Journal of Innovations in Engineering Education
JIEE 2025, Vol. 8, Issue 1.

https://doi.org/10.3126/jiee.v8i1.81156

THAPATHALI CAMPUS
Institute of Engineering
Tribhuvan University

Mitigating vehicular emissions in Kathmandu valley by a clean energy approach

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ARTICLE INFO

Article history:

Received 7 July 2025
Revised in 29 October 2025
Accepted 24 November 2025

Keywords:

Urban air pollution
Vehicular emissions
Diesel Bus replacement
Sustainable mobility

Abstract

The Kathmandu Valley has experienced a sharp decline in air quality over the last few decades, primarily due to a surge in vehicular emissions driven by rapid and unmanaged urbanization. This study aimed to quantify the annual emissions from the vehicular sector and assess the potential reductions achievable through the electrification of public buses. A bottom-up approach was employed, incorporating real-time traffic data, structured surveys, and localized emission factors to quantify the total vehicular emissions. Approximately 1235 kilotons of GHGs and 85 kilotons of ambient air pollutants were estimated annually. Public buses, although comprising only 6% of the vehicle fleet, contributed nearly half of the total GHG emissions due to their use of diesel fuel, longer travel distances, and low fuel economy. The study presents the first scenario-based replacement analysis conducted in the context of Kathmandu. The results demonstrate that replacing 100% of diesel buses with electric alternatives could reduce GHG emissions by 49% and air pollutants by 17%. Additionally, a review of national and local policies highlights ambitious but under-implemented targets for transport electrification. The study provides valuable insights for emission mitigation through targeted electrification, emphasizing the need for infrastructure, incentives, and coordinated policy support at both the national and local levels to realize sustainable urban mobility in Nepal.

1. Introduction

Air pollution remains one of the most critical health challenges. The World Health Organization (WHO) reports that 99% of people worldwide breathe air that exceeds its recommended thresholds [1]. This issue is particularly severe in developing countries due to increased population, rapid urbanization and minimal regulatory oversight. In such countries, one of the most significant contributors to deteriorating air quality is the transportation sector. While it serves as the backbone of economic growth [2][3][4], this growth comes at an environmental cost. It is not only a major cause of air pollution but also contributes to global greenhouse gas (GHG) emissions [5]. The transportation sector accounts for approximately 24% of global carbon dioxide (CO_2) emissions that come from energy use, making it the second largest source of such emissions [6]. Nepal reflects this global trend, with rapidly growing transport emissions affecting air quality and public health, mostly in Kathmandu Valley [7][8]. Within the capital region, rapid urbanization and increased vehicle numbers have contributed to a sharp rise in emissions [9], and its bowl-shaped topography traps emissions and increases pollutant concentration, significantly affecting public health. As a result of these conditions, air pollution has been considered the top health risk factor in Kathmandu Valley [10][11]. Therefore, a transition toward cleaner and more sustainable transportation systems is essential to reduce air pollution and address broader environmental issues [12].

The increase in vehicular activity has intensified both

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local air pollution and greenhouse gas emissions, posing serious challenges for public health and climate sustainability [13]. The Kathmandu Valley's fleet of vehicles has grown by 45% in the last ten years, reaching 2.2 million as of 2024, which has culminated in declining air quality and increased GHGs [14]. According to a 2018 random emission test, 51% of the diesel-powered vehicles and 37% of the gasoline-powered vehicles were found to be producing more pollutants than the permissible limits [15]. These statistics have raised concerns among researchers, environmentalists, and policymakers. Several investigations have been conducted to assess local air quality, with an emphasis on emissions of pollutants [16][17][18]. Due to persistent air quality challenges and rising energy demands, Kathmandu Valley has been identified as a high-priority location for low-carbon urban development initiatives [19]. Recent developments in increased vehicle and elevated emissions in Kathmandu underscore the urgency of intervention.

Numerous studies have demonstrated that industrial activities, vehicle emissions, and biomass burning are major contributors for deteriorating air quality in the Kathmandu Valley. Among these, emissions from transport, particularly heavy-duty vehicles, have been identified as the dominant source around 50% of total vehicular emissions, followed by light-duty vehicles with 27% and motorcycles with around 22%, as reported by Ghimire et al. [20]. These numbers highlight how prevalent vehicle emissions are in the valley's air pollution profile. However, this study lacks consideration of variations in traffic conditions across different times of day or months which limits its temporal applicability. Further, a recent study estimated that implementing a bus rapid transit system could reduce daily transport emissions by 7,500 tons [21]. Although this study offers insightful information about transportation-based mitigation techniques, it overlooked ambient air pollutants such as nitrous oxides (NO_x), particulate matter (PM), and hydrocarbons (HC) that have greater detrimental effects on health. Another assessment estimated that adopting Euro III technology could result in a 31% reduction in global warming potential (GWP) and a 44% reduction in toxic air pollutants, based on vehicle fleet composition in Kathmandu [22]. Despite these insights, further research is needed to extend monitoring to various times of day and to include a wide range of vehicle types, such private vehicles and diesel trucks.

To contextualize the related research, Table 1 summarizes the methodological approaches, scopes, and key limitations of prior work. The identified limitations directly inform the methodological design of the present study.

