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Air Quality and Climate Co-Benefits of Pakistan's Transport Sector: A Multi-Pollutant Scenario Assessment

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Abstract

The transport sector is a major contributor to urban air pollution and greenhouse gas emissions in Pakistan, posing significant challenges to sustainable development and climate commitments. This study develops the first technology-resolved, high-resolution, multi-pollutant emission inventory and scenario analysis for Pakistan's transport sector, addressing key gaps in previous studies that lacked integrated multi-pollutant assessments, comprehensive coverage of non-road sources, and long-term scenario comparisons. The analysis integrates road and non-road transport sources within the Greenhouse Gas–Air Pollution Interactions and Synergies (GAINS) modeling framework. Emissions are projected for 2024–2050 under a business-as-usual (BAU) scenario and three mitigation pathways: an Electric Vehicle Transition (EVT) emphasizing transport electrification, a Euro-VI scenario focusing on stringent fuel and vehicle emission standards, and an integrated nationally determined contribution strategy (NDC+) scenario combining electrification, regulatory improvements, and structural transport reforms. In 2024, transport-related emissions are estimated at approximately 22 kt of fine particulate matter ($PM_{2.5}$), over 300 kt of nitrogen oxides (NO_x), and nearly 39 Mt of carbon dioxide (CO_2), alongside substantial emissions of other gaseous pollutants and short-lived climate forcers. By 2050, the NDC+ scenario achieves the largest reductions relative to business-as-usual, demonstrating that coordinated electrification and emission control strategies can simultaneously reduce air pollution and greenhouse gas emissions. The results demonstrate strong synergies between climate mitigation and air quality improvement, showing that integrated strategies combining electrification with stringent emission standards can simultaneously reduce greenhouse gas emissions and major air pollutants while advancing cleaner and more sustainable mobility. This analysis provides a consistent and policy-relevant evidence base derived from best-available data and modeling tools to support Pakistan's NDC implementation, sustainable mobility planning, and integrated air quality and climate strategies, with lessons transferable to other rapidly developing economies.

Keywords: transport sector; air pollution; greenhouse gas; emission inventory; multi-pollutant modeling; sustainable mobility; electric vehicles; GAINS model; Pakistan

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1. Introduction

Transport-related emissions represent one of the most persistent challenges for countries striving to reconcile economic growth with environmental sustainability [1–3]. Rapid urbanization, rising incomes, expanding industrial activity, and growing mobility demand have driven sustained growth in transport activity across developing economies [4–6], making it increasingly difficult to decouple emissions from economic expansion [7–9]. Consequently, the transport sector has emerged as a critical pressure point for both local air quality and global climate change [10–12], with far-reaching implications for public health [13–15], energy security [16–18], and long-term sustainable development [19]. Globally, the transport sector is a major source of fine particulate matter, ground-level ozone, and greenhouse gas (GHG) emissions, accounting for approximately 14–16% of total global GHG emissions, primarily from road transport [20]. These emissions disproportionately affect urban populations [21] and low- and middle-income countries [22], where rapid motorization often outpaces regulatory capacity and infrastructure development [7,8]. Addressing transport emissions is therefore central to achieving multiple Sustainable Development Goals (SDGs), including those related to health, sustainable cities, clean energy, and climate action.

Pakistan exemplifies these interconnected challenges. As one of South Asia's fastest urbanizing countries, its transport sector plays a central role in economic and social development, contributing approximately 10.5% to gross domestic product (GDP) and providing employment to nearly 5.8% of the national workforce [23]. However, rapid urbanization, population growth, and rising vehicle ownership—combined with continued dependence on fossil fuels—have led to a sharp increase in transport-related emissions [24–26]. At the national scale, transport fuel consumption has grown steadily, making the sector responsible for roughly one-quarter of Pakistan's energy-related GHG emissions [27,28]. Empirical and scenario-based studies consistently show that road transport dominates energy use and emissions, driven by high reliance on private vehicles, freight trucking, and motorcycles, alongside limited modal share for rail and public transport [29–32].

Decomposition and decoupling analyses further indicate that Pakistan has largely failed to decouple transport-sector emissions from economic growth. CO_2 emissions remain strongly coupled with GDP, with only short periods of weak decoupling observed historically [33–36]. Infrastructure-led growth strategies, particularly road expansion, have reinforced this coupling, raising concerns regarding long-term environmental sustainability [37,38].

1.1. Urban Air Pollution and Transport Sector Contributions

Urban air pollution represents one of Pakistan's most severe environmental challenges. Major cities—including Lahore, Karachi, Islamabad, Rawalpindi, Faisalabad, and Quetta—regularly experience concentrations of $PM_{2.5}$, PM_{10}, SO_2, NO_x, and other pollutants far exceeding national and World Health Organization (WHO) guidelines [39–44]. Recent studies have also highlighted the role of integrated urban transport planning, accessibility, and environmental co-benefits in shaping sustainable mobility transitions [45,46]. Transport emissions are widely recognized as major contributors to these exceedances, particularly along congested traffic corridors. Road transport contributes substantially to emissions of particulate matter, nitrogen oxides, carbon monoxide, volatile organic compounds, black carbon, and carbon dioxide [31,39,47]. These pollutants play a key role in smog formation, secondary aerosol production, and ground-level ozone, especially during winter stagnation episodes in cities such as Lahore [48–51]. However, the precise contribution of transport to urban air pollution remains uncertain. Source apportionment and sectoral inventory studies attribute anywhere from less than 10% to more than 80% of urban pollution to vehicular sources, depending on methodology, pollutant coverage, and spatial resolution [26]. This uncertainty has direct implications for policy design, complicating

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prioritization of transport-focused interventions relative to other sectors such as residential combustion and industry.

The health consequences of transport-related air pollution in Pakistan are substantial and well documented. Exposure to fine particulate matter and black carbon is associated with increased risks of respiratory and cardiovascular diseases, adverse pregnancy outcomes, and premature mortality [52–54]. Systematic reviews and city-specific studies report elevated disease burdens linked to traffic emissions, particularly among vulnerable urban populations [43,55,56].

Beyond air pollution, transport systems also contribute to noise exposure, road traffic injuries, and reduced physical activity, further compounding public health challenges [55]. These impacts undermine progress toward multiple SDGs, notably SDG 3 (Good Health and Well-Being), SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action) [57,58]. Reducing emissions from the transport sector is therefore not only an environmental priority but also a critical component of inclusive and sustainable development.

1.2. Transport Policies and Implementation Challenges

In response to rising emissions and deteriorating air quality, Pakistan has introduced several policy instruments aimed at promoting cleaner transport. These include commitments under its nationally determined contribution (NDC), the New Energy Vehicle Policy 2025, and the National Clean Air Policy 2023 [59–61]. These frameworks emphasize vehicle electrification, improved fuel quality, tighter emission standards, and expansion of cleaner transport technologies.

Modeling studies suggest that such measures could deliver substantial reductions in both GHG emissions and local air pollutants if implemented effectively [30,62–65]. However, implementation has been uneven. Electric vehicle uptake remains limited despite fiscal incentives [60,66,67], inspection and maintenance systems suffer from weak enforcement [68,69], and nationwide availability of low-sulfur fuels remains incomplete. Institutional fragmentation and limited coordination between transport, energy, and environmental authorities further constrain progress [64].

Experience from neighboring countries illustrates the potential benefits of coordinated action. India's phased adoption of Bharat Stage emission standards, supported by fuel quality upgrades, has resulted in measurable improvements in urban air quality and health outcomes [70–72]. In Bangladesh, interventions such as cleaner bus fleets and compressed natural gas programs have reduced selected local pollutants, although long-term climate benefits depend on system-level integration [73–75]. Recent studies on hybrid energy systems and sustainable energy optimization further highlight the importance of integrated approaches for reducing emissions while enhancing system efficiency and resilience, particularly in resource-constrained environments [76,77]. These experiences underscore the importance of integrated, multi-pollutant transport strategies.

1.3. Research Gaps and Objectives

Despite growing scholarly attention, research on transport emissions in Pakistan remains fragmented. Existing studies have developed city-level assessments [41,78–80], national emission inventories and projections [23,24,31], or evaluated individual policies and technologies [26,62,64,81]. Others focus on specific pollutants, modes, or health outcomes [49,65,81].

However, few studies employ integrated, technology-resolved, multi-pollutant frameworks capable of simultaneously capturing interactions among electrification, advanced emission standards, fuel quality improvements, and non-road sources within a single con-

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sistent assessment [26,59,82,83]. This gap limits policymakers' ability to assess combined and potentially synergistic air quality and climate co-benefits of integrated transport strategies. In developing country contexts such as Pakistan—characterized by rapid motorization, data constraints, and enforcement challenges—there is a pressing need for comprehensive, policy-relevant assessments that explicitly quantify multi-pollutant outcomes over long-term horizons [64].

