



ASSESSMENT OF ALTERNATIVE FUEL TECHNOLOGIES FOR SUSTAINABLE URBAN TRANSPORTATION SYSTEMS: CASE STUDY OF INDIA

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Abstract: This study investigates the feasibility and performance of alternative fuel technologies (AFTs) for urban transportation in India, focusing on Battery Electric Vehicles (BEVs). The research includes a comprehensive literature review, a case study of Pune's electric bus program, and a comparative analysis of AFTs based on emissions, costs, and operational feasibility. The findings highlight the environmental and economic benefits of BEVs, while also addressing the challenges and policy implications for large-scale adoption.

IndexTerms - Alternative Fuel Technologies, Battery Electric Vehicles, Sustainable Urban Transportation, Emissions, Cost Analysis, Policy Implications

I. INTRODUCTION

Background

India's urban transportation systems are under significant stress due to rapid urbanization, leading to increased vehicular emissions and environmental degradation. The growing population and economic expansion have resulted in a surge in vehicle ownership and reliance on road-based public transport. This unprecedented growth has placed significant stress on the environment, infrastructure, and public health. Alternative fuel technologies (AFTs) such as Battery Electric Vehicles (BEVs), Compressed Natural Gas (CNG), biofuels, and hydrogen fuel cells offer promising solutions to these challenges by reducing emissions, improving energy efficiency, and decreasing dependency on fossil fuels.

Problem Statement

Public transportation in Indian cities relies heavily on diesel-powered buses, which are known for their high emissions of carbon dioxide (CO₂), nitrogen oxides (NO_x), and particulate matter (PM). While alternative fuels like CNG and electric power have been introduced in certain fleets, there remains a lack of a comprehensive, data-driven evaluation of these alternatives. Critical knowledge gaps persist in understanding the comparative performance of AFTs in terms of emissions reduction potential, lifecycle costs, infrastructure requirements, and suitability for urban operating conditions. These gaps hinder the ability of policymakers and transit authorities to make informed decisions regarding the transition to sustainable urban bus fleets.

Objectives

1. Compare AFTs based on emissions, operating costs, and infrastructure requirements.
2. Assess the real-world implementation of electric buses in Pune.
3. Identify barriers to AFT adoption.
4. Recommend policy interventions for sustainable urban transport.

Scope of Study

This dissertation focuses on urban public transport, specifically evaluating alternative fuels used in city buses. The scope includes:

- **Technologies Evaluated:** Battery Electric Buses (BEBs), Compressed Natural Gas (CNG), Biodiesel (B20/B100), and Hydrogen Fuel Cell Buses.
- **Study Area:** Emphasis on Indian urban conditions, with a specific case study of Pune under PMPML operations.
- **Impact Dimensions:** Environmental (tailpipe emissions), economic (cost/km, CAPEX/OPEX), and operational (range, charging/fueling time, reliability).
- **Policy Perspective:** Review and analysis of current national/state-level EV and AFT policies to identify support mechanisms and policy gaps.

II. LITERATURE REVIEW

Alternative Fuel Technologies Reviewed

- **Battery Electric Vehicles (BEVs):** BEVs are powered by rechargeable lithium-ion batteries and produce zero tailpipe emissions, making them one of the cleanest forms of urban public transport. They are widely considered the future of

sustainable transportation due to advancements in battery technology and supportive government policies globally. However, they face challenges such as high upfront costs, limited range, and dependency on coal-based electricity grids in some regions.

- **Compressed Natural Gas (CNG):** CNG buses operate on natural gas, which is a cleaner-burning fossil fuel compared to diesel. They emit lower levels of CO₂, NO_x, and particulate matter, making them an effective transitional fuel for reducing urban air pollution. Despite their advantages, CNG buses still rely on fossil fuels and have higher maintenance costs compared to electric buses.
- **Hydrogen Fuel Cell Vehicles:** Hydrogen fuel cell buses use hydrogen gas to generate electricity, producing water vapor as the only byproduct. They are highly suitable for heavy-duty applications and long-range operations. However, the high production costs for hydrogen fuel and limited refueling infrastructure are significant challenges.
- **Biofuels:** Biofuels are renewable fuels produced from organic materials such as agricultural waste, algae, or plant oils. They can be blended with conventional fuels to reduce emissions and improve sustainability. However, they face challenges such as competition with food production, lower energy efficiency, and high production costs for advanced biofuels.