Although prior studies have explored vehicular emissions in Kathmandu, few provide recent, region-specific estimates for different vehicle types, and none incorporated realistic replacement scenarios. To address this gap, this study conducts a thorough and recently updated examination of vehicle emissions in Kathmandu Valley. The study employed a mixed-methods approach, combining traffic video recordings for vehicle counting, a structured survey targeting vehicle owners and operators, a bottom-up estimation of emission loads, scenario analysis for evaluating electric vehicle adoption, and a comprehensive policy review to assess the regulatory landscape for emission reduction. The study will estimate emissions by vehicle type and assess the potential impact of clean vehicle transitions under different replacement scenarios. By utilizing localized emission variables and recent vehicle data, the study produces updated estimates to inform targeted emission reduction strategies and support sustainable transport planning.

This study contributes to the existing body of knowledge by including localized vehicular emissions using real time vehicle fleet for Kathmandu Valley. It is the first to model replacement scenarios of public transport to estimate potential emission reductions. These scenario analyses provide actionable policy insights for decision-makers targeting electrification and sustainable urban mobility planning in Nepal.

2. Methodology

The study began with primary data collection through traffic video recordings for vehicle counting and surveys of local commuters. These data were then used to calculate emission load and subsequently used for scenario analysis. Finally, a comprehensive policy review was carried out to contextualize the findings. Figure 1 presents the graphical representation of the methodology employed in this study.

2.1. Data collection

Vehicle numbers and activity data were collected using video recordings at five strategically selected locations (Kalanki, Balkhu, Narayan Gopal Chowk, Sinamangal, and Koteshwor). The sites were chosen to represent major intersections across the Ring Road with high vehicle density to capture the spatial variation in traffic flow. This selection ensured coverage of key transport corridors and intersections that mostly connects both inter and intra valley roads, making the dataset representative of the Kathmandu Valley's overall traffic flow. Recordings were taken for two different seasons; winter (December/January) and summer (July/August), on both working and non-working days. Four time slots including both peak hours (9:00-10:00 am and 5:00-6:00 pm) and non-peak hours (5:00-6:00 am and 9:00-10:00 pm)

Table 1: Methodological review of past studies on vehicular emissions in Nepal and their identified limitations

Study	Methodology / Data Used	Emission Types	Limitations Identified
Shrestha et al. [22]	International Vehicle Emission Model	CO_2, CO, NO_x, HC, PM	Scenario analysis based on Euro III adoption; does not analyze cleaner production pathways
Ghimire et al. [20]	Survey data and emission-factor-based estimation	CO_2, CO, NO_x, HC, PM	Broad estimates with static emission factor assumptions; lacks scenario analysis
Shrestha et al. [23]	Vehicle registration data (1990–2011), survey of daily travel distances and fuel mileage	CO_2	Data limited to reported vehicle registrations only
Mool et al. [15]	Roadside observations and survey of vehicle owners; small-sample emission measurements of super emitters	$PM_{2.5}$, Black Carbon (BC)	Focused only on diesel vehicles; limited generalization to entire fleet composition
Poudal et al. [24]	Fuel-based inventory using aggregate fuel sales data	CO_2	Limited real-time traffic data; lacks pollutant-level analysis and scenario modeling

