



Estimation of CO₂ Emission Savings from a Metro Rail System Using Different Methodologies: A Case Study of Mumbai, India

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Abstract

Estimating 'CO₂ emission savings' of a mass rapid transit system (MRTS) project shall give an opportunity to earn carbon credits under clean development mechanism (CDM) of Kyoto protocol for 'Non-Annex I' countries like India. In this study, two methodologies for estimating 'CO₂ emission savings' were demonstrated with a case study of Mumbai 'metro line 1'. One considers actual reduction in vehicular traffic and the other considers the commuter shift to metro from other modes estimating the savings as 38.02 t/day and 27.63 t/day, respectively. Subsequently, sensitivity analysis was conducted to identify the optimal scenario for 'CO₂ emission savings' supported by both the methods. Further, a breakeven scenario for 'annual net CO₂ emission savings' after considering the indirect emissions due to electricity consumption by the metro system was also analysed as 1,008 t/year by the end 2019. These savings are analysed to further reach 32,537 t/year by 2025.

Keywords: CO₂ emission savings; Carbon credits; Kyoto protocol; MRTS; Environmental benefits; Metro Rail.

1. Background and Study Objective

With rapid urbanization and growth of urban sprawl in India, travel demand has seen unprecedented growth during the last few decades. However, the corresponding growth in urban transport infrastructure was found to be deficient with comparatively slower growth rate (Padam and Singh 2004). This has resulted in a huge gap between demand and supply. The overcrowded scenario of Mumbai suburban system with 16 pax/sq.m (MMRDA 2008) resulting in 9 accidents per day (MMRDA 2017) is a definite evidence to this gap. Such devastating situations are forcing the users towards private modes. Strengthening this observation, the compounded annual growth rate of motor vehicles for 2011-2016 was also observed to be 94.40% (MoRTH 2016). Discouraging scenario in public transport coupled with the increased private vehicle ownership is leading to negative extremities such as increased production of greenhouse gases (GHG), resulting in a very serious consequence of climate change. The GHGs contributing to such climate change effect are carbon dioxide (CO₂), methane (CH₄), Nitrous oxide (N₂O),

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hydrofluorocarbons (HFC), perfluorocarbons (PFC), sulphur hexafluoride (SF₆) (UN 1998). Amongst these gases, CO₂ is often referred to as the major pollutant as it contributes 76% of the total GHG emissions (IPCC 2014) and its impacts affect various dimensions of sustainability such as environmental, economic and social (Nocera, S. *et al.* 2012). The 'Transport' sector contributes 11% to the total global carbon footprint. Also, with a 40.5% increase in global coal consumption between 2004-05 to 2013-14, the largest increase was observed to be in the 'transport' sector (Maheshwari, H. and Jain, K., 2017). Keeping in view the impact of CO₂ emissions towards climate change and significant contribution of these emissions by 'transport' sector, this article concentrates on estimation of 'CO₂ emission savings' from a 'metro rail' system with a case study of Mumbai.

Metro rail is a very popular mass rapid transport system (MRTS) alternative across the countries to alleviate urban travel and control CO₂ emissions. In addition to the socio-economic benefits such as reduction in travel time, travel cost, accident rate, per capita vehicle ownership etc., the ability of metro system towards substantial reduction in per capita pollution emission is considered as one of the major benefits. Litman, T. (2005) indicates that the environmental, economic and social benefits enlarge as the rail-based transit system expands. Realizing this fact, development of sustainable public transport network was prioritized in "National Urban Transport Policy – 2014" and financial assistance up to 20% was offered for 'metro rail' projects in India (MoRTH 2016). Currently India has an operational 'metro rail' network of around 425 km with another 700 km under fast track implementation by several special purpose vehicles (SPVs) in various cities (MoHUA 2018).

Metro rail system being a highly expensive alternative amongst the available public transport modes, its benefits against the cost incurred are always debated. O'Toole (2008) states that the rail transit contributes to a higher GHG emissions in comparison with road travel. The recently issued "Appraisal Guidelines for Metro Rail Project Proposals" by Ministry of Housing and Urban Affairs (MoHUA), Govt. of India has also prescribed a detailed 'alternative analysis' focusing on identifying the best alternative either at the city or at sub-area level, for the existing scenario by considering feasible alternatives of various modes of transport (MoHUA 2017). However, if the benefits offered by the metro system such as reduced traffic congestion, GHG emissions, accident rates, savings in travel time and cost, safety and comfort are assessed and quantified collectively, the metro projects could become the most cost effective projects than the other public transport project alternatives (Litman, T., 2010). Sharma *et al.*, (2014) estimated a CO₂ emission saving for Delhi as 724 t/day with a 190 km network by 2011. Hadadi and Lee (2019) also estimated a 3% CO₂ emission savings through commuter shift from car for the Algiers metropolitan area (AMA).