To address this need, the present study applies the Greenhouse Gas–Air Pollution Interactions and Synergies (GAINS) model to develop Pakistan's first technology-resolved, multi-pollutant emission inventory and scenario analysis for the entire transport sector. The assessment covers both road and non-road sources and quantifies emissions of particulate matter, black carbon, organic carbon, nitrogen oxides, sulfur dioxide, carbon monoxide, volatile organic compounds, and key GHGs including carbon dioxide, methane, and nitrous oxide. Informal transport activities in Pakistan present a key source of uncertainty in emissions modeling. Within the GAINS framework, such activities are primarily captured through aggregate fuel consumption statistics [27], which inherently include fuel use from both registered and unregistered vehicles. As a result, emissions from informal transport are not entirely omitted, even though individual vehicle categories are not explicitly represented in the stock database. For instance, unregistered loaders and tractors used for urban freight are likely reflected within non-road sectors depending on fuel allocation, while modified three-wheelers (e.g., Chingchi rickshaws) are implicitly included in the two- and three-wheeler category through gasoline and CNG consumption. However, the allocation of fuel use across sectors and vehicle types remains uncertain, particularly in cases of cross-sectoral or informal usage, which may affect the accuracy of sub-sectoral emission estimates. Emissions are estimated for the 2024 base year and projected through 2050 under four policy scenarios: Business-as-Usual (BAU), Electric Vehicle Transition (EVT), Euro VI emission standards (Euro-VI), and an integrated NDC+ pathway.

This study makes three principal contributions. First, it provides a high-resolution, vehicle-class-disaggregated emission inventory for Pakistan's transport sector, addressing critical data gaps for both road and non-road sources. Second, it quantifies air quality and climate co-benefits of alternative policy pathways within a unified multi-pollutant framework, enabling direct comparison of electrification, emission standards, and integrated strategies. Third, it delivers policy-relevant insights to support implementation of Pakistan's climate and clean air commitments while offering a transferable analytical approach for other rapidly motorizing developing economies.

The remainder of the paper is structured as follows. Section 2 describes the methodology, data sources, and scenario design. Section 3 presents the baseline emission inventory and projected pathways to 2050. Section 4 discusses the implications for policy, sustainability, and co-benefits, along with key limitations. Section 5 concludes with the main findings and recommendations for future research and decision making.

2. Materials and Methods

This study applies the GAINS (available online: https://gains.iiasa.ac.at/gains/, accessed on 28 December 2025) model to develop a comprehensive emissions inventory and to assess mitigation pathways for Pakistan's transport sector. GAINS is an integrated modeling framework that quantifies emissions of key air pollutants and GHGs by explicitly linking transport activity, fuel consumption, vehicle technologies, and emission control measures within a consistent scenario-based structure [84–86].

The regional GAINS framework for South Asia, originally developed for large scale assessments of air pollution and climate interactions [12,87–89], was substantially adapted and refined to reflect Pakistan specific transport system characteristics. Model updates incorporated country level data on vehicle fleet composition, fuel consumption, technology penetration, and regulatory conditions, drawing on recent GAINS applications for Pakistan [12,26,64,86]. These refinements allow for a detailed and policy relevant representation of both road and non-road transport sources.

Emission factors were adapted to Pakistan-specific conditions using regionally calibrated parameters within the GAINS framework, further refined with country-specific fleet composition and activity data (Supplementary Tables S2 and S3). Adjustments incorporate age-dependent deterioration functions to account for engine wear, degraded after-treatment systems, and poor maintenance, which typically increase emissions from older vehicles. Fuel quality characteristics were also considered through sulfur-dependent correction factors influencing emission control efficiencies and fuel-type emission patterns. These approaches are consistent with established regional studies. However, due to limited availability of local Portable Emissions Measurement Systems (PEMS) or dynamometer measurements—particularly for VOC and CO emissions from two- and three-wheelers—these estimates should be interpreted as best-available approximations rather than direct measurements.

The analysis adopts 2024 as the base year, reflecting the most recent availability of comprehensive national data on vehicle activity, fuel use, and technology distribution. Emissions are projected annually through 2050 under a set of contrasting policy scenarios that reflect alternative development pathways for Pakistan's transport sector.

2.1. Transport Sector Representation in GAINS

The GAINS model employs a bottom up, technology explicit approach in which transport emissions are calculated as a function of activity levels, fuel consumption, pollutant specific emission factors, and the effectiveness of emission control technologies [64,86,90]. The transport sector is disaggregated into detailed vehicle categories, fuel types, and technology vintages, allowing emissions to be quantified for heavy-duty trucks, buses, light-duty vehicles, motorcycles, three-wheelers, agricultural machinery, construction equipment, and railway systems.

Emissions of particulate matter (PM) with aerodynamic diameters below 2.5 µm ($PM_{2.5}$) and 10 µm (PM_{10}), nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), volatile organic compounds (VOCs), black carbon (BC), and organic carbon (OC) are estimated using the GAINS Tier 2 methodology, which explicitly accounts for real-world fleet composition, emission factors, and the penetration of emission control technologies across different sectors and regions [90]. Carbon dioxide (CO_2) emissions are calculated following the IPCC 2006 Tier 1 approach, considering fuel consumption and carbon content. Methane (CH_4) and nitrous oxide (N_2O) emissions are quantified based on sector-specific emission factors, including contributions from combustion processes, agricultural activities, and other technology-specific parameters embedded within the GAINS modeling framework [91,92]. This comprehensive approach allows for a consistent assessment of the technical mitigation potential and associated costs of reducing air pollutants and GHGs globally.

Figure 1 illustrates the structure of Pakistan's transport sector as represented in the GAINS model, including the segmentation of road and non-road sources and the associated fuel and technology pathways.

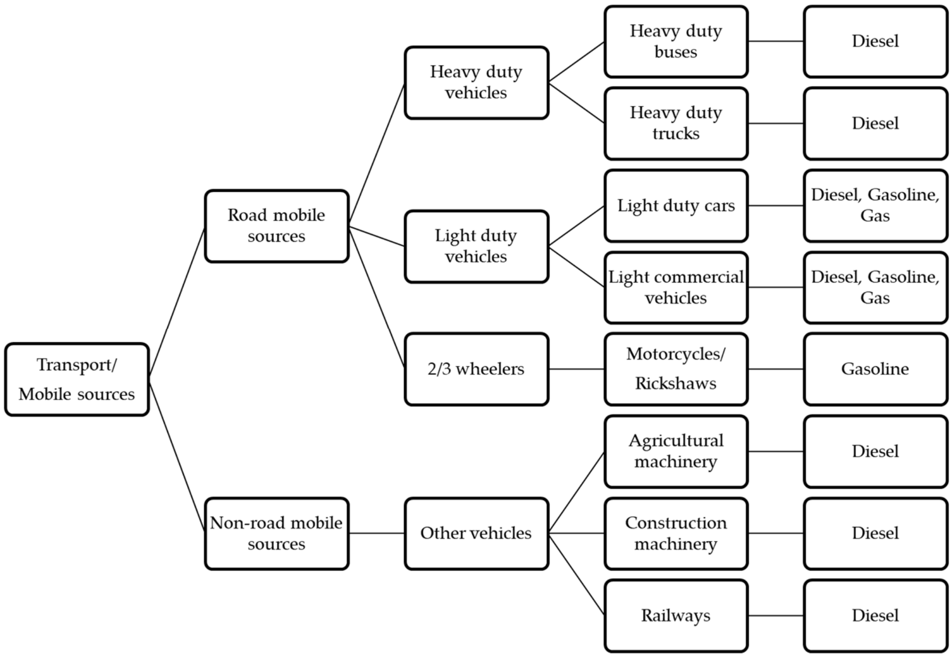

Figure 1. Transport sector structure for Pakistan in the GAINS model.

2.2. Data Sources and Activity Projections

Model calibration relies on a combination of national statistical data, sectoral reports, and integrated energy modeling outputs. Fuel consumption data for road and non-road transport were obtained from the Pakistan Energy Yearbook 2024 published by the Hydrocarbon Development Institute of Pakistan [27]. Vehicle stock data, including fleet size, vehicle categories, and technology classifications, were sourced from the Pakistan Economic Survey 2025 [23].

The baseline vehicle fleet structure was derived from national transport statistics, vehicle registration data, and energy balance reports. The dataset includes the total number of vehicles and their distribution across major categories, including passenger cars, light commercial vehicles, buses, trucks, and motorcycles/three-wheelers. In addition, the fleet was disaggregated by emission standard categories (e.g., Euro I–III for baseline conditions), with detailed distributions of vehicle categories by emission standard over time (2025–2050), expressed as shares of fuel use/activity. This classification allows the GAINS model to represent technology-specific emission factors and control measures. Detailed summary tables on activity data, fleet composition assumptions, emission factor parameters used, and distribution of vehicle categories by emission standard application rates in the modeling framework are provided in the Supplementary Material (Tables S1–S4) to facilitate reproducibility of the analysis.

Transport activity indicators and long-term projections of vehicle kilometers traveled, modal distribution, and efficiency improvements were derived from the EnerNEO (available online: https://www.enerdata.net/solutions/national-energy-outlook-model.html, accessed on 28 December 2025) Pakistan energy system model [93]. EnerNEO provides internally consistent projections of energy demand that are aligned with national macroeconomic and demographic assumptions used in climate planning exercises. Vehicle activity (VKT) is treated as an exogenous input derived from EnerNEO projections and is applied consistently across all scenarios; potential rebound effects associated with lower operating costs of electric vehicles are not explicitly modeled. The integration between EnerNEO and GAINS follows a soft-linking approach, whereby activity and energy demand projections from EnerNEO are used to initialize and update the GAINS model through a unidirectional data transfer. No iterative feedback loop is implemented between the two models.

Default emission factors, technology parameters, and control efficiencies were drawn from the GAINS regional database [94] and subsequently adjusted to reflect Pakistan specific fuel quality standards, regulatory documents, and peer reviewed literature [62,68,95]. Future transport energy demand trajectories for the period 2024 to 2050 were harmonized between EnerNEO and GAINS following established mapping procedures used in previous Pakistan focused studies [65].