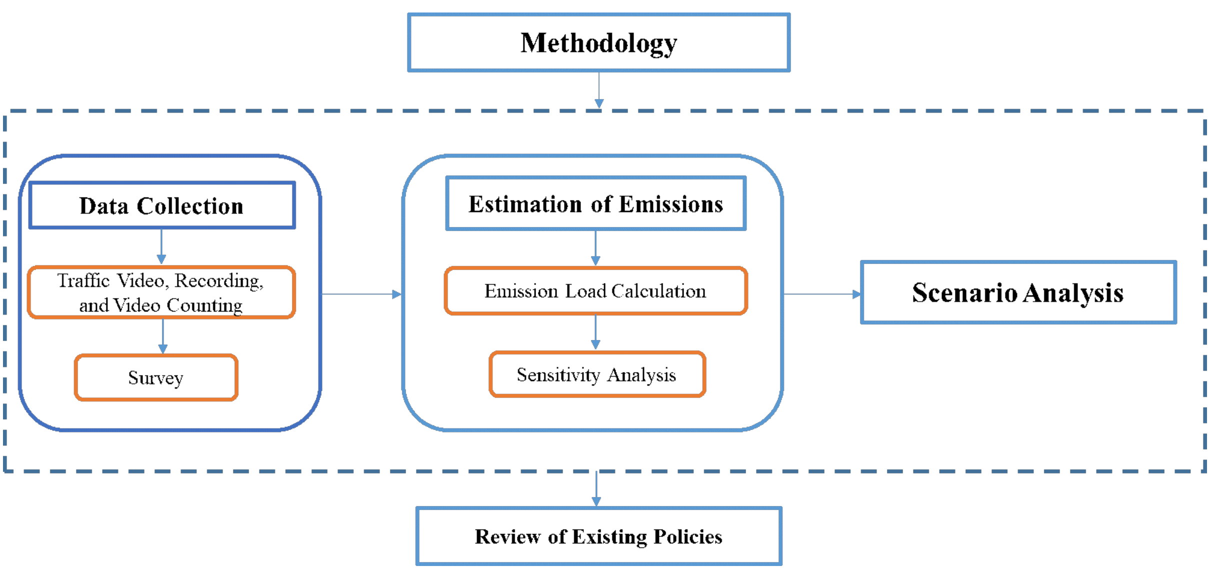

Figure 1: Overview of method employed in this study

were chosen per day. These time windows were selected based on local traffic patterns and prior studies [20][25]. Camera recordings were used to count the flow of different vehicle types at selected locations. Diesel buses, vans, taxis, and motorcycles were observed and counted, as these forms of transportation represent the dominant percentage of vehicles that are used in the valley.

A survey was conducted with vehicle owners and operators. The survey mainly focused on operators of public transport such as Sajha Yatayat, Nepal Yatayat, Mahanagar Yatayat and Gokarneshwar Yatayat, which cover a significant portion of public transport. Additional respondents included motorcycle riders, taxi drivers and private vehicle owners. The survey used stratified random sampling. The key points taken included driving and fuel consumption patterns, maintenance practices, emissions awareness, and adoption of cleaner transport including EVs, perceived barriers, and policy options. This was conducted in the same period as the video recording. The responses were recorded both manually and digitally to ensure completeness and accuracy.

2.2. Emission estimation

The emissions from the vehicles were estimated using the Emission Factor (EF) approach [26], which calculates the pollutants based on fuel consumption and vehicle activity data given by Equation 1.

$$E_j(t) = \sum_i V_i(t) \times \mathrm{VKT}_i(t) \times \mathrm{EF}_{ij}(t) \times F_i(t) \quad (1)$$

where $E_j(t)$ is the total emissions of emission type j in year t from passenger transportation (in tons); $V_i(t)$ is the vehicle population on the street; $\mathrm{VKT}_i(t)$ is the average annual distance travelled by a vehicle of type i in year t; $F_i(t)$ is the fuel economy of vehicle type i in year t (in liters per kilometer); and $\mathrm{EF}_{ij}(t)$ represents the emission factor of pollutant type j for vehicle type i in year t, expressed in grams per liter (g/L) of fuel consumed. The pollutant j refers to either an ambient air pollutant (CO, NO_x, HC, PM_{10}) or a greenhouse gas (CO_2), depending on the emission category under analysis. The emission factors used in this study are presented in Table 2. Emissions were calculated separately for light-duty vehicles, heavy-duty vehicles, two-wheelers, and public transport (buses) to identify high-contributing sources. $PM_{2.5}$ emissions were estimated from PM_{10} values using a $PM_{2.5}/PM_{10}$ conversion ratio of 0.74 [27].

2.3. Sensitivity analysis

A sensitivity analysis was conducted to evaluate the impact of uncertainties in key input variables, vehicle kilometers travelled per year (VKT) and fuel economy, on the emission estimation [28][29]. To assess the variability in key parameters, a One-At-a-Time sensitivity analysis was conducted. This approach evaluated the influence of uncertainties in two critical input variables: VKT and fuel economy. Each parameter was independently varied by ±10% and ±5% respectively, while holding the others constant, to understand their individual effects on total emission outputs. VKT is inherently more variable than fuel economy due to daily traffic fluctuations and uncertainties in travel behavior modeling. Therefore, a larger percentage variation (±10%) was applied to VKT for the sensitivity analysis [30] compared to fuel economy (±5%) which tends to be more stable and constrained by vehicle design and operational efficiency.

2.4. Replacement analysis

A replacement scenario targeting the highest emitting vehicle type was conducted. To assess the potential emission reductions from transitioning public buses to electric alternatives, a phased replacement scenario analysis was conducted. The analysis focused on the contribution of diesel-powered public buses, identified as the largest emitters within Kathmandu Valley's vehicular fleet. Three hypothetical replacement levels were modeled: 25%, 50%, and 100%. This method is consistent with previous studies [31][32][33], which used VKT and EF-based emission estimation to simulate the impact of fleet electrification. The emission reduction was calculated using Equation 2:

$$E_{\mathrm{scenario}} = E_{\mathrm{baseline}} - \left(N_{\mathrm{replaced\ buses}} \times \mathrm{EF}_{\mathrm{bus}} \times \mathrm{VKT}_{\mathrm{bus}}\right) \quad (2)$$

Where,

- **Emissions:** Total emissions under a replacement scenario (tons/year), denoted as E_{scenario}.
- **Baseline Emissions:** Emissions from the current diesel fleet (tons/year), denoted as E_{baseline}.
- **Replaced Buses:** Number of diesel buses replaced in each scenario, denoted as $N_{\mathrm{replaced\ buses}}$.
- **EF:** Emission factor for buses (g/L of fuel), denoted as $\mathrm{EF}_{\mathrm{bus}}$.
- **VKT:** Average vehicle kilometers traveled by a bus per year, denoted as $\mathrm{VKT}_{\mathrm{bus}}$.

