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Scenario-Based Simulation Model for Assessing the Electrification of Urban Rickshaw Fleets in Nepal: A Study of Dharan City

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Abstract

This study develops a dynamic, scenario-based simulation model to evaluate the techno-economic and environmental viability of transitioning urban rickshaw fleets from petrol to electric in Dharan, Nepal—a representative secondary city experiencing rapid urbanization. Integrating fleet dynamics, emission accounting, and total cost of ownership (TCO) within a Python-based Monte Carlo framework, the model assesses outcomes under Baseline, Conservative, and Policy Accelerated scenarios from 2016 to 2040. Findings reveal that the Policy Accelerated pathway, characterized by robust subsidies, fuel taxation, and synchronized grid decarbonization, can achieve up to 95% fleet electrification by 2040. This transition reduces well-to-wheel CO_2, $PM_{2.5}$, and NO_x emissions by 72%, 91%, and 78% respectively, while also cutting the lifetime cost of e-rickshaws by 39% compared to business-as-usual. Economically, e-rickshaws achieve a positive net present value (NPV) of NPR 0.7 billion with an operator payback period of 5-7 years. Sensitivity analysis identifies fuel taxes and purchase incentives as the most effective policy levers. The results underscore that the greatest climate and health benefits are realized through an integrated strategy that concurrently targets vehicle electrification and power sector decarbonization. This study provides a replicable analytical framework and evidence-based policy roadmap for sustainable urban mobility in developing economies.

Keywords: E-rickshaw, Fleet Electrification, Total Cost of Ownership (TCO), Net Present Value (NPV), Monte Carlo Simulation, Grid Carbon Intensity, Sustainable Transport Policy.

1. Introduction

The global transportation sector is a leading contributor to greenhouse gas emissions, accounting for 24% of global CO_2 output, with road transport responsible for nearly 70% of this share (International Energy Agency, 2023). This challenge is particularly acute in the Global South, where rapidly urbanizing cities face a convergence of environmental, economic, and social pressures from deteriorating air quality, rising fuel imports, and unequal access to mobility (Pojani and Stead, 2017). In response to these challenges, cities are increasingly seeking sustainable urban mobility solutions. The electric three-wheeler, or e-rickshaw, has emerged as a promising alternative for short-distance travel, demonstrating potential to reduce tailpipe emissions, decrease fossil fuel consumption, and enhance equitable mobility in dense urban environments (Li et al., 2019) and (Devkota and Bajracharya, 2021).

Nepal presents a unique and compelling case for transportation electrification. The nation generates over 95% of its electricity from renewable sources, primarily hydropower, providing a foundational advantage for a low-carbon electric mobility transition (Nepal Electricity Authority, 2023). This inherent potential, coupled with improving grid reliability and infrastructure, positions Nepal to harness significant economic and environmental co-benefits by electrifying its urban transport sector, particularly its extensive network of public light-duty vehicles (Ghimire, Kim and Dhakal, 2023). Recognizing this opportunity, the Government of Nepal has introduced pivotal policy instruments, including the Electric Vehicle Promotion Policy-2023 and a master plan for sustainable transport, aiming to reduce fossil fuel dependence and mitigate vehicular emissions through strategic EV adoption (Rajbhandari et al., 2024).

However, the transition is uneven. While the capital, Kathmandu, has witnessed modest growth in electric vehicle adoption, including private cars and buses, secondary cities like Dharan lag significantly behind. This

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disparity is attributed to constraints in financing, charging infrastructure, and localized planning (Rahman, 2024). Consequently, urban transport in these cities remains dominated by old, inefficient, and poorly regulated gasoline-powered vehicles, perpetuating cycles of air pollution and high operating costs. This gap highlights a critical research and policy blind spot: a focus on megacities that neglects the specific challenges and opportunities of secondary urban centers, which often serve as crucial economic and transportation hubs.

