RESEARCH & INNOVATION DIVISION
IJIST

Eco-Mobility in Lahore, Pakistan: Assessing the Role of Electric Vehicles in Air Pollution Mitigation

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Citation | Saeed. M. F, Mahmood. S, "Eco-Mobility in Lahore, Pakistan: Assessing the Role of Electric Vehicles in Air Pollution Mitigation", IJIST, Special Issue pp. 527-539, June 2024
Received | June 15, 2024 **Revised |** June 19, 2024 **Accepted |** June 26, 2024 **Published |** June 30, 2024.

Introduction/Importance of the Study: This study investigates the potential of electric bikes to replace fossil fuel-powered motorbikes as a solution to reduce air pollution in Lahore. Globally, the transport sector relies heavily on fossil fuels, which are a major contributor to air pollution. In Pakistan, 23% of greenhouse gas (GHG) emissions come from road transport. Lahore alone has 4.2 million petrol-based motorbikes, significantly contributing to deteriorating air quality and posing serious health and environmental risks. Transitioning to electric vehicles, particularly in Punjab's major cities like Lahore, offers a promising approach to reduce harmful air pollutants. However, Pakistan faces various challenges that hinder the rapid adoption of electric vehicles.

Novelty Statement: This research highlights key policies needed for infrastructural and technological advancements to accelerate the adoption of electric bikes. The study is unique in that it focuses on controlling emissions in Lahore by replacing petrol motorbikes with electric bikes, using empirical data specific to the city. The analysis includes a detailed examination of daily and annual emissions from petrol-based motorbikes, focusing on pollutants like carbon monoxide, hydrocarbons, and sulfur and nitrogen oxides.

Materials and Methods: A questionnaire-based survey was conducted to determine the average daily mileage and annual working days of motorbikes in Lahore. Emission data for petrol and electric bikes was sourced from secondary sources, allowing a comparison between vehicles powered by renewable and non-renewable energy. Additionally, emissions from coal-based power plants generating electricity for electric bikes were also analyzed using secondary data.

Results and Discussion: The results indicate that electric bikes powered by renewable energy produce negligible emissions compared to petrol and diesel vehicles. However, when electricity is generated from non-renewable sources, such as coal-fired power plants, the emissions remain high and continue to contribute to air pollution.

Concluding Remarks: The study recommends that policymakers prioritize renewable energy sources for powering electric bikes. It also stresses the need for public-private partnerships, tax exemptions, and cost reductions to promote electric bike schemes for the general public.

Keywords: Electric Vehicles; Air Pollution; Emission count; Average daily mileage; Particulate matter.

Introduction:

The total CO2 emissions from the transport sector are estimated to be about 16% of the global total, with around half of these emissions coming from road passenger vehicles, which are predominantly powered by internal combustion (IC) engines running on fossil fuels. Moreover, automotive emissions are a significant source of local air pollution. According to a survey conducted by the International Energy Agency, road transport accounts for approximately 27% of global urban air pollution. The excessive emission of greenhouse gases is a major challenge for global environmental change, particularly in the transportation sector. Although Pakistan does not contribute significantly to global GHG emissions, it is one of the most vulnerable countries to the impacts of global warming. Urban air pollution in Pakistan is primarily caused by the emission of gaseous pollutants from transport and industries in major cities. These pollutants include heavy metals, SOx, NOx, CO, and particulate matter (PM) [1]. It is widely acknowledged that the transportation sector, especially vehicles that rely on oil and petroleum products, is a key driver of environmental change and global warming due to excessive CO2 and other GHG emissions [2].

Pakistan, with over 240 million people, is the fifth most populous country in the world, yet it has a sub-0.5% share of global GHG emissions, contributing minimally to global warming. However, road transportation is a significant source of emissions in Pakistan, accounting for 23% of the country's GHG emissions. These emissions are largely attributed to the transport sector. Despite this, urban areas in Pakistan continue to experience record levels of air pollution, with the country ranking last on the global air quality index, occupying the 180th position out of 180 countries [3]. Like other developing countries' urban centers, Lahore is undergoing rapid economic and industrial growth, which has led to increased air pollution. This situation has exposed residents to severe health risks. Urbanization has increased reliance on motor vehicles, which are major contributors to air pollution, resulting in environmental problems such as air pollution, traffic congestion, and carbon emissions.