The analysis assumed that electric buses produce zero tailpipe emissions, allowing for the isolated estimation of avoided emissions attributable to diesel replacement. Each scenario modeled progressively greater emission reductions, allowing comparison against the baseline emissions of the diesel fleet.

2.5. Policy review and recommendation

The purpose of the policy investigation was to examine the regulatory and policy frameworks currently in place to lessen vehicle emissions through the promotion of sustainable energy sources. Local and national policies that facilitate the transportation sector's shift to clean energy sources; specifically electric mobility and the integration of renewable energy sources, was documented in chronological order. The efficacy and intent of these policy initiatives, including key pollution mitigation targets were also studied, such as emission reduction targets, vehicle electrification timeframes, and incentives for the use of renewable energy. This was done to provide more effective and updated recommendation for future policies.

3. Results

The study identified the vehicle fleet composition of five major areas within Kathmandu Valley. Among the

Table 2: Emission factor taken for the study

Vehicle Types	Fuel Types	CO_2	CO	NO_x	HC	PM_{10}
Bus	Diesel	3440	24	35.61	11.1	11.7
Mini bus / Mini truck	Diesel	3440	24.8	11.2	10.4	8.1
Car / Van	Gasoline	3985	261.9	29.6	87.9	2.27
Motor bike	Gasoline	3766	726.3	11.3	69.9	4.3

pollutants, CO_2 was found to be the most significant pollutant. Estimates from different vehicle types showed public buses being a major contributor of CO_2 emission in the major areas.

3.1. Vehicular composition and Traffic characteristics

The traffic survey conducted at five major arterial points in Kathmandu Valley revealed that two-wheelers constitute the highest share of vehicular traffic, accounting for approximately 65%, followed by car: 24%, bus/minibus: 6% and other vehicle types approximately 5%.

Figure 2 shows the distribution of vehicle fleet characteristics across five key locations within the ring road of Kathmandu Valley. Among the sites, Koteshwor recorded the highest average number of vehicles during the study period, followed by Narayan Gopal Chowk, Kalanki, Sinamangal, and Balkhu respectively. The results indicate varying levels of vehicular density across the five different locations, with Koteshwor experiencing the highest traffic volume, suggesting a significant contribution to vehicular emissions in the Kathmandu Valley.

3.2. Annual emission load by Vehicle category

The total annual vehicular emissions were estimated using emission factor-based calculations for GHGs and air pollutants (CO, HC, NO_x, PM). The estimated total emissions from all vehicles amounted to approximately 1235 kilotons of GHGs and 847 kilotons of air pollutants per year as shown in Table 3. Using a $PM_{2.5}/PM_{10}$ conversion ratio, total $PM_{2.5}$ was estimated approximately 3 kilotons per year. These values are used as the baseline for further scenario-based mitigation analysis. Figure 3(a) shows that public buses contribute the largest share of GHG emissions, emitting nearly 600 kilotons annually. Despite having a smaller fleet share, buses far exceed emissions from cars, motorbikes, and mini-trucks due to their heavy diesel use and longer operational distances. Similarly, Figure 3(b) shows air pollutants emitted by all vehicle types.

3.3. Sensitivity analysis of emission estimates

A sensitivity analysis was performed on two key parameters; VKT and fuel economy, to assess the robustness of the emission estimates. Among all variables, these parameters are more sensitive and significantly influence emission estimates, especially in data-scarce settings like the Kathmandu Valley. Figure 4(a) illustrates the impact of uncertainty on GHG emissions, showing that a $\pm 10\%$ variation in VKT results in a range from approximately 1112 kilotons to 1359 kilotons, indicating high sensitivity to distance traveled. Similarly, a $\pm 5\%$ variation in fuel economy results in range from 1173 to 1297 kilotons. Similarly, Figure 4(b) presents the sensitivity results for pollutant emissions, where VKT causes emission to vary between 762 and 931 kilotons, while fuel economy changes lead to a range of 804 to 889 kilotons. This analysis supports the reliability of the base estimates while also identifying which input parameters most critically impact the final emission outputs.

3.4. Scenario based emission reduction analysis

To assess the emission mitigation potential of electrifying the public bus fleet, three replacement scenarios were analyzed: 25%, 50%, and 100% of diesel buses replaced by electric buses. The results clearly demonstrate that complete electrification of diesel buses could reduce GHG emissions by nearly 49% of GHGs and air pollutants by around 17% as summarized in Table 4. Even a 50% replacement scenario would yield substantial reductions (24.26% in GHG and 8.49% in pollutants), supporting the importance of prioritizing electrification of public transport.

