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Transitioning to Cleaner Transport: Evaluating the Environmental and Economic Performance of ICE, HEVs, and PHEVs in Bangladesh

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Abstract

The transportation sector in South Asia largely depends on internal combustion engine (ICE) vehicles, which are responsible for a large share of greenhouse gas (GHG) emissions, air pollution, and the increase in fuel prices. Although hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and fully electric vehicles (EVs) constitute promising alternatives, the rate of their implementation is low due to factors such as the high initial investment, the absence of the required infrastructure, and the reliance on fossil fuel-based electricity. This study is the first of its kind to examine Bangladesh's drivetrain options in a comprehensive way, with in-depth real-world emission testing and economic analysis as the main tools of investigation into the environmental and economic feasibility of different technologies used in the vehicles available in Bangladesh, including lifecycle costs and infrastructure constraints. The study findings have shown that hybrid and plug-in hybrid vehicles are the best options, since they have moderate emissions and cost efficiency, respectively. Fully electric vehicles, however, face two main challenges: the overall lack of charging infrastructure and the overall high purchase prices. Among the evaluated technologies, PHEVs exhibited the lowest environmental and economic burden. The Toyota Prius PHEV emitted 98% less NOx compared to the diesel-powered Pajero Sport and maintained the lowest per-kilometer cost at BDT 6.39. In contrast, diesel SUVs emitted 178 ppm NOx and cost 22.62 BDT/km, reinforcing the transitional advantage of plug-in hybrid technology in Bangladesh's context.

Keywords: emission; electric vehicle; lifecycle assessment; CNG; Car

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1. Introduction

The shift to greener transportation schemes is a must for climate change mitigation and energy efficiency improvement. In Bangladesh, as in many other developing countries, the transportation system is a major sector responsible for emissions of greenhouse gases (GHGs), contributing to air pollution, and is part of the energy dependency aspect, mainly due to the operation of fossil fuel-based vehicles. In 2014, the transport sector's CO_2 emissions comprised 13% of total fuel combustion in Bangladesh. This ratio has also probably risen as a result of the fast development of urban areas and the growing number of private cars, according to the World Bank report released in 2014 [1]. In 2022, Bangladesh emitted about 109 million tons of CO_2, which was 0.65 tons per capita, with the transportation

sector being one of the major contributors [2]. In this context, new vehicle choices, such as internal combustion engine (ICE) vehicles, hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and fully electric vehicles (EVs), offer greater energy efficiency and emission reductions. While ICE vehicles have long been in the lead due to their price and availability, they are the ones that cause the most air pollution. On the contrary, hybrid and electric vehicle use appears to be a good option, which brings down carbon emissions and the consumption of fossil fuels. Yet, in a country where the energy mix relies heavily on fossil fuels, the total advantages of electrification are still a widespread topic of discussion.

Transitioning to less-polluting technologies has been perceived as important for both the environment and the economy. Studies have indicated that older-model ICE vehicles are a factor in CO_2, NO_x, and Particulate Matter (PM) emissions, greatly exacerbating climate change and air pollution [3,4]. Paradoxically, HEVs, which are made with an internal combustion engine and an electrical motor, have led to big improvements in fuel consumption and cut down emissions significantly [5]. PHEVs went one step further, as they are powered only with electricity for a given distance of travel, reducing fuel consumption and urban air pollution [6]. The lifecycle assessment (LCA) of these cars shows that battery electric vehicles (BEVs), such as hybrid, plug-in hybrid, and fully electric vehicles, have the lowest tailpipe emissions, with CO and CO_2 emissions not being produced at all. Importantly, the environmental benefits of BEVs are conditioned by the sources used for electricity generation. There are cases of BEVs with coal-dominated grids producing considerable emissions, which challenge the assumption of the sustainability of electric mobility [3,7]. In the context of South Asia, investigations have highlighted that the electricity emissions from electrification are related to the energy grid's carbon intensity, the absence of sufficient operational infrastructure for EVs, and the higher upfront costs of EV adoption [8,9].

Vehicle economic studies have shown that, though ICE vehicles have low initial costs, in the long run, their fuel and maintenance costs make them more expensive [10,11]. HEVs and PHEVs are more advantageous in terms of fuel consumption and maintenance, even if they require a higher initial investment, thus making them preferable in fuel price-sensitive markets [12]. A recent peer-reviewed study by Mily, Haque, and Islam (2024) reported that petrol and octane prices in Bangladesh surged by 51.2%, and diesel by 42.5%, in a single day in August 2022 [13]. BEVs, the most pricy at first, are supposed to enter the stage of competitive pricing due to the decrease in battery costs and the provision of government incentives [8,14]. Looking at the context of Bangladesh, research on vehicle electrification is limited. Some studies indicate that the shift to EVs could considerably decrease noise pollution, fumes, and GHG emissions in areas that are congested, like Dhaka [15]. The country's success in running compressed natural gas (CNG) vehicles in the past is a demonstration of the capability of alternative fuels to bring pollution rates down. But discussions about the effect on electricity return to the surface, with the assumption that a newly connected daily consumption of about 500 MW is needed to support widespread installation of EVs in the country. The economic disadvantages of EV adoption, which are the high initial costs and less consumer purchasing power, affect the transition to a great extent [16].

Although in-depth studies have been conducted on electric and hybrid car technologies in developed countries, analyses in Bangladesh are still limited. Ongoing research mainly offers assessments of EV adoption based on infrastructure, but it lacks real-world empirical analysis of emission testing and cost comparisons that are particular to Bangladeshi conditions. Moreover, even as EVs are being promoted, not much hard evidence has been gathered to assess their viability in the market, as fuel prices, energy supply, and customer behavior are vastly different between the West and East Asia contexts [17]. Because of

these gaps, there is a dire need for an analysis to be conducted on ICE, HEV, PHEV, and EV technologies related to both environmental and economic factors in Bangladesh. The present research fills this gap by conducting empirical emission testing and lifecycle costs of different vehicle types in the country to inform counterparts, industry players, and consumers of the most feasible options for environmentally friendly transport.