A successful metro system attracts mode shift from various private modes, thus controlling the carbon emissions at source. The current study is aimed to demonstrate two alternative methodologies for estimation of CO₂ emission savings in different situations with a case study of Mumbai. The first is a planned situation in which, the traffic volume counts along the 'metro rail' corridor are collected before and after commencement of the commercial operations. The second is an unplanned situation in which, the commercial operations of a 'Metro Rail' were commenced and there is no previous traffic volume data available. While the first method estimates the CO₂ emission savings by considering the actual reduction in vehicular traffic volume along the metro corridor, the second method considers the commuter shift to the metro from other modes. These methods help

public transport agencies (PTA) and urban local bodies (ULB) to estimate CO₂ emission savings in both the situations. In addition, the indirect CO₂ emissions being contributed by the metro system due to consumption of electricity were also analysed to estimate the 'net CO₂ emission savings'. Further, the results from both the methods are compared and a sensitivity analysis was conducted for two cases. The first case identifies the optimal scenario of emission savings with varying commuter shift supported by both the methods. The second case identifies the breakeven scenario for 'net CO₂ emission savings' with varying ridership and electricity consumption.

Before discussing the methodologies and its demonstration for estimation of CO₂ emission savings, a major international attempt towards mitigating the GHG emissions and climate change effect is to be briefly understood. Kyoto protocol, which is a legally binding international agreement that commits its parties towards reduction and control of GHG emissions. This is also considered as the profound agreement ever adopted on environment and sustainable development (Gupta, A., 2012).

2. Kyoto Protocol and its mechanisms

The 'Kyoto protocol' was adopted in Kyoto, Japan, on 11 December 1997 and entered into force on 16 February 2005. *The 'Kyoto Protocol' is an international agreement linked to the United Nations Framework Convention on Climate Change (UNFCC), which commits its parties by setting internationally binding emission reduction targets (UNFCC, 2018).* The 'Kyoto protocol' aims at reducing CO₂ emissions and presence of GHGs and classifies the participating countries into two groups namely 'Annex I' and 'Non-Annex I' which includes developed and developing nations respectively. Emission limitations are imposed only on 'Annex I' nations where as the 'Non-Annex I' nations participate by investing in projects that lower emissions in their own countries and certified emission reduction (CER) credits can be earned on these projects. These credits can be traded or sold to 'Annex I' countries, which allow them a higher level of maximum carbon emissions for that period.

The three flexible mechanisms in Kyoto protocol to support developed countries in achieving emission reduction are:

- i. Emissions Trading (ET)
- ii. Joint Implementation (JI)
- iii. Clean Development Mechanism (CDM)

These mechanisms allow 'Annex I' countries to meet their GHG emission reduction targets by purchasing from other countries. These can be achieved either by simple financial exchanges through ET or by participating in emission reduction projects in 'Annex I' countries through JI or in other 'Non-Annex I' countries under CDM.

'Metro rail' system being an eco-friendly mode, the Public Transport Agencies (PTAs) can substantiate the reduction in CO₂ emissions and can avail CER credits, each equivalent to one tonne of CO₂ as part of CDM. The earned CERs can be traded to the industrialized countries to meet their emission reduction targets under 'Kyoto protocol' (CDM, 2018).

With such a deep-rooted significance, estimation of CO₂ emission savings due to metro system is worth studying. Delhi Metro Rail Corporation Ltd. (DMRC) has been certified by United Nations (UN) for reduced emissions and earned carbon credits worth 47 Cr annually for the next seven years. Also, this has been certified as the first metro rail and

rail-based system which will get carbon credits of 6.3 lakh tons every year (DMRC, 2018).

3. Estimation of CO₂ Emission Savings

Mumbai is ranked as the sixth largest metropolitan in the world with one of the highest PT modal share of 78% (MMRDA, 2008). Since 2014, Mumbai has an operational metro rail network of 11.4 km in the form of a single elevated corridor (metro line 1) connecting the eastern and western suburbs (Versova-Andheri-Ghatkopar). The corridor comprises of 12 stations carrying an average daily ridership of 3.4 lacs approximately as on 2018. This study attempts to estimate the CO₂ emission savings due to the implementation of the Mumbai ‘metro line 1’ with two different methodologies presented below.

- i. Method I: Estimation of CO₂ emission savings from Reduction in Vehicular Traffic
- ii. Method II: Estimation of CO₂ emission savings from commuter shift

The requisite database for analysing CO₂ emission savings using the above methods is presented in Table 1.

Table 1: Requisite database for analysing CO₂ emission savings

<i>S.No.</i>	<i>Requisite Database</i>	<i>Method I</i>	<i>Method II</i>
i.	Traffic volume counts along the metro corridor in ‘pre-metro’ condition	✓	✗
ii.	Traffic volume counts along the metro corridor in ‘post-metro’ condition	✓	✗
iii.	Commuter shift to metro from non-commercial vehicles (%)	✗	✓
iv.	Occupancy of non-commercial vehicles in the study area	✗	✓
v.	Avg. daily ridership	✗	✓
vi.	Fuel based vehicular classification in the study area	✓	✓
vii.	CO ₂ emission factors (EF) (gm/km)	✓	✓
viii.	‘Avg. trip length’ of the metro corridor	✓	✓

From Table 1 it can be understood that both the methods require primary and secondary data. While ‘Method I’ demands more primary data, ‘Method II’ depends more on secondary data. A detailed demonstration of these two methods to estimate CO₂ emission savings is discussed in the following sub-sections.