Pakistan is a net importer of oil, as domestic production of crude oil and its derivatives is insufficient to meet national demand. Additionally, transport is the second-largest consumer of energy, following the industrial sector, accounting for 34% of the final energy demand and 59% of the liquid fuel demand in the country. The transport sector consumes the highest percentage of oil at 59%, which is divided among air, sea, and road transport, while the power sector consumes 32%, and the industrial sector consumes only 8% [4].

An increase in population leads to heightened economic activity, which in turn enhances the purchasing power of residents and businesses, driving the development of public and commercial infrastructure. These factors contribute to a rise in the number of vehicles on the road. The surge in personal and commercial vehicles, due to increased economic means and mobility, results in greater congestion. Additionally, more people move into the area for better economic opportunities and improved transport infrastructure. Consequently, the volume of vehicular traffic and the energy consumption-related pollution define the net vehicular pollution of the area [5].

This study reveals that net vehicular pollution is directly related to the number of vehicles and the emissions they produce. If population growth and emissions continue to rise unchecked, the risks of serious health conditions and reduced life expectancy will escalate. As population density and emissions increase, environmental degradation will intensify, forcing people to migrate to other cities. Those unable to leave will be left in a degraded environment, with their livelihoods under threat. Over time, cities may become barren due to overpopulation, environmental damage, and mass migration. The only solution to breaking this cycle is transitioning from non-green to green products. The transport sector remains a significant contributor to emissions in Pakistan, with sector emissions reaching approximately 2,763 kT in

2020, mostly from carbon monoxide. Between 1990 and 2020, the sector saw a sharp rise in emissions due to the growing number of vehicles [6].

Globally, Pakistan ranks as the second most polluted country after Bangladesh. With an Air Quality Index (AQI) of 153, Pakistan's air quality is considered unhealthy, five times higher than WHO's recommended exposure limits. According to reports, Pakistan's cities, such as Karachi and Lahore, are among the top 10 most polluted cities globally, with Lahore ranked 9th. The PM2.5 concentration in Lahore is two to three times higher than WHO's recommended exposure limits [7].

The introduction of electric vehicles (EVs) is a positive step toward reducing reliance on traditional fossil fuel-based products. Hybrid and EVs are often recommended by governments and NGOs as effective tools to address GHG emissions and energy consumption [8]. Although Pakistan's EV market is not growing as rapidly as neighboring India, it has significant potential. The adoption of EVs could lower smog and air pollution in major cities of Punjab, such as Lahore, Faisalabad, and Gujranwala. However, rapid economic and industrial expansion in these cities has heightened vulnerability to pollution-related illnesses. Lahore, ranked 20th among the most polluted cities globally, consistently exceeds WHO air quality guidelines for particulate matter [9].

Many developed countries are adopting electric vehicles to combat environmental pollution and move away from depleting and costly fossil fuels by embracing renewable energy. Compared to traditional fuel-driven vehicles, EVs can reduce CO2 emissions by 30–50% and improve fuel efficiency by 40–60% [10]. However, EVs are more expensive than traditional vehicles, and countries like Pakistan, India, and Malaysia face challenges in market penetration and public acceptance. The government's growing interest in electric vehicles stems from the link between the transport sector and rising air pollution. Each year, approximately 310,000 people die from air pollution-related causes, highlighting the urgency of addressing this issue. The link between fossil fuel-based transportation and ongoing air pollution problems has spurred government interest in EVs as an environmentally friendly alternative [11].

Recognizing the impact of climate change and the global shift toward EV policies, Pakistan introduced its National Electric Vehicle Policy (NEVP) [12]. According to this policy, by 2030, 30% of new four-wheel vehicles and 50% of new two-wheel vehicles sold will be electric. By 2040, 90% of all new passenger vehicles are expected to be electric. To meet these ambitious goals, it is crucial to identify policies and strategies that can accelerate EV market growth in Pakistan. The technological and infrastructural challenges hindering the implementation of EV policies and the reduction of air pollution are major concerns. It is essential to conduct rigorous, scenario-based environmental assessments of proposed technologies before widespread adoption to ensure they reduce GHG emissions without leading to unintended consequences [13].