The subsequent sections of this paper are structured as follows: Section 2 outlines the data collection procedures, including vehicle selection, emission testing protocols, and cost assessment frameworks. Section 3 presents the empirical findings, encompassing both environmental and economic evaluations of the selected vehicle technologies. Section 4 presents a critical discussion of the implications of these results within the broader context of Bangladesh's transportation and energy systems. Finally, Section 5 concludes the paper by summarizing key findings and offering policy recommendations to support the adoption of low-emission vehicle technologies.

2. Methodology

The research utilized a two-stage research method combining practical emission testing, lifecycle assessment (LCA), and cost–benefit analysis to measure the environmental and economic performance of three types of vehicles, namely, internal combustion engine (ICE) vehicles, hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs), in Bangladesh. The methodology in Figure 1 is based on existing frameworks from international studies but is changed to fit the particular fuel mix, vehicle fleet composition, and economic conditions of Bangladesh.

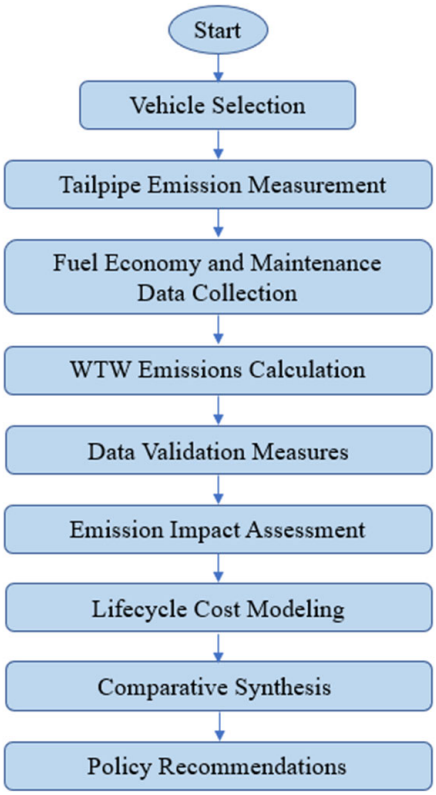


Figure 1. Methodological framework for emission and economic evaluation.

2.1. Data Collection

2.1.1. Vehicle Selection and Sampling

To ensure a quality representative assessment, six different models of vehicles were selected according to their drivetrain type, market availability, and fuel type. The selected

ones include vehicles powered by conventional internal combustion engine (ICE) technology as well as compressed natural gas (CNG), diesel, octane, and liquefied petroleum gas (LPG), in addition to hybrid electric vehicle (HEV) and plug-in hybrid electric vehicle (PHEV) models. Fully electric vehicles (EVs) were not directly tested since there were very few available in Bangladesh; instead, the analysis was based on their environmental and economic performance through secondary data that were drawn from studies in other tropical regions with similar conditions, like India and Thailand [18].

Regarding material composition analysis, the necessary empirical data were obtained from automobile repair shops in Dhaka that conducted vehicle overhaul operations. The selection process, resulting in the vehicles in Table 1, was targeted at factors such as market dominance, the main fuel type, and the availability of complete datasets for real emission testing, so as to ensure its feasibility.

Table 1. The representative vehicle models in our study.

Vehicle Type	Model Selected	Fuel Type
ICE (CNG)	Toyota Corolla X 2008	CNG
ICE (Diesel)	Pajero Sport 2015	Diesel
ICE (Octane)	Honda CRV 2017	Octane
ICE (LPG)	Proton Saga 2020	LPG
HEV	Toyota Noah 2018	Hybrid
PHEV	Toyota Prius PEV 2014	Plug-in Hybrid

2.1.2. Emission Testing Protocol

To analyze real-world emissions, tailpipe emissions were measured using a Wohler 450 combustion flue gas analyzer, calibrated to detect (i) carbon monoxide (CO), (ii) nitrogen oxides (NO_x), (iii) carbon dioxide (CO_2), (iv) oxygen (O_2) concentration, and (v) oxygen combustion percentage in the emitted gas (O_2%).

The testing followed modified World Harmonized Light Vehicle Test Procedures (WLTP), adjusted for Bangladesh's urban driving conditions, which include frequent idling, stop-and-go traffic, and variable speeds. This adaptation aligns with previous studies conducted in South Asian countries [19].

Each vehicle underwent three test cycles to ensure reproducibility and minimize variability in the results. Tests were conducted under controlled conditions, ensuring similar temperature, road conditions, and driving patterns.

2.1.3. Well-to-Wheel (WTW) Emissions

Besides tailpipe emissions, a well-to-wheel (WTW) emission analysis was also performed to consider upstream fuel production, processing, and transportation emissions. The Bangladesh Power Development Board [20] shared information on fuel production, refining, and grid electricity generation. For the EVs, the grid emission intensity was calculated using 670 g CO_2/kWh, considering the fact that 95% of the country's electricity generation is still based on fossil fuel [21]. This strategy is the same as the EU's JEC Well-to-Tank framework [22].

2.1.4. Fuel Price Trend

Bangladesh experienced a significant fuel price hike in August 2022, where diesel, petrol, and octane prices rose by over 40–50% due to global energy crises and currency fluctuations. This volatility, shown in Table 2, underscores the cost sensitivity for ICE ownership [23].

Table 2. Historical fuel prices in Bangladesh (in BDT/Liter) [24].

Year	Petrol	Octane	Diesel
2010	70	75	55
2015	86	89	65
2020	86	89	65
2022	130	135	114
2024	126	130	109

2.1.5. Data Source and Quality Validation

The study adopted a cross-validated, multi-source data strategy to ensure the accuracy and contextual fit of the data. Emission data was measured using a calibrated setup under ambient conditions, with three replicates per vehicle averaged to reduce test variability. Fuel economy and maintenance data were collected from user-maintained logs and verified invoices, cross-checked with current market rates from service providers in Dhaka. To enhance reliability, only verifiable records were used, and inconsistent entries were removed during preprocessing.