3.1 Estimation of CO₂ Emission Savings from Reduction in Vehicular Traffic

This methodology can be adopted in a planned situation, where a PTA or an ULB decides to quantify the expected environmental benefits by a metro corridor before the commencement of commercial operations. The traffic volume counts are to be conducted just before the commencement of commercial operations as a ‘pre-metro’ condition and repeat the same after commencement of commercial operations as a ‘post-metro’ condition. In the current study, the traffic volume counts along the ‘metro line 1’ corridor were conducted during May and June 2014 for ‘pre-metro’ and ‘post-metro’ conditions respectively. Subsequently, the CO₂ EFs (gm/km) from Automotive Research Association of India (ARAI 2008) and the ‘avg. trip length’ of ‘Metro line 1’ are

considered in conjunction with the above traffic volumes to estimate the CO₂ emission savings as presented following steps.

Step I: The ‘metro line 1’ corridor was strategically divided into three sections i.e. Versova- Andheri, Andheri – Airport Road, Airport Road – Ghatkopar and traffic volume counts were conducted on these sections before and after commencement of metro for ‘pre-metro’ and ‘post-metro’ scenarios respectively. The traffic volume counts were conducted at 3 mid-block locations during morning and evening peak for 9 hours i.e. 0800 hrs – 1300 hrs and 1600 hrs to 2000 hrs namely, near ‘Azad Nagar Metro Station’, ‘Chakala Metro Station’ and ‘Sakinaka Jn’. The summary of vehicular reduction along the corridor in both the conditions is presented in Table 2.

Table 2: Traffic volumes of pre and post metro condition along metro corridor

Location	Towards	Pre-Metro				Post Metro			
		2W	3W	CAR	BUS	2W	3W	CAR	BUS
Azad Nagar	Versova	1,387	6,079	4,108	549	1,978	4,885	4,210	423
	Andheri	1,841	4,927	4,649	398	1,684	4,450	3,077	262
Chakala	Andheri	2,617	11,472	7,753	1,037	3,390	8,371	7,214	725
	Ghatkopar	3,601	9,633	9,091	779	3,590	9,496	6,549	557
Sakinaka	Andheri	3,002	13,160	8,893	1,189	3,721	9,188	7,919	796
	Ghatkopar	3,847	10,294	9,715	832	2,535	6,706	4,624	393
Grand Total		16,296	55,565	44,209	4,785	16,897	43,096	33,592	3,157
Source:	Secondary data by Mumbai Metropolitan Region Development Authority (MMRDA)								

From this it is evident that the total vehicular volume (non-commercial) along the ‘metro line 1’ corridor has been reduced by 19.95%. Bus, car and 3W traffic has seen considerable drop in the ‘post-metro’ condition by 34.03%, 24% and 22% respectively. However, the 2W traffic has seen a slight increase of 3.69%, which could be due to its preference as ingress/egress mode by the commuters.

Step II: Now, the mode wise vehicular traffic variation in both ‘pre-metro’ and ‘post-metro’ conditions is available. In order to assess the reduction in CO₂ emissions, the fuel type of all these non-commercial vehicles is to be taken into consideration as the emission rate vary based on the fuel type. Hence the same has been referred from the vehicular statistics from MMRDA (2017). In addition, the mode wise CO₂ emissions (g/km) based on the fuel type has been referred to from the emission factors published by ARAI (2008). The required mode wise average CO₂ emission is then calculated by taking the weighted average of CO₂ emission factors (g/km) in accordance to the fuel type of respective vehicular volumes. Table 3 presents the summary of this calculation.

Table 3: Fuel based vehicular classification and respective avg. CO₂ Emission (gm/km)

Fuel Type	2W		3W/Auto		Cars		Buses	
	% Volume	CO ₂ EF (gm/km)	% Volume	CO ₂ EF (gm/km)	% Volume	CO ₂ EF (gm/km)	% Volume	CO ₂ EF (gm/km)
Petrol	100.00	28.12	0.00	0.00	66.40	128.55	0.00	0.00
Diesel	0.00	0.00	0.00	0.00	25.39	151.06	18.26	768.95
CNG	0.00	0.00	100	67.71	8.21	141.36	81.74	806.50
Total/weighted	100.00	28.12	100.00	67.71	100.00	128.55	100.00	787.73
Source:	i. Fuel based vehicular classification: MMRDA (2017) ii. CO ₂ Emission Rate: ARAI (2008)							

Step III: From the above database, the ‘daily CO₂ emissions’ and ‘vehicle Kilometers’ (VKM) generated by vehicular traffic are calculated as shown in Table 4 and Table 5 for ‘pre-metro’ and ‘post-metro’ conditions respectively. The ‘avg. trip length’ of ‘metro line 1’ was analysed from commuter survey data collected by MMRDA during August 2014 with a large sample size of 14,560. The same has been considered as the ‘trip length’ of non-commercial motorised vehicles to estimate the ‘VKM generated’ and ‘daily CO₂ Emissions’.