Pollutant / Parameter	CNG	Diesel	Petrol	Electric Vehicle (EV)
CO ₂ (Tank-to-Wheel)	~107.7 g/km	~132.2 g/km	~113.5 g/km	0 g/km (no tailpipe emissions)
CO ₂ (Well-to-Wheel)	~170 g/km	~210 g/km	~190 g/km	~80–120 g/km (<i>India grid mix</i>)
CO (g/km) – BS-VI Limit	1.0	0.5	1.0	0
HC (g/km)	0.05–0.1	~0.1	~0.1	0
NO _x (g/km) – BS-VI Limit	0.06–0.08	0.08	0.06	0
NO _x (Real-World NCR)	Up to 14× BS-VI	Up to 5× BS-VI	Up to 4× BS-VI	0
PM (g/km) – BS-VI Limit	0.0045	0.0045	0.0045	0 (tailpipe) – brake/tire PM possible
CH ₄ (Methane)	High (~50–300 mg/km)	Negligible	Negligible	None
N ₂ O (g/km)	0.001–0.003	0.003–0.037	0.001–0.014	Negligible (depends on grid source)
SO ₂ (ppm)	~22–25	~115–125	~21–45	Indirect via grid power (coal plants)
Cold Start Emissions	High NO _x & CH ₄	High PM & CO	Moderate CO & NO _x	None
On-Road Compliance Issues	NO _x exceedances	PM & NO _x spikes	NO _x from taxis	None (subject to battery degradation)
Tailpipe Emissions	✓	✓	✓	✗ (Zero tailpipe emissions)
Lifecycle GHG Emissions	Medium	High	Medium	Low–Medium (<i>varies by electricity</i>)
Maintenance Needs	Moderate	High (DPF/SCR)	Moderate	Low (no engine oil, filters, etc.)

Global Best Practices

- **Shenzhen, China:** Shenzhen is the first city in the world to fully electrify its public bus fleet, consisting of over 16,000 electric buses. This transformation was achieved through substantial government subsidies, advanced battery technology, and the establishment of a comprehensive charging infrastructure network.
- **European Union:** Several European cities have adopted hybrid and hydrogen buses under the EU Clean Bus Initiative, aiming to achieve zero-emission urban transport by 2030. Cities like Amsterdam and Oslo have pioneered hydrogen fuel cell buses, while others have integrated hybrid-electric buses into their fleets.

- **California, USA:** California has integrated zero-emission vehicle mandates into its state transit policies, requiring public transit agencies to transition to fully electric or hydrogen-powered fleets by 2040. Programs like the California Air Resources Board (CARB) provide funding for fleet electrification and infrastructure development.

Indian Context

- **FAME Scheme:** The Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) scheme is India's flagship program for promoting electric vehicles, including buses. FAME-II allocated ₹10,000 crore for subsidies on electric buses, charging infrastructure, and battery manufacturing.
- **City-Level Initiatives:** Several Indian cities have initiated electric bus programs under the FAME-II scheme, including Pune, Delhi, Bangalore, and Hyderabad.
- **State EV Policies:** States like Maharashtra, Delhi, and Karnataka have introduced EV policies to incentivize electric bus adoption and infrastructure development.

III. RESEARCH METHODOLOGY

Research Design

The study adopts a mixed-methods research design, combining quantitative and qualitative analysis to evaluate AFTs for urban buses. This approach ensures a comprehensive evaluation of the environmental, economic, and operational feasibility of AFTs.

Qualitative Research

The qualitative component focuses on reviewing existing literature, policy documents, and case studies to understand the broader context and challenges surrounding AFT adoption. This includes:

Literature Review:

A comprehensive review of national and international studies on alternative fuels, emissions data, cost factors, and implementation strategies. This helps in identifying the current state of research, technological trends, and policy frameworks.

- **Policy Analysis:** Reviewing policies and incentives such as India's FAME-I and FAME-II schemes, which promote electric vehicle adoption. This analysis helps in understanding the support mechanisms and policy gaps that influence the adoption of AFTs.
- **Case Studies:** Analyzing global best practices in cities like Shenzhen (China) and California (USA), where large-scale deployment of AFTs has been successful. These case studies provide insights into the strategies and challenges faced by other cities in adopting AFTs.

Quantitative Research

The quantitative component involves numerical analysis of AFTs based on measurable indicators such as cost per kilometer, emissions per kilometer, and infrastructure requirements. The data-driven evaluation provides objective insights into the comparative advantages of various AFTs, ensuring informed decision-making. Key aspects include:

- **Data Collection:** Compilation of data from government reports (e.g., MoRTH, NITI Aayog), academic studies, and industry publications regarding fuel efficiency, costs, and emissions.
- **Statistical Analysis:** Using statistical tools to analyze the collected data and derive meaningful insights. This includes calculating the average emissions, operational costs, and lifecycle costs of different AFTs.
- **Comparative Analysis:** Evaluating AFTs based on key performance indicators (KPIs) such as CO₂ emissions per kilometer, cost per kilometer, infrastructure and charging/fueling needs, and urban feasibility.