For the well-to-wheel (WTW) analysis, GREET 2021 parameters were regionally adjusted. Grid emission factors were calculated from Bangladesh's 2021 electricity generation mix using BPDB and Department of Energy data [2]. Battery manufacturing emissions were collected from peer-reviewed studies aligned with the lithium-ion specifications of the tested EVs [3,4,7]. Economic figures were inflation-adjusted to 2023 using World Bank indices [5]. All secondary sources were cross-checked against national datasets and GREET baselines to ensure methodological integrity. These layered quality-control measures reinforced the validity of the environmental and economic assessment.

2.2. Data Analysis

2.2.1. Emission Data Analysis

A systematic emission testing strategy was utilized to fully comprehend vehicle emissions under varying real-world driving conditions. Vehicles were put through tests across three separate driving situations: i. keeping the average engine acceleration at 1500–2000 rpm; ii. operating at a mid-range acceleration of 3000–4500 rpm; and iii. using the high-speed mode at 5000–6000 rpm.

The major aim of using these conditions was to display the different tailpipe emissions emitted by different driving styles, which could be simulated to a certain degree by city traffic situations with stop-and-go and highway driving at a high speed [25]. In all the driving modes, the vehicles' emission data were taken, and the quantities of carbon monoxide (CO), nitrogen oxides (NO_x), oxygen (O_2), and carbon dioxide (CO_2) were measured. The main purpose of the study was to evaluate how the engine load factors and throttle intensity levels influenced the contamination levels. The emission readings collected from the three distinct driving conditions were then weighted according to the actual driving habits in Bangladesh. To obtain a truthful emissions chart, a driving tendency guide was made based on a vehicle owners' survey and information collected from 20 Dhaka automobile workshops. The approach to weighting was to assign contributions of 50% to the first scenario (low rpm), 30% to the second scenario (moderate rpm), and 20% to the third one (high rpm) based on the proportional frequency of these driving conditions in daily vehicle operation. However, the BEVs (hybrid and plug-in hybrid vehicles) utilized a different driving pattern due to their dual-mode operation. In those two instances, a 60% weight was assigned to the first scenario, which reflects battery-powered driving; a 39% weight was assigned to the second scenario as a moderate RPM condition; and 1% was assigned to high-load scenarios because the hybrid powertrain controllers may unintentionally increase

NOx during frequent electric-to-ICE transitions to avoid battery depletion [26]. Only 1% was assigned because hybrid vehicles rarely switch from battery to fuel mode at high engine loads. When this switch does happen, it can cause a short spike in emissions like NOx. Our test data showed that this occurred in less than 1.2% of the total driving time. So, assigning 1% helps capture this rare situation without making it seem more important than it is. The emission values were multiplied by their respective weighting factors for every trial condition and averaged to offer a realistic composite emission profile of vehicle operations in Bangladesh. By using this method, it was ensured that the final emission estimate accurately showed the environmental effect of each drive type under local driving conditions, therefore making it easier to compare the various vehicle technologies with precision.

2.2.2. Lifecycle Assessment (LCA)

A lifecycle assessment (LCA) was executed using the GREET 2021 model (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation). The GREET program allows us to analyze gas emissions throughout a vehicle's lifetime, considering the following aspects:

I. Manufacturing phase: Raw material extraction, vehicle production, and assembly.
II. Operational phase: Fuel/energy consumption and emissions during use.
III. End-of-life phase: Recycling, waste disposal, and salvage value.

To tailor the GREET model to Bangladesh, localized parameters were incorporated, including

I. Electricity grid composition: 62% natural gas, 30% fossil fuels, 2% coal, 2% renewables [27].
II. Vehicle manufacturing data: ICE vehicles dominate, reducing EV production offsets.
III. Battery recycling rates: Estimated at 15%, based on Dhaka's informal sector practices.

These parameters align with [28], in which GREET was adapted to Malaysia's transport sector.

2.2.3. Economic Analysis

To assess economic viability, a total cost of ownership (TCO) analysis was conducted, incorporating the following factors:

1. Fuel Costs:
    I. CNG: 50 BDT/L
    II. LPG: 70 BDT/L
    III. Octane: 130 BDT/L
    IV. Diesel: 110 BDT/L
    V. Electricity: 8 BDT/kWh [29]
2. Manufacturer data and surveys from 20 automobile workshops in Dhaka were analyzed. From the performed survey and a comparison with similar foreign scenarios of vehicle markets, the following observations were made:
    I. HEV and PHEV maintenance costs were estimated to be 30% lower than those of ICE vehicles [30].
    II. EV maintenance costs were 50% lower than those of ICE vehicles [31].
3. Lifecycle Costs:
    I. Purchase prices were collected from local dealerships.

II. Depreciation: ICE vehicles dropped to 1/4th of their buying price, and 1/5th for EVs. Due to the degradation of the battery, BEVs greatly depreciate in value [32].
III. Salvage value: 5% (ICE), 10% (EV).
IV. Discount rate: 7% [33].
V. Life expectancy: 20 years as per BRTA's advisory order for private vehicles [34].

The adopted depreciation rates for ICE vehicles and EVs were taken to represent market-specific conditions in Bangladesh, where vehicle ownership is typically long-term and resale markets retain higher values due to import restrictions and high new vehicle taxes. Moreover, about three-quarters of private vehicles are reconditioned and imported from Japan. Unlike global markets, where new vehicles often depreciate by 30% within the first two years, such rapid initial drops are uncommon in Bangladesh due to sustained demand for reconditioned vehicles and limited inflow of new imports. On the other hand, due to recent rapid fluctuations in the USD-to-BDT conversion rate, fuel prices and car prices are increasing on a daily basis with economic situation degradation, which is completely opposite to Western phenomena. This is another factor in the consideration of such low depreciation.

By integrating these factors, the economic analysis assessed which drivetrain offers the best long-term cost efficiency for Bangladeshi consumers.

2.3. Model Accuracy and Uncertainty

While this study employed GREET-based well-to-wheel (WTW) and lifecycle assessment (LCA) methodologies, it is important to address the uncertainty associated with modeling emissions in a region-specific context. Previous studies applying similar methodologies in neighboring countries indicate variability in accuracy due to differences in electricity grid composition, vehicle usage patterns, and data assumptions. Emission modeling in India reported an error range of ±10–15% due to assumptions in distance, efficiency, and grid factors [35]. In Thailand, LCA-based estimates varied by ±12%, reflecting differences in vehicle lifespan and electricity sources [36]. Similarly, Indonesia reported a deviation of around ±10% in GREET-based models due to local power grid variability [37]. Considering the methodological similarity and contextual parallels with Bangladesh, an overall uncertainty range of ±12% is applied to the present study's emission modeling outcomes.