Table 4: Daily CO₂ emission (gm/km) and fuel miles generation (pre-metro)

Total Vehicular Traffic in MP & EP (A)		Daily Traffic* (B)	Emission of CO ₂ (Weighted) (gm/km)	Trip Length (km) (D)	VKM Generated (F= BxD)	Daily CO ₂ Emissions (t/day) (E= BxCxD)
2W	16,296.09	32,592.18	28.21	5.33	173,722.28	4.90
3W/Auto	55,565.09	111,130.18	67.71	5.33	592,344.25	40.10
CAR	44,209.37	88,418.74	135.32	5.33	471,288.12	63.77
BUS	4,784.66	9,569.32	799.64	5.33	51,006.23	40.79
Total/Avg.	120,855.21	241,710.42	257.72	5.33	1,288,360.87	149.57
Source:	i. Trip Length: Analysed from commuter survey data shared by MMRDA					
*Note: The daily traffic is estimated as twice of peak hour volume						

Table 5: Daily CO₂ emission (gm/km) and fuel miles generation (post-metro)

Total Vehicular Traffic in MP & EP (A)		Daily Traffic* (B)	Emission of CO ₂ (Weighted) (gm/km)	Trip Length (km) (D)	VKM Generated (F= BxD)	Daily CO ₂ Emissions (t/day) (E= BxCxD)
2W	16,897.50	33,794.99	28.21	5.33	180,133.51	5.08
3W/Auto	43,095.98	86,191.96	67.71	5.33	459,418.93	31.1
CAR	33,592.12	67,184.23	135.32	5.33	358,104.27	48.46
BUS	3,156.56	6,313.12	799.64	5.33	33,650.07	26.91
Total/Avg.	96,742.15	193,484.30	257.72	5.33	1,031,306.79	111.55
Source:	i. Trip Length: Analysed from commuter survey data shared by MMRDA					
*Note: The daily traffic is estimated as twice of peak hour volume						

From the above comprehensive analysis towards assessing the ‘CO₂ emission savings’ it is derived that, the ‘CO₂ emission/day’ along the ‘metro line 1’ corridor due to vehicular traffic has come down to 111.55 t/day from 149.57 t/day resulting in the savings of 38.02 t/day i.e. 25.42%. A graphical representation of mode-wise variation in ‘CO₂ emission/day’ for ‘pre-metro’ and ‘post-metro’ conditions is shown in Fig. 1. Similarly, the ‘fuel miles’ by non-commercial vehicles has come down from 1.28 million km to 1.03 million km resulting in a saving of 19.95%.

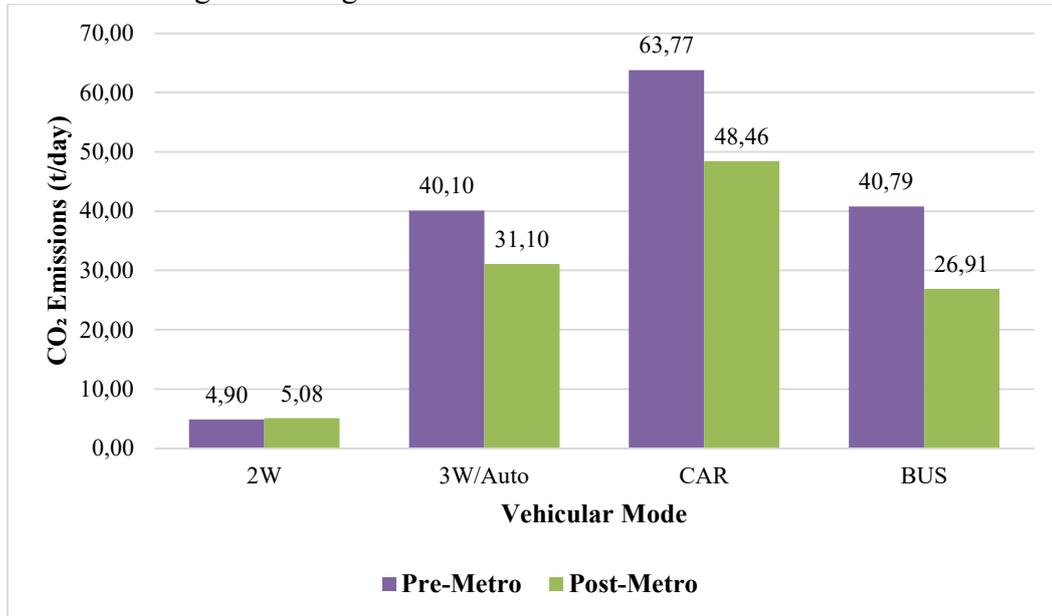


Figure 1: Mode-wise variation in ‘CO₂ emission/day’ in ‘pre-metro’ and ‘post-metro’ conditions

3.2 Estimation of CO₂ Emission Savings from commuter shift

This methodology can be adopted in an unplanned situation, where a PTA or an ULB decides to quantify the environmental benefits by a metro corridor after the commencement of commercial operations. This method shall support such spontaneous decisions towards assessment of CO₂ emission savings with no past data of traffic volumes along the corridor. The commuter shift to metro from other modes is to be collected through commuter survey alongside the ‘avg. trip length’ of the ‘Metro line 1’ corridor. In the current study, such database was developed through commuter survey analysis of the collected sample of 14,560. As mentioned earlier, the commuter survey was conducted in August 2014 by MMRDA and data was collected from the organisation. Subsequently, the ‘vehicle shift/day’ and ‘vehicle kilometers’ (VKM) were calculated from ‘avg. daily ridership’, ‘vehicular occupancy’ and ‘avg. trip length’. finally, the ‘CO₂ emission/day’ were calculated in conjunction with ‘vehicle kilometers’ and CO₂ emission factors (ARAI 2008). A detailed step by step procedure adopted under this methodology is presented below.