Table 1 summarizes the key datasets used for model calibration and scenario development, including base year information and principal data sources.

Table 1. Key datasets used for GAINS model calibration and transport-sector projections.

Data Category	Description	Base Year	Main Sources
Vehicle fleet stock	Number of vehicles by mode, class, technology type, and vintage	2024	[23]
Fuel consumption	Final energy use by fuel type for road and non-road transport	2024	[27]
Activity data	Annual vehicle-km traveled (VKT), occupancy/load factors, freight/passenger shares	2024	[93]
Emission factors (EFs)	Pollutant- and technology-specific EFs for tailpipe emissions	Regional defaults updated for Pakistan	[62,94]
Control technology coverage	Penetration of standards (Euro classes), after-treatment devices	2024	[62,94]
Non-road mobile sources	Activity and fuel consumption for agriculture, construction, and rail	2024	[27]
Macro drivers for projections	GDP growth, population, urbanization, modal shift	2024–2050	[93]

2.3. Emission Estimation Methodology

The GAINS model estimates pollutant emissions using the following equation that integrates activity levels, uncontrolled emission factors, efficiencies of control technologies, and their application rates. The emissions for a given pollutant are calculated as:

$$EM_{i,p} = \sum_k \sum_m A_{i,k}\, EF_{i,k,m,p}\, X_{i,k,m,p} \quad (1)$$

where i represents the country, k the type of activity, m the abatement or control measure, and p the specific pollutant. Here, $EM_{i,p}$ is the total emission of pollutant p in country i, $A_{i,k}$ is the level of activity k, $EF_{i,k,m,p}$ is the emission factor for pollutant p after applying measure m, and $X_{i,k,m,p}$ represents the fraction of activity k to which control measure m is applied.

Air pollutant emissions were estimated using pollutant and technology specific emission factors embedded within GAINS, which reflect both uncontrolled emissions and reductions achieved through emission control technologies such as diesel particulate filters, selective catalytic reduction systems, exhaust gas recirculation, and three-way catalytic converters. The fleet is classified according to Euro equivalent emission standards, enabling explicit representation of technology turnover and regulatory progression over time. Emission factors in GAINS are technology-specific and represent average performance under regionally representative operating conditions; however, the model does not explicitly incorporate functional adjustments for fuel sulfur content, operating temperature effects, or degradation of emission control technologies with vehicle age.

Fuel quality assumptions incorporate sulfur content limits consistent with national regulations and policy targets [59]. Annual shares of emission control technologies and cleaner vehicle standards evolve dynamically in the model based on scenario specific assumptions regarding regulatory enforcement, fleet renewal, and technology adoption.

GHG emissions of methane and nitrous oxide are calculated using GAINS default parameters, which capture the influence of fuel type, combustion technology, and emission controls. This integrated treatment ensures consistency across air pollutants and GHG estimates and allows for direct assessment of co benefits across policy scenarios.

The modeling framework does not explicitly account for fuel consumption penalties associated with advanced emission control technologies (e.g., DPF and SCR systems). As a result, small increases in fuel use associated with these technologies are not reflected in the CO_2 emission estimates.

2.4. Policy and Regulatory Context

Scenario development was grounded in Pakistan's existing transport and climate policy framework, including national strategies, regulatory instruments, and recent policy reforms related to vehicle emission standards, fuel quality, and electrification. Key policy documents informing the analysis include the National Transport Policy 2018, the New Energy Vehicle Policy 2025, the National Clean Air Policy 2023, and Pakistan's Third Nationally Determined Contribution submitted under the UNFCCC [59–61,96].

These instruments provide the basis for assumptions regarding vehicle technology transitions, electrification rates, fuel quality improvements, and emission control adoption across the four scenarios examined in this study. Table 2 presents an overview of the relevant policy instruments, their objectives, and their role in informing model assumptions.

Table 2. Key transport and climate policy instruments in Pakistan relevant for emissions and mitigation strategies.

Policy	Description	Relevance to Emissions Modeling	Implementation Status (as of 2024–2025)
National Transport Policy (2018) [96]	Provides a long-term framework for multimodal transport, road safety, public transit expansion, and infrastructure development.	Offers baseline assumptions for modal distribution, vehicle growth, and non-road infrastructure expansion.	Partly implemented; major infrastructure projects underway, but modal shift and public transit targets lagging.
New Energy Vehicle Policy (2025) [60]	Targets electrification of new light-duty vehicle sales, supports EV incentives, charging infrastructure development, and cleaner mobility.	Basis for EVT and NDC+ scenarios' electrification assumptions; shifts part of fuel demand from liquid fuels to electricity.	Recently introduced; EV market penetration remains limited; incentives under early implementation.
National Clean Air Policy 2023 [59]	Aims to improve ambient air quality, tighten fuel and vehicle emission standards, and regulate key pollution sources including mobile emissions.	Provides support for Euro-VI scenario assumptions, fuel sulfur reductions, and enhanced emission control standards.	Adopted in 2023; regulatory enforcement and fuel-quality upgrades still in initial phases.

Table 2. *Cont.*

Policy	Description	Relevance to Emissions Modeling	Implementation Status (as of 2024–2025)
Pakistan's Third NDC 2025 [61]	Commits to economy-wide GHG mitigation, including transport sector as a key contributor, targets emissions reductions, modal shift, and clean mobility.	Serves as overarching mitigation ambition guiding the NDC+ scenario; frames long-term emission reduction goals.	Submitted in 2025; formal endorsement in progress; sectoral sub-targets under consultation.
Fuel Quality and Emission Standards Regulations [94,95]	Regulates fuel sulfur content and vehicle Euro-equivalent emission standards for new sales, with timeline for phasing out older vehicles and upgrading fuel quality.	Underpin control technology mapping and fuel-quality assumptions in all scenarios (particularly Euro-VI and NDC+).	Regulations in place; low-sulfur fuel supply limited; enforcement uneven across regions.
Non-road Mobile Source Regulations	Covers emission controls for construction, agricultural, and rail machinery; includes fuel standards and retrofit requirements.	Supports inclusion of non-road sources in emission inventory and prospects for mitigation under policy scenarios.	Regulatory draft exists; implementation and monitoring remain weak, source data uncertain.

2.5. Scenario Design and Model Integration

Four internally consistent scenarios were developed to evaluate alternative mitigation pathways for Pakistan's transport sector. The BAU scenario reflects continuation of existing policies with limited enforcement and gradual fleet modernization based on historical trends. The Electric Vehicle Transition scenario assumes progressive electrification of major gasoline powered vehicle categories, while internal combustion engine technologies evolve in line with the BAU trajectory.

The Euro-VI scenario assumes accelerated implementation of Euro VI equivalent emission standards supported by nationwide availability of ultra-low sulfur fuels and widespread adoption of advanced after treatment technologies, particularly for heavy-duty diesel vehicles. Electric vehicle uptake in this scenario remains consistent with baseline assumptions.

The NDC+ scenario combines accelerated electrification with the introduction of stringent vehicle emission standards. Electrification primarily affects passenger vehicles and two- and three-wheelers, while heavy-duty vehicles increasingly adopt Euro-VI equivalent emission standards. By 2050, electric vehicles represent approximately 85–90% of the light-duty vehicle fleet, while conventional internal combustion vehicles that remain in operation comply with advanced emission control technologies. The NDC+ scenario represents an ambitious, policy-driven pathway assuming accelerated electrification and regulatory implementation. It is designed as a technically feasible transition and does not explicitly account for macroeconomic constraints, fiscal limitations, or infrastructure investment requirements such as grid reinforcement and charging deployment. This scenario is designed to align with Pakistan's long term climate mitigation ambitions.

In the BAU scenario, fleet modernization refers to the gradual replacement of older vehicles with newer models in line with historical fleet turnover trends and currently implemented emission standards. The analysis assumes a continuation of recent vehicle growth trends and an average fleet renewal rate consistent with national vehicle registration statistics. Under this assumption, newer vehicles gradually replace older high-emitting vehicles, resulting in modest improvements in fleet emission performance over time without the introduction of additional policy measures.

A key methodological feature of this study is the integration of EnerNEO and GAINS. EnerNEO provides projections of transport activity, fleet evolution, modal shares, and fuel demand, which are mapped into GAINS to update activity levels, technology shares, and emission control penetration under each scenario. This integrated workflow ensures internal consistency between energy demand, technology transitions, and emissions outcomes. Figure 2 illustrates the interaction between the two modeling frameworks.

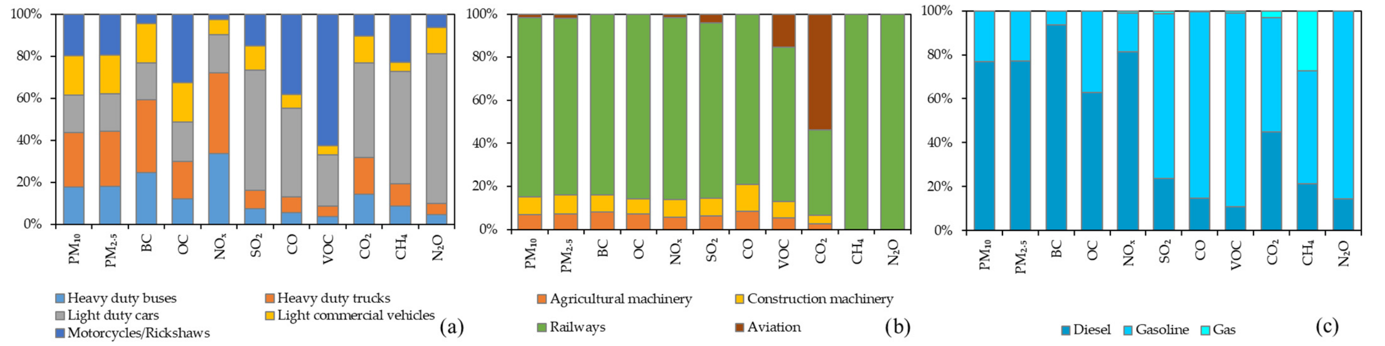

Figure 2. Percentage contributions of (**a**) road transport categories, (**b**) non-road transport categories, and (**c**) fuel types to multi-pollutant emissions in Pakistan's transport sector, 2024.