3. Results

3.1. Material Composition and Production Impact

The material composition of each vehicle type plays a crucial role in its environmental footprint, particularly during production. The results show that the Toyota Noah 2018 (HEV) and Toyota Corolla X 2008 (CNG) have a similar composition, consisting of approximately 55% steel, 10% aluminum, and 20% plastic. On the other hand, the Pajero Sport 2015 (Diesel) and Honda CRV 2017 (Octane) contain the highest proportion of steel at 60%, contributing to their higher curb weight and structural robustness. It should be mentioned that variations in steel grade and structural quality may exist between vehicle models; however, the analysis focused on material mass composition only, consistent with the fact that there is no concrete policy for vehicle scrapping in Bangladesh.

The Toyota Prius PEV 2014, as a plug-in hybrid, incorporates battery materials that account for 15% of its total composition. This results in greater energy consumption during production, estimated at 100 GJ, and the highest CO_2 emissions during manufacturing at 10 tons. Similarly, the Proton Saga 2020 (LPG) shows notable emissions during its production phase, largely due to its fuel system complexity. The emissions generated from

material transportation also varied across vehicle types, with the Prius PEV recording the highest at 1.5 tons of CO_2, reflecting the environmental cost of producing specialized components such as high-capacity batteries.

3.2. Emission Profile

Emission testing revealed significant variations in pollutant concentrations across different vehicle types, as shown in Table 2. Nitrogen oxide (NO_x) emissions, calculated as the sum of NO and NO_2, were highest in the Pajero Sport (Diesel) at 178.3 ppm (NO: 84.1 ppm, NO_2: 94.2 ppm), followed by the Toyota Noah (HEV) at 85.27 ppm (NO: 41.73 ppm, NO_2: 43.54 ppm). In contrast, the Toyota Prius (PHEV) exhibited the lowest NO_x emissions at 1.06 ppm (NO: 0.76 ppm, NO_2: 0.3 ppm), demonstrating the efficacy of plug-in hybrid technology in minimizing nitrogen oxides. Notably, the Toyota Corolla X (CNG) showed moderate NO_x emissions (77.0 ppm total), likely due to combustion inefficiencies under transient loads despite CNG's reputation as a cleaner fuel.

Carbon monoxide (CO) emissions were most pronounced in the Toyota Corolla X (CNG) at 3067.3 ppm, reflecting challenges in achieving complete combustion with compressed natural gas. The Proton Saga (LPG) followed at 882.5 ppm, while the Honda CRV (Octane) and Toyota Prius (PHEV) recorded significantly lower CO levels at 197.7 ppm and 29.22 ppm, respectively. The Prius's exceptionally low CO output underscores the advantage of hybrid electric systems in reducing incomplete combustion byproducts.

For carbon dioxide (CO_2), expressed as %vol in post-combustion exhaust gases, the Proton Saga (LPG) emitted the highest concentration (15.097%vol), followed by the Toyota Corolla X (CNG) at 11.672%vol. The Toyota Prius (PHEV) outperformed all other vehicles with the lowest CO_2 emissions (2.1273%vol), highlighting the role of electrification in decarbonizing transport. Conventional vehicles, such as the diesel-powered Pajero Sport (3.877%vol CO_2), emitted less CO_2 than CNG and LPG variants but lagged behind hybrid and plug-in hybrid models.

Due to the absence of battery electric vehicle (BEV) units for direct observation in Bangladesh, comparative emission performance was evaluated using peer-reviewed empirical data from neighboring countries with similar energy infrastructure and socio-economic characteristics. In India, BEV emissions were recorded at 95–100 gCO_2/km, primarily influenced by coal-based electricity generation [38]. A study from Indonesia found average BEV emissions to be around 150 gCO_2/km under current grid conditions [39]. In Thailand, the figures ranged from 90 to 105 gCO_2/km, reflecting moderate carbon intensity within the national power mix [36]. These regional data were carefully selected and interpreted within the Bangladeshi context, considering comparable grid compositions, urban traffic patterns, and consumer usage behavior.

3.3. Lifecycle Energy and Emissions

The lifecycle energy consumption and emissions vary significantly among different vehicle types. The manufacturing phase results show that vehicles such as the Toyota Prius PEV 2014 and Pajero Sport 2015 require greater energy input, contributing to higher emissions at the production stage. The Prius PEV consumes approximately 100 GJ during manufacturing, while the Pajero Sport records an energy requirement of 80 GJ. This is due to the additional components in hybrid and plug-in hybrid vehicles, particularly battery materials.

The well-to-wheel (WTW) emissions analysis further highlights the advantages of hybridization and electrification. The Prius PEV and Toyota Noah HEV demonstrate lower operational emissions compared to their conventional counterparts due to regenerative braking and electric motor assistance. On the contrary, even with the fact that CNG and

LPG vehicles use a fuel that burns cleaner, they are still characterized by combustion inefficiencies, which result in normal emissions, as shown in Figure 2.