Step I: The ‘avg. daily ridership’ (week days) for the month of August 2014 has been analysed as 257,431. Subsequently, the commuter shift from other CO₂ emitting modes viz., 2W, 3W/auto, car, bus is calculated from the commuter survey data and presented in Table 6 (Col. B and C).

Step II: Parallely, the occupancy of each mode is referred from MMRDA (2007) and a total ‘vehicle shift/day’ is calculated accordingly as presented in Table 6 (Col. E).

Step III: The ‘avg. trip length’ of the ‘metro line 1’ corridor is analysed from the commuter survey data as 5.33 km and the total VKM per mode is calculated and presented in Table 6 (Col. G). Subsequently, the CO₂ EFs are referred from ARAI (2008) to calculate the daily CO₂ emissions per mode as presented in Table 6. (Col.I).

Table 6: Estimation of CO₂ emission (gm/km) form commuter shift

Mode (A)	% Commuter Shift (B)	Commuters (C=(B/100)x257,431)	Vehicular Occupancy (D)	Vehicle Shift/Day (E=C/D)	Avg. Trip Length (F)	VKM (G=ExF)	Emission of CO ₂ (Weighted) (gm/km) (H)	Total CO ₂ Emission Savings (gm/day) (I)
2W	4.48	11,527	1.40	7,685	5.33	40,958	28.21	11,55,520
3W/Auto	25.37	65,318	2.30	26,127		139,259	67.71	94,28,512
CAR	2.99	7,685	2.30	3,202		17,066	135.32	23,09,330
BUS	67.16	172,902	56.00	3,458		18,431	799.64	14,738,445
Total/Avg.	100	257,431	N/A	40,472		215,714	257.72	27,631,806
The ‘Total CO₂ emission savings’(t/day)								27.63
Source	i. Occupancy of 2W, 3W and Car: MMRDA (2008 ^a) ii. Occupancy of Bus: MMRDA (2017) iii. Ridership Data: Collected as secondary data from MMRDA							

By adopting the said methodology, the daily ‘CO₂ emission savings’ along the ‘metro line 1’ corridor are estimated to be 27.63 t/day. This is 27.31% lesser than the estimated ‘CO₂ emission savings’ from ‘Method I’.

3.3 Discussion

Both the methodologies demonstrated above, successfully determines the daily estimated ‘CO₂ emission savings’ by a metro corridor. However, a difference of 27.31% is observed due to the differential approach in both the methodologies. When the methodological approaches and the requisite data are closely examined, the ‘CO₂ emission savings’ estimated by ‘Method I’ appears to be more reliable due to the following observations.

- i. The ‘Method II’ estimates the ‘CO₂ emission savings’ based on the analysed commuter shift from other non-commercial CO₂ emitting modes. Despite the fact that a sample size of 14,560 is sufficient to estimate the commuter shift, this method ignores the actual traffic volume plying on the road along the metro corridor.
- ii. Though a metro corridor is expected to reduce the vehicular moment of private vehicles along the road network, it will also attract new trips in the form of ingress and egress travel. This will increase CO₂ emissions to certain extent. Whereas, ‘Method I’ automatically captures all the vehicular moment as there is a traffic volume count conducted at the same locations in both ‘pre-metro’ and ‘post-metro’ conditions.

However, few situations where ‘Method II’ can be exercised for estimation of ‘CO₂ emission savings’ are as discussed below.

- i. The ‘Method II’ can be chosen over ‘Method I’ when the ‘CO₂ emission savings’ are to be estimated for an upcoming metro corridor before commencement of

commercial operations. In such situations, the estimated commuter shift through mode choice modelling can be taken as an input along with the estimated ridership and the ‘CO₂ emission savings’ can be estimated. This shall give a preliminary understanding on the expected scenario upon commencement of commercial operations. This is generally practiced by PTAs and ULBs to for carbon trading under CDM of Kyoto protocol.

- ii. The ‘Method II’ shall remain as the only alternative when there is no traffic volume data collected before commencement of commercial operations of a metro corridor. In such cases, this method can act as a good alternative to substantiate the ‘CO₂ emission savings’ by a metro corridor.

Based on the analysis approach, requisite data and situation, one can adopt the following decision-making process towards selection of appropriate method for estimation of ‘CO₂ emission savings’ as presented in Fig. 2.