All scenarios are initialized using identical base year assumptions for fleet composition, fuel use, and technology distribution to ensure comparability of results across policy pathways. Table 3 summarizes the main assumptions and timelines associated with each scenario through 2050.

Table 3. Summary of policy scenarios and key assumptions for Pakistan's transport sector.

Scenario	Description and Key Assumptions
Business-as-Usual (BAU)	Continuation of the existing policy framework with limited enforcement of emission standards and gradual fleet modernization following historical trends. Advanced emission control technologies achieve minimal market penetration by 2050. Vehicle technology shares and fuel quality specifications remain largely static, reflecting a baseline regulatory environment and market-driven adoption rates.
Electric Vehicle Transition (EVT)	Progressive electrification of gasoline-powered vehicle categories, with EV market shares increasing from 1% in 2025 to 30% by 2035 and 90% by 2050 [60]. Internal combustion engine (ICE) fleet evolution and emission control adoption follow the BAU trajectory for non-electrified segments. Electricity demand projections account for EV efficiency advantages (3–4× higher energy efficiency) and anticipated grid decarbonization.
Euro-VI	Mandatory implementation of Euro-VI equivalent emission standards from 2026, supported by nationwide provision of ultra-low-sulfur fuels (<10 ppm). Heavy-duty vehicles adopt diesel particulate filters (DPF) and selective catalytic reduction (SCR) systems by 2035. Gasoline vehicles employ durable three-way catalytic converters. EV penetration remains at BAU levels.
Nationally Determined Contribution Plus (NDC+)	Comprehensive policy package combining accelerated electrification (EVT timeline advanced by five years) with Euro VI implementation and broad structural reforms. Measures include vehicle efficiency improvements, modal shift toward public and non-motorized transport, expansion of compressed natural gas use in heavy-duty segments, and strengthened vehicle inspection and maintenance programs. The scenario is designed to achieve Pakistan's 50% GHG reduction target by 2035.

3. Results

3.1. Baseline Emission Inventory

3.1.1. Overall Emission Profile

The Pakistan transport sector represents a major source of air pollutants and GHGs, with road transport overwhelmingly dominating total emissions. The 2024 national emission inventory quantifies emissions for eleven pollutants and climate-relevant gases including PM_{10}, $PM_{2.5}$, BC, OC, NO_x, SO_2, CO, VOCs, CO_2, CH_4, and N_2O. Results indicate that road mobile sources account for more than 97 percent of total emissions for nearly all pollutants, as summarized in Table 4. In contrast, non-road mobile sources, including agricultural machinery, construction equipment, and railways contribute a relatively minor share, remaining below 3 percent for all pollutants, with their largest contribution observed for CO_2 at approximately 2 percent.

Table 4. Multi-pollutant emissions from road and non-road sources in Pakistan's transport sector, 2024, with percentage contributions. Units: kt; CO_2 in Mt.

Pollutants	Road Mobile Sources		Non-Road Mobile Sources		Total (kt)
	Emission (kt)	Contribution	Emission (kt)	Contribution	
PM_{10}	22.27	97.5%	0.58	2.5%	22.85
$PM_{2.5}$	21.52	97.5%	0.55	2.5%	22.07
BC	11.78	97.9%	0.25	2.1%	12.03
OC	7.95	98.3%	0.14	1.7%	8.09
NO_x	294.53	97.6%	7.11	2.4%	301.64
SO_2	97.20	99.1%	0.93	0.9%	98.13
CO	986.18	99.8%	2.34	0.2%	988.52
VOC	142.32	99.2%	1.11	0.8%	143.43
CO_2	38.00	98.2%	0.70	1.8%	38.70
CH_4	14.02	99.7%	0.04	0.3%	14.06
N_2O	3.10	99.4%	0.02	0.6%	3.12

These results reflect structural characteristics of Pakistan's transport system, where heavy-duty diesel vehicles operate with higher fuel consumption rates and often older engine technologies, leading to disproportionate contributions to particulate matter and nitrogen oxide emissions. In contrast, gasoline-powered passenger vehicles and two- and three-wheelers dominate emissions of carbon monoxide and volatile organic compounds due to incomplete combustion in spark-ignition engines.

3.1.2. Pollutant-Specific Patterns

Particulate matter emissions constitute a critical component of the transport sector's air quality burden. Total $PM_{2.5}$ and PM_{10} emissions in 2024 are estimated at 22.07 kt and 22.85 kt, respectively, with road transport responsible for over 97 percent of both totals. Heavy-duty diesel vehicles dominate emissions of black carbon, with trucks contributing 35 percent and buses contributing 25 percent of the national total of 12.03 kt. This pattern reflects the widespread use of diesel engines with limited emission control technologies [65]. In contrast, organic carbon emissions amounting to 8.09 kt are largely driven by motorcycles and three-wheelers, which together account for 33 percent of the total. This reflects incomplete combustion associated with small gasoline engines and limited regulatory oversight in these vehicle categories. It should be noted that the reported PM_{10} and $PM_{2.5}$ emissions represent exhaust emissions only and do not include non-exhaust sources such as brake wear, tire wear, and road dust resuspension, which can be substantial in urban environments.

Gaseous air pollutant emissions exhibit distinct source profiles across vehicle types. National NO_x emissions in 2024 reach 301.64 kt, with heavy-duty trucks and buses accounting for 38 percent and 34 percent, respectively. SO_2 emissions total 98.13 kt and originate almost entirely from road transport, reflecting the continued use of sulfur-containing fuels. Passenger cars alone contribute 57 percent of SO_2 emissions, followed by light commercial trucks with 11 percent. Carbon monoxide and VOC emissions are dominated by two- and three-wheelers, which together account for 38 percent of CO emissions and 63 percent of VOC emissions. These high shares are driven by inefficient combustion, aging vehicle fleets, and the limited penetration of emission control technologies in this segment [95].

Transport-related GHG emissions display similar patterns. Total CO_2 emissions from the transport sector in 2024 are estimated at 38.70 Mt, with road transport accounting for 98.2 percent of the total. Passenger cars represent the largest contributing category at 45 percent, followed by trucks at 18 percent and buses at 14 percent. From a fuel perspective, gasoline and diesel together account for more than 97 percent of transport CO_2 emissions, while compressed natural gas contributes approximately 3 percent. Emissions of CH_4 and N_2O amount to 14.06 kt and 3.12 kt, respectively. Passenger cars dominate emissions of both gases, contributing 53 percent of CH_4 and 71 percent of N_2O emissions. Non-road sources contribute marginally to GHG emissions, with railways representing the largest share among these sources, although absolute emissions remain very small. Figure 2 illustrates the percentage contributions of road transport categories, non-road transport categories, and fuel types to multi pollutant emissions in 2024.

3.1.3. Vehicle Category Contributions

The vehicle specific contributions summarized in Table 5 highlight pronounced heterogeneity across vehicle categories. Heavy-duty diesel vehicles dominate $PM_{2.5}$, PM_{10}, black carbon, and NO_x emissions. Motorcycles and three-wheelers are the primary sources of VOC and CO emissions, while passenger cars contribute the largest shares of CO_2, CH_4, N_2O, and SO_2. These patterns highlight the necessity of differentiated, vehicle-specific mitigation strategies rather than uniform regulatory approaches.

Table 5. Contribution of major transport categories to multi-pollutant emissions in Pakistan's transport sector, 2024.

Pollutant	Top Contributing Category	Share of Total Emissions (%)	Second Major Contributor	Share of Total Emissions (%)
PM_{10}	Heavy-duty trucks	26%	Heavy-duty buses	18%
$PM_{2.5}$	Heavy-duty trucks	26%	Heavy-duty buses	18%
BC	Heavy-duty trucks	35%	Heavy-duty buses	25%
OC	Motorcycles/Rickshaws	33%	Light-duty Cars	19%
NO_x	Heavy-duty trucks	38%	Heavy-duty buses	34%
SO_2	Light-duty Cars	57%	Light commercial trucks	11%
CO	Light-duty Cars	42%	Motorcycles/Rickshaws	38%
VOC	Motorcycles/Rickshaws	63%	Light-duty Cars	25%
CO_2	Light-duty Cars	45%	Heavy-duty trucks	18%
CH_4	Light-duty Cars	53%	Motorcycles/Rickshaws	23%
N_2O	Light-duty Cars	71%	Light commercial vehicles	12%

The dominance of heavy-duty trucks and buses in particulate matter and NO_x emissions is primarily driven by their reliance on diesel engines, higher engine loads, and longer annual travel distances compared to other vehicle categories. Diesel combustion typically generates higher levels of nitrogen oxides and particulate matter, particularly in fleets with limited penetration of advanced emission control technologies. Conversely, the relatively high contribution of passenger cars to SO_2 emissions reflects the sulfur content in gasoline and the large share of gasoline-powered vehicles in the national fleet. Non-road sources such as railways and construction machinery contribute comparatively small shares to total emissions due to their limited fleet size and overall lower activity levels relative to road transport.