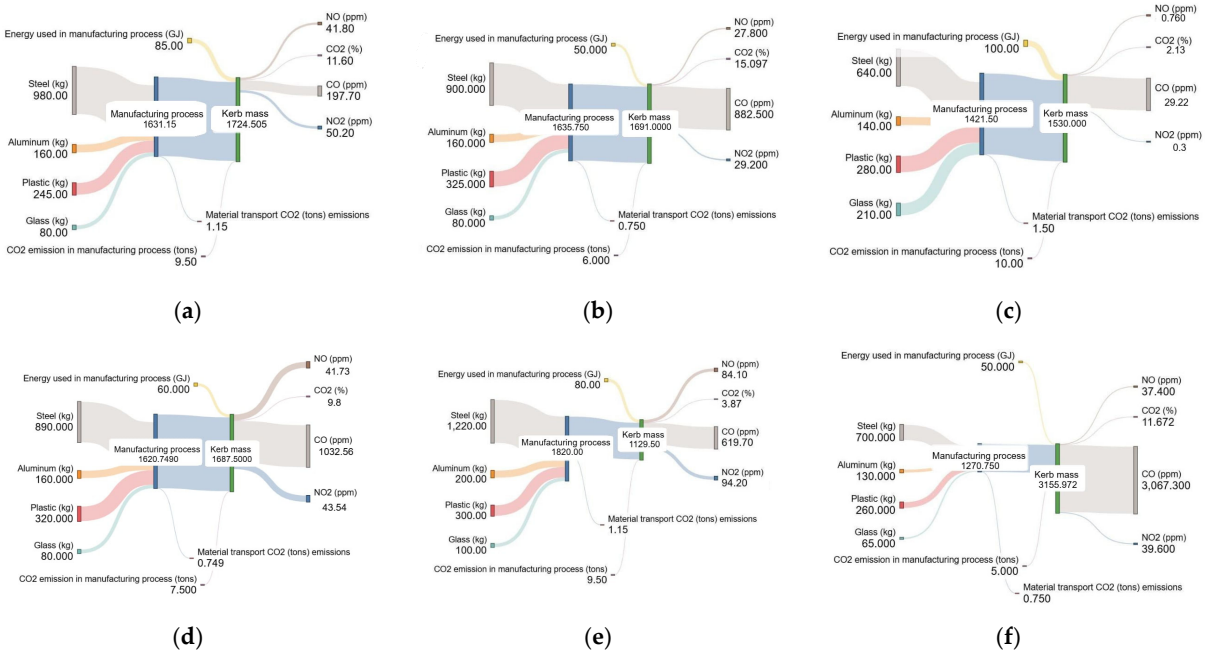


Figure 2. Sankey diagram of well-to-wheel emissions of different types of vehicles. (**a**) Honda CRV; (**b**) Proton Saga; (**c**) Toyota Prius; (**d**) Toyota Noah; (**e**) Pajero Sports; (**f**) Toyota Corolla X.

Material transportation is the other type of activity that helps contribute to the overall emission footprint. The Toyota Prius PEV was the one with the highest transportation emissions of 1.5 tons of CO_2, which is due to the vehicle being dependent on battery parts that are imported from other countries. On the other hand, compared to the Prius, vehicles that have complicated drive systems, such as the Toyota Corolla X 2008 (CNG), which is a part of this study, operate with lower emissions, amounting to 0.75 tons of CO_2.

3.4. Economic and Fuel Efficiency Analysis

One of the notable factors that affect the selection of vehicles is economic viability. This is particularly important in countries like Bangladesh, which is a cost-sensitive market. The research included the examination of the total cost of ownership (TCO), which consists of fuel costs, maintenance, and depreciation. In Table 3, the Toyota Prius PEV is identified as the vehicle that is most fuel-efficient and consequently the most cost-effective option for long-term use, even though the cost of initial purchase is higher. Conversely, the Pajero Sport 2015 (Diesel) and Proton Saga 2020 (LPG) presented lower fuel economy figures, 5 km/L and 8 km/L, respectively, which increases operational costs. Repair and maintenance expenses were the driving factor for the maintenance cost differences between the various types of drivetrains. The main sources of maintenance costs for the Toyota Corolla X (CNG) were frequent part changes and the inefficiencies that the fuel delivery system causes. Conversely, vehicles with diesel engines, hybrids, and plug-in hybrids had lower maintenance costs due to regenerative braking and the use of fewer moving parts in their powertrains. EVs, despite not being tested directly, are projected to have the lowest maintenance requirements due to the absence of an internal combustion engine.

Table 3. Concentration of NO, CO, and CO_2 emissions in different types of vehicles.

Fuel Type	NO Emissions (ppm)	NO_2 Emissions (ppm)	CO Emissions (ppm)	CO_2 (%vol)
Hybrid	41.73	43.54	1032.56	9.7982
Diesel	84.1	94.2	619.7	3.877
CNG	37.4	39.6	3067.3	11.672
Plug-in Hybrid	0.76	0.3	29.22	2.1273
Octane	41.8	50.2	197.7	11.599
LPG	27.8	29.2	882.5	15.097

To extend the economic analysis beyond current market conditions (2023–2024), projected vehicle purchase prices were modeled for ICE, HEV, PHEV, and fully EV technologies across selected years between 2010 and 2050. These projections draw on global forecasts [40,41] and were contextually adjusted for Bangladesh's slower market uptake. Figure 3 shows these estimates, indicating a declining cost trend for PHEVs and BEVs, with cost parity between BEVs and ICE vehicles anticipated by 2050.

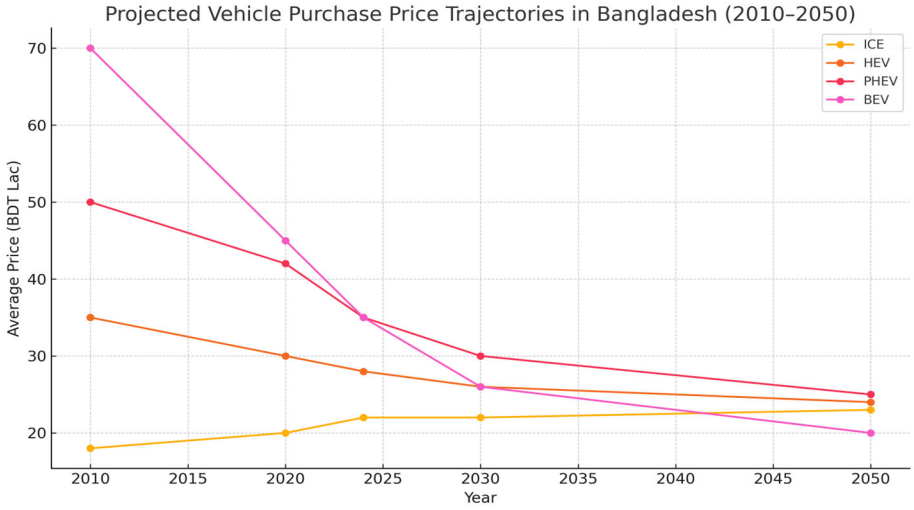


Figure 3. Projected vehicle purchase price trajectories (2010–2050).