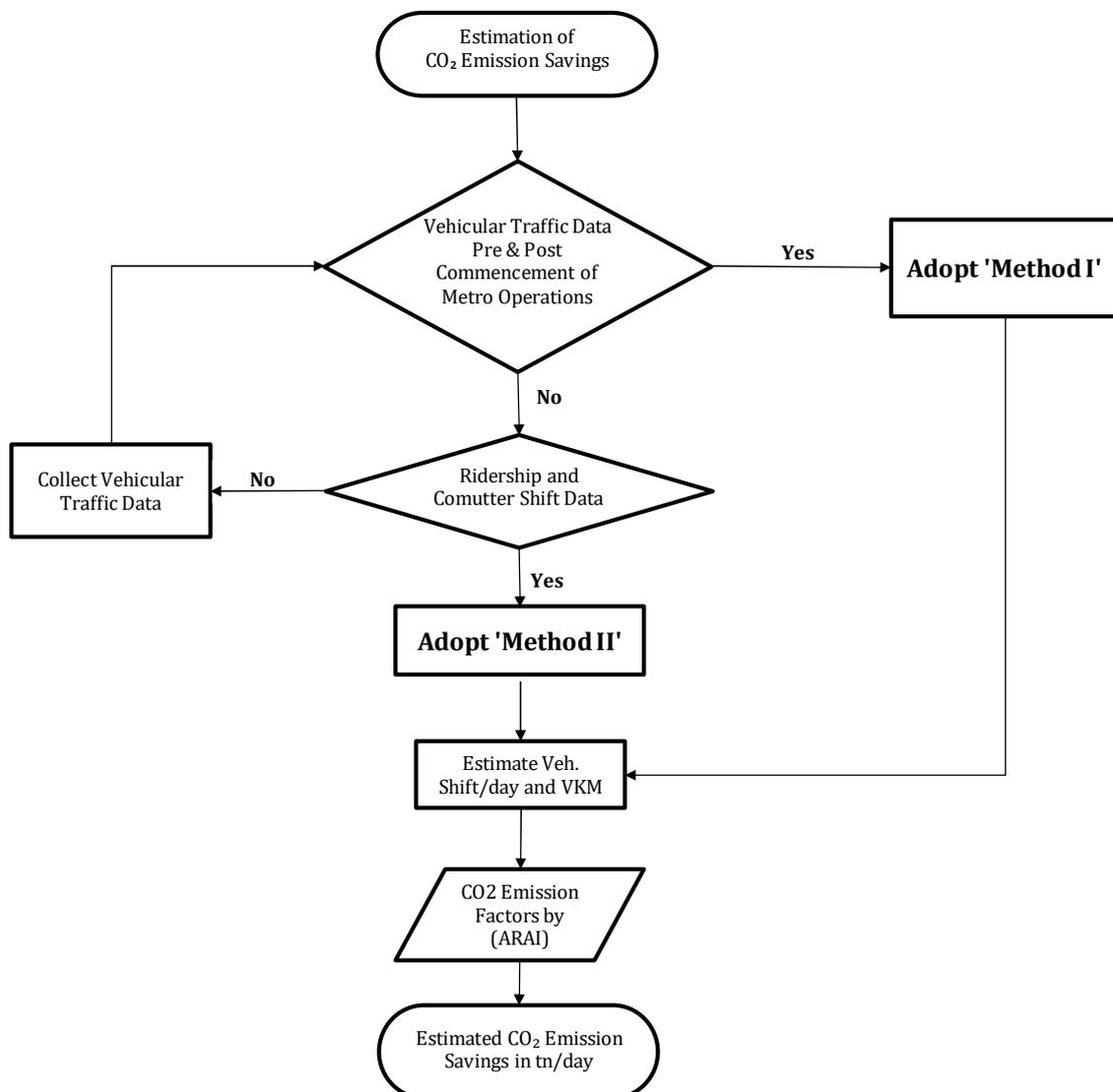


Figure 2: Recommended decision-making process for selection of appropriate method

4. Sensitivity Analysis

The sensitivity analysis was conducted for two different cases. The former case analyses the ‘CO₂ emission savings’ using ‘Method I’ and ‘Method II’ with varying vehicular shift. Whereas the latter case analysis the ‘CO₂ emission savings’ with varying ridership by considering the indirect CO₂ emissions contributed by the metro rail system during electricity generation.

4.1 Case I: Sensitivity Analysis Considering Varying Vehicular Shift

The approach towards analysing the daily vehicular shift is different in both the methods, one estimates it from direct traffic volume count and the other estimates it based on the % commuter shift. Subsequent to this analysis, both the methods estimate the CO₂ emission savings with the help of VKM and emission factors. Hence, the vehicular shift is a key variable in estimating the CO₂ emission savings and conducting sensitivity analysis based on such key variable would be practical and reliable. Accordingly, multiple hypothetical scenarios were developed with varying vehicular shifts from different modes and the resultant ‘CO₂ emission savings’ from both the methods were determined. As attracting riders from private modes is a key measure of performance for any MRTS towards achieving long term sustainable goals, modal shift from 3W/Auto and Cars was prioritised while defining these hypothetical scenarios. Subsequently, the optimal and practically possible scenario supported by both the methods has been determined as presented in Fig. 3.

