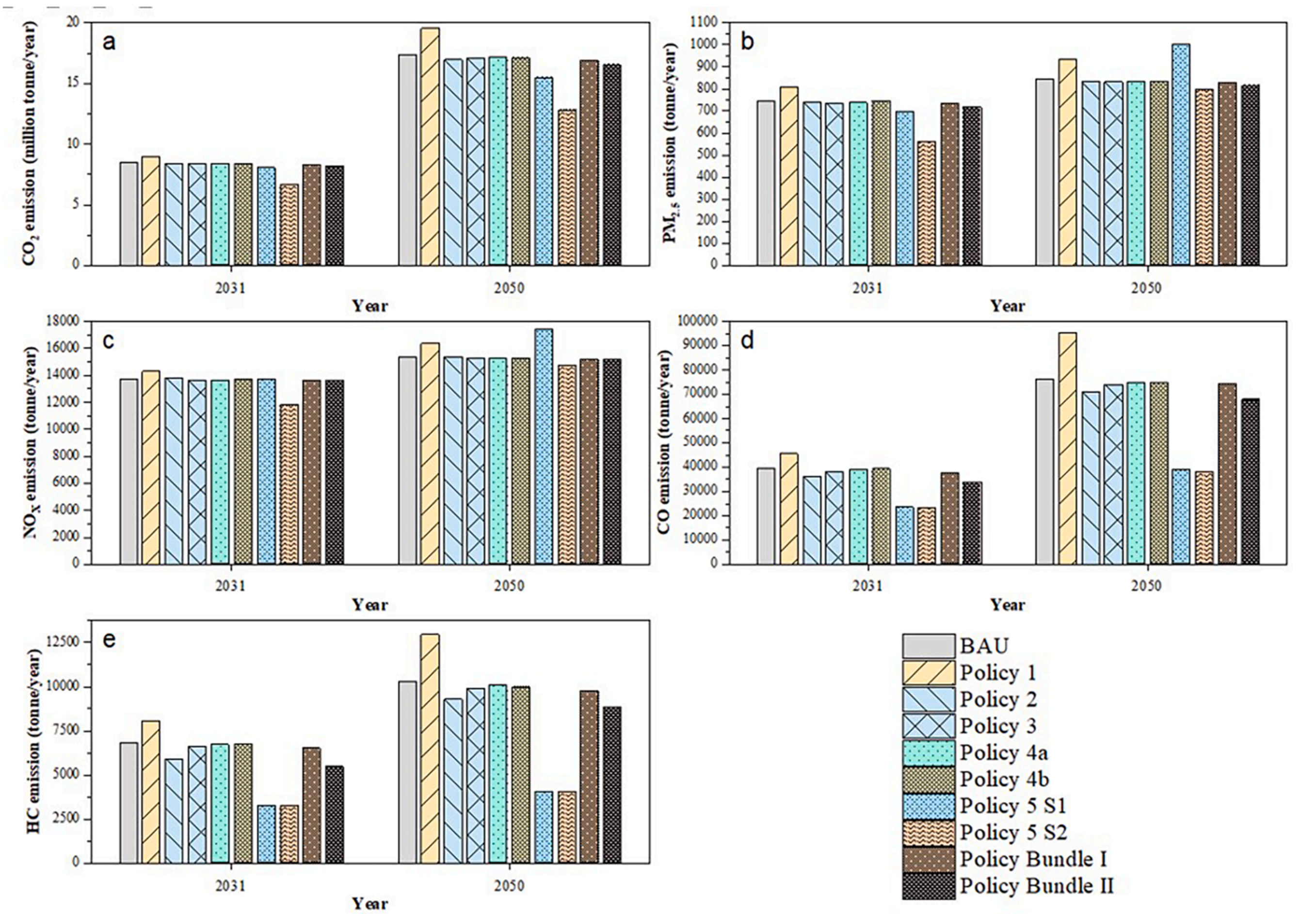

Fig. 9. Emissions from urban transport of MMR under business as usual (BAU) scenario, policies and bundles in 2031 and 2050: a. CO2 emission (million tonne/year), b. PM2.5 emission (tonne/year), c. NOX emission (tonne/year), d. CO emission (tonne/year) and e. HC emission (tonne/year).

rail's share decreased by 4% and 8% in Bundle I and II compared to BAU in 2050. Metro's share decreased by 4% in Bundle I, while it is unaffected in Bundle II in 2050. The share of monorail decreases by 34% and 42% in Bundle I and II, respectively, in 2050.

The decrease of cars and two-wheelers in all policies as compared to BAU may be attributed to the inclusion of additional transport infrastructure in policies (Policy 2 and Policy 3), redistribution of the population (Policy 1 and 2), and the discourage the use of private mode (Policy 4). However, the maximum and minimum decrease in private mode share in Policy 1 and Policy 4 indicates that population redistribution is important in shifting from private mode to public transport. The increase in the share of taxis and three-wheelers, collectively known as IPT, in all the policies, except policy 3, may be attributed to the addition of BRTS infrastructure. The maximum increase in IPT share in Policy 2 corresponds to decreasing the distance between home and workplace as IPT provides better door-to-door connectivity for small distances compared to other modes of public transport. A maximum increase in the share of the bus in Policy 3 may be attributed to the effectiveness of the BRTS infrastructure. Suburban rail's share is only increasing in Policy 4 due to the shift of trips from private mode to public transport. The maximum increase in the share of Metro in Policy 1 can be attributed to the effectiveness of population redistribution. However, the Metro and monorail record a maximum decrease in Policy 3, which may be attributed to the shift of trips to the bus because of the inclusion of BRTS infrastructure. In the case of policy bundles, Bundle II records a maximum decrease in private mode share compared to Bundle I, which may be attributed to the combined effect of redistribution of population and employment, including new transport infrastructure, and restricting the use of private mode. This decrease in the share of private mode will be complemented by a maximum increase in the share of public transport in Bundle II as compared to Bundle I. Therefore, Bundle II may be regarded as the best scenario.