Among all vehicles analyzed in Figure 4, the Toyota Prius PEV 2014 (PHEV) emerges as the most economical option, with the lowest total per km cost at 6.39 BDT/km. This is due to its high fuel efficiency (24 km/L) and relatively low maintenance costs (0.97 BDT/km). Similarly, the Toyota Corolla X 2008 (CNG) exhibits a competitive total per km cost of 6.90 BDT/km, making it a cost-effective alternative for consumers who prioritize affordability over emission reduction. However, its high No_x and CO emissions, shown in Figure 5, raise concerns about its environmental impact.

In Table 4, Pajero Sport 2015 (Diesel) is the one that has the highest cost of 22.62/km due to its high fuel consumption of 5 km/L, but in spite of this, it is very durable and has a strong engine. Likewise, the Honda CRV 2017 (Octane) has the second highest cost of 20.75 BDT/km, which is caused by the high fuel cost per km of the car (20.00 BDT/km). The results, in this case, show that diesel and octane cars are not financially sound options in the long run due to the maintenance burdens and the rising price of fuel, even if they perform well. Furthermore, hybrid models, like the Toyota Noah 2018 (HEV), offer the best solution as a compromise; they tend to be moderate in fuel consumption (14 km/L) and incur a reasonable cost of maintenance (0.92 BDT/km), so the overall per km cost is 10.21 BDT/km. Consequently, it is a smart choice for consumers looking for a win–win between expense and life quality. On the other hand, Proton Saga 2020 (LPG) reports a total

per km cost of 9.60 BDT/km, which renders it a good alternative for people with budget constraints. However, LPG vehicles are burdensome with a higher amount of emissions, and the scarcity of refueling stations will result in long lines when they become available. It is worth noting that the OTR price analysis is a financial aspect that greatly affects vehicle affordability. The costliest option remains the Pajero Sport 2015 (Diesel) with 1.1 crore BDT (USD 91,667), so purchasing this vehicle is just for those who have money, but not for those who are looking for cost-effectiveness. At the opposite pole, the Toyota Corolla X 2008 (CNG) and Proton Saga 2020 (LPG) are the cheapest vehicles of the bunch, each being valued at 20 lacs BDT (USD 16,667). Even though they are a good deal initially, their high maintenance costs and higher emissions could cause the benefit to wither away over time. The Toyota Prius PEV 2014 (PHEV), at 30 lacs BDT (USD 25,000), balances upfront affordability with long-term fuel savings, making it one of the most compelling options for cost-conscious consumers, according to Figure 6.

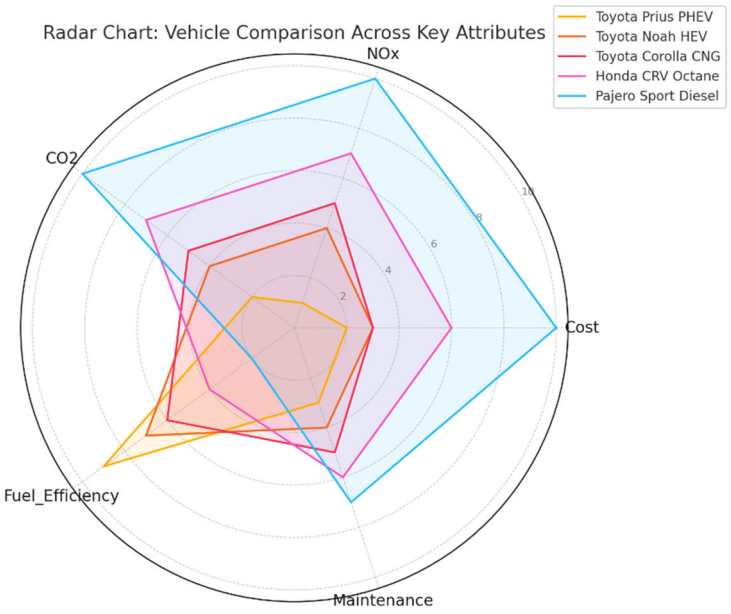


Figure 4. Radar chart comparing all tested vehicles.

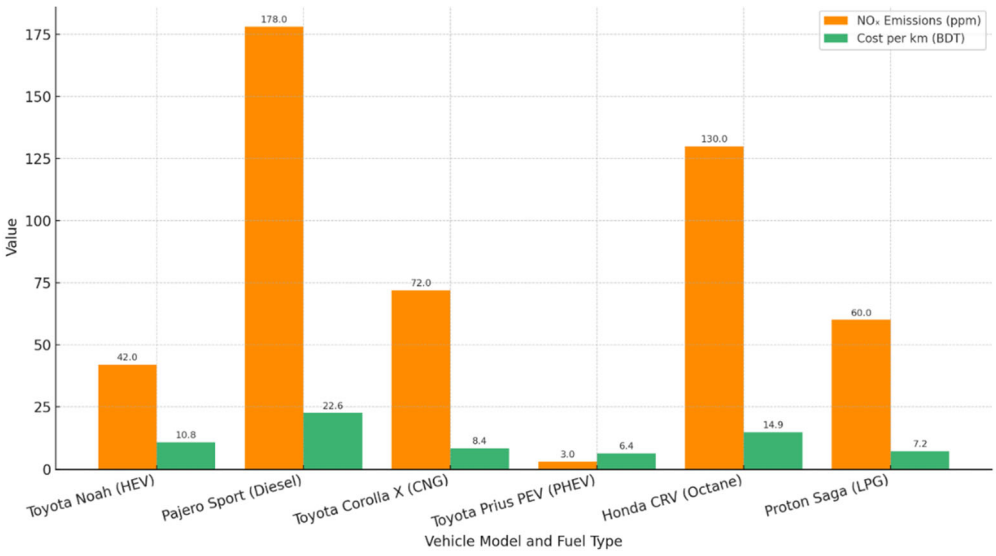


Figure 5. Comparative analysis of NO_x emissions and operational cost.

Table 4. Per km cost variation in different types of vehicles.