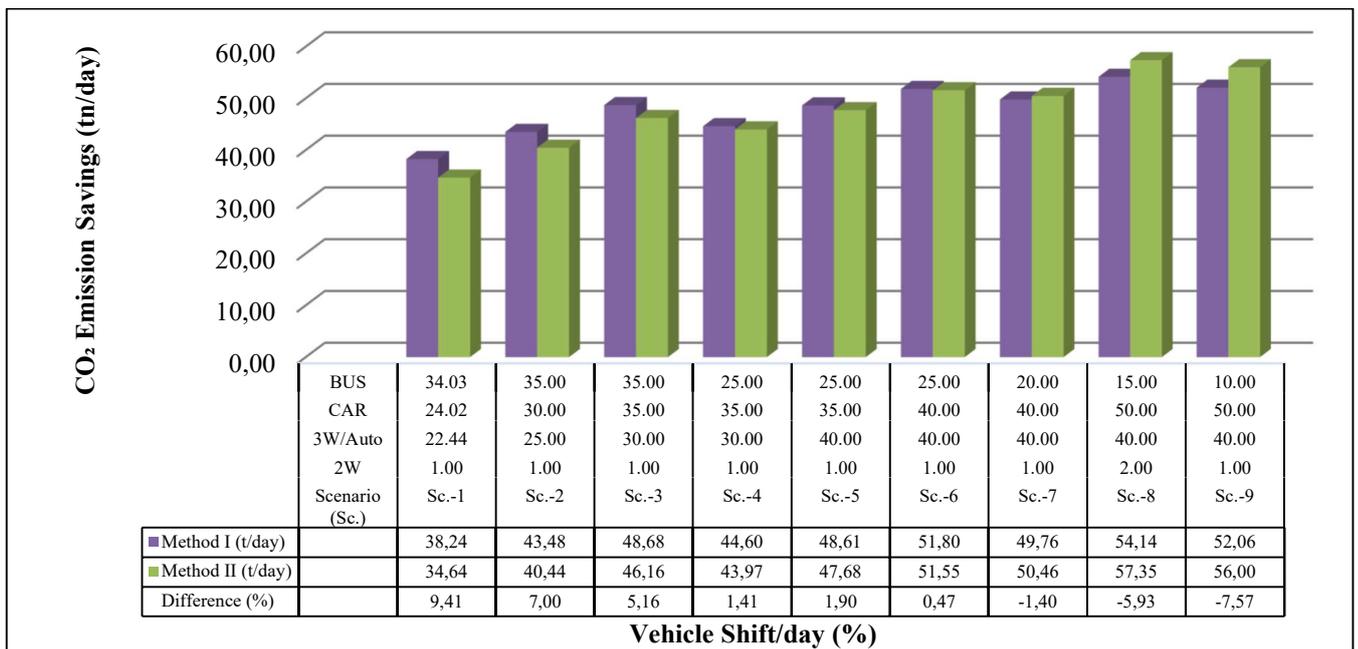


Figure 3: Sensitivity analysis for estimation of CO₂ emission savings from both the methods

From the sensitivity analysis above it is evident that ‘Scenario-8’ would be the most optimal scenario towards achieving the highest ‘CO₂ emission savings’ with 54.14 t/day and 57.35 t/day when analysed from ‘Method I’ and ‘Method II’ respectively. This is due to the highest commuter shift from the private mode like ‘car’. Further, this is also supported by both the methods as the optimal scenario with a difference of 5.93%.

Furthermore, it has been identified that the emission savings estimated for ‘Scenario-4’ to ‘Scenario-7’ exhibit similar results with both the methods. The difference observed was less than 2% with ‘Scenario-6’ being the closest with 0.47%.

4.2 Case II: Sensitivity Analysis Considering Varying Ridership and Indirect CO₂ Emissions by Metro System

Metro is an eco-friendly urban transport mode driven by electricity with zero in-situ emissions. However, it contributes to indirect emissions when the requisite electricity was generated from power plants. Hence, the same is to be taken into consideration when the ‘net CO₂ emission savings’ are estimated for a metro project. The electricity consumption by ‘Mumbai Metro Line 1’ for the FY 2014-15 and 2015-16 are 27,122,451 kWh and 27,237,360 kWh (MMOPL-RTI 2017) respectively with an annual growth rate in consumption by 0.42%. The CO₂ emission factor for the Indian powers sector as per ‘Central Electricity Authority’ (CEA) (2018), is 0.82 tCO₂/MWh. Accordingly, an indirect CO₂ emission of 60.93 t/day and 61.19 t/day is emitted by Mumbai ‘metro line 1’ for the FY 2014-15 and 2015-16 respectively. Whereas, the ‘CO₂ emission savings’ estimated by any method are not beyond 38.02 t/day, resulting in an indirect contribution of 22.91 t/day by Mumbai ‘metro line 1’ for the FY 2014-15. In this context, the ‘net CO₂ emission savings’ can be taken as -22.91 t/day. If this fact is considered, metro projects are increasing CO₂ emissions instead of savings. On the other side, the ‘avg. daily ridership’ of 257,431 in August 2014 had increased to 380,235 in March 2018 with an annual growth rate of 8.80%. Hence, by considering these growth rates of electricity consumption and ridership, multiple scenarios were developed in this ‘Case II’ of sensitivity analysis to identify the breakeven scenario for achieving positive ‘net CO₂ emission savings’. The ridership and electricity consumption are projected using the derived growth rates up to 2025 and the resultant ‘net CO₂ emission savings’ are estimated as shown in Fig. 4. The ridership forecast is observed to be within the capacity of the metro system as verified from the ‘estimated ridership’ figures of the governing authority (MMRDA, 2019). The commuter shift estimated for the base year i.e. 2014 is kept constant for all the scenarios.