4.2.2. Vehicle kilometer travelled

Estimated VKTs portrayed in Fig. 8 indicate the decreasing trend of VKTs in all the policies except Policy 1. In 2050, Policy 2 would have a maximum decrease (∼12%) in VKTs, while Policy 1 will have a maximum increase of ∼39% compared to the BAU scenario. The major contribution to the VKTs is from private mode (∼50% in BAU in 2050), which decrease by 8% in Policy 2, attaining a proportion of 46% in 2050. This major contribution is followed by external and commercial vehicles, increasing 14% in Policy 2 attaining 48% from 42% in the BAU scenario in 2050.

For Policy bundles, VKTs decrease by 7% and 19% in Bundle I and II in 2050 as compared to the BAU scenario. The contribution of VKTs from private mode decreases by 10% and 18% in Bundle I and II in 2050. However, the contribution of VKTs from external and commercial vehicles increased by 8% and 23% in Bundle I and II in 2050. The decreasing trend of VKTs in all the policies, except Policy 1, is because of the absence of new public transport infrastructure to supplement the population redistribution. This increases the usage of private mode to longer trip lengths. Among all the policies, policy 2 records the maximum reduction in VKTs, which attributes to the low population redistribution and inclusion of new transport infrastructure. The major contribution to the VKTs is from private mode because of its less occupancy and larger trip lengths than public transport. This major

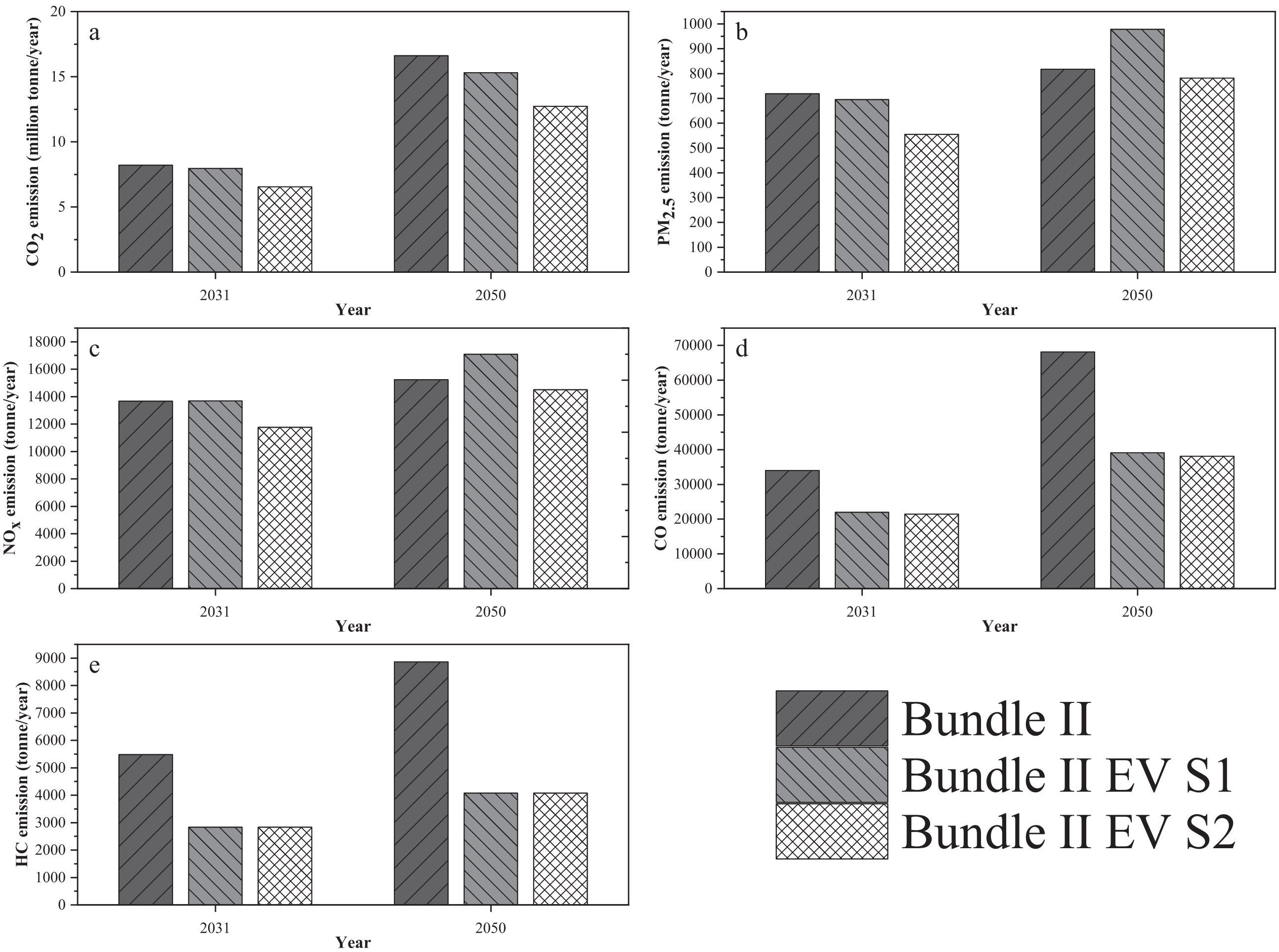

Fig. 10. Comparison of emissions in Bundle II and its electrification in 2031 and 2050: a. CO_2 emission (million tonne/year), b. $PM_{2.5}$ emission (tonne/year), c. NO_X emission (tonne/year), d. CO emission (tonne/year) and e. HC emission (tonne/year).