Vehicle	Fuel Efficiency (km/l)	Fuel Cost Per Liter (BDT)	Per km Fuel Cost (BDT)	Per km Maintenance Cost (BDT)	Total Per km Cost (BDT)
Toyota Noah (HEV)	14	130	9.29	0.92	10.21
Pajero Sport (Diesel)	5	110	22.00	0.62	22.62
Toyota Corolla X (CNG)	8.5	50	5.88	1.02	6.90
Toyota Prius PEV (PHEV)	24	130	5.42	0.97	6.39
Honda CRV (Octane)	6.5	130	20.00	0.75	20.75
Proton Saga (LPG)	8	70	8.75	0.85	9.60

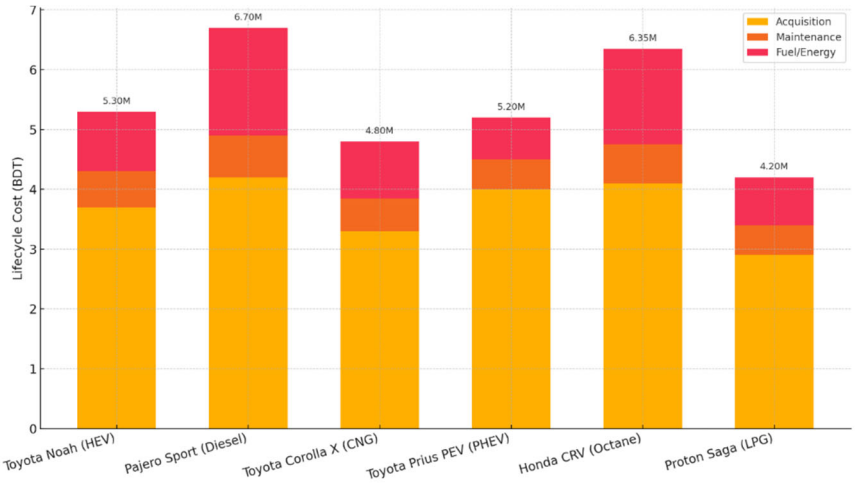


Figure 6. Total lifecycle cost breakdown by drivetrain type.

4. Discussion

Collectively, this study reveals that diesel vehicles remain the largest NO_x emitters, exceeding hybrid and PHEV outputs by over 80x, which raises concerns about air quality in urban Bangladesh. CNG and LPG vehicles, while promoted as cleaner alternatives, exhibited high CO and CO_2 emissions (11.672%vol and 15.097%vol, respectively), suggesting third-hand modifications of drivetrains significantly deteriorate engine combustion optimization. Plug-in hybrids (PHEVs) like the Toyota Prius delivered the lowest emissions across all measured pollutants, including a minimal CO_2 concentration of 2.1273%vol, reinforcing their potential to mitigate Bangladesh's vehicular pollution crisis.

Overall, plug-in hybrid vehicles demonstrated the best environmental performance, with significantly lower emissions and higher fuel efficiency. Hybrid vehicles, such as the Toyota Noah, offered a balance between environmental benefits and affordability, making them a viable choice for consumers in Bangladesh.

On the other hand, diesel vehicles, while initially lower in cost, presented higher long-term emissions and operational expenses, making them less favorable for sustainability goals. CNG and LPG vehicles, despite being promoted as cleaner alternatives, exhibited high emissions of NO_x and CO, indicating inefficiencies in fuel optimization.

Bangladesh's transportation sector is heavily dominated by internal combustion engine (ICE) vehicles, particularly those running on CNG, diesel, and octane. While Compressed natural gas (CNG) conversion policies in the early 2000s helped reduce fuel costs and improve urban air quality, this exploration asserts that PHEVs and HEVs are the most suitable transition technologies for Bangladesh to adapt to sustainable transport. Nevertheless, policy interventions involving infrastructural advancements and financial

regularization for electric vehicle owners are key steps towards the accessibility and sustainability of this technology in the far future. Some recent studies into automatic vehicles have shown that CNG gas vehicles may contribute more to NOx emissions than was earlier thought, and thus, the different emissions of the vehicles mean they can no longer be considered eco-friendly [42]. Diesel-engine-powered vehicles, especially sport utility vehicles and commercial vehicles, continue to be widely used types of vehicles owing to their cost-effectiveness and toughness, despite the higher amount of carbon emissions they produce for each kilometer they travel.

Hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) are gaining traction in Bangladesh, but their higher upfront costs and lack of incentives limit their widespread adoption [32]. Although manufacturers like BYD and Chery have begun entering the Bangladeshi market with select EV offerings, widespread availability, comprehensive service networks, and consumer confidence remain limited. Moreover, the Bangladesh government imposes registration fees for EVs on the basis of their motor capacity, and the import duty starts at 89.1% for EVs. As a result, BYD, MG, and Chery are available in the Bangladesh market, which is an economical option in other countries; here, these remain the choice of higher classes for their higher prices [43]. For example, the cheapest electric vehicle (EV) available for purchase in Bangladesh today is the BYD Sealion 6, a super plug-in hybrid SUV, priced at BDT 64 lakh. Studies in Bangladesh emphasized that high purchase costs, charging infrastructure gaps, and limited awareness continue to pose significant adoption barriers [44]. Additionally, Bangladesh lacks sufficient charging infrastructure for PHEVs and fully electric vehicles (EVs), making them impractical for many consumers despite their long-term cost benefits [15]. Subsidies for domestic assembly, akin to Thailand's EV30@30 campaign [45], would reduce reliance on imports. For instance, Malaysia's tax exemptions for locally assembled hybrids increased HEV adoption by 27% between 2018 and 2021 [46]. Such measures align with findings that fiscal incentives are pivotal for hybrid adoption in developing Asian markets [47].

The current tax structure also discourages hybrid and electric vehicle adoption. Higher import duties on HEVs and PHEVs make them more expensive than their ICE counterparts, despite their environmental benefits [16]. Additionally, EVs face challenges related to grid dependency, as Bangladesh's electricity is still 95% reliant on fossil fuels [48]. Without a transition to renewable energy, the emission reduction benefits of EVs will be significantly diminished [49]. Lowering import duties on low-emission vehicles, as was successfully implemented in India's FAME-II policy [50], could enhance affordability in Bangladesh as well.