3.5. Review of existing policy

Nepal has implemented several national policies and regulations to address vehicular emissions and improve air quality. These frameworks range from regulatory instruments to strategic development plans aimed at promoting cleaner transportation systems. Table 5 shows major policy interventions targeting vehicular emissions between 1993 and 2025. To regulate vehicle emissions and promote environmental sustainability, the vehicle and transport management regulation (1994) and the environment protection act and regulation (1996) placed

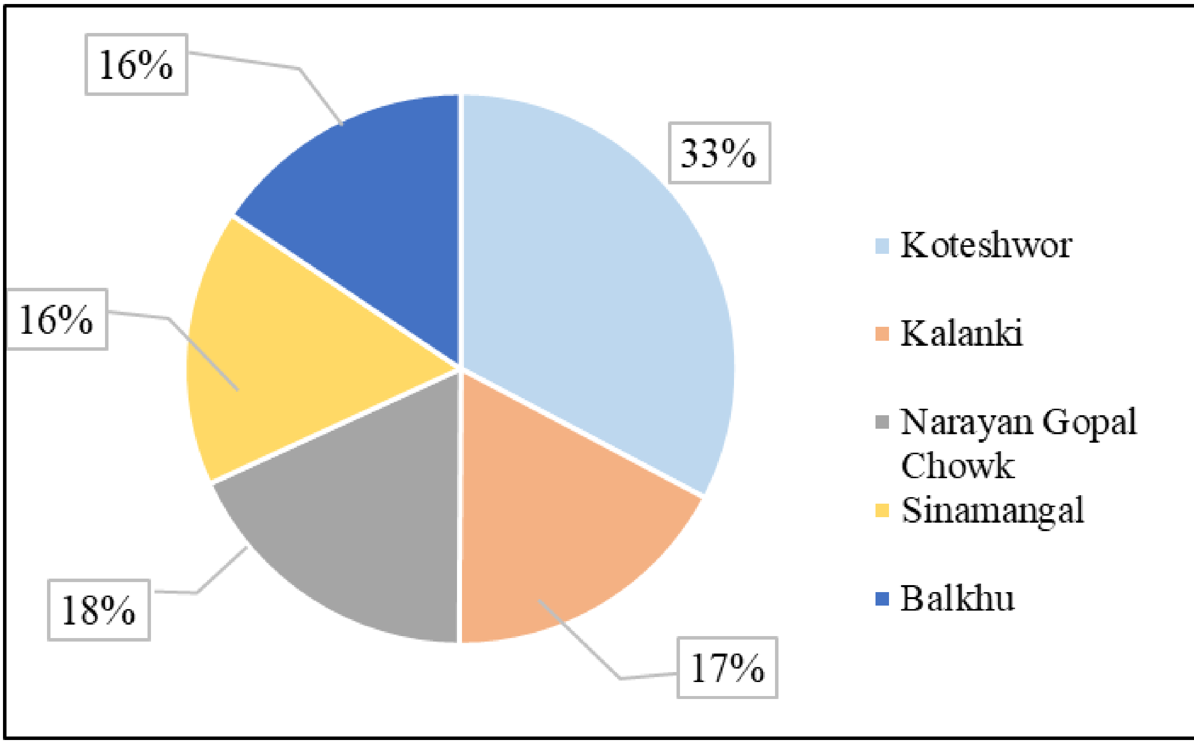

Figure 2: Observed vehicular flow at selected locations across Kathmandu Valley

Table 3: Emission from vehicles (kilotons/year)

Vehicle Types	**CO**	**NO_x**	**HC**	**PM_{10}**	**CO_2**
Bus	4.184	6.209	1.935	2.040	599.757
Mini bus / Mini truck	1.459	0.659	0.612	0.477	202.429
Car / Van	14.362	1.623	4.820	0.124	218.529
Motor bike	41.330	0.643	3.978	0.245	214.305
Total	61.336	9.134	11.345	2.886	1235.020

the foundation for emission control. These were the earliest efforts to formalize environmental standards in the transportation sector. Similarly, in 1998, the nation's first significant move toward more stringent vehicular emission control came with the adoption of Euro I standards under the Nepal vehicle mass emission standards act [34]. Later initiatives, such as the urban policy (2001/2) and the climate change policy (2010), put even more emphasis on environmental preservation and sustainable urban growth [35]. The most recent 16th Periodic Plan [36] reinforces Nepal's commitment to ongoing efforts in reducing vehicular emissions and promoting sustainability and emphasizes ongoing initiatives in this regard.

Furthermore, Third Nationally Determined Contribution (NDC 3.0), presents ambitious climate targets proposing a 26.79% reduction in GHG emissions by 2035 [37]. These actions represent a strong commitment to reducing both greenhouse gas emissions and urban air pollution by shifting away from fossil fuel-based transportation.

Guided by national legislation, local level initiatives(Table 6) have also been crucial in lowering air pollution, especially in cities. One of the earliest initiatives was Kathmandu Valley Development Authority Act 1998, which addressed urban planning and transportation. The Kathmandu Sustainable Urban Transport Project (2010) laid out a more focused strategy that aimed to increase the effectiveness of public transportation and encourage alternative modes of transportation. Setting stringent regulations by prohibiting public vehicles older than 20 years, policies like the air quality management action plan, vehicle-free zones, and the introduction of Euro IV gasoline were put into effect in 2016 by specifically targeting high-emission vehicles, these policies helped mitigate pollution. Furthermore, a major