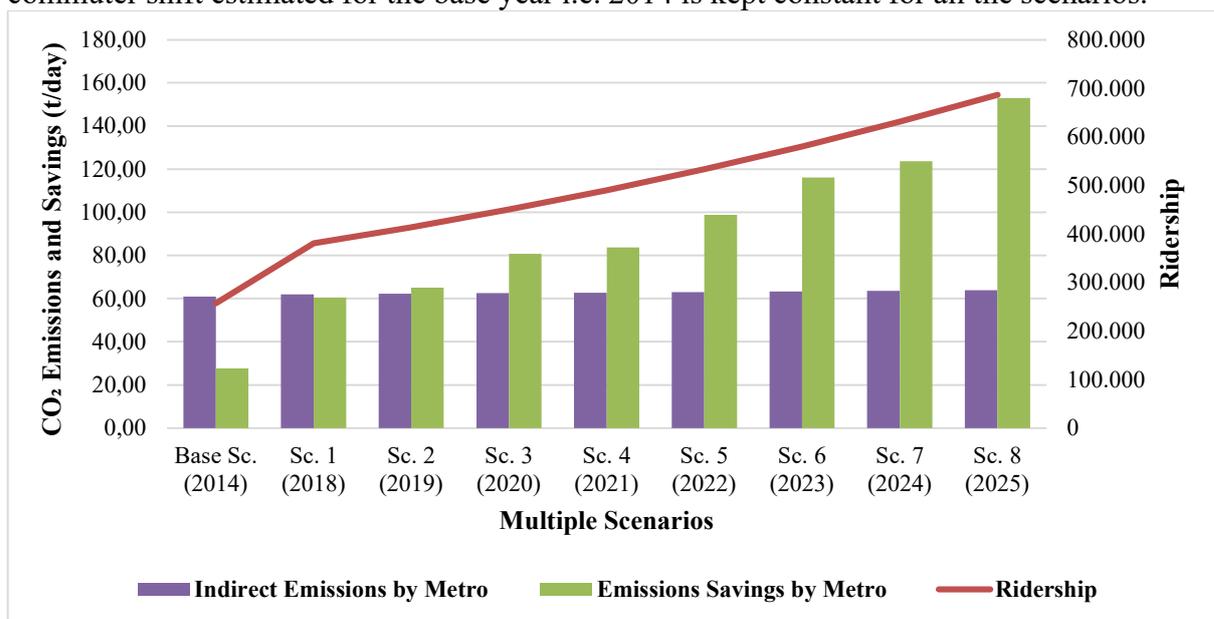


Figure 4: Sensitivity analysis for estimation of net CO₂ emission savings

From the sensitivity analysis above it is evident that Mumbai 'metro line 1' is achieving the breakeven in 'net CO₂ emission savings' with 2.76 t/day in 'scenario 2' i.e. by 2019. However, the emission savings are gradually increasing with the increase in ridership even with the constant commuter shift. By 2025 the 'net CO₂ emission savings' by Mumbai 'metro line 1' are estimated to be 89.14 t/day. With this an 'annual net CO₂ emission savings' of 32,537 t/year are estimated to be achieved by the 11.4 km Mumbai 'metro line 1' corridor alone.

5. Conclusions and Discussion

The article discussed and demonstrated two different methodologies for estimation of 'CO₂ emission savings' from a 'metro rail' system with a case study of Mumbai 'metro line 1'. 'Method I' estimates based on the actual vehicular traffic in both pre-metro and post-metro conditions. Whereas, 'Method II' considers the commuter shift from non-commercial vehicles along with occupancy and average daily ridership to estimate the emission savings. While 'Method I' estimates the 'CO₂ emission savings' as 38.02 t/day, 'Method II' estimates 27.63t/day, a difference of 27.31% is observed. However, multiple scenarios supporting similar results as close as less than 2% were identified with the help of sensitivity analysis (Case-I). 'Scenario-6' was the closest with a negligible difference of 0.47% supporting a 'CO₂ emission savings' of 52 t/day. 'Method I' and 'Method II' have a differential analytical approach towards estimation of 'CO₂ emission savings' and can be exercised in different situations as presented in this article. This study proposed and demonstrated the methodologies in a way that the estimation of 'CO₂ emission savings' can be carried out with a minimally available data. In addition a decision-making process was also suggested on choosing between 'Method I' and 'Method II' along with the demonstration for capturing the realistic scenario.

As there are few strong arguments over net CO₂ emission savings by a metro system, sensitivity analysis was also conducted considering the indirect CO₂ emissions contributed by the metro system due to electricity consumption. This revealed few interesting results that the Mumbai 'metro line 1' would achieve an 'annual net CO₂ emission savings' of 32,537 t/year even with the current commuter shift (modal share) by the year 2025. Analysis also revealed that a breakeven scenario of 'annual net CO₂ emission savings' of 1,008 t/year would be achieved by the end of 2019, based on the data collected in 2014.

From the current study, it is evident that both the methods can be engaged to estimate the 'CO₂ emission savings' for a metro rail project. However, the selection of the method depends on the factors such as data collection and availability, stage of the project. In simple terms, if the 'CO₂ emission savings' of a proposed metro rail system are to be estimated, 'Method I' shall stand as the only reserve, whereas if the 'CO₂ emission savings' of an operational metro rail system is to be estimated, 'Method II' shall be more accurate.

Further, similar sensitivity analysis is firmly recommended for all the operational and upcoming metro rail corridors to find out a breakeven scenario towards 'annual net CO₂ emission savings'. This shall also facilitate the PTAs and local governments to substantiate the costs incurred in the metro rail projects.

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