If electric mobility is introduced in Pakistan, it could theoretically lower carbon emissions and reduce transportation costs. However, these proposals require careful analysis and detailed research before implementation. Given Pakistan's electric and environmental challenges, the most efficient form of EV must be chosen to address the country's electrical, economic, and environmental concerns optimally. This study aims to propose recommendations to overcome technological and infrastructural challenges in the development and introduction of electric vehicles in major cities of Pakistan. The results and recommendations will assist authorities in replacing fossil fuel vehicles with electric ones to reduce air pollution in Lahore.

Objectives:

- To propose recommendations for policy development aimed at addressing technological and infrastructural challenges in the advancement of electric vehicles in Pakistan.
- To evaluate the effectiveness of electric bikes in reducing air pollution in Lahore.

Novelty Statement:

This study emphasizes various policies focused on infrastructural and technological advancements to accelerate the development of electric bikes. The novelty of the research lies in its unique focus on controlling pollutant emissions through the replacement of petrol bikes with electric bikes in Lahore, using empirical data and city-specific analysis—an area that has not been previously explored.

Study Area:

The study area focuses on Lahore district to analyze eco-mobility through electric vehicles for reducing air pollution. Lahore (31.5204° N, 74.3587° E) is located in northeastern Pakistan, just a few kilometers from the Indian border. It is approximately 25 kilometers from the Wagha Border, which separates Pakistan and India. Situated along the banks of the River Ravi, Lahore is a key cultural, commercial, and educational hub, with a well-developed transport infrastructure including roads, railways, and air links, forming a critical connection between the two countries. As the capital of Punjab, Lahore faces severe air pollution challenges due to a growing population and increasing traffic congestion. Covering 1,772 square kilometers, it is the second most populous city in Pakistan, with a mix of commercial, residential, and industrial areas.