Overall, the baseline inventory demonstrates that road transport overwhelmingly drives Pakistan transport emissions, with diesel powered trucks and buses responsible for most particulate and NO_x emissions, while gasoline powered passenger cars and two- and three-wheelers dominate emissions of GHGs and incomplete combustion pollutants. The relatively low contribution of non-road sources reflects currently available activity data and fuel consumption statistics; however, given limited monitoring and potential underreporting of informal activities—particularly in construction and agricultural sectors—these estimates may represent a lower-bound of actual emissions. These findings underscore the need for targeted mitigation strategies that address specific vehicle categories and fuel types rather than relying on uniform policy approaches. The 2024 baseline inventory provides a robust foundation for evaluating future emission trajectories under alternative policy scenarios. Details of sector- and category-wise emissions for road (Table S5) and non-road transport (Table S6), along with fuel-type–wise emissions across both sectors (Table S7), for the baseline year 2024 are provided in the Supplementary Materials.

To assess the robustness of the baseline inventory, modeled estimates of vehicle activity, fleet composition, and fuel consumption were systematically compared with official national datasets, including vehicle registration statistics and energy consumption records. As shown in Figure A1 (Appendix A) and Table S1, total transport-sector energy consumption (in Mtoe) from the GAINS model closely aligns with official estimates, with differences remaining within a narrow margin. Consistent agreement is also observed across major fuel types, including diesel and gasoline, and, where data are available, for vehicle stock in key categories. These comparisons indicate that both the aggregate energy balance and the distribution of activity across fuels and vehicle types are well captured by the model.

Minor discrepancies are primarily associated with underreported or informal segments, particularly motorcycles and three-wheelers, as well as fuel use that is not fully captured in official reporting systems. Such differences are characteristic of transport-sector datasets in developing-country contexts and reflect structural data limitations rather than model inconsistencies. Overall, the close agreement across multiple validation dimensions supports the internal consistency and empirical grounding of the inventory, indicating that it provides a credible and policy-relevant representation of real-world transport emissions for subsequent scenario analysis.

Uncertainties remain due to limited monitoring of non-road activity, variability in vehicle maintenance practices, fuel adulteration, and incomplete coverage of informal transport modes. These uncertainties reflect structural data constraints common in developing country contexts rather than methodological shortcomings. Although a quantitative uncertainty analysis is beyond the scope of this study, explicitly acknowledging these limitations provides important context for interpreting the results and highlights priorities for future data improvement. Building on this validated baseline, the following section evaluates how alternative policy strategies influence future emission pathways.

3.2. Emission Pathways and Mitigation Potential for 2024 to 2050

Future emission pathways for Pakistan transport sector were assessed through 2050 under four policy scenarios using the integrated EnerNEO and GAINS modeling framework. Between 2024 and 2050, Pakistan is projected to undergo significant demographic and economic change. Population growth of approximately 42 percent, nearly threefold growth in gross domestic product, and continued urbanization are expected to substantially increase transport demand. Urban population is projected to rise from 94 million in 2024 to 122 million by 2050, while per capita income increases from EUR 1629 to EUR 3060. These structural drivers form the basis for evaluating emission outcomes under alternative policy pathways.

Energy demand projections reveal substantial divergence across scenarios, as shown in Figure 3. Under the Business as Usual and Euro VI scenarios, final transport energy demand nearly doubles from 609.6 PJ in 2024 to approximately 1211.6 PJ by 2050. This increase reflects continued reliance on fossil fuels and illustrates the limitations of end of pipe emission control measures that do not address underlying growth in transport activity. In contrast, the Electric Vehicle Transition and NDC+ scenarios significantly moderate energy demand growth, limiting final energy consumption to approximately 852.3 PJ by 2050. These reductions result from higher vehicle efficiency, electrification, and fuel diversification. Relative to Business as Usual, this represents nearly a 50 percent reduction in projected energy demand by mid-century.

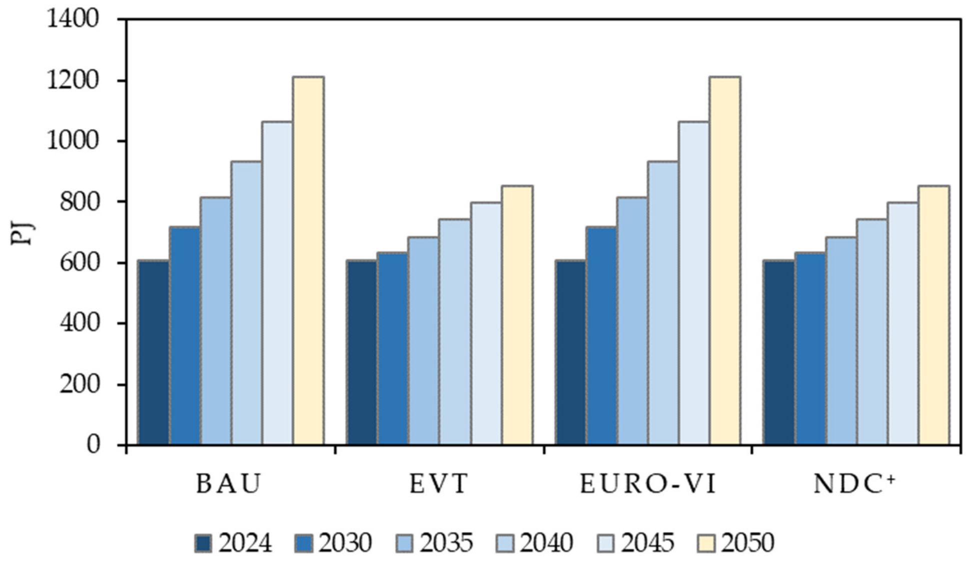

Figure 3. Projected energy demand in Pakistan's transport sector under four policy scenarios (BAU, EVT, Euro-VI, and NDC+) for the period 2024–2050, expressed in petajoules (PJ).

Changes in energy demand directly influence emission trajectories because fuel consumption is the primary determinant of both greenhouse gas emissions and many air pollutants. Electrification scenarios reduce energy demand due to the substantially higher efficiency of electric drivetrains compared to internal combustion engines. In contrast, the Euro-VI scenario primarily targets pollutant emissions through improved after-treatment technologies but does not substantially alter total energy demand, as vehicle propulsion systems remain largely unchanged.

The divergence in energy demand translates directly into differences in air pollutant emissions, as illustrated in Figure 4. Under the BAU scenario, emissions of nearly all pollutants increase steadily through 2050. $PM_{2.5}$ emissions rise from 22.1 kt in 2024 to 36.2 kt by 2050, representing an increase of 64 percent, while NO_x emissions increase from 302 kt to 500 kt. Black carbon emissions increase by nearly 50 percent, reaching 18.2 kt by 2050, driven by sustained diesel fuel use in the absence of stringent emission controls. Further, under the BAU scenario, total emissions increase over time primarily due to continued growth in transport demand and expansion of the vehicle fleet. Although gradual fleet modernization introduces newer vehicles with improved emission performance, these improvements are insufficient to offset the overall increase in activity levels. As a result, aggregate emissions of several pollutants continue to rise despite modest technological progress.