Table 2
Social cost factors of emissions adopted from Song (2017) and derived weight.

Pollutant	Social cost factor (US $/tonne)	Weight
CO	1,964	0.0141
HC	2,985	0.0214
NO_x	7,565	0.0543
CO_2	32	0.0002
$PM_{2.5}$	126,799	0.9100
Total	*139,345*	*1.0000*

contribution was followed by external and commercial vehicles with a maximum increase in Policy 2. Since external and commercial vehicles have been excluded from policy evaluations, their contribution to the total VKTs will increase in policies and bundles. Among policy bundles, Bundle II records the maximum decrease in the VKTs and hence can be regarded as the best scenario.

4.2.3. Emissions

The estimated emissions from urban transport of MMR under the BAU scenario, policies, and bundles in 2031 and 2050 are presented in the following sections (Fig. 9). For brevity, the upcoming subsections discuss the total emission (adding emission of all vehicles), and the vehicle-wise distribution of these emissions is included in Appendix C (Figure C1, C2, C3, C4 and C5).

4.2.3.1. CO_2 emission. CO_2 emissions illustrated in Fig. 9a depict a decreasing trend in all the policies except Policy 1. Policy 5 under scenarios S1 and S2 record the maximum reduction of ~10% and ~26% compared to BAU in 2050. However, Policy 1 will have an increase of ~12% compared to BAU in 2050. External and commercial vehicles contribute to ~54% of CO_2 emissions in BAU in 2050, increasing to a maximum of ~64% in Policy 5 S2 of the electricity grid mix. This share will be followed by public transport contributing ~29% in BAU with a maximum increase of 34% in Policy 5 S1 of electricity grid mix in 2050. Among policy bundles, CO_2 emissions will decrease by ~2% and ~4% in Bundle I and II compared to BAU in 2050. Contribution to CO_2 emissions from private vehicles will decrease by ~14% and ~30% in Bundles I and II in 2050.

4.2.3.2. PM2.5 emission. $PM_{2.5}$ emission also follows a decreasing trend in all the policies except Policy 1 and Policy 5 under scenario 1 in 2031 and 2050 compared to BAU (Fig. 9b). Policy 5, S2 will record a maximum reduction of ~5%. In contrast, Policy 5 S1 will record a maximum increase in $PM_{2.5}$ emission in 2050 as compared to BAU. Public transport will be the major contributor (~52%) to total $PM_{2.5}$ emission in BAU and will decrease by 7%, reaching ~48% in Policy 5 S2. Among bundles, Bundle I and II will record a reduction of ~2% and ~3% in $PM_{2.5}$ emissions as compared to BAU in 2050.

4.2.3.3. Nox emission. NO_x emission will decrease in all the policies except Policy 1 and Policy 5 S1 (Fig. 9c). The maximum reduction will be in policy 5 S2, whereas the maximum increase will be in Policy 5 S1

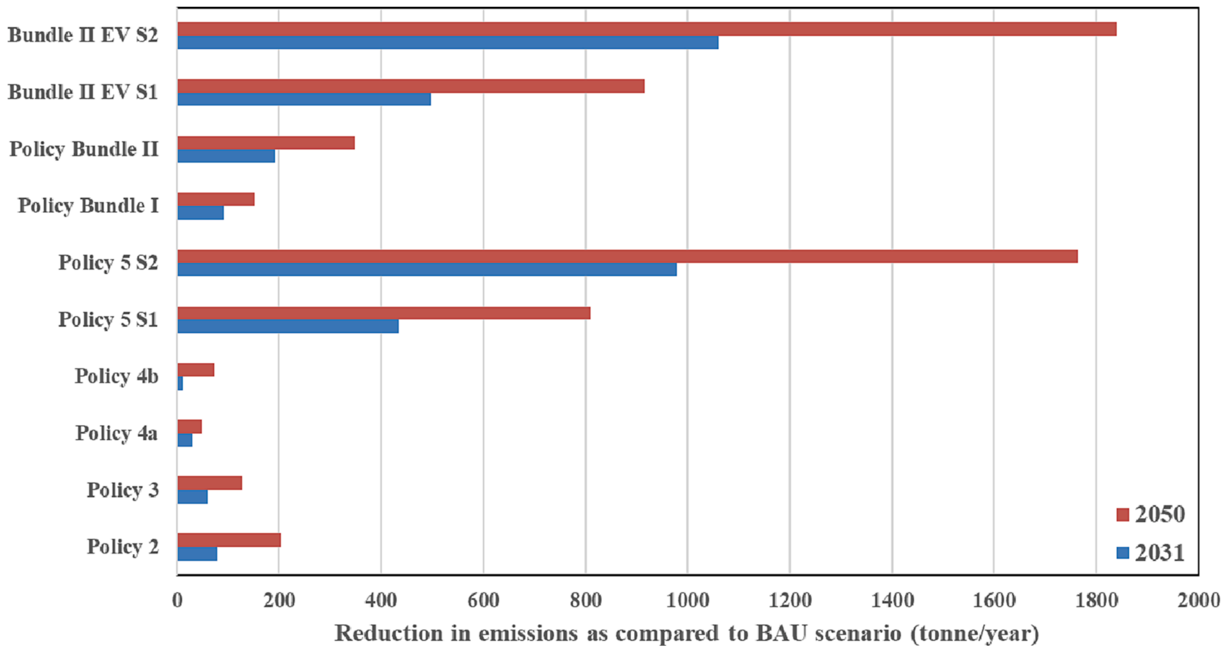

Fig. 11. Reduction in emissions (combined as per Table 2) as compared to the BAU scenario.