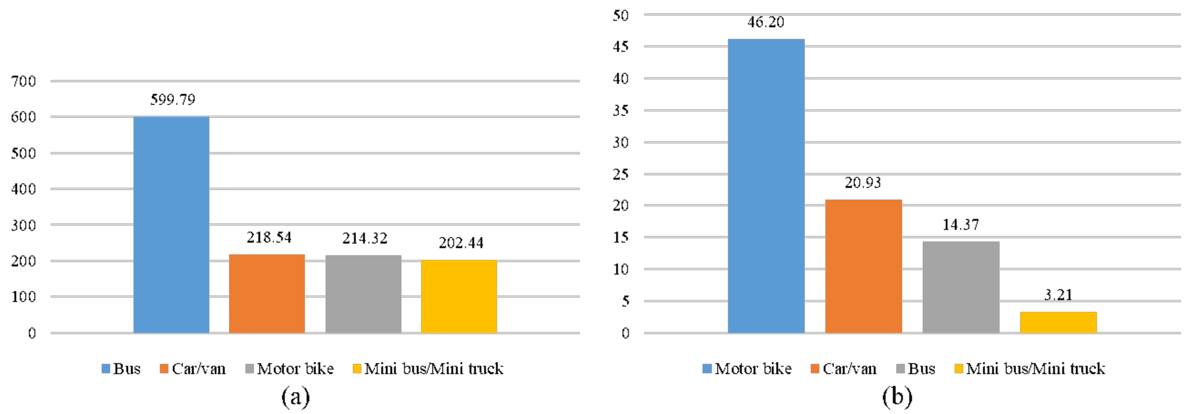

Figure 3: Total emissions vehicle wise in kilotons/year (a) GHG emission (b) Ambient air pollutant emission

Table 4: Emission Reduction by Replacement Level

Emission Type	Total Vehicular Emission	After 25% Replacement	After 50% Replacement	After 100% Replacement
GHG	1235.02	1085.14	935.19	635.29
Pollutants	847	811.08	775.17	703.33

step towards reducing transportation emissions is outlined in the second periodic plan of Bagmati province, which targets to remove petroleum-powered cars from metropolitan areas by 2028 [38].

3.6. Critical observations

A cornerstone of NDC 3.0 is the electrification of the transport sector, with specific goals that 95% of private and 90% of public vehicle sales will be electric by 2035 [37]. The NDC also proposes a major expansion of electrified infrastructure, all aimed at mitigating both GHG emissions and urban air pollution through the transition from diesel and gasoline vehicles to clean electric alternatives. Compared to NDC 2.0, which only aimed for 25% electric vehicle sales by 2025 and 20% reduction in transport emissions by 2030 [39], making NDC 3.0 a marked increase in ambition. These policies and plans are ambitious in their targets across all sectors, particularly in transport electrification and GHG reduction. However, the implementation framework remains limited, and the targets remain unmet as evidenced from NDC 2.0. This is primarily due to lack of infrastructure development, concrete programs, financial incentives, and regulatory enforcement mechanisms.

Similarly, local policies, although ambitious, are often fragmented, project-based, and lack long-term institutional or financial support. Lack of active involvement of regulatory bodies further hinders effective implementation. Additionally, weak coordination and alignment of local and national policy undermines unified progress toward sustainable urban mobility.

4. Discussion

This study quantified annual vehicular emissions in Kathmandu Valley using a bottom-up approach that combines traffic volume data, fuel-type disaggregation, and emission factor-based calculations. Results show emissions of 1235 kilotons of GHG and 85 kilotons of pollutants annually. Despite representing only 6% of the total vehicle composition, diesel powered buses emit nearly half of the total GHGs. The primary causes of this are the use of diesel fuel, their poor fuel economy and long travel distances followed by their poor maintenance practices. Scenario-based replacement analysis revealed that fully electrifying the diesel bus fleet could lead to a 49% reduction in GHG emissions and a 17% decrease in ambient air pollutants, underscoring the substantial mitigation potential of targeting high-emission vehicle categories.

This study makes several contributions to the existing body of literature. It is among the few studies to combine real-time disintegrated vehicle data to estimate emissions in Kathmandu Valley. Most notably, it presents a phase wise replacement scenario model for public transport which has not been previously applied in the context of Kathmandu. This scenario based design provides practical insight to support electric mobility transitions in developing urban settings like Kathmandu.