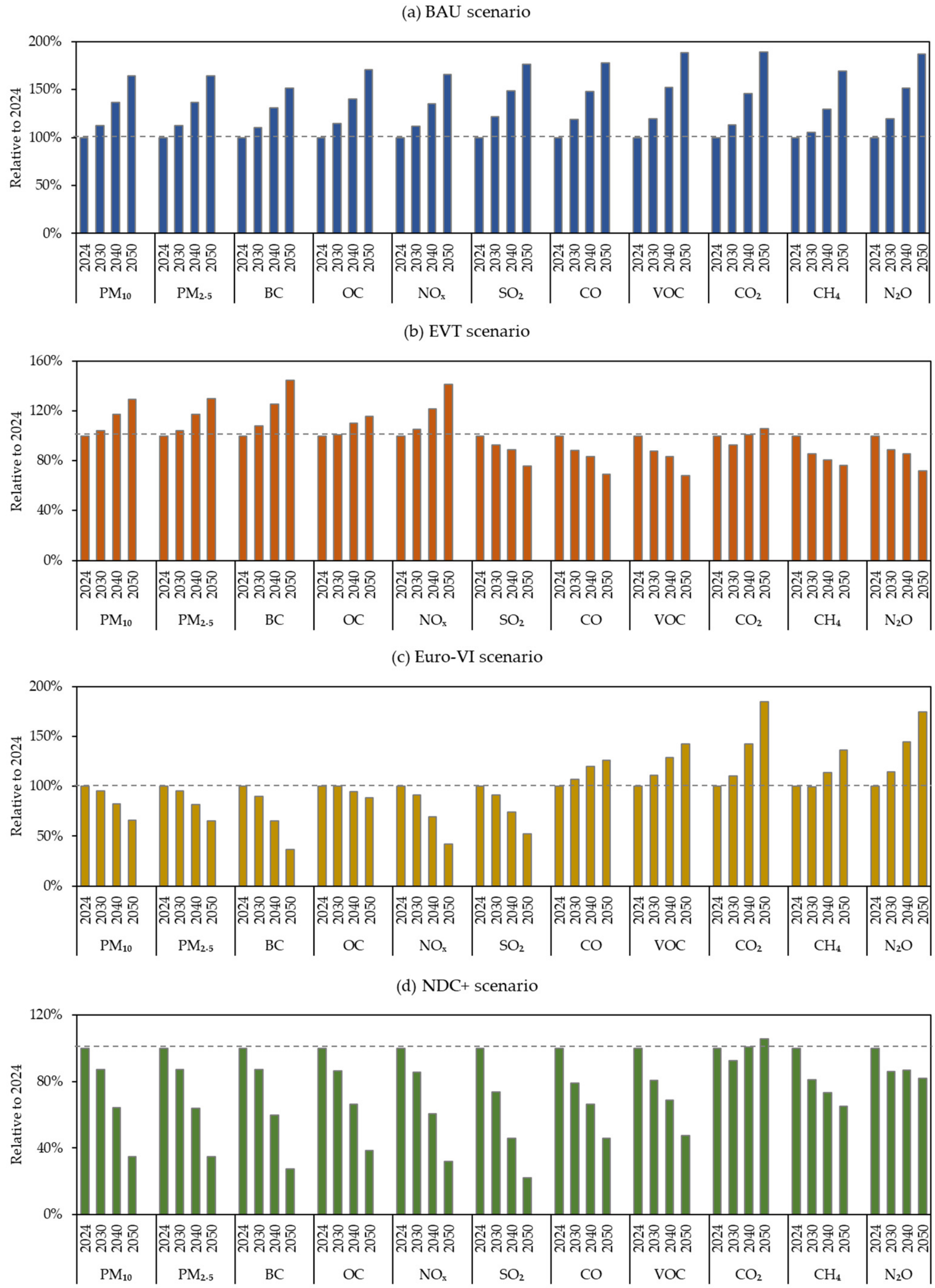

Figure 4. Projected trajectories of multi-pollutant emissions ($PM_{2.5}$, BC, NO_x, SO_2, CO, VOC, CO_2, CH_4, and N_2O) from Pakistan's transport sector under four policy scenarios: (**a**) BAU, (**b**) EVT, (**c**) Euro-VI, and (**d**) NDC+ for the period 2024–2050. The horizontal dashed line at 100% represents the baseline emission level for the year 2024, against which all scenario projections are expressed.

Mitigation oriented scenarios yield substantially different outcomes. The Electric Vehicle Transition scenario delivers moderate improvements in air quality by reducing $PM_{2.5}$ emissions to 28.7 kt by 2050, approximately 20 percent lower than Business as Usual levels. Carbonaceous emissions also decline due to reduced combustion-based vehicle activity. The Euro VI scenario produces the largest reductions in conventional air pollutants, reducing $PM_{2.5}$ emissions by approximately 60 percent and NO_x emissions by approximately 75 percent relative to Business as Usual by 2050, resulting in emissions of 14.5 kt and 127 kt, respectively. These reductions reflect the effectiveness of stringent emission standards supported by low sulfur fuels and advanced exhaust after treatment technologies [93].

The integrated NDC+ scenario delivers the most comprehensive emission reductions across all pollutants. By 2050, $PM_{2.5}$ emissions decline to 7.7 kt, black carbon emissions to 3.3 kt, and NO_x emissions to 97 kt. Substantial reductions are also observed for SO_2, CO, and VOC emissions. These results demonstrate the strong synergies that arise when electrification, emission standards, and structural transport reforms are implemented together.

GHG emission trajectories show distinct scenario dependent patterns. Under Business as Usual, CO_2 emissions increase from 38.7 Mt in 2024 to 72.9 Mt by 2050, reflecting rising fossil fuel consumption. The Euro VI scenario achieves only marginal reductions in CO_2 emissions relative to Business as Usual, highlighting the limited climate mitigation potential of emission control technologies that do not involve fuel switching [64]. In contrast, the EVT and NDC+ scenarios stabilize CO_2 emissions at approximately 41 to 42 Mt by 2050 despite continued growth in transport activity. Methane and nitrous oxide emissions follow similar trends, with the NDC+ scenario achieving nearly 60 percent reductions relative to Business as Usual by 2050.

A comparison of the mitigation scenarios indicates that the Euro-VI pathway delivers the largest reductions in conventional air pollutants due to stringent emission control technologies, while the EVT scenario achieves the most substantial reductions in carbon dioxide emissions through electrification. The integrated NDC+ scenario combines these approaches and therefore provides the most balanced outcome, delivering substantial improvements in both air quality and climate mitigation relative to the business-as-usual trajectory.

The most important insight from Figure 4 is the magnitude of emission reductions achievable through integrated mitigation strategies, particularly under the NDC+ scenario, which demonstrates the largest simultaneous decline across both air pollutants and greenhouse gases.

Category specific emission dynamics further inform policy priorities, as shown in Figure 5. Heavy-duty vehicles remain the dominant contributors to $PM_{2.5}$, black carbon, and NO_x emissions throughout the projection period, particularly under BAU conditions. Two- and three-wheelers continue to dominate VOC and CO emissions due to persistent incomplete combustion and limited technology upgrades. Passenger cars remain the largest source of CO_2 emissions, although their contribution declines substantially under electrification focused scenarios.

Figure 5 illustrates a structural shift in the composition of transport emissions over time, with electrification and stricter emission standards gradually reducing the contribution of high-emitting vehicle categories. However, residual emissions remain even under ambitious mitigation scenarios, indicating the continued importance of complementary policy measures.

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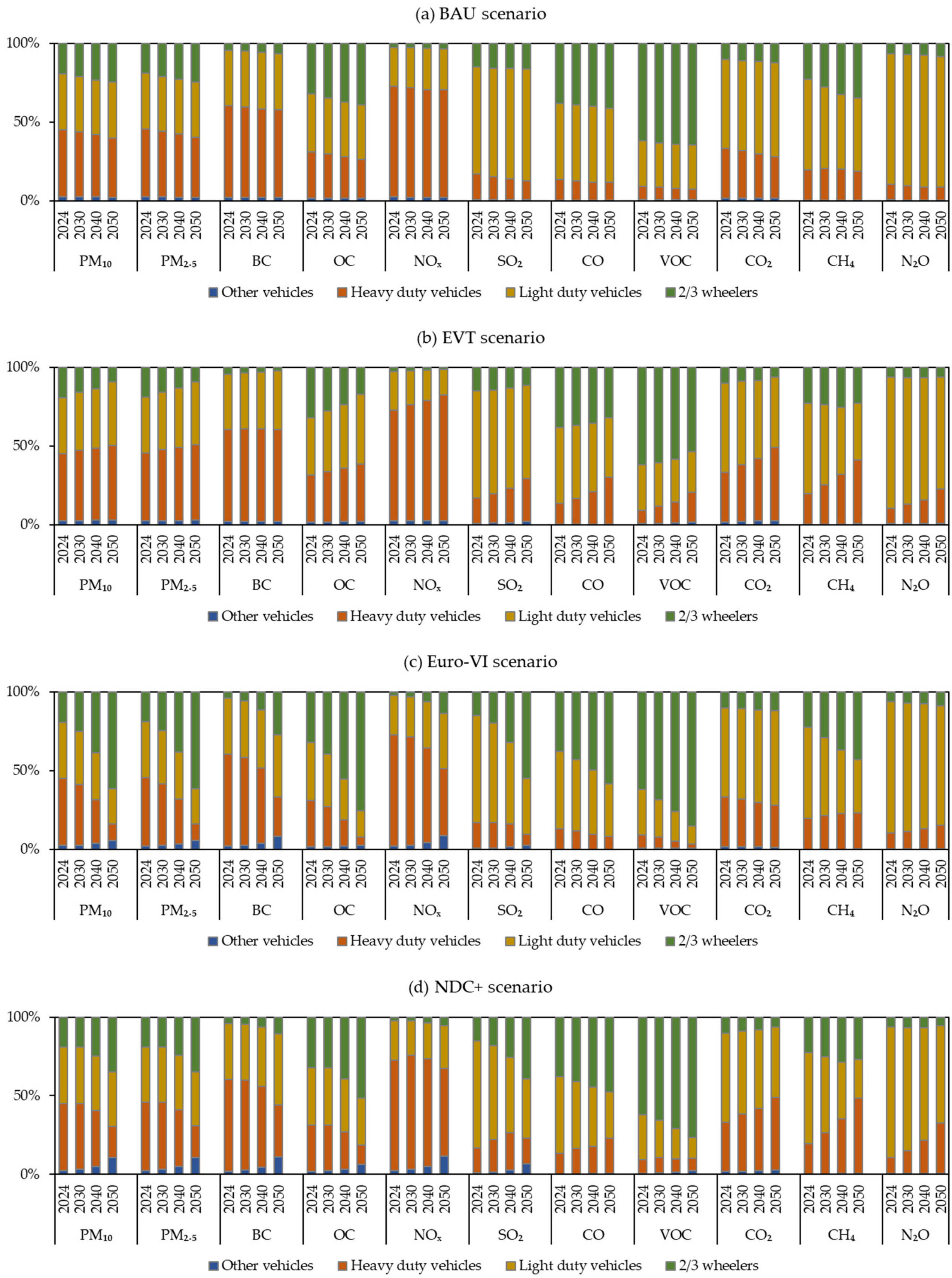

Figure 5. Relative contributions of transport sector source categories (road and non-road) to selected air pollutants and GHGs in Pakistan, 2024–2050, under different policy scenarios.