Table A1
Private, commercial, bus & IPT vehicle flows (PCU).

Location	Observed	Assigned	Difference
IC1	64,532	45,384	30%
IC2	57,032	57,684	−1%
IC3	129,111	90,377	30%
IC4	65,220	82,612	−27%

(adopted from Sharma and Chandel (2020a)).

Table A2
Rail passenger flows.

Location	Observed Peak Passengers	Assigned Peak Passengers	Difference
IC1	393,968	443,825	−13%
IC2	766,927	806,114	−5%
IC3	1,270,867	1,315,117	−3%
IC4	991,761	768,223	23%

(adopted from Sharma and Chandel (2020a)).

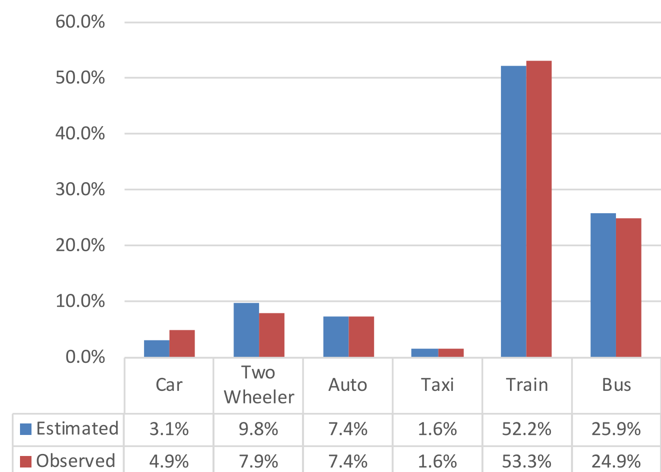

Fig. A1. Comparison of estimated and observed Mode Share of Base Year (adopted from Sharma and Chandel (2020a)).

compared to BAU in 2005. Public transport and commercial vehicles will have a major share of ∼42% and ∼42% in BAU in 2050. The public transport's contribution will decrease maximum in Policy 5 S2 of the electricity grid mix. Both the bundles will have a ∼1% decrease as compared to BAU in 2050.

4.2.3.4. CO and HC emissions. CO and HC emissions will decrease in all the policies except Policy 1, as depicted in Fig. 9d and Fig. 9e. The maximum reduction of ∼50% and ∼60% in CO and HC emissions, respectively, will be in Policy 5 S2 in 2050 as compared to BAU. However, Policy 1 will have a maximum increase of ∼25% and ∼26% in CO and HC emissions in 2050. A major contribution to CO and HC emissions will be from commercial vehicles (∼46% and ∼40%), seeing a maximum increase in Policy 5 S2 of the electricity grid mix. In both the bundles, CO and HC emissions are decreasing as compared to BAU. CO emissions are decreasing by ∼2% and ∼11% in Bundle I and Bundle II. In contrast, HC emissions will decrease by ∼5% and ∼14% in Bundle I and II, respectively, compared to the BAU scenario in 2050. The minuscule contribution to total CO and HC emissions will be from public transport (∼8% and ∼3%) in both the bundles in 2050.

CO_2, CO, and HC emissions decrease in all the policies except Policy 1. However, $PM_{2.5}$ and NO_x emissions decrease in all the policies except Policy 1 and Policy 5 S1 of the electricity grid mix. The increase in the emissions in policy 1 is because of the rise in VKTs. Policy 5 S2 would record the maximum reduction in all the emissions which can be attributed to the electrification of the vehicles and the generation of 50% of the electricity from renewable sources. Bundle II will record more reduction in all the emissions compared to Bundle I. However, the reduction in Policy 5 beats Bundle II in such reductions, which can be attributed to EVs' greater emission mitigation potential. In this direction, we also explored the possibilities of electrifying Bundle II under both electricity generation mix scenarios. The results are shown in Fig. 10.

After the electrification of Bundle II, CO_2 emissions would reduce further by ∼8% and ∼23% under S1 and S2 of the Indian electricity grid mix, respectively, as compared to Bundle II in 2050 (Fig. 10a). Therefore, a total reduction in CO_2 emission in Bundle II compared to the BAU