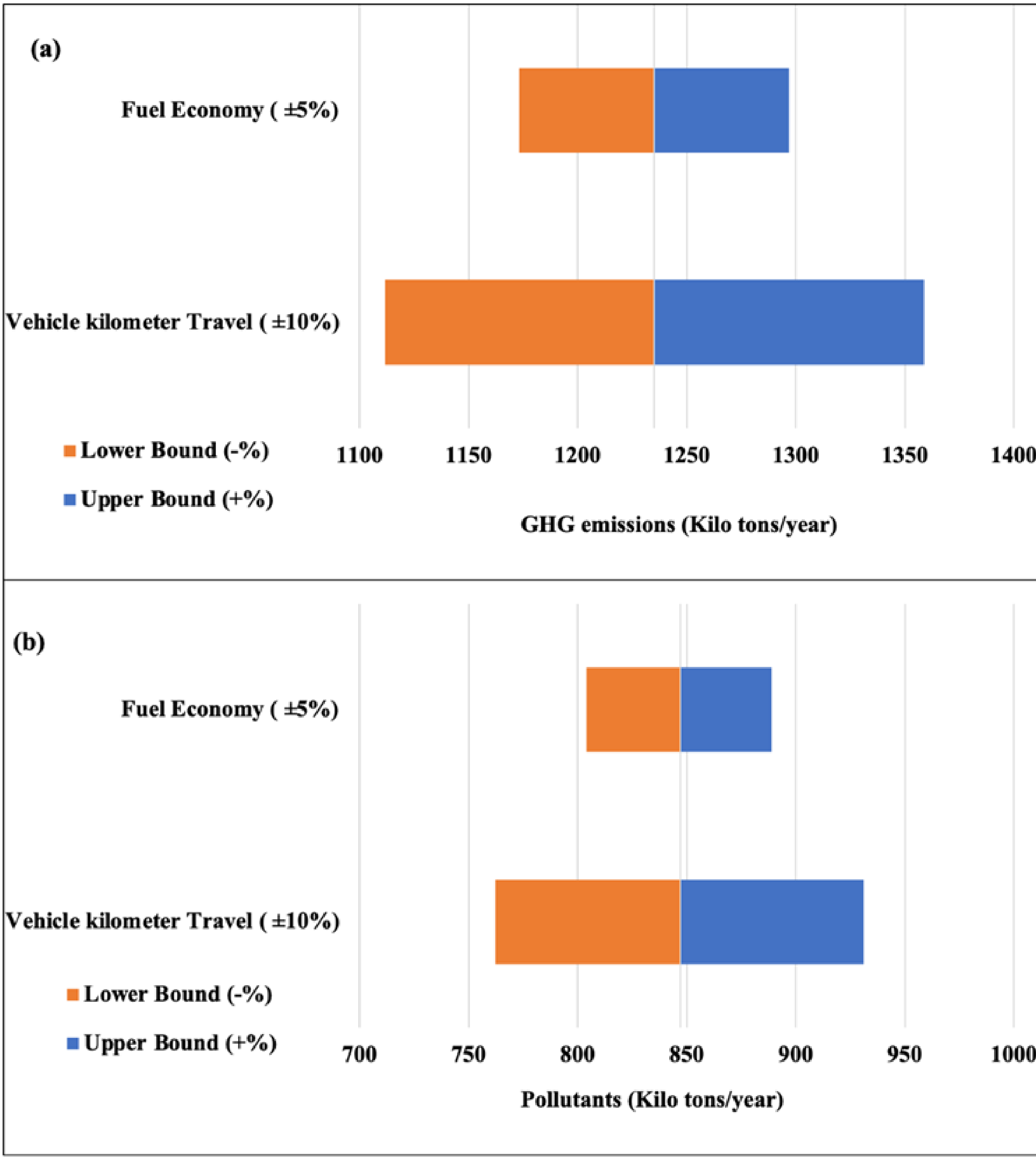

Figure 4: Sensitivity analysis of vehicular emission estimates to input parameters: (a) GHG emissions (kilotons/year) and (b) air pollutant emissions (kilotons/year), under variation in vehicle kilometer travel (±10%) and fuel economy (±5%)

Compared to regional studies, such as Zhou et al. [40], which evaluated the impact of EVs in Chinese megacities, our results align in demonstrating that electrifying heavy-duty vehicles yields the greatest impact per unit replaced. While Zhou et al. reported a 20 to 30% reduction in urban CO_2 levels through electric bus integration, our full-replacement scenario shows approximately 49% CO_2 reduction, emphasizing the relatively greater benefits for cities like Kathmandu. These findings are also consistent with national level analyses such as Shakya and Shrestha [41], who underscored the co-benefits of transport electrification for environmental protection and climate mitigation. The results validate and extend prior findings with more granular and location-specific

Table 5: Timeline of National-Level Act, Regulations Policies and Plan in Nepal Related to Vehicular Emissions and Pollution Mitigation (1993 - 2025)

Year	National Level Policies & Regulations	Key Target of Pollution Mitigation
1993	Motor Vehicles and Transportation Management Act	Establishes criteria for vehicle examination, including pollution control and roadworthiness.
1996	The Environment Protection Act	Provides a framework for controlling vehicular emissions and air pollution.
1998	Nepal Vehicle Mass Emission Standards Act / Euro I Introduced	Introduces Euro I standards to regulate vehicular emissions.
2001	National Transport Policy	To develop a transport system that is sustainable, dependable, less expensive, safe, comfortable and self-reliant.
2006	National Ambient Air Quality Standard (NAAQS)	Set ambient air quality standards and limits for various pollutants, including PM_{10}, $PM_{2.5}$, and other transport-related emissions.
2011	Climate Change Policy	Introduces cleaner Euro III fuels to reduce vehicular emissions.
2013	Nepal Road Safety Action Plan	Update emission standards for vehicles, aligning with Euro III norms.
2014	Environment Friendly Vehicle and Transport Policy	To promote environment-friendly vehicles in Nepal, targeting more than 20% of vehicle fleets to be environment-friendly by 2020.
2020	National Climate Change Policy	Fosters electric and alternative energy cars, develops charging infrastructure, and supports environmentally friendly public transport systems to reduce fossil fuel dependence.
2022	National Strategy for Electrification of Public Transport	Promotes electrification of public transport with incentives for scrapping old diesel vehicles and expanding charging infrastructure.
2024	16th Periodic Plan of Nepal	Continues focus on sustainable electric transport projects.
2025	Nationally Determined Contribution (NDC)	Sets targets for reducing transport sector emissions and increasing electric vehicle adoption.

insights, affirming the outsized impact of diesel buses on urban emissions and reinforcing the benefits of electrification. The findings provide actionable insights for urban planners and policymakers, particularly in aligning NDCs and the Bagmati province periodic plan [38], which aims of transition from fossil fueled vehicles to EVs by 2028. Nepal, being rich in renewable sources [42][43], could largely benefit from this transition, both economically and environmentally.