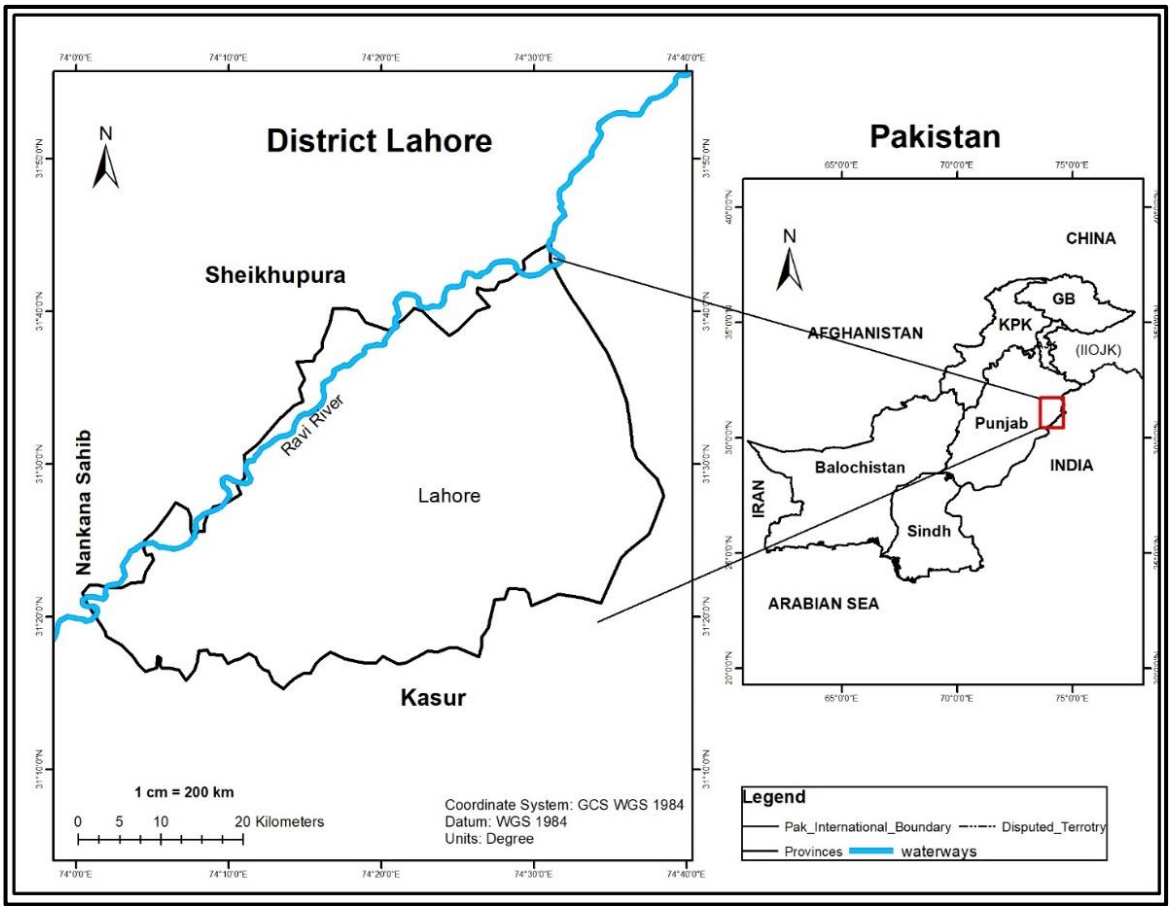

Figure 1. Shows the Study Area Map of District Lahore, Pakistan

Lahore's air quality is primarily affected by pollutants such as ground-level ozone, CO, NO2, PM2.5, PM10, and SO2, which contribute to its consistently poor air quality ratings. Lahore is ranked as the second most polluted city globally in terms of PM2.5 and PM10 levels [14]. The problem worsens during winter when pollutants accumulate, leading to higher air quality index (AQI) readings. Common pollutants in the city include particulate matter, carbon dioxide, carbon monoxide, nitrogen oxides, sulfur oxides, and hydrocarbons. Key contributors to these emissions are vehicular traffic, particularly from petrol-powered motorbikes and diesel-

fueled heavy vehicles, as traffic congestion remains a significant issue. Lahore's extensive network of roads is densely packed with vehicles during peak hours, and with a road density of 0.47 kilometers per square kilometer, it exceeds that of other cities in Punjab [15].

Lahore is administratively divided into nine major towns: Data Gunj Baksh Town, Gulberg Town, Wahgah Border, Ravi Town, Aziz Bhatti Town, Iqbal Town, Samanabad Town, Shalimar Town, and Nishtar Town. Several local and provincial government bodies, along with transport authorities and environmental agencies, are responsible for governance, urban planning, transportation, and environmental regulation in the city. This research focuses on engaging these relevant government departments and policymakers to facilitate the transition toward a sustainable transportation system in Lahore.

Materials and Methodology:

The methodology outlined in Figure 2 was utilized to calculate the environmental impact of fossil fuel-based motorbikes compared to electric vehicles (EVs), considering both non-renewable and renewable energy sources.