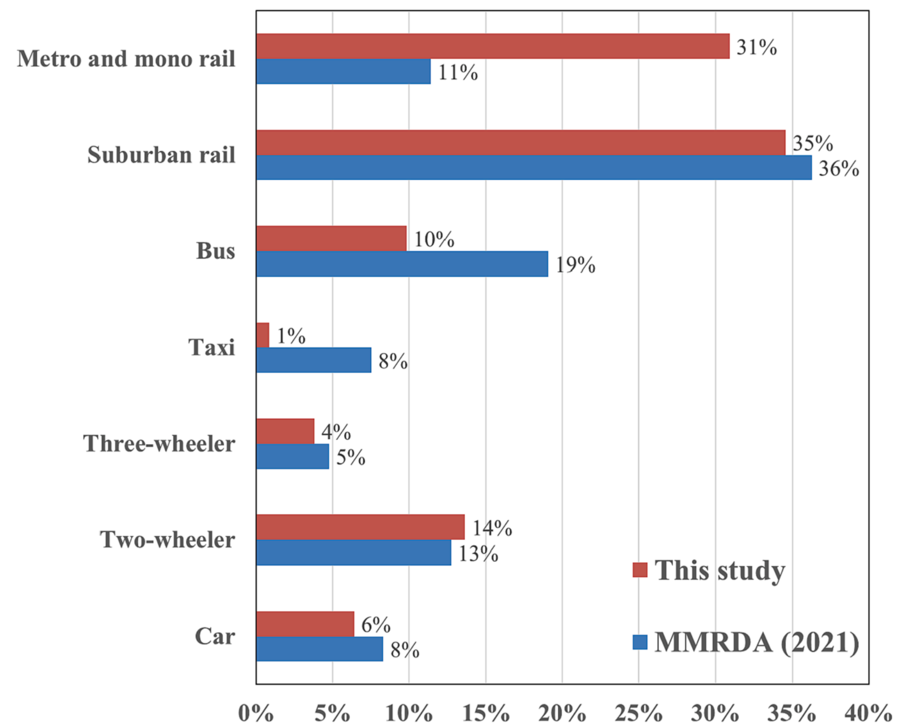

Fig. A2. Comparison of estimated mode share of the horizon year 2021 with MMRDA (2021).

Table B1
Emission factors of conventional vehicles (g/km) (Adopted from Sharma and Chandel (2020a)).

Vehicle Class	Year	CO	HC	NO_x	CO_2	$PM_{2.5}$
Car/Taxi	2005	2.444	0.267	0.344	133.58	0.0276
	2031	0.528	0.133	0.130	144.29	0.004
	2050	0.528	0.133	0.020	147.12	0.0038
Two-Wheeler	2005	1.153	0.790	0.112	31.07	0.022917
	2031	0.933	0.201	0.057	42.71	0.011
	2050	0.994	0.099	0.06	43.61	0.004
Three-Wheeler	2005	4.468	1.889	0.558	77.17	0.203
	2031	0.487	0.316	0.147	81.74	0.017
	2050	0.302	0.206	0.084	67.53	0.011
Bus	2005	7.997	1.601	11.96	789.18	1.38
	2031	2.877	0.202	1.319	611.15	0.0225
	2050	2.877	0.191	0.774	611.15	0.0178
Light Commercial Vehicle (LCV)	2005	3.256	1.736	2.594	353.965	0.741
	2031	0.915	0.946	0.302	401.25	0.015
	2050	0.623	0.946	0.103	401.25	0.005
Heavy Commercial Vehicle (HCV)	2005	14.72	1.852	12.28	811.435	1.715
	2031	4.345	0.101	1.549	762.39	0.03
	2050	4.345	0.074	0.795	762.39	0.024

scenario would increase from ~4% to ~12% and ~27% due to EVs under S1 and S2 of electricity generation in 2050. $PM_{2.5}$ emission would increase by ~20% and decrease by ~4% in Bundle II, EVs under S1 and S2 of electricity generation, respectively, compared to Bundle II in 2050 (Fig. 10b). The total reduction in $PM_{2.5}$ emission would increase from ~3% in Bundle II to ~7% due to the electrification of Bundle II under S2 as compared to BAU in 2050. NO_X emission will increase by ~12% and decrease by ~5% in Bundle II electrified under S1 and 2 of electricity generation, respectively, compared to Bundle II in 2050 (Fig. 10c).

The total reduction in NO_X emission will increase from ~1% in Bundle II to ~6% due to Bundle II, S2 electrification compared to BAU in 2050. CO and HC emissions will decrease further by ~44% and ~54% due to Bundle II's electrification compared to Bundle II in 2050 (Fig. 10d and Fig. 10e). Total CO and HC emission reduction will increase from ~11% and ~14% in Bundle II to ~50% and ~60% in the electrification

Table B2
Emission factors of EVs under Scenario 1 (g/km) (Adopted from Sharma and Chandel (2020a)).

Vehicle Class	**Year**	**CO**	**HC**	**NO_x**	**CO_2**	**$PM_{2.5}$**
Electric Car/Taxi	*2005*	0.058	1.10E-05	0.390	129.555	0.064
	2031	0.059	1.13E-05	0.225	134.65	0.016
	2050	0.054	1.02E-05	0.149	119.57	0.011
Electric Two-Wheeler	*2005*	0.011	2.14E-06	0.076	25.17	0.012
	2031	0.012	2.20E-06	0.044	26.16	0.003
	2050	0.010	1.99E-06	0.029	23.23	0.002
Electric Three-Wheeler	*2005*	0.021	3.95E-06	0.140	46.52	0.023
	2031	0.021	4.07E-06	0.081	48.35	0.006
	2050	0.019	3.68E-06	0.053	42.94	0.004
Electric Bus	*2005*	0.508	9.71E-05	3.442	1144.03	0.568
	2031	0.523	1.00E-04	1.987	1189.04	0.142
	2050	0.473	9.04E-05	1.313	1055.83	0.097
Suburban Rail/ Train	*2005*	2.497	4.77E-04	16.913	5621.01	2.790
	2031	2.572	4.91E-04	9.764	5842.13	0.696
	2050	2.324	4.44E-04	6.452	5187.66	0.476
Metro/Mono Rail	*2005*	7.950	1.52E-03	53.837	17892.66	8.883
	2031	8.186	1.56E-03	31.080	18596.52	2.217
	2050	7.397	1.41E-03	20.538	16513.23	1.516

Table B3
Emission factors of EVs under Scenario 2 (g/km) (Adopted from Sharma and Chandel (2020a)).