Despite certain limitations, the study provides an indicative baseline for assessing vehicular emissions and evaluating phased replacement. Emission estimates were based on vehicle fleet data taken from five major intersections, which, while not fully representative of entire Kathmandu, offer valuable insights into valley traffic dynamics. Furthermore, the overall emission may be marginally impacted by the exclusion of pollutants like NMVOC, SO_x, and GHGs such as N_2O and CH_4. To enhance future studies, lifecycle assessments, and economic feasibility analysis will be essential. Additionally, research on alternative fuels like hydrogen and biodiesel, along with modeling grid readiness for electric fleets, will enhance the discourse of sustainable mobility in developing urban centers.

Overall, the study shows that progressively electrifying vehicles can have a significant impact on both urban air quality and mitigate the effects of climate change. Combining empirical data with replacement scenario modeling, the study bridges a key research gap and supports evidence based transport planning in Kathmandu and similar emerging urban cities.

5. Conclusion

The study estimated vehicular emissions in Kathmandu Valley and assessed the potential reduction achievable through public transport replacement with cleaner alternatives. Using localized traffic counts, fuel-based emission factors, vehicular emissions were estimated

Table 6: Local-Level Measures for Reducing Vehicular Emissions in Kathmandu Valley and Bagmati Province

Year	Local Level Initiatives	Key Target of Pollution Mitigation
1988	Kathmandu Valley Development Authority Act	Focused on urban planning and development, including measures to reduce vehicular congestion and pollution through controlled zoning and infrastructure improvements.
2010	Kathmandu Sustainable Urban Transport Project	Aimed to implement sustainable transport systems such as improved public transport, pedestrian-friendly infrastructure, and reduced reliance on fossil-fuel-based vehicles.
2016	Air Quality Management Action Plan for Kathmandu Valley	Introduced Euro IV fuel standards, established vehicle-free zones to reduce emissions in key areas, banned public vehicles older than 20 years, and drafted a comprehensive air quality management plan targeting vehicular pollution.
2020	Kathmandu Valley Air Quality Management Action Plan	Focused on reducing $PM_{2.5}$ and PM_{10} levels by promoting electric vehicles, enhancing emission testing systems, and implementing stricter regulations for high-emission vehicles.
2024	Bagmati Province Periodic Plan	Promotes clean energy adoption in transportation by expanding electric vehicle infrastructure, incentivizing electric public transport, and phasing out older fossil-fuel vehicles.

at approximately 1235 kilotons of GHGs and 85 kilotons of ambient air pollutants annually. Replacement analysis showed that a full replacement of diesel buses by electric alternatives could reduce GHG emissions by up to 49%, affirming the high impact of electrifying heavy-duty public transport.

A full transition may be too ambitious but it is not impossible. High upfront capital expenses, limited EV charging infrastructure, and lack of reliable power supply at charging stations are some of its obstacles for developing nations like Nepal. Additionally, inadequate government incentives and an effective battery waste management system may also hinder the rate of shift. For this, the government should prioritize a phased transition approach that targets high-emission vehicles such as public buses, while also strengthening infrastructure and regulatory frameworks. For the sustainability of electric mobility, comprehensive planning, infrastructure development, environmentally sound battery disposal practices, and active regulatory mechanisms are essential. The findings of this study not only inform policy development in Nepal but also contribute to broader discussions on sustainable urban mobility in rapidly urbanizing regions.

Credit author contribution statement

Pitambar Chaulagain: Conceptualization, Writing - original draft, Writing - review & editing, Methodology, Investigation, Visualization.

Binaya Kumar Lamichhane: Methodology, Data Collection, Data Analysis, Writing-review & editing.

Rush Pradhan: Writing-original draft, Methodology, Data Curation, Data Analysis, Writing-review & editing.

Gyan Prasad Bhusal: Data collection, Data analysis, Writing - review & editing.

Kedar Prasad Bhandari: Data collection, Data analysis, Writing - review & editing.

Bishworam Parajuli: Conceptualization, Supervision, Writing-review & editing, Visualization, and funding acquisition

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.

Acknowledgment

The authors acknowledge the Kathmandu Valley Traffic Police for providing video recordings of traffic data and the Research and Development Unit, Institute of Engineering, Thapathali Campus, for the financial support in carrying out this research. Their contributions were instrumental in facilitating data collection and analysis.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used GPT-4 OpenAI model in order to enhance readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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