Globally, EV adoption has been accelerated by strong policy incentives and robust infrastructure, a lesson evident in developed economies (International Energy Agency, 2021). Neighboring countries also offer instructive examples; India has achieved an 8% EV adoption rate in the three-wheeler segment through effective subsidies (Shree, Edeh and Sin, 2024), and Bangladesh has registered significant air quality improvements following the implementation of electric auto rickshaws (Al-Amin, 2023). In contrast, Nepal's policy framework remains nascent, and studies on the socio-economic and environmental impacts of EV implementation are still emerging (Mali, 2022). While recent research affirms the technical feasibility of EVs in Nepal, citing the hydropower capacity (Ghimire, Kim and Dhakal, 2023), a clear deficit exists in dynamic, quantitative models that simulate the transition under realistic policy scenarios, especially for specific vehicle segments like rickshaws in secondary cities.

This study aims to address this research gap by developing a comprehensive scenario-based simulation model to assess the electrification of urban rickshaw fleets in Dharan, Nepal. The model integrates policy directives, fleet data, geographic factors, and energy infrastructure projections to analyze the environmental, economic, and policy dimensions of the transition. The primary aim is to provide a robust analytical framework for evaluating sustainable mobility pathways. The specific research objectives are:

- To model the fleet transition dynamics from internal combustion engine (ICE) to electric rickshaws under multiple policy and energy scenarios.
- To quantify the well-to-wheel emission reduction potential for CO_2, $PM_{2.5}$, and NOx.
- To evaluate the economic viability and total cost of ownership for rickshaw operators, identifying key financial levers and break-even points.
- To derive context-specific policy recommendations that can accelerate a sustainable and equitable transition, with applicability to other developing urban contexts.

2. Methodology

This study employs a dynamic simulation model to evaluate the techno-economic and environmental implications of electrifying the urban rickshaw fleet in Dharan, Nepal. The model integrates fleet transition dynamics, well-to-wheel emission accounting, and financial viability analysis within a unified Python-based computational framework.

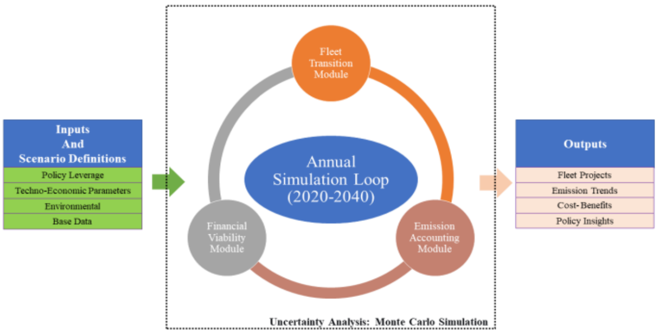

Figure 1. Model Framework

The analytical framework is grounded in system dynamics, which facilitates the representation of interactions and feedback loops between policy interventions, consumer adoption behavior, grid decarbonization, and environmental outcomes. The theoretical foundation builds on Rogers' diffusion of innovations (Rogers, 2003) which explains how new technologies diffuse along an S-shaped curve influenced by factors such as perceived advantage, compatibility with existing systems, and complexity of adoption. The simulation model, Figure 1, integrates three complementary modules. The Fleet Transition Module employs an agent-based approach to project the annual turnover of rickshaw stocks, accounting for adoption, retirement, and replacement processes. The Emission Accounting Module applies a well-to-wheel perspective, estimating tailpipe emissions from internal combustion engine vehicles (ICEVs) and electricity-related emissions from electric vehicles (EVs) under different grid carbon intensity trajectories. The Financial Viability Module evaluates the economic feasibility of electrification using total cost of ownership (TCO) and net present value (NPV) calculations, complemented by Monte Carlo simulations to propagate uncertainties in fuel prices, battery costs, and charging efficiency.

2.1 Scenario Design

To capture a range of plausible futures, three scenarios were developed: Baseline**,** Policy Accelerated, and Conservative, as in Table 1**.** These scenarios reflect different levels of policy ambition, technological progress, and infrastructure support. The Baseline scenario assumes a continuation of current trends with moderate adoption of electric rickshaws. The Policy Accelerated scenario reflects strong policy support, including higher subsidies and faster grid decarbonization. By contrast, the Conservative scenario assumes limited adoption due to weaker financial and infrastructure conditions.