Vehicle Class	Year	CO	HC	NO_x	CO_2	$PM_{2.5}$
Electric Car/Taxi	*2005*	0.058	1.10E-05	0.390	129.555	0.064
	2031	0.008	1.60E-06	0.041	0.00	0.003
	2050	0.008	1.46E-06	0.029	0.00	0.002
Electric Two-Wheeler	*2005*	0.011	2.14E-06	0.076	25.17	0.012
	2031	0.002	3.11E-07	0.008	0.00	0.001
	2050	0.001	2.84E-07	0.006	0.00	0.000
Electric Three-Wheeler	*2005*	0.021	3.95E-06	0.140	46.52	0.023
	2031	0.003	5.75E-07	0.015	0.00	0.001
	2050	0.003	5.24E-07	0.010	0.00	0.001
Electric Bus	*2005*	0.508	9.71E-05	3.442	1144.03	0.568
	2031	0.074	1.41E-05	0.362	0.00	0.024
	2050	0.067	1.29E-05	0.257	0.00	0.017
Suburban Rail/Train	*2005*	2.497	4.77E-04	16.913	5621.01	2.790
	2031	0.364	6.95E-05	1.777	0.00	0.115
	2050	0.331	6.33E-05	1.265	0.00	0.083
Metro/Mono Rail	*2005*	7.950	1.52E-03	53.837	17892.66	8.883
	2031	1.157	2.21E-04	5.656	0.00	0.368
	2050	1.055	2.02E-04	4.027	0.00	0.263

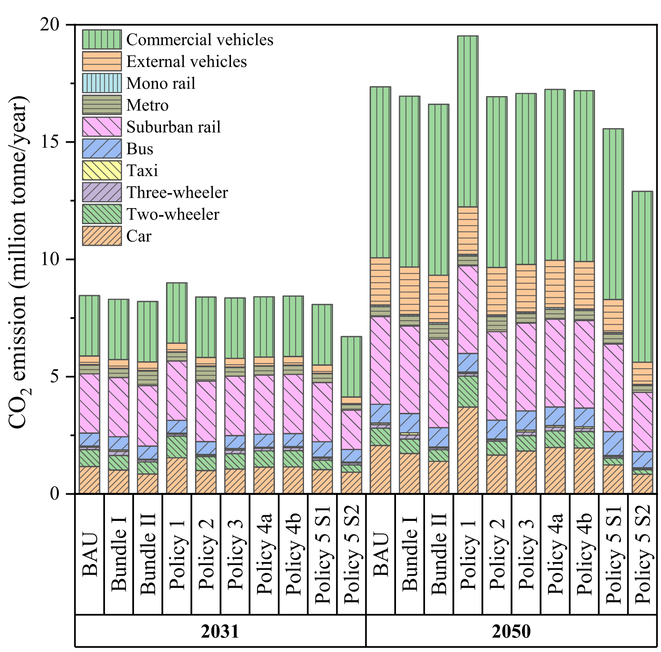

Fig. C1. Vehicle-wise distribution of CO_2 emissions(million tonne/year) from urban transport of MMR under business as usual (BAU) scenario, policies and bundles in 2031 and 2050.

of Bundle II in 2050 compared to the BAU scenario. After the electrification of vehicles, a major contribution to the emissions will be from commercial vehicles as these vehicles have been excluded from the electrification. Therefore, special regulations and measures are required to curb emissions from commercial vehicles.

In some cases, public agencies might be interested in deciding the best policy from a multi-objective perspective, i.e., policy scenario mitigating all five emissions while considering their respective harmful effects on the environment. In this direction, we calculated the total reduction of emissions in Policies 2, 3, 4, and 5 and two bundles from BAU scenarios based on the social cost of each pollutant. We derived the weight of each pollutant based on their social cost factors adopted from Song (2017) and are provided in Table 2. After multiplying the derived weight of each pollutant with its respective reduction in each alternative policy scenario from the BAU scenario, we plotted the results in Fig. 11. As per the results, Bundle II with S2 electrifications will still be the best-performing policy alternative in emission mitigation.

5. Policy implications

This study offers numerous policy implications for planners and policymakers in MMR based on the key findings related to emission inventory and alternative mitigation policy scenarios. We categorize these implications into three major categories: Limiting the use of private vehicles, improving public transport services, and encouraging EV adoption.

As per the findings, private mode (cars and two-wheeler) would be the principal contributor to emissions in the MMR. Policies focused on discouraging the use of private vehicles through congestion pricing and parking management contributed to a decrease in emission levels. Hence practitioners are encouraged to apply such demand management strategies in private vehicle dominant areas to mitigate emissions. The adoption of BS-VI emission standards contributes significantly to the reduction in $PM_{2.5}$ emissions. In this direction, policymakers can favor stringent guidelines to boost the proportion of BS-VI private vehicles in MMR.

Suburban rail is set to remain the dominant mode of public transport in MMR even in horizon years. In contrast, the mode share of the bus is expected to reduce. Policy focused on introducing BRTS corridors can help to improve the mode share of the bus in the future and help mitigate the emissions due to the shift of passengers to private vehicles or taxis. In private vehicle dominant areas, minibus shuttles can be operated on a trial basis in combination with congestion pricing or parking management to nudge private vehicles to shift to public transport.