Case Study Integration

The case study of Pune's electric bus deployment was selected to provide practical insights into the real-world effectiveness of AFTs in Indian urban settings. By examining PMPML's operational data, infrastructure details, and emission reductions, the case study complements the broader comparative analysis. The case study methodology includes:

- **Case Study Selection:** Pune was chosen due to its large-scale deployment of electric buses under the FAME-II scheme and its diverse urban landscape, which provides a realistic setting for assessing the feasibility of AFTs.
- **Data Analysis:** Analyzing performance metrics such as daily range, energy consumption, and maintenance costs of electric buses compared to diesel buses. This also includes evaluating the emission reductions achieved by transitioning to electric buses.
- **Infrastructure Details:** Examining the locations and specifications of charging stations installed at PMPML depots, and the challenges related to land allocation and power supply for charging infrastructure.
- **Emission Savings:** Calculating the CO₂ emissions avoided through the deployment of electric buses and assessing the grid dependency and renewable energy integration for charging stations.

Data Collection Sources

- **Government Reports:** NITI Aayog, Ministry of Housing and Urban Affairs (MoHUA), and FAME-II documents.
- **PMPML Operational Reports:** Performance data from PMPML's electric bus fleet, including energy consumption, maintenance costs, and daily range.
- **International Case Studies:** Deployment strategies from cities like Shenzhen, Oslo, and Amsterdam.
- **Technology Specifications:** Detailed technical data on electric buses, hydrogen fuel cells, and biofuel vehicles sourced from industry papers and manufacturer reports.

Comparison Framework

To evaluate alternative fuel technologies comprehensively, the study employs a structured comparison framework based on key performance indicators (KPIs). These indicators address the environmental, economic, and operational aspects of AFTs, including CO₂ emissions per kilometer, cost per kilometer, infrastructure and charging/fueling needs, and urban feasibility.

Indicator	Weight	Electric Buses	Diesel Buses	Hydrogen Buses
CO ₂ Emissions per Kilometer	0.4	10 (score: 4.0)	3 (score: 1.2)	9 (score: 3.6)
Cost per Kilometer	0.3	8 (score: 2.4)	5 (score: 1.5)	6 (score: 1.8)
Infrastructure and Charging/Fueling Needs	0.2	7 (score: 1.4)	8 (score: 1.6)	5 (score: 1.0)
Urban Feasibility	0.1	9 (score: 0.9)	7 (score: 0.7)	8 (score: 0.8)

IV. CASE STUDY: ELECTRIC BUS IMPLEMENTATION IN PUNE

Deployment Overview

- **Strategic Planning:** PMPML adopted a phased rollout strategy for its electric bus deployment, ensuring technical preparedness, operator training, and infrastructure development. The deployment was divided into pilot deployment, scaling phase, and expansion phase.
- **Fleet Composition:** PMPML's fleet includes 9-meter mid-size and 12-meter full-size AC buses, deployed on high-density corridors and various urban routes.
- **Operational Model:** The Gross Cost Contract (GCC) model ensures risk-sharing and cost efficiency, with private operators managing the buses and maintenance.

Technical Specifications

- **9-meter Electric Bus:** Battery capacity of 124 kWh, range of 150 kilometers per charge, seating for 24–30 passengers, and charging time of 2–4 hours.
- **12-meter Electric Bus:** Battery capacity of 250 kWh, range of 200–220 kilometers per charge, seating for 35–45 passengers, and charging time of 4–6 hours.

Operational Comparison (vs. Diesel)

- **Energy Costs:** Electric buses require significantly less energy per kilometer compared to diesel buses, resulting in operational savings of ₹13/km.
- **Maintenance Costs:** Electric buses have fewer moving parts and simpler mechanical systems, reducing maintenance costs by an average of ₹2.3/km compared to diesel buses.
- **Net Savings:** The combined savings from energy and maintenance costs result in a 40% reduction in operational expenses for electric buses.