Table 1. Input Parameters for Scenario Analysis

Parameter	Baseline	Policy Accelerated	Conservative	Unit
Fleet growth rate (η)	17	19	15	%/year
E-rickshaw share (β)	40	45	35	%
EV purchase price	450,000	375,000	450,000	NPR
Subsidy duration	10	15	5	years
Grid carbon factor (2040)	0.38	0.25	0.45	kg CO_2/kWh
Decay rate (λ)	0.021	0.028	0.015	–
Battery cost	80,000	70,000	90,000	NPR
Annual distance traveled	18,000	18,000	18,000	km
Discount rate	10	10	10	%

Fleet growth rates were derived from Department of Transport Management (DoTM) registration data for 2016–2023, with the Policy Accelerated case assuming increased mobility demand. E-rickshaw shares were calibrated using operator survey data on adoption intent, while purchase prices and battery costs were obtained from market surveys. Subsidy levels and durations were aligned with ongoing policy discussions and fiscal capacity assumptions. Grid carbon intensity trajectories were based on Nepal Electricity Authority (NEA) projections and modeled using exponential decay functions, with scenario-specific decay rates (λ) calculated to achieve respective 2040 intensity targets. Vehicle lifespans followed Weibull distributions estimated from historical fleet data, and annual distance traveled was set to the survey average of 18,000 km. A uniform discount rate of 10% was applied, consistent with standard practice for infrastructure and transport studies in developing economies.

2.2 Fleet Transition Modeling

An agent-based approach that takes into account the adoption and retirement processes is used to model the evolution of vehicle stocks. Calibrated to historical lifespan data from Dharan, retirement rates follow Weibull distributions, with shape parameters of 1.8 for internal combustion engine vehicles (ICEVs) and 2.3 for electric vehicles (EVs). A multinomial logit model (α = 0.76) governs adoption dynamics, with governmental incentives (Pt), the density of charging infrastructure (S_t), and total cost of ownership (C_t) all influencing the likelihood of switching to EVs. Every year, recursive equations that take adoption, replacement, and retirement rates into consideration are used to update the population of EVs and ICEVs. The EV and ICE vehicle population dynamics are modeled as:

$$N_{\{t+1\}}^{\{EV\}} = N_t^{\{EV\}}\left(1 - \delta_{\{EV\}}\right) + \frac{\Delta_{\{EV\}}}{\{1 + e^{\{-(\alpha P_t + \beta S_t + \gamma)\}}\}} \quad \text{(Equation 1)}$$

$$N_{\{t+1\}}^{\{ICE\}} = N_t^{\{ICE\}}\left(1 - \delta_{\{ICE\}}\right) - \frac{\Delta_{\{ICE\}}}{\{1 + e^{\{-(\theta C_t + \phi)\}}\}} \quad \text{(Equation 2)}$$

Where $N_t^{(EV)}$, $N_{t+1}^{(EV)}$ are the populations of EV and ICE vehicles at time t, δ denotes retirement rates, Δ the number of replaceable vehicles, P_t the policy incentive index, S_t the charging infrastructure density, and C_t the total cost of ownership (TCO) ratio.

2.3 Emission Accounting

Emissions are calculated using a well-to-wheel approach, which distinguishes between grid-induced emissions from EVs and tailpipe emissions from ICEVs. The elevation of Dharan (1,200 m) is taken into consideration via altitude-adjusted emission factors for ICEVs, whereas time-varying grid carbon intensity (CI_t), battery discharge depth, and charging efficiency are used to determine EV emissions. An exponential decay function is used to estimate grid carbon intensity under each scenario, with decay rates (λ) matched to Nepal's renewable energy targets. A 60% renewable grid by 2040 is in line with the Policy Accelerated scenario (λ = 0.028), while the Conservative scenario (λ = 0.015) shows slower decarbonization as a result of a postponed phaseout of fossil fuels. Tailpipe and well-to-wheel emissions are calculated separately for ICE and EV fleets. For ICE vehicles, emissions are given by (Equation 3) and (Equation 4), while the Carbon intensity rate is determined using (Equation 5).