Finally, electrification of all private vehicles under a plausible electricity grid mix with an equal share of renewable and non-renewable sources promises the maximum emissions reduction mitigation potential. In this direction, policymakers can focus on policies discouraging the heavy reliance of the existing electricity grid mix on coal power plants. Furthermore, policies are required to encourage EV purchases among the general public through incentives, tax rebates, and discounts over conventional vehicles.

6. Conclusion

We analyze the impact of different policy scenarios on emissions from urban transport in the Mumbai Metropolitan Region (MMR). The results show that Bundle II is the best scenario to reduce all the emissions. Bundle II includes a modal shift due to redistributing population and employment, implementing BRTS infrastructure, and enforcing higher parking, fuel, registration, and congestion charges. This scenario would witness a ~19% decrease in the VKT which would decrease CO2 emissions by ~4%, and other emissions by ~1–14% compared to the BAU scenario in 2050. This decrease in VKT and emissions was mainly due to the modal shift from private to public transport (primarily bus and suburban rail).

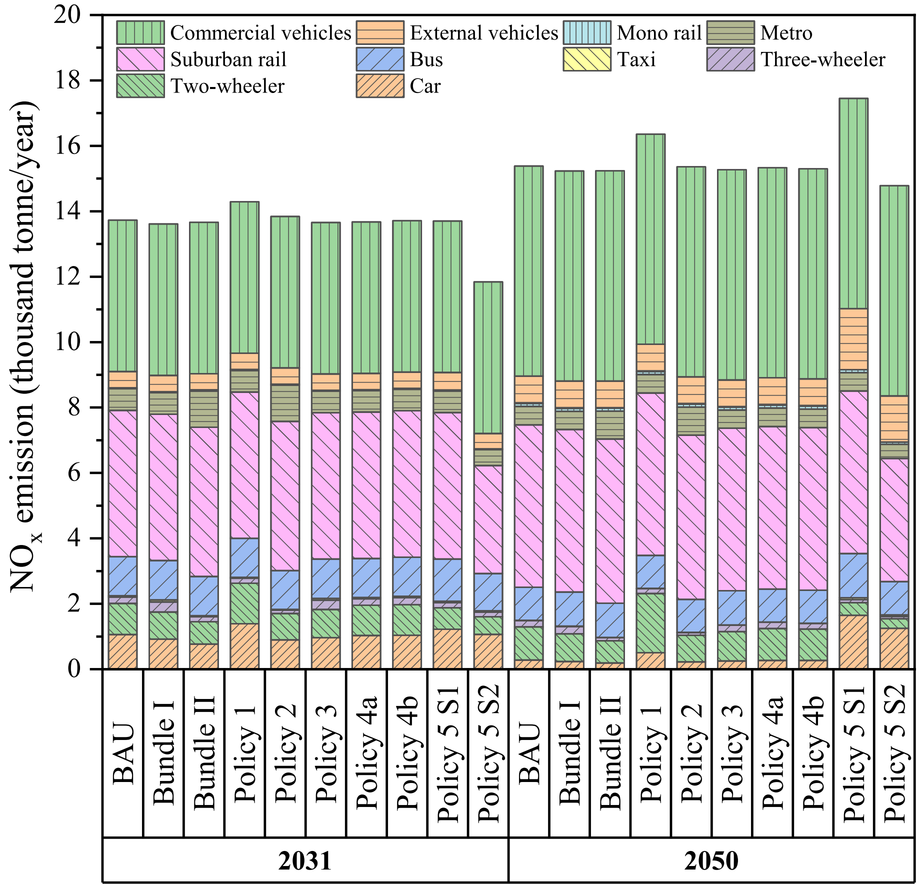

Fig. C2. Vehicle-wise distribution of NO_x emissions(thousand tonne/year) from urban transport of MMR under business as usual (BAU) scenario, policies and bundles in 2031 and 2050.

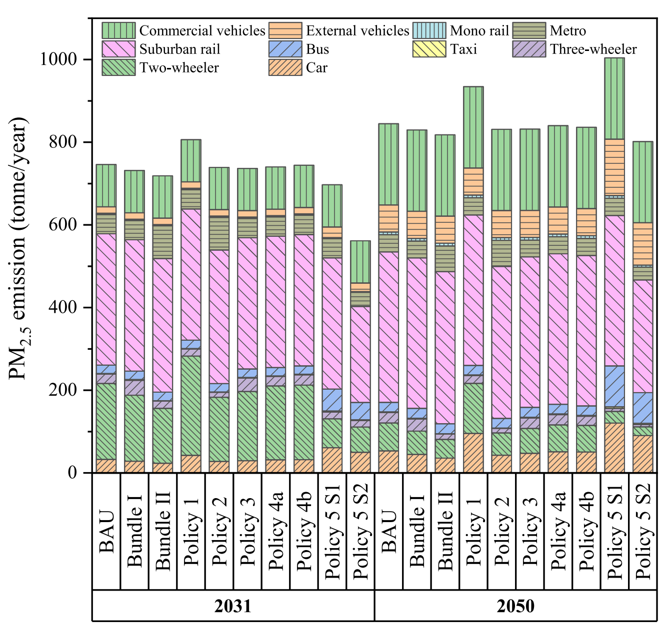

Fig. C3. Vehicle-wise distribution of $PM_{2.5}$ emissions(tonne/year) from urban transport of MMR under business as usual (BAU) scenario, policies and bundles in 2031 and 2050.