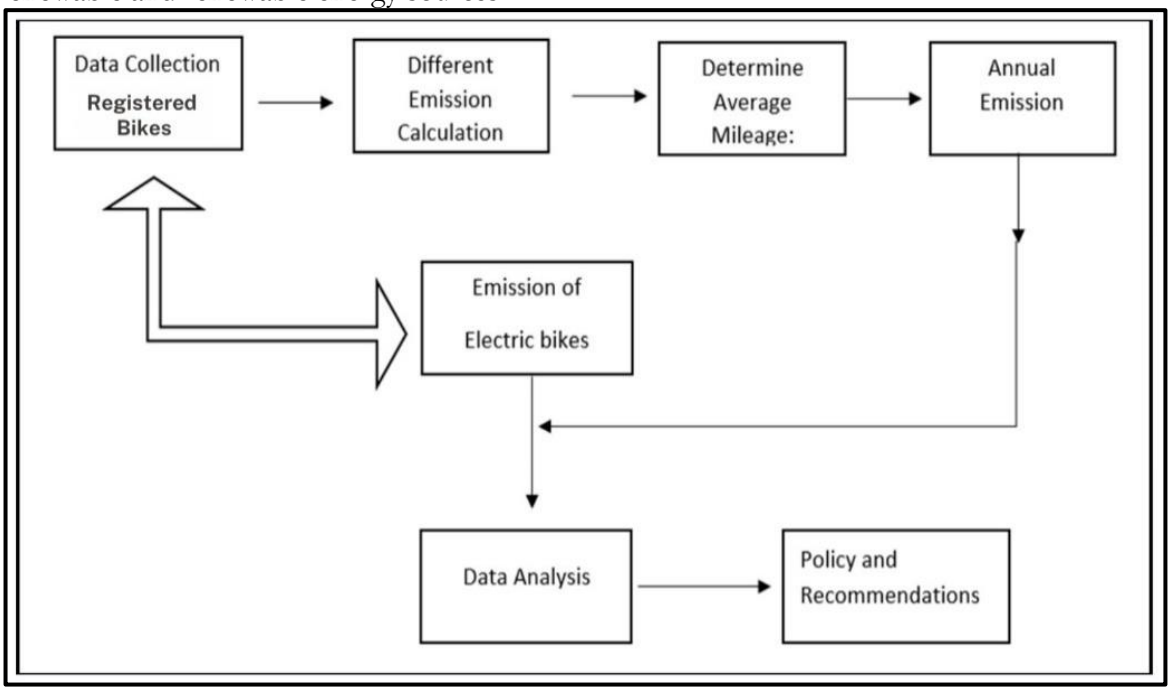

Figure 2. Shows the methodological framework of research

- Data collection on the number of registered motorbikes in Lahore.
- Calculation of emitted pollutants from a single motorbike throughout the day.
- Determination of the average daily mileage covered by motorbikes through surveys conducted at various locations.
- Estimation of the annual pollutant emissions for the year.
- Calculation of emissions from electric bikes.

Based on the collected data, Lahore has a total of approximately 6.2 million vehicles, of which 4.2 million are motorcycles. In Punjab, there are 19.6 million vehicles, with one-third concentrated in Lahore alone. This high concentration makes Lahore the most air-polluted urban center in Punjab, characterized by numerous heat islands [16]. As the cost of four-wheel vehicles rises, more people are shifting to motorbikes, which significantly increases air pollutants such as particulate matter, hydrocarbons, carbon monoxide, and nitrogen oxides in the city.

Types of Tailpipe Emissions:

The primary tailpipe emissions from vehicles running on gasoline fuel include the following:

Oxides of Carbon (CO_2 and CO):

Carbon monoxide (CO) is a toxic pollutant released from vehicle exhaust. It is an odorless, colorless gas, heavier than air, and harmful to both the environment and human health. When inhaled, CO combines with hemoglobin to form carboxyhemoglobin, reducing oxygen levels in the blood. Motorbike exhaust has been observed to emit 2.93 grams of CO per kilometer [17]. Additionally, carbon dioxide (CO_2) emissions from motorbikes average 55.1 grams per kilometer [18].

Oxides of Sulfur (SO_3 and SO_2):

Vehicle exhaust is a major source of sulfur oxides, particularly sulfur dioxide (SO_2) and sulfur trioxide (SO_3). These gases contribute to respiratory problems and lung diseases. Motorcycles are observed to release approximately 320 $\mu g/m^3$ per kilometer of sulfur oxides [17].

Oxides of Nitrogen (NO and NO_2):

Nitrogen oxides (NO and NO_2) are also emitted from vehicles alongside sulfur oxides. Nitric oxide (NO) is a colorless gas, while nitrogen dioxide (NO_2) is reddish-brown. Both are hazardous to human health. The concentration of nitrogen oxides in motorcycle exhaust is recorded to be 2.2 grams per kilometer, which accounts for 83.33% of NO emissions [17].

Hydrocarbons:

Vehicle exhaust contains various unburnt hydrocarbons, which are toxic and carcinogenic. These hydrocarbons contribute to both smog formation and the greenhouse effect. Motorbike exhaust contains hydrocarbons at levels higher than the standard, with a concentration of 0.35 grams per kilometer [17].

Hydrogen Sulfide (H_2S):

Hydrogen sulfide (H_2S) is a colorless, flammable, and toxic gas known for its distinctive odor. It is readily absorbed by the lungs and can be fatal at high concentrations. Although present in low amounts in motorbike emissions, it remains a significant concern. Lead is also emitted in small quantities from motorbikes, posing environmental and human health risks [19].

Results:

Emission by motorcycle (per km):

- **Carbon Monoxide** 2.93 gram per km was observed in motorbike.
- **Carbon Dioxide** 55.1 gram per km
- **Sulphur Dioxide** 350 g/km
- **Nitrogen Oxides** 2.2 g/km
- **Hydrocarbons** higher as compared to the standard value

Specifically, gasoline motorcycles emit 13% more CO_2, 36% more NOx, and 335% more hydrocarbons**.**

Average Mileage Per Day:

To assess the average daily usage of motorbikes in Lahore, interviews were conducted with 50 bike users at various bus stops across the city. The findings revealed that most bike users belong to low-income groups, with an average daily travel time of 2 hours for commuting to and from work. The daily mileage covered varies based on factors such as commute length, travel purpose, infrastructure, and personal preferences. Taking these factors into account, the average daily mileage was estimated to be 26 kilometers.