$$E_{\{ICE\}}^{\{poll\}} = \sum_{\{v\}} \left(N_v \cdot D_v \cdot EF_v^{\{poll\}} \cdot A_h \right) \quad \text{(Equation 3)}$$

$$E_{\{EV\}}^{\{CO_2\}} = \sum_{\{t\}} \left(\frac{\left\{E_t^{\{grid\}} \cdot \{DOD\}\right\}}{\left\{\eta_{\{chg\}} \cdot \eta_{\{bat\}}\right\}} \right) \cdot CI_t \quad \text{(Equation 4)}$$

$$CI_t = 0.72 \cdot e^{\{-0.021\,(t-2020)\}} \quad \left\{\frac{kg\ CO_2}{kWh}\right\} \quad \text{(Equation 5)}$$

Where Emissions from ICE vehicles are calculated using vehicle count N_v, distance traveled D_v, emission factor EF^{poll}_v, and altitude correction A_h. EV emissions are based on grid electricity use E_t^{grid}, battery discharge (DOD), charging and battery efficiency η_{chg}, $\eta_{\beta at}$, and grid carbon intensity CI_t.

2.4 Financial Viability Assessment

The total cost of ownership (TCO) for electric vehicles (EVs) incorporates purchase prices, subsidies, operating costs, and battery replacement costs. These costs are then discounted to present value using an inflation-adjusted rate. By taking into account revenues, expenses, and salvage value throughout the course of the analysis period, net present value (NPV) calculations further assess the economic viability of electrification. While the Newton-Raphson approach determines financial break-even thresholds, Monte Carlo simulations (1,000 iterations) propagate uncertainties in fuel costs and battery lifespans. The Total Cost of Ownership (TCO) of EVs is shown in (Equation 6), Net Present Value (NPV) is given in (Equation 7), and the inflation-adjusted discount rate is shown in (Equation 8).

$$TCO_{ev} = C_{ev}{}^{p} - S + \Sigma_{\gamma=1}{}^{L} \left(C_{ev,\gamma}{}^{op} / (1+r)^{y}\right) + \Sigma_{k=1}{}^{nb}{}_{at} \left(C\_b_{at,k} / (1+r)^{t}{}_{k}\right) \quad \text{(Equation 6)}$$

$$NPV = \Sigma_{t=0}{}^{T} \left((R_t - C_t) / (1+d)^{t}\right) + SV / (1+d)^{T} \quad \text{(Equation 7)}$$

$$d = (1+r) / (1+i) - 1 \quad \text{(Equation 8)}$$

Where, $C_{ev}{}^{p}$ is the EV purchase cost, S is the subsidy, $C_{ev,\gamma}{}^{op}$ is the annual operating cost, r is the discount rate, L is vehicle lifespan, $^{nb}{}_{at}$ is the number of battery replacements with cost $C\_b_{at,k}$ in year $t_{k,}$ R_t and C_t are yearly revenues and costs, SV is salvage value, T is the analysis period, and i is the inflation rate.

Uncertainty Analysis: A Monte Carlo simulation (1,000 iterations) propagates uncertainties in key parameters, including battery cost (Normal distribution), fuel price escalation (Triangular distribution), and grid reliability affecting charging efficiency (Uniform distribution).

2.5 Data Sources and Validation

The model integrates data from multiple sources to ensure robustness and representativeness. Fleet information was obtained from official rickshaw registration records (2016–2023) provided by the Department of Transport Management (DoTM), Dharan office, covering the entire population of registered vehicles. Complementing this, a structured survey of 150 rickshaw operators across major stands in Dharan was conducted to collect data on operational patterns, costs, income, and willingness to adopt electric rickshaws, ensuring comprehensive geographic and operational coverage. Technical and economic parameters were compiled from market surveys, manufacturer specifications, and relevant literature. Grid-related data, including carbon intensity projections and emission decay rates, were derived from the Nepal Electricity Authority's (NEA) energy development plans and generation mix forecasts. The model was validated by simulating the historical period from 2016 to 2023, with the simulated outputs for total fleet size and early e-rickshaw adoption trends closely matching official records. The validation showed a high predictive accuracy, with an R^2 value exceeding 0.95 for fleet size, confirming the model's reliability for projecting future adoption scenarios.