Overall, the scenario analysis demonstrates that continuation of current policies leads to unsustainable growth in emissions and energy demand. Electrification focused pathways are effective in reducing GHG emissions, while stringent emission standards are essential for improving air quality. The integrated NDC+ scenario achieves the most balanced and robust outcomes across both air quality and climate objectives, highlighting the importance of comprehensive policy packages that combine electrification, emission standards, and broader structural reforms. Despite significant reductions under the NDC+ scenario, some emissions persist due to remaining internal combustion vehicles, heavy-duty transport segments that are more difficult to electrify, and continued growth in transport demand. These findings provide strong empirical support for integrated transport strategies aligned with Pakistan long term sustainability goals. Detailed projections of air pollutant and greenhouse gas (GHG) emissions under different policy scenarios for 2024–2050 are provided in the Supplementary Materials, including total transport sector emissions (Table S8) and disaggregated emissions by source categories (road and non-road) (Table S9).

4. Discussion

The results of this study demonstrate that emissions from Pakistan's transport sector are highly sensitive to the design and coherence of policy interventions. Under the BAU pathway, emissions of both air pollutants and GHGs rise substantially through 2050 due to sustained growth in vehicle activity, energy consumption, and continued reliance on fossil fuels. These trajectories conflict with Pakistan's climate commitments and national air quality objectives, exacerbating public health, environmental, and economic challenges. In contrast, mitigation-oriented scenarios, EVT, Euro VI, and the integrated NDC+ pathway, significantly alter emission trajectories through cleaner technologies, improved fuel quality, and structural reforms. These results highlight that long-term sustainability outcomes are determined primarily by policy direction rather than incremental technological change [81].

Distinct differences in mitigation performance emerge across scenarios. The Euro VI scenario achieves the largest reductions in conventional air pollutants, particularly particulate matter, nitrogen oxides, and black carbon, driven by advanced exhaust after-treatment technologies and ultra-low sulfur fuels. These reductions demonstrate the effectiveness of stringent emission standards in reducing urban exposure to harmful pollutants. However, carbon dioxide reductions remain limited, underscoring that end-of-pipe controls alone are insufficient for deep decarbonization in the transport sector [64]. This implies that CO_2 emissions under the Euro-VI scenario may be slightly underestimated; however, the magnitude of this effect is expected to be small relative to overall energy demand trends.

The Electric Vehicle Transition scenario delivers the most pronounced climate benefits, reducing carbon dioxide, methane, and nitrous oxide emissions through large-scale displacement of internal combustion engines and reduced reliance on petroleum fuels. While this scenario improves tailpipe emissions moderately, particularly for particulate matter and nitrogen oxides, legacy vehicle fleets and non-electrified segments continue to operate under weak emission standards. These results emphasize that electrification, while essential for climate mitigation, must be paired with stringent emission controls to deliver comprehensive air quality improvements. The integrated NDC+ scenario consistently outperforms single policy approaches, combining accelerated electrification, Euro VI implementation, fuel quality improvements, vehicle efficiency gains, modal shift, and strengthened inspection and maintenance programs. This coordinated approach achieves the largest cumulative reductions in both air pollutants and GHGs by mid-century, demonstrating strong synergies between climate and air quality objectives [64]. This scenario aligns closely with Pakistan's third Nationally Determined Contribution, which emphasizes maximizing cross-sectoral co-benefits first rather than pursuing isolated mitigation actions.

It should be noted that the present analysis focuses on exhaust emissions and does not explicitly account for non-exhaust particulate matter sources such as tire and brake wear or road dust resuspension. As electric vehicles tend to be heavier than conventional vehicles, non-exhaust emissions may increase, implying that the reported reductions in particulate matter represent exhaust emission reductions and may therefore be somewhat overestimated in terms of total PM impacts.

Vehicle-category disaggregation further identifies priority intervention areas. Heavy-duty diesel vehicles remain the dominant contributors to black carbon and nitrogen oxide emissions, reflecting high activity levels, fuel consumption, and emission intensity [65]. They are therefore critical targets for stringent emission standards, fuel quality enforcement, and maintenance programs. Passenger cars contribute the largest share of carbon dioxide emissions, highlighting the importance of accelerating electrification and efficiency improvements in this segment. Two- and three-wheelers persist as major sources of volatile organic compounds and carbon monoxide due to incomplete combustion, aging fleets, and limited regulatory oversight. Addressing emissions from these largely informal segments requires tailored policy instruments, including fleet renewal incentives, compliance support, and improved monitoring, rather than uniform regulations. Transport energy demand projections reinforce the broader development implications of policy choices. Under BAU, energy demand nearly doubles by 2050, increasing dependence on imported fuels and exposure to international price volatility. Electrification-driven pathways moderate energy demand growth due to the higher efficiency of electric drivetrains. This reduction not only lowers emissions but also enhances energy security, reduces pressure on foreign exchange reserves and strengthens macroeconomic resilience, highlighting the dual environmental and economic benefits of transport electrification [97,98].

Several sources of uncertainty should be noted. Emission estimates for VOCs and carbon monoxide are particularly sensitive to variability in driving conditions, fleet maintenance, and fuel sulfur content. Two- and three-wheelers, as well as informal transport fleets, carry additional uncertainty due to limited activity and composition data. Limitations in policy implementation, including availability of charging infrastructure, enforcement capacity, and investment access, further affect outcomes [69]. The absence of local Portable Emissions Measurement Systems (PEMS) or dynamometer data represents a further key uncertainty in this study. While the GAINS framework uses regionally calibrated emission factors and multiple data constraints (including national fuel consumption statistics and vehicle registration records) to ensure consistency, direct validation against real-world driving conditions in Pakistan is not possible with currently available data. This limitation is particularly relevant for pollutants such as VOCs and CO, which are highly sensitive to driving conditions and maintenance practices. Future research incorporating local PEMS measurements would substantially improve the accuracy of emission estimates.

Furthermore, the NDC+ scenario assumes high compliance with inspection and maintenance (I&M) programs, reflecting an idealized implementation of regulatory measures. In practice, compliance rates may be lower due to institutional and enforcement constraints, which could reduce the magnitude of projected emission reductions. As compliance leakage is not explicitly modeled, the estimated mitigation—particularly for particulate matter—should be interpreted as an upper-bound outcome under effective policy enforcement.

This study adopts a tank-to-wheel (TTW) perspective, meaning that upstream emissions from electricity generation and fuel refining are not included in the transport-sector emission estimates. The net GHG reductions from electrification reported here therefore reflect tailpipe emissions only. A well-to-wheel (WTW) analysis would likely yield lower net reductions under current conditions, given Pakistan's relatively carbon-intensive electricity grid (approximately 0.45–0.55 kg CO_2/kWh) and transmission losses (on the order of

15–20%) [99–101]. The net climate benefits of transport electrification thus depend critically on the emissions intensity of the electricity supply. With a generation mix that currently relies heavily on thermal sources (natural gas, furnace oil, and coal), the life-cycle GHG reductions from EV adoption may be lower than the tailpipe reductions reported here. However, under national energy transition plans, grid carbon intensity is expected to decline substantially by 2050, improving the life-cycle benefits of EVs over time.

Furthermore, electrification may shift air pollutant emissions from urban traffic corridors to power plant locations, with implications for population exposure and health impacts. While total emissions depend on the power sector, reductions in tailpipe emissions (e.g., NO_x, $PM_{2.5}$, and VOCs) provide clear air quality benefits in urban areas, particularly along traffic corridors, and represent an important co-benefit of electrification. Future research integrating well-to-wheel analysis with spatially resolved power sector modeling would provide a more comprehensive assessment of the climate and air quality implications of transport electrification in Pakistan. Overall, achieving sustained improvements in air quality and climate outcomes in Pakistan's transport sector requires comprehensive, integrated policy packages rather than isolated interventions. Coordinated deployment of electrification, stringent emission standards, fuel quality upgrades, and structural transport reforms is essential for meeting national climate and clean air goals. Future research should build on this framework by incorporating health impact assessments, cost benefit analysis, financing mechanisms, and equity considerations to support evidence-based policy design and implementation.

5. Conclusions

This study develops the first comprehensive and technology detailed emission inventory and scenario-based assessment of Pakistan's transport sector, covering both air pollutants and GHGs for the 2024 base year with projections through 2050. The analysis confirms that road transport overwhelmingly dominates sectoral emissions, contributing more than ninety-seven percent of total emissions for most pollutants. At the same time, pronounced differences in emission profiles across vehicle categories and fuel types highlight the structural complexity of Pakistan's transport system and the need for differentiated mitigation strategies. Heavy-duty diesel vehicles are identified as the principal sources of black carbon and nitrogen oxides, while gasoline powered passenger cars and two- and three-wheelers dominate emissions of carbon dioxide, sulfur dioxide, volatile organic compounds, and carbon monoxide. These findings demonstrate that uniform policy approaches are unlikely to deliver optimal outcomes and that targeted interventions aligned with vehicle type and fuel use are essential.