The actual number of working days varies based on job nature, specific circumstances, weather conditions, and personal choices. With six working days in a week in Lahore, the weekly distance traveled is 156 kilometers. Consequently, the annual distance traveled can be calculated as follows:

Total number of days in a year = 365 Days

Estimated public holidays = 13 Days
Weekend holiday Sunday = 52
Total working days = 365-(13)-52 = 300 Working days
Average total distance commuted yearly = 300*26= 7800km

Table 1: Shows per km daily and annual emission count of a single bike

Pollutant	Per km emission	Yearly Emission
Oxides of carbon CO	2.93 gram/km	22.854 kg
Oxides of carbon CO_2	55.1 gram/km	429 kg
Sulphur dioxide SO2	320 μg/m³ /km 0.00032 grams per km	2.496 kg
Oxides of Nitrogen	2.2 gram/km	17.16 kg
Hydrocarbons	0.35 gram/km	2.73 kg

Emission of Electric Vehicles:

The popularity of electric vehicles, particularly electric bikes, is increasing due to their environmental benefits, such as improved fuel efficiency, lower costs, and ease of use. However, the claim of a zero-carbon footprint for electric bikes is not entirely accurate. In countries like Pakistan, where energy is primarily generated from coal and oil-based power plants, the electricity used by electric bikes is associated with emissions of SO_2, CO_2, and NO_x, which contribute to environmental pollution. Additionally, lead batteries used in electric bikes release significant amounts of lead pollutants during production and disposal. The production of electric bikes also generates waste from materials such as rubber and steel. Research in various countries has quantified the impact of e-bikes on behavior and emissions. Some studies have shown that existing e-bike users, on average, reduce their transport CO_2 emissions by 272 kg per year [21]. Other research estimates that each e-bike in use results in a net CO_2 reduction of 460 kg per year [22], indicating a positive, albeit partial, impact on emissions.

Table 2: Shows the Emission count for generating 1Kwh of energy through non-renewable sources and the emission count of Electric bike

Pollutants	Emission Count Non-Renewable Power Source	Renewable Source
Oxides of carbon CO	3.58×10-4 kg	Nil
Oxides of carbon CO_2	1.01 KG	Nil
Sulfur dioxide SO_2	1.04×10-2 kg	Nil
Oxides of Nitrogen	1.12×10-3 kg	Nil
Hydrocarbons	1.81×10-4 kg	Nil

Electric bikes have zero tailpipe emissions, but the electricity powering them often comes from burning fossil fuels. When electricity is generated from hydroelectric sources, the carbon footprint is minimized. An electric bike with a 350W motor typically covers 43 km on average and consumes 1.5 kWh per 100 km. The production of 1 kWh of electricity at coal-fired thermal power stations results in emissions of CO_2 (1.01 kg), SO_2 (1.04×10^{-2} kg), NO_x (1.12×10^{-3} kg), CO (3.58×10^{-4} kg), HC (1.81×10^{-4} kg), and PM (3.59×10^{-5} kg), along with 51.136 g of ash and slag. Over the lifetime of an electric bike, which consumes 1935 kWh of electricity (equivalent to 791.4 kg of anthracite), the emissions amount to CO_2 (1954.4 kg), SO_2 (20.1 kg), NO_x (2.2 kg), CO (0.7 kg), PM (0.1 kg), and solid ash and slag (98.9 kg). Lead is another significant pollutant, but its emissions could be reduced with the use of high-performance batteries such as NiMH or Li-ion batteries. The primary emissions associated with electric bikes occur during their use if the electricity is generated from coal-based power plants, as well as from waste materials during battery replacement. Despite these issues, the overall emissions from electric bikes are significantly lower than those from petrol and diesel vehicles, comparable to buses, and higher than those from bicycles [23].

Discussion:

A few years ago, Pakistan aimed to transition from conventional motor vehicles to electric ones. However, recent developments suggest that establishing a robust electric vehicle (EV) industry may be challenging in the near future. Major obstacles must be addressed for the rapid advancement of electric vehicles.