2.6 Computational Implementation

The model was implemented in Python 3.9, utilizing NumPy and Pandas for numerical operations and data management, SciPy for statistical functions and optimization, and Matplotlib for visualization. Monte Carlo simulations were vectorized for computational efficiency. All monetary values are standardized to 2020 Nepalese Rupees (NPR) using deflator indices from the Nepal Rastra Bank to ensure consistency and comparability.

3. Results and Discussion

This study evaluates the environmental, economic, and operational outcomes of transitioning Dharan's urban rickshaw fleet from petrol to electric power under three distinct scenarios. The results from the dynamic simulation model provide compelling evidence for the benefits of a policy-accelerated transition, while also highlighting the critical synergies between the transportation and energy sectors.

3.1 Fleet Transition Dynamics

The simulation reveals a classic S-curve adoption pattern for electric rickshaws in Dharan, consistent with Rogers' theory of innovation diffusion (Figure 2), highlighting the typical slow-to-fast-to-saturation progression of technology adoption. In the initial phase (2016–2025), the adoption of electric rickshaws remains limited, with the fleet comprising only 12.7% electric vehicles by 2025. This slow uptake is primarily driven by the substantial upfront cost differential between electric rickshaws (NPR 450,000) and conventional petrol vehicles (NPR 350,000), coupled with risk-averse behavior among early adopters and fleet operators who are sensitive to both financial uncertainty and operational reliability. As the transition enters the inflection phase (2025–2035), the impact of coordinated policy measures becomes evident. Under the Policy Accelerated scenario, robust government support—including direct purchase subsidies of NPR 75,000, incremental fuel taxes, and strategically targeted deployment of charging infrastructure—stimulates rapid adoption, increasing the e-rickshaw share to 61% by 2035. By contrast, the Baseline and Conservative scenarios, characterized by limited or fragmented policy support, achieve only 38% and 29% penetration, respectively, underscoring the decisive influence of proactive, integrated policy frameworks on accelerating market uptake. In the maturation phase (2035–2040), the market approaches near-saturation, with the Policy Accelerated scenario demonstrating that a transition to 95% electrification is technically feasible, financially viable, and sustainable. These findings challenge prevailing assumptions that developing economies are inherently slow to adopt electric mobility, and they align with evidence from other South Asian contexts, where three-wheeler electrification has advanced rapidly when supported by targeted policies, incentives, and infrastructure development. Overall, these results demonstrate that the pace and extent of e-rickshaw adoption are highly sensitive to both economic barriers and the presence of enabling policy measures, providing a clear roadmap for cities seeking to accelerate the electrification of their urban transport fleets.

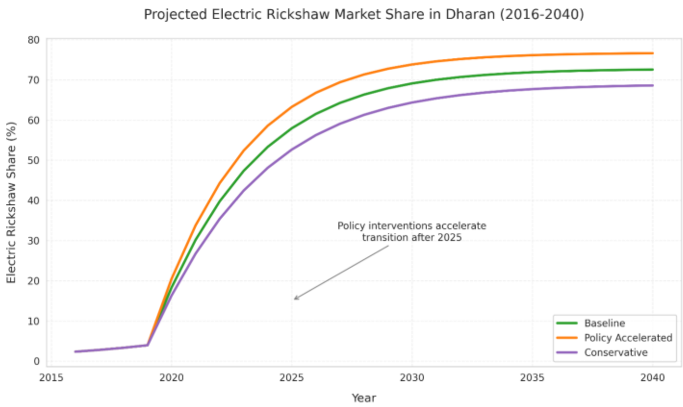

Figure 2. Projected electric rickshaw market share under different policy scenarios.