Emissions

- **CO₂ Emissions Avoided:** On average, electric buses avoid approximately 110 tons of CO₂ emissions per day, amounting to nearly 40,000 tons per year.
- **Air Quality Improvement:** The reduced emissions from electric buses contribute to improved air quality, particularly in areas with high vehicular density.
- **Long-Term Environmental Impact:** By adopting electric buses, PMPML is contributing to Pune's broader environmental goals, including compliance with India's Nationally Determined Contributions (NDCs) under the Paris Agreement.

Factor	Electric Buses	Diesel Buses
Initial Cost (₹)	1.2–1.5 crore/unit	40–60 lakh/unit
Operating Cost (₹/km)	5–7/km	15–20/km
Maintenance	Lower	Higher
Total Cost of Ownership (TCO)	Competitive over 8–10 years	Higher due to fuel and maintenance
Tailpipe Emissions	Zero	High (CO ₂ , NO _x , PM)
Lifecycle Emissions	Depends on electricity source	High
Noise Pollution	Minimal	Significant
Charging Infrastructure	Requires investment	Existing fuel stations
Range (km)	150–250 per charge	300–500 per tank
Deployment Readiness	Moderate (charging, training needed)	High

Government Support	Strong (FAME II, state EV policies)	Limited
CO2 Emission (g/km)	0	1300
Nox Emissions (g/km)	0	8
PM Emissions (g/km)	0	0.1

V. CHALLENGES

- **Charging Infrastructure Setup:** Land constraints and power supply issues were major challenges in setting up charging depots.
- **Driver Training:** Specialized training programs were required for drivers and maintenance staff.
- **Battery Planning:** Efficient battery management systems were necessary to optimize range and performance.
- **Power Demand Management:** Upgrades to Pune's power grid were needed to meet the increased demand for electricity from charging stations.

VI. RESULTS AND DISCUSSION

Opportunities

- **Low Emissions and Operating Costs:** Electric buses produce zero tailpipe emissions, making them an ideal solution for reducing urban air pollution and greenhouse gas emissions. Studies show that transitioning to EVs can reduce CO₂ emissions by 35–40%, even when accounting for grid emissions. In cities like Pune, this has led to a significant improvement in air quality. Additionally, EVs offer lower operating costs compared to diesel buses:
- **Energy Costs:** EVs consume electricity at a cost of ₹6–8/km, compared to ₹19–21/km for diesel-powered buses.
- **Maintenance Costs:** EVs have fewer moving parts, reducing maintenance costs to ₹3.2/km versus ₹5.5/km for diesel buses. This combination of environmental and cost advantages makes EVs financially viable for fleet operators in the long term.

Government Incentives (FAME, EV Policies): The Indian government has introduced several incentives to promote the adoption of EVs under schemes like FAME-II (Faster Adoption and Manufacturing of Hybrid and Electric Vehicles) and state-specific EV policies. Key initiatives include:

- **Subsidies:** FAME-II offers financial assistance for the purchase of electric buses and the development of charging infrastructure, reducing upfront costs for fleet operators.
- **Tax Benefits:** State EV policies provide tax exemptions for electric bus manufacturers and operators, improving financial feasibility. These incentives are critical for accelerating EV deployment and addressing cost-related barriers.

Local Job Creation and Technology Development: The adoption of AFTs creates opportunities for local job creation and technology development in India. Key areas include:

- **Manufacturing:** Expansion of EV manufacturing plants and component production (e.g., batteries, motors) generates employment opportunities.
- **Infrastructure Development:** Construction and maintenance of charging stations, depots, and renewable energy projects create jobs in urban and rural areas.
- **Skill Development:** EV adoption necessitates specialized training programs for drivers, technicians, and fleet managers, fostering new skill sets and career opportunities. Technological advancements in battery production, energy storage, and renewable energy integration further position India as a leader in green mobility solutions.

Barriers

High Capital Costs of Electric Buses: The upfront cost of electric buses is significantly higher than diesel buses, which discourages fleet operators from transitioning to EVs. For example:

- A 12-meter diesel bus costs approximately ₹50–60 lakh, while a 12-meter electric bus costs ₹1.2–1.5 crore.
- Charging infrastructure (e.g., fast DC chargers) and depot upgrades further increase the financial burden. Although government incentives reduce costs, the price difference remains a major barrier for cash-strapped municipal transport agencies.