The growth of the electric car industry relies on stable and consistent policies. Historically, Pakistan has seen many policy drafts and plans, but implementation often falters with changing governments. In November 2019, the Federal Cabinet approved the first electric vehicle policy to address climate change and rising transport costs [24]. The goal was to convert 30% of vehicles to EVs in the first phase. However, political and economic instability, including bans on imports and energy crises, have hindered progress. Pakistan's severe energy crisis has negatively impacted the economy, with energy deficits estimated to have cost over 4% of GDP in recent years. Numerous factories, including over five hundred in Faisalabad alone, have shut down, exacerbating unemployment [25]. The high demand for electricity compared to supply results in power rationing, with urban areas experiencing 6 to 8 hours of load shedding daily and rural areas 8 to 16 hours [26]. Deploying EVs under these conditions would strain the already overloaded grid infrastructure, making it difficult to establish sufficient charging facilities. The motor industry in Pakistan faces instability due to taxes and heavy duties, and the high cost of electric vehicle batteries further complicates cost-effectiveness. Despite government incentives for local EV manufacturing and hybrid vehicle promotion, the market remains small, and manufacturers have requested additional 'own money' from customers, adding to the challenges.

Battery electric vehicles (EVs) are notably more expensive than gasoline vehicles in Pakistan, posing a barrier to widespread adoption. Battery limitations and high prices due to technology advancements contribute to the cost issue. For instance, EVs in Pakistan are over twice as expensive as other vehicles, presenting a significant obstacle to their widespread adoption. Lack of awareness and education about electric vehicles is another challenge. Public understanding of environmental benefits, such as reduced air and noise pollution, is minimal. Raising awareness about the health benefits of improved air quality, especially for those with respiratory disorders, is crucial. Promoting electric bikes can help drive general health improvements and environmental benefits [27][28].

Misconceptions about electric vehicles, such as their high cost and limited range, contribute to hesitation and reluctance. To overcome these barriers, government, automobile companies, and stakeholders must highlight the advantages of EVs and educate the public. Importing EVs involves significant costs due to dollar payments, heavy import duties, and complex documentation. Simplifying the import process and addressing bureaucratic hurdles are essential for market entry.

Although the running cost of EVs is only one-third of fossil fuel-based vehicles (FFVs), their high capital cost remains a concern. To encourage EV adoption, it is recommended to reduce EV duties and taxes. As technology advances, EV prices are expected to decrease and become more competitive with FFVs. A proposed tax reduction of 5% could be implemented as EV prices drop. Government agencies and ministries need to collaborate on a comprehensive strategy to support EV deployment. Initially, tax relief on completely built units and imports should be considered, as indigenous EV development is challenging in the short term. This exemption could be reviewed after 2020-21. Savings from energy efficiency and reduced fuel costs could offset this tax relief. Additionally, provinces should reduce registration fees and token taxes for EVs and hybrid vehicles. Hybrid vehicles can address 'range anxiety' by allowing use of gasoline when charging stations are unavailable, thereby facilitating the transition from FFVs to EVs.

Electricity Generation Units:

For the full environmental benefits of electric vehicles (EVs), it is essential to develop renewable energy sources to power these vehicles. Introducing half a million electric vehicles would require approximately 1000 MW of electricity. The annual energy requirement for these vehicles would be around 4.8 TWh, which is a manageable load given the potential for increasing power capacity. This demand can be effectively managed if there is a continued expansion of power generation capacity.

Conventional vehicles with internal combustion engines emit direct emissions from the tailpipe, including those from fuel evaporation and during refueling. In contrast, all-electric vehicles produce no direct emissions since their power source is electricity. Plug-in hybrid vehicles emit no direct emissions when operating in all-electric mode, though evaporative emissions are possible. Well-to-wheel emissions encompass the full range of emissions involved in fuel production, including extraction, refining, transportation, and end-use. Even though electric vehicles themselves do not emit tailpipe pollutants, the power plants that generate electricity and the processes involved in fuel extraction and transport contribute to indirect emissions.

A study by [7] confirms that electric vehicles offer significant environmental benefits, with CO_2 equivalent emissions 97% lower than those of petrol vehicles and 70% lower than diesel vehicles. These benefits are closely tied to the use of clean energy resources and efficient battery technologies. The study also highlights potential reductions in emissions due to the longer lifespan of EVs, recycling opportunities, and advancements in battery technologies, such as the use of Li-ion batteries as secondary energy storage. However, challenges remain with raw materials, particularly rare earth elements critical for EV technology development.