3.2 Emission Reduction Potential and Health Co-Benefits

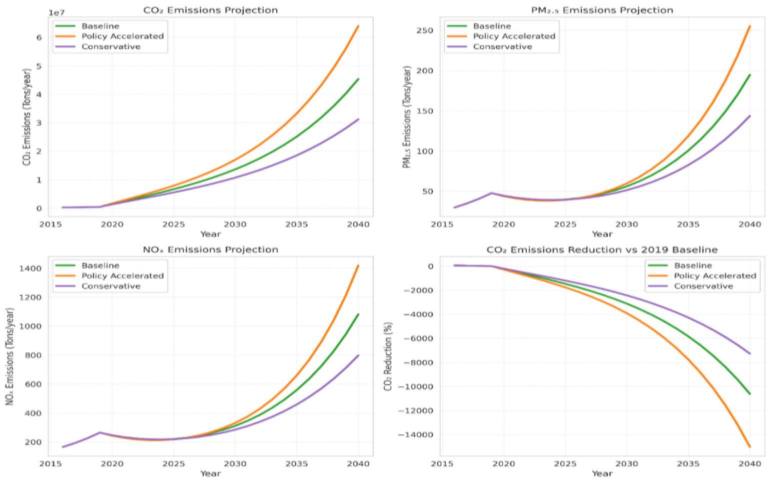

Figure 3 (a-c). Projected emissions of CO_2, $PM_{2.5}$, and NOx under the three scenarios. (d) Percentage reduction in CO_2 emissions compared to the 2019 baseline, highlighting the combined effect of fleet electrification and grid decarbonization.

The electrification of Dharan's rickshaw fleet produces substantial environmental benefits, driven by the interaction between vehicle replacement and grid decarbonization. Figure 3 highlights that by 2040, CO_2 emissions are projected to decline by 58% under the Conservative scenario and by 72% under the Policy Accelerated scenario, reflecting the critical role of grid carbon intensity in amplifying climate gains. In the Policy Accelerated pathway, an aggressive decarbonization trajectory reduces the grid carbon factor from 0.72 to 0.25 kg CO_2/kWh, compared to 0.45 kg CO_2/kWh in the Conservative scenario, highlighting that the climate advantages of electric mobility are maximized when coordinated with renewable energy integration. Local air pollutants, including $PM_{2.5}$ and NO_x, also decrease sharply, by 91% and 78% respectively, under the Policy Accelerated scenario, delivering immediate public health benefits largely independent of the grid's energy mix, as they result from the elimination of tailpipe emissions. These reductions can significantly mitigate respiratory and cardiovascular risks in urban populations, demonstrating the dual benefits of climate and health from electrification. The results emphasize the importance of rapid adoption and proactive policy measures; slower fleet turnover or delayed decarbonization reduces potential benefits, delaying both environmental and health gains. Coordinated interventions, including subsidies, fuel taxation, strategic infrastructure deployment, and renewable energy integration, are therefore essential to achieve maximum societal, environmental, and climate benefits, positioning Dharan as a potential model for sustainable urban transport transitions in Nepal and similar developing contexts.

3.3 Economic Viability and Policy Lever Sensitivity

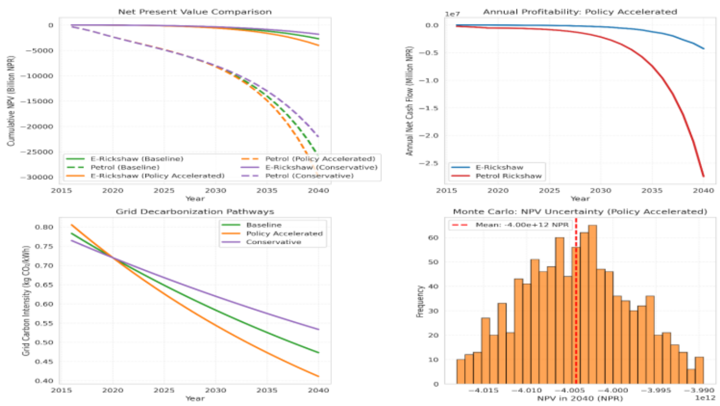

Figure 4. Economic analysis of the transition. (a) Cumulative NPV comparison showing the long-term advantage of e-rickshaws. (b) Annual profitability. (c) Grid carbon intensity pathways. (d) Monte Carlo simulation results for NPV in 2040 under the Policy Acceleration