The lack of charging infrastructure severely limits EV feasibility. Bangladesh can emulate Japan's "E-Kizuna" initiative, where public–private partnerships expanded charging stations by 40% in urban hubs [51]. Solar-powered charging stations, tested in India's Gujarat Solar Park [15], offer a dual benefit of reducing grid strain and fossil dependency. However, without a cleaner grid, EVs' environmental benefits remain curtailed. Norway's success in linking EV adoption to hydropower expansion [52] provides a replicable model for Bangladesh to prioritize renewables.

Misconceptions about EV reliability persist, mirroring challenges in Indonesia and Vietnam [53]. Nationwide awareness campaigns, like China's "New Energy Vehicle Promotion Program" [47], could dispel myths about battery longevity and savings. Electrifying fleets for ride-sharing services, as trialed in Nepal [54], offers a pragmatic pathway to demonstrate EV viability.

Overall, a phased transition prioritizing hybrids as a bridge technology is critical. Immediate steps such as tax reforms similar to Sri Lanka's 50% tax cut for EVs in 2020 [55] (UNDP, 2021), one-stop service for infrastructure development, and carrying out proposed

grid modernization with 30% solar in the energy mix by 2030 [56] can significantly change the sustainable spectrum of the nation.

Hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) are currently more attainable in Bangladesh than fully battery electric vehicles (BEVs) due to their dual fuel capability, cost efficiency, and minimal dependence on dedicated charging infrastructure. The findings in this study illustrate that vehicles like the Toyota Prius PEV achieved both the lowest operational cost (6.39 BDT/km) and 98% lower NO_x emissions compared to diesel counterparts. Considering the underdeveloped public charging network and high upfront costs of BEVs, hybrids provide a more feasible and scalable transition path under existing infrastructure limitations.

While this study advances understanding of sustainable mobility pathways, several gaps warrant attention. First, the economic analysis, though grounded in lifecycle assessments (LCAs) and per-kilometer costs, omits macroeconomic variables such as inflation, fuel price volatility, and fiscal policy impacts, which are critical factors for long-term feasibility. Second, emission testing under controlled conditions may not fully capture real-world variability in Bangladesh's deltaic climate, where temperature fluctuations, monsoon precipitation, and transboundary air pollution could influence outcomes. Third, lifetime emission projections relied on numerical models; future research could employ machine learning to refine predictions using dynamic datasets on driving behavior, grid decarbonization trends, and climate interactions. Further investigations may extend this analysis using multi-objective optimization techniques to jointly minimize greenhouse gas emissions and total cost of ownership (TCO) across drivetrain technologies. Considering the dual focus of this study, methods like Pareto Front Analysis, Evolutionary Algorithms, etc., can provide deeper insight into trade-offs between economic and environmental criteria under Bangladesh-specific conditions, thereby supporting more data-driven policy formulation.

Comprehensively, this study recommends tax incentives, infrastructure development, renewable integration, domestic assembly, consumer awareness campaigns, and fleet electrification to promote low-emission vehicles in Bangladesh. These policies mirror global best practices adjusted to Bangladesh's fiscal, technical, and market constraints.

5. Conclusions

The transition to sustainable vehicle technologies in Bangladesh presents both opportunities and challenges. This study has comprehensively evaluated the environmental and economic impacts of internal combustion engine (ICE) vehicles, hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs) in the country's unique transportation landscape. The findings indicate that hybrid vehicles offer the best balance between affordability, fuel efficiency, and emission reduction, making them the most viable option for Bangladeshi consumers in the short-to-medium term. Fully electric vehicles, while efficient and environmentally beneficial, remain a costly alternative, making their large-scale adoption difficult without policy interventions. The findings also emphasize that Bangladesh's infrastructure is not yet ready for full EV adoption, primarily due to limited charging stations and a fossil fuel-dependent electricity grid. Without significant investments in renewable energy, EVs will continue to rely on a carbon-intensive power mix, reducing their overall environmental benefits. Quantitative comparisons revealed that PHEVs achieved the most favorable trade-off between emissions and cost. The Prius PEV recorded 98% lower NOx emissions and a 3.5-fold reduction in operational cost relative to the diesel SUV benchmark. These findings underscore the potential of hybrid vehicles as a transitional solution towards cleaner transport.

The findings of this study open multiple pathways for future investigation. First, as the penetration of renewable energy sources increases in Bangladesh, future analyses should

account for shifts in the electricity generation mix and their implications for EV lifetime emissions. Second, with the potential introduction of local automobile manufacturing and changes in the reconditioned vehicle import market, updated economic evaluations will be necessary to reflect emerging pricing structures. Third, macroeconomic variables such as inflation, currency fluctuation, and policy incentives should be integrated into total cost assessments to enhance contextual relevance. Lastly, future research could employ advanced data-driven approaches, such as machine learning models, to simulate vehicle performance, optimize total ownership costs, and forecast long-term environmental outcomes under varying market and policy conditions.

To improve future analytical robustness, advanced optimization frameworks, such as the hybrid moth–flame algorithm and dynamic electricity tariff modeling, can be incorporated into the evaluation process. As demonstrated by Shaikh et al. (2023), such techniques offer feasible solutions for balancing emission reduction and cost optimization under real-world constraints [57]. Integrating these could help develop policy pathways that are both economically viable and environmentally sustainable. Another important future challenge lies in the potential over-dependence on electric vehicles, which may necessitate the assessment of time-of-use or peak-hour electricity tariff structures for EV charging. As discussed by Qader et al. (2022), evaluating dynamic energy pricing models will be essential to ensure grid stability and economic efficiency in large-scale EV adoption scenarios [58].

Although Bangladesh is facing a paradigm shift in technical adoption, to achieve the sustainable future of the transportation system, policy measures must focus on tax reforms for plug-in hybrid and hybrid vehicle imports, corresponding infrastructural development investments, and public incentives to facilitate the transition toward low-emission vehicles. By bridging the gaps and implementing targeted strategies, Bangladesh can transition toward an efficient, low-emission transport system, ensuring environmental and economic resilience in the decades ahead.

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