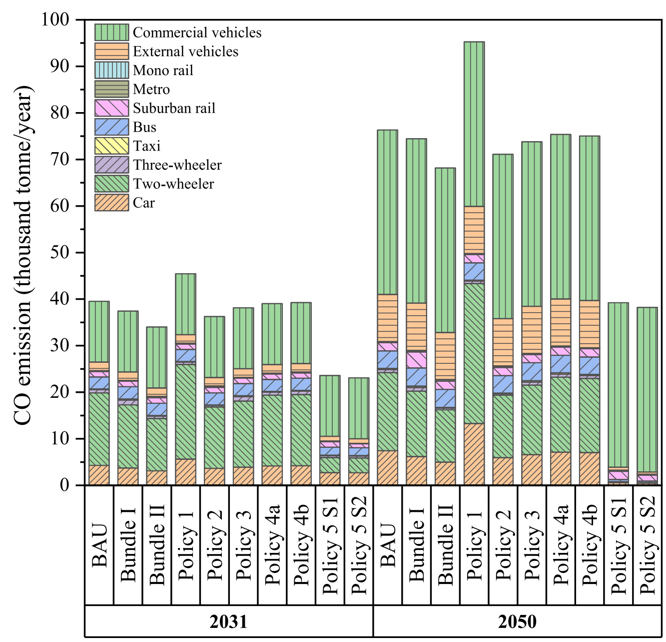

Fig. C4. Vehicle-wise distribution of CO emissions(thousand tonne/year) from urban transport of MMR under business as usual (BAU) scenario, policies and bundles in 2031 and 2050.

Furthermore, penetration of EVs in Bundle II could further reduce CO_2 by 23% and other emissions by 5–54%. In the Bundle II scenario with EV penetration, the CO_2 emissions would be reduced by 27% and other emissions by 6–60% compared to the BAU scenario. A combination of various policies, including the redistribution of population and

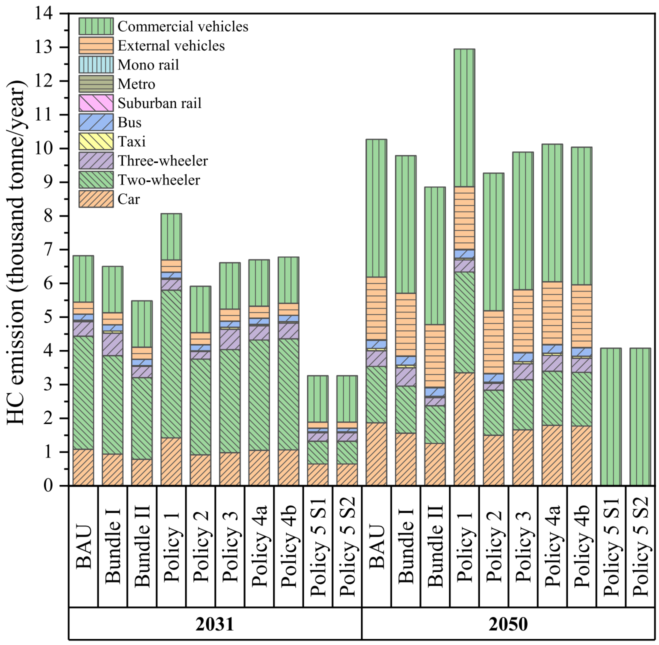

Fig. C5. Vehicle-wise distribution of HC emissions(thousand tonne/year) from urban transport of MMR under business as usual (BAU) scenario, policies and bundles in 2031 and 2050.

employment, improvement in public transport infrastructure, discouragement of private mode, and penetration of EVs, will be required to curb the emissions from the transport sector. Furthermore, policies to curb emissions from commercial vehicles will be required in the future to achieve deep reductions. These policies may include stringent emission standards, the introduction of EVs, etc. The findings of this study are expected to provide useful insights to policymakers involved in planning and implementing the various mitigation policies for emissions in the urban transportation system, especially in developing countries. Changing nature of employment and work-related travel patterns during the COVID-19 pandemic and other land-use based developments have short-term and long-term impacts on the MMR's population redistribution and travel demand management scenarios, which could be studied further. We utilized a traditional four-step travel demand modeling framework to estimate travel activity in MMR. Generally, such a framework suffers from some limitations in terms of lack of integrity (among all four sub-models), disaggregation (focused on traffic analysis zones rather than individuals), and behavioral realism (like trip chaining, induced travel) (Rasouli and Timmermans, 2014). Future studies can address these limitations by utilizing activity and tour-based travel demand models.

CRediT authorship contribution statement

Ishant Sharma: Conceptualization, Methodology, Writing – original draft, Validation. **Rajashree Padmanabhi:** Methodology, Writing – original draft. **Anil K. Dikshit:** Supervision, Writing – review & editing. **Munish Kumar Chandel:** Supervision, Methodology, Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

A.1 Model validation

Table A.1, Table A.2 & Figure A.2 show the validation results for Vehicle flows (PCU), Rail passenger flows, and mode share, respectively. As the difference was within the acceptable limit of +-30%, the model was considered as validated.

A.1 Addition of Transport Infrastructure in Policy 1 and Policy 2

The transportation infrastructure is added to the network as proposed in the MMRDA (2016). It is as follows:

(1) Suburban Rail
- Panvel to Karjat
- Panvel to Roha

(2) Metro
- JVLR-Koparkhairane-Kalyan
- Mira Bhayander- Kharbav-Nashik Road
- Thane-Bhiwandi-Kalyan, and
- Mankhurd-Vashi-Kharghar-Ambernath

(3) Tunnels
- Vashi to Kharghar
- Airoli to Katai Naka

(4) Creek Bridges
- JVLR to Koparkhairane across Thane Creek
- Uran to Rewas across Dharamtar Creek

Appendix B

Appendix C

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