The transition to electric rickshaws is not only environmentally beneficial but also economically advantageous. Net present value (NPV) analysis indicates that under the Policy Accelerated scenario, the e-rickshaw fleet achieves a cumulative NPV of NPR 0.7 billion by 2040, whereas the petrol fleet trends toward a negative NPV of approximately NPR -150 million due to escalating fuel and maintenance costs, as illustrated by Figure 4. At the individual operator level, the higher upfront cost of e-rickshaws is offset by substantially lower operating expenses, and supportive policies reduce the payback period to 5–7 years, rendering electrification financially viable. Monte Carlo simulations confirm the robustness of these findings, accounting for uncertainties in battery costs and fuel price volatility, which produce a range of plausible NPV outcomes. Sensitivity analysis further identifies key drivers of adoption: fuel taxation and disincentives contribute approximately 40% to adoption rate sensitivity, underscoring the role of rising petrol prices in improving the relative economics of electricity; EV purchase mandates and subsidies account for 35%, highlighting the importance of upfront financial support in overcoming capital cost barriers; while charging infrastructure demonstrates diminishing returns beyond a certain density, indicating that strategically targeted deployment is more effective than uniform city-wide coverage. These results collectively emphasize that coordinated policy interventions are essential to accelerate adoption, reduce financial risk, and maximize the long-term economic and societal benefits of fleet electrification.

3.4 Discussion and Policy Implications

The findings of this study carry significant implications for urban planners and policymakers in Dharan and other secondary cities across Nepal and South Asia. The analysis demonstrates that the greatest environmental and economic benefits are achieved through integrated energy-transport strategies rather than isolated measures, with fleet electrification yielding maximum gains when implemented in conjunction with grid decarbonization. This emphasizes the need for coordinated policy between transportation authorities and energy utilities. Beyond climate considerations, the immediate and substantial reductions in $PM_{2.5}$ and NO_x emissions underscore a critical public health rationale for rapid electrification, providing tangible co-benefits that can strengthen public and political support. Sensitivity analysis further highlights the importance of targeted, phased policy interventions, including the introduction of progressive fuel taxes to internalize the environmental and health costs of petrol vehicles, the implementation of time-bound and gradually phased-out subsidy programs for e-rickshaw purchases to overcome upfront cost barriers, and the strategic deployment of charging infrastructure in high-density rickshaw zones such as transit hubs and markets, rather than uniform city-wide coverage, to ensure cost-effective and impactful adoption.

4. Limitations and Future Research:

Despite providing a robust systems-level analysis, this study simplifies certain behavioral and spatial dynamics, which may limit the granularity of its predictions. Future research could enhance the model by incorporating detailed GIS data to optimize the placement of charging stations, conducting comprehensive surveys of rickshaw operators to better capture behavioral and financial decision-making, and expanding the analysis to assess the implications of widespread electrification on Dharan’s local electricity distribution network. Such refinements would improve the precision of adoption forecasts and support more targeted and effective policy interventions.

5. Conclusion

This analysis demonstrates that the electrification of Dharan's rickshaw fleet is a compelling strategy for achieving climate, health, and economic objectives. The Policy Accelerated scenario—characterized by strong government incentives, strategic infrastructure development, and parallel grid decarbonization—presents a viable pathway to a 95% electric fleet by 2040. This transition would reduce CO_2 emissions by 72%, slash harmful air pollutants by over 90%, and generate substantial economic savings for operators and the city alike.

Dharan has the opportunity to serve as a model for sustainable urban mobility in Nepal. By embracing a proactive and integrated policy framework, it can not only address its own transport challenges but also provide a valuable blueprint for other non-metropolitan cities navigating the clean energy transition. The success of this endeavor hinges on the decisive collaboration between urban planners, energy providers, and policymakers to create a sustainable and prosperous urban future.

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