To accelerate the development of electric vehicles in Pakistan, the government should foster public-private partnerships. Charging stations can be established in various locations, including hotels, restaurants, offices, homes, and shopping malls. Initially, these charging stations may not be profitable, so the government should consider tax relief to support their establishment. This tax exemption could be phased out once a sufficient number of EVs are on the road. In the early stages, charging units should be placed on main roads in major metropolitan areas and be staffed for vehicle maintenance at no cost. These incentives can encourage greater adoption of electric vehicles.

Additionally, research and development (R&D) facilities are crucial for maximizing the benefits of EVs in Pakistan. Universities should promote research in this field to foster indigenous technology development for electric vehicles. Such R&D efforts can also stimulate entrepreneurial activities, potentially boosting exports and contributing to economic growth.

Conclusion:

In response to global energy challenges and fluctuating oil prices, many countries are transitioning to electric vehicles (EVs) to reduce oil import expenditures. Economic powerhouses like the United States and China are leading the charge in manufacturing and converting vehicles to electric power, aiming to conserve foreign exchange and promote a cleaner environment. Conversely, developing countries, including Pakistan, face obstacles such as limited technology and low public awareness. Although Pakistan began producing and assembling electric bikes two years ago, many companies are still struggling to establish a viable market.

Cost Effectiveness and Environmental Benefits:

Electric bikes offer significant savings compared to cars or public transport. In Pakistan, where fuel prices are high relative to average salaries, electric bikes provide a cost-effective alternative. Purchasing an electric bike is a one-time investment that reduces daily transportation expenses. An affordable electric bike that consumes 2 units of electricity per full charge can travel 80 to 100 kilometers, providing 5 to 6 hours of use. Prices for these bikes range from

Rs150,000 to Rs360,000 depending on the model and features. In Lahore, the popularity of electric bikes is growing due to their lower operating costs—ranging from Rs1 to Rs1.50 per kilometer compared to Rs6 to Rs7 per kilometer for fuel-driven bikes—and the decreasing price gap between electric and traditional bikes.

Electric bikes also contribute to reducing CO_2 emissions and air pollution. They produce no emissions during operation because they are fully electric, leading to a lower carbon footprint compared to conventional vehicles. This reduction in emissions can alleviate traffic congestion and improve air quality, especially in crowded urban areas. Electric bikes are smaller and lighter than cars, easing traffic flow and reducing congestion. Additionally, they emit fewer toxic gases, which helps lower air pollution levels. In Lahore, where traffic congestion contributes to higher carbon footprints, electric bikes could help reduce congestion and improve air quality.

Minimizing CO_2 Emissions and Improving AQI:

Vehicles emit CO_2, CH_4, and N_2O, which worsen air quality and contribute to global warming. A passenger vehicle typically emits 4.6 tons of CO_2 annually, with larger and more powerful vehicles emitting even more. These emissions contribute to acid rain, ground-level ozone formation, and disruptions to ecosystems. Electric bikes, by contrast, offer an innovative alternative. They can assist with pedaling up to 15.5 miles per hour and help avoid traffic. As the adoption of electric bikes increases in Lahore, air quality is expected to improve, benefiting individuals with respiratory issues and enhancing overall quality of life.

Recommendations:

- To improve air quality, electric bikes should be integrated with renewable energy sources for charging. As noted by [29], increasing the use of efficient natural gas and renewable energy (including nuclear) can significantly reduce emissions compared to coal-powered electricity. Pakistan's climate offers substantial potential for solar energy, which could be harnessed for charging units along roads.
- The government should implement additional schemes to replace fossil fuel-powered vehicles. Tax relief should be provided for establishing domestic production units, with the understanding that long-term energy efficiency will counterbalance these tax incentives by reducing oil import bills.
- Manufacturing and assembling electric bikes in Pakistan require a viable market. Government-led awareness campaigns through electronic and social media are needed to promote the benefits of electric bikes.
- Electric bikes can significantly reduce air pollution and improve the AQI in Lahore, especially during winter when vehicle emissions contribute to dense smog. The adoption of electric vehicles can help lower particulate matter and enhance air quality.

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