The scenario analysis illustrates that continuation of current trends under a BAU pathway would result in substantial growth in both air pollutants and GHG emissions by mid-century, driven by rising transport activity and sustained dependence on fossil fuels. Such trajectories are incompatible with Pakistan's climate commitments and clean air objectives. In contrast, mitigation-oriented pathways show that strategic policy choices can fundamentally alter future emission outcomes. The electric vehicle transition scenario delivers substantial reductions in carbon dioxide emissions by displacing fossil fuel consumption and improving overall energy efficiency. The Euro VI scenario achieves the strongest reductions in conventional air pollutants, particularly fine particulate matter, nitrogen oxides, and black carbon, through the deployment of advanced emission control technologies and improved fuel quality. Most importantly, the integrated NDC+ scenario consistently outperforms individual policy pathways by combining electrification, stringent emission standards, and broader structural reforms. This integrated approach delivers the

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largest simultaneous reductions in air pollutants and GHGs, confirming the presence of strong air quality and climate co benefits.

Energy demand projections further reinforce the strategic value of integrated transport mitigation. Under BAU conditions, transport energy demand nearly doubles by 2050, increasing reliance on imported petroleum fuels and heightening energy security risks. Electrification focused pathways significantly moderate this growth due to the higher efficiency of electric drivetrains, thereby reducing fuel import dependence and exposure to international price volatility. These results demonstrate that transport decarbonization offers not only environmental benefits but also important economic and energy security advantages, strengthening the case for its prioritization within national development planning.

Several limitations should be acknowledged. Despite the use of extensive national datasets and technology explicit modeling, uncertainties remain related to informal vehicle fleets, non-road mobile sources, future fuel quality improvements, and assumptions regarding electricity sector decarbonization. In addition, this study does not explicitly quantify implementation costs, financing requirements, behavioral responses, or monetized health benefits. Given the magnitude of projected reductions in fine particulate matter and other pollutants, the associated public health and economic gains are likely to be substantial and warrant dedicated analysis in future research. Further extensions of this framework could incorporate health impact assessment, cost benefit analysis, and equity considerations to strengthen policy relevance and support implementation.

Overall, this study demonstrates that ambitious yet technically feasible interventions in the transport sector can deliver substantial improvements in air quality, climate mitigation, and energy system performance in Pakistan. The results provide robust evidence in support of integrated policy packages that align electrification, emission standards, and structural reforms with national climate commitments. By adopting such coordinated strategies, Pakistan can advance cleaner mobility, reduce public health risks, and enhance long term economic and environmental resilience. The analytical approach and insights presented here are also applicable to other rapidly motorizing developing economies facing similar challenges, reinforcing the broader relevance of integrated transport planning for sustainable development.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su18083954/s1, Table S1: Transport sector fuel consumption by vehicle category (2024), GAINS vs. official statistics; Table S2: Baseline fleet composition used in the modeling framework (unit: 1000 vehicles); Table S3: Energy consumption by transport categories under different scenarios for 2024–2050 (unit: PJ); Table S4: Baseline distribution of vehicle categories by emission standard application rates (units: % of fuel use/activity); Table S5: Sector- and category-wise air pollutant and greenhouse gas (GHG) emissions from Pakistan's road transport sources in 2024 (units: kt; CO_2 in Mt); Table S6: Sector- and category-wise air pollutant and greenhouse gas (GHG) emissions from Pakistan's non-road transport sources in 2024 (units: kt; CO_2 in Mt); Table S7: Fuel-type–wise air pollutant and greenhouse gas (GHG) emissions from Pakistan's road and non-road transport sources in 2024 (units: kt; CO_2 in Mt); Table S8: Air pollutant and greenhouse gas (GHG) emissions from Pakistan's transport sector under different policy scenarios for 2024–2050 (units: kt; CO_2 in Mt); Table S9: Air pollutant and greenhouse gas (GHG) emissions from Pakistan's transport sector source categories (road and non-road) under different policy scenarios for 2024–2050 (units: kt; CO_2 in Mt).

Author Contributions: Conceptualization, K.A.M. and P.P.; methodology, K.A.M. and P.P.; software, K.A.M.; validation, K.A.M. and P.P.; formal analysis, K.A.M.; investigation, K.A.M. and P.P.; data curation, K.A.M.; writing—original draft preparation, K.A.M.; writing—review and editing, P.P., S.M. and A.G.; visualization, K.A.M. and P.P. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

BAU	Business-as-Usual
BC	Black Carbon
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DPF	Diesel Particulate Filter
EF	Emission Factor
EnerNEO	Energy–New Economic Outlook
Euro-VI	Euro VI Vehicle Emission Standards
EV	Electric Vehicle
EVT	Electric Vehicle Transition
GAINS	Greenhouse Gas–Air Pollution Interactions and Synergies
GCISC	Global Climate Change Impact Studies Centre
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HDIP	Hydrocarbon Development Institute of Pakistan
HEI	Health Effects Institute
ICE	Internal Combustion Engine
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
MoCC	Ministry of Climate Change
MoCC&EC	Ministry of Climate Change and Environmental Coordination
MoF	Ministry of Finance
MoIP	Ministry of Industries and Production
Mt	Megaton
N_2O	Nitrous Oxide
NDC	Nationally Determined Contribution
NO_x	Nitrogen Oxides
OC	Organic Carbon
Pak-EPA	Pakistan Environmental Protection Agency
PJ	Petajoule
PM	Particulate Matter
$PM_{2.5}$	Fine Particulate Matter
SCR	Selective Catalytic Reduction
SDGs	Sustainable Development Goals
SO_2	Sulfur Dioxide

UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
VKT	Vehicle Kilometers Traveled
VOCs	Volatile Organic Compounds
WHO	World Health Organization

Appendix A

The energy demand of road transport is estimated using a bottom-up modeling approach, which explicitly accounts for vehicle fleet composition, vehicle activity levels, fuel efficiency, and technology-specific parameters. This approach enables the estimation of both baseline fuel consumption and potential reductions under alternative technological or policy scenarios.

Total annual fuel consumption (*AFC*) in year (*t*) is estimated by aggregating fuel use across all vehicle categories (*k*) and fuel types (*f*). Fuel consumption is calculated as the product of the number of vehicles, annual vehicle activity, and fuel-specific energy intensity, expressed as:

$$AFC = \sum_{f,k} N_{f,k} VKM_{f,k} SFC_{f,k} \quad \text{(A1)}$$

where $N_{f,k}$ denotes the number of active vehicles in category k operating on fuel f; $VKM_{f,k}$ represents the average annual vehicle kilometers traveled per vehicle, averaged across vehicle sizes and age cohorts; and $SFC_{f,k}$ is the specific fuel consumption, accounting for variations in vehicle technology, age, and driving conditions.

Vehicle stock data were obtained from official national statistics published by the Ministry of Finance [23]. Estimates of annual vehicle mileage were derived from the GAINS model, which incorporates national vehicle usage surveys, while specific fuel consumption values were obtained from established technical assessments and transport emission models [88,96].

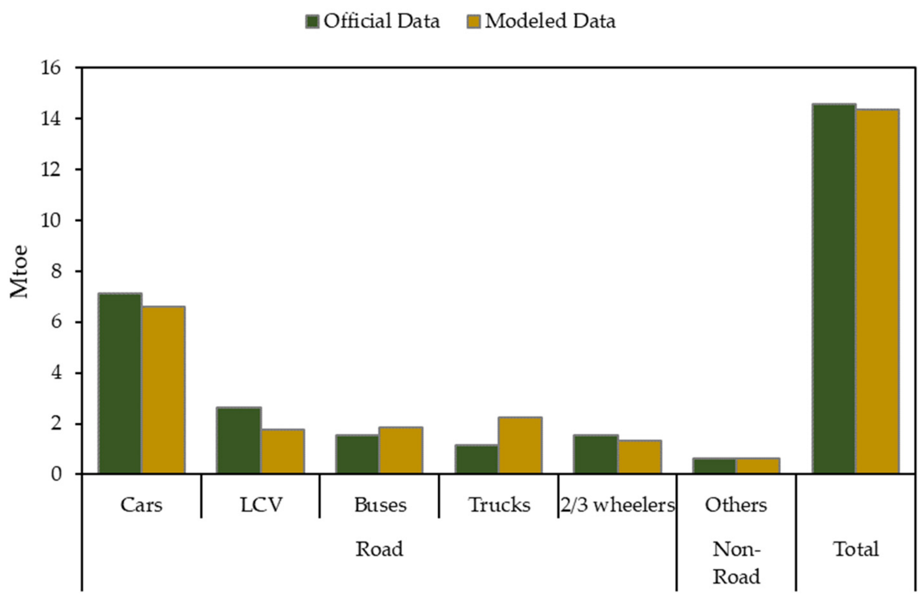

Figure A1. Comparison of transport sector fuel consumption by vehicle category in the base year 2024 as estimated by the GAINS model and reported in official national statistics (Energy Yearbook/EnerNEO).

Figure A1 compares road and non-road transport fuel consumption by vehicle category for the base year 2024, as estimated by the GAINS model and as reported in official national statistics derived from the Energy Yearbook [27] and the EnerNEO energy model.

The comparison shows a high level of consistency in total transport fuel use, indicating that the bottom-up modeling framework successfully reproduces aggregate national energy balances. At the category level, the relative ordering and magnitude of fuel consumption across major vehicle groups are broadly aligned between the two datasets, supporting the representativeness of the modeled fleet structure and activity assumptions. Moderate category-specific differences reflect known uncertainties in registered vehicle data, variations in real-world vehicle usage, and challenges in allocating fuel consumption across heterogeneous vehicle classes, particularly for light commercial vehicles and heavy-duty trucks. Overall, the close agreement at the aggregate level and reasonable correspondence across vehicle categories provide confidence that the GAINS-based baseline inventory captures Pakistan's transport fuel consumption patterns with sufficient accuracy for scenario-based emission analysis.

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