Limited Charging Infrastructure and Grid Dependency: The lack of adequate charging stations is one of the most critical barriers to EV adoption in India. Challenges include:

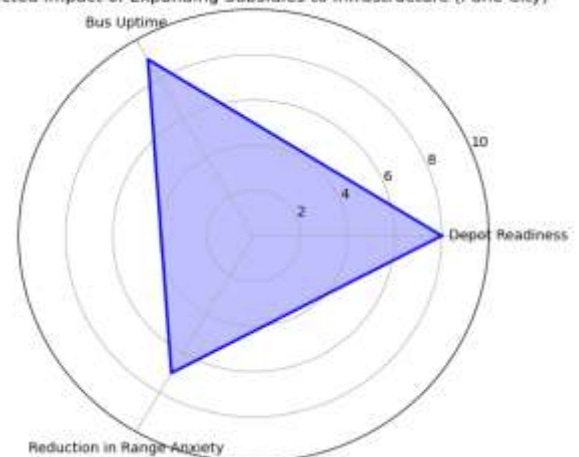
- **Land Availability:** Urban areas face land constraints, making it difficult to set up charging depots.
- **Power Supply:** India's electricity grid is heavily dependent on coal, which limits the environmental benefits of electric buses.
- **Charging Times:** Even with fast chargers, charging an electric bus takes 2–4 hours, impacting operational schedules. To address these issues, cities must invest in renewable energy integration and innovative charging solutions such as on-route charging stations.

Training Gaps, Public Awareness, and Range

Anxiety: Operational challenges also hinder EV adoption:

- **Training Gaps:** Drivers and maintenance staff require specialized training to operate and maintain EVs, which delays fleet deployment.

Expected Impact of Expanding Subsidies to Infrastructure (Pune City)



- **Public Awareness:** Many commuters are unaware of the environmental and economic benefits of EVs, reducing public acceptance.
- **Range Anxiety:** Concerns about battery range and charging availability discourage fleet operators and commuters from fully trusting EVs as reliable transportation options.

Policy Suggestions

Expand Subsidies to Infrastructure, Not Just Vehicles: Current subsidies focus primarily on reducing vehicle costs. To ensure holistic adoption of EVs, subsidies must also cover:

- **Charging Infrastructure:** Financial assistance for setting up fast DC chargers and depots.
- **Renewable Energy Integration:** Incentives for solar and wind energy projects to power EV charging stations. Including infrastructure in subsidy programs will reduce long-term operational challenges and improve the feasibility of EV adoption.

Skill Training for EV Maintenance: The adoption of EVs necessitates specialized skill development programs for drivers, technicians, and fleet managers. Recommended initiatives include:

- **Driver Training:** Modules on battery management, charging protocols, and eco-driving techniques.
- **Technical Skill Development:** Vocational courses focused on EV maintenance, charging station management, and renewable energy integration.
- **Public Awareness Campaigns:** Educational programs to improve public understanding of EV benefits and operational reliability.

PPP-Based Fleet Adoption (GCC Model): The Gross Cost Contract (GCC) model, successfully implemented in Pune, should be expanded to other cities. In this model:

- Private operators manage electric bus fleets and charging infrastructure, reducing financial burdens on municipal transport agencies.
- Governments provide operational subsidies to ensure cost-effectiveness. PPP-based approaches improve efficiency, reduce risks, and foster collaboration between public and private sectors.

Urban EV Transition Roadmaps and Scrappage Integration: Cities must develop specific roadmaps for transitioning to EVs, including:

- **Fleet Electrification Targets:** Set clear timelines for replacing diesel buses with EVs.
- **Scrappage Policies:** Introduce programs for phasing out old diesel buses and integrating EVs into public transport systems.
- **Renewable Energy Mandates:** Ensure charging stations are powered by renewable energy to maximize environmental benefits.

Lessons from Pune

Fleet Planning: Proper fleet sizing and route planning are essential to maximize operational efficiency. Electric buses must be deployed on routes with high passenger density to achieve cost-effectiveness.

Parameter	Details
Fleet Size	Over 480 e-buses operational as of 2024
Bus Types	9-meter mid-size and 12-meter full-size AC buses
Deployment Routes	High-density corridors, school routes, PMRDA zones
Route Examples	Swargate–Pimpri, Hadapsar–Kothrud, Pune Station–Wagholi

Depot Readiness: Charging infrastructure requires thorough planning, with adequate land allocation and power supply to avoid operational disruptions. Depots must be equipped with safety features, battery monitoring systems, and backup power supplies.

Vendor Coordination: Close collaboration with manufacturers ensures timely delivery of buses and technical support for maintenance issues. PMPML's partnership with suppliers like Olectra-BYD and Tata Motors highlights the importance of vendor reliability.

Public Satisfaction: Commuters respond positively to EVs when comfort, reliability, and uptime are ensured. Surveys conducted in Pune indicate high public satisfaction with the smooth operation and environmental benefits of electric buses.

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