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Low Transportation Emission Analysis and Projection Using LEAP: The Case of Qatar

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Abstract: The transportation sector is a significant source of pollution and greenhouse gas (GHG) emissions contributing to global warming. Although research on the actual emissions from transport has been conducted in several parts of the world, very limited outcomes in this field have been reported in the Gulf region. This is especially true for road transportation, one of Qatar's most significant sources of air pollution. To address this research gap, this study provides an invaluable resource for policymakers as it is the first to quantify the current and forecast future transport emissions. In this work, actual data on traffic counts were input into the Low-Emissions Analysis Platform (LEAP) tool, which has never been used in the context of Qatar, making it an outstanding addition to the research in this domain. The ultimate goal is to estimate the transportation emissions from road traffic in Qatar and investigate how different actions lead to three different scenarios that can impact it. Considering that the policy reformation in the transportation sector is crucial to reducing greenhouse gas emissions and climate change, a scenario analysis can provide theoretical support for policy development and implementation. The investigation used the actual vehicle count data from 2017 to 2021, while all future projections considered the duration from 2022 to 2050 using three scenarios. The first was based on the historical growth in the number of vehicles; the second was based on the business-as-usual scenario (BAU); and the third considered that the public transport shall be divided into three sub-scenarios, namely fuel-economy improvement, the electrification of public transportation, and the replacement of diesel or petrol fuel with compressed natural gas (CNG). The results show that carbon dioxide (CO_2) emissions were the highest in all scenarios. Moreover, it was found that in the BAU, the light-duty vehicles (LDVs) category is the most significant contributor to GHG emissions compared to motorcycles and heavy-duty vehicles (HDVs). In addition, it was found that emissions can be reduced by improving public transportation, switching to a cleaner fuel, and reducing reliance on private vehicles.

Keywords: transport emissions; air pollution; LEAP; road traffic; scenario analysis; Qatar

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1. Introduction

Climate change is a severe problem affecting people worldwide and threatening their existence [1]. Human activities, mainly burning fossil fuels in developed countries, have caused a significant increase in greenhouse gas emissions since the Industrial Revolution. These emissions have contributed to the problem of climate change, specifically global warming [2]. To actively address the issue of climate change, despite the significant expansion in industry, population, and urbanization in Qatar over the past 30 years [3], the country has placed a strong emphasis on addressing environmental issues and tackling climate change, as evidenced by its early adoption of international agreements, such as the United Nations Framework Convention on Climate Change in 1996, the Kyoto Protocol in 2005, and the Paris Agreement in 2016, which they formally ratified in 2017 [4]. This emphasis on environmental issues is a response to the impacts of expansion, which has increased greenhouse gas emissions and the potential effects of climate change. In addition, various documents have been created to regulate and manage these changes, including Qatar National Vision 2030 [5], Qatar National Development Strategy 2011–2016 [6], and Qatar Second National Development Strategy 2018–2022 [7]. Multiple plans have noted the potential impact of climate change on Qatar, which has been ranked as having the highest per-person carbon dioxide emissions in the world in 2014, according to the United Nations Climate Change Secretariat, and the highest per-capita greenhouse gas emissions from transportation among the Gulf countries, as reported by the World Resources Institute in 2012 [3]. The high per-capita greenhouse gas emissions from transport in Qatar can be attributed to the country's large number of registered vehicles and motorcycles. According to data from sources [8,9], the number of registered vehicles and motorcycles in Qatar has risen significantly over the past decade. In 2010, there were 772,539 registered vehicles and motorcycles. This number increased to 816,883 in 2011, 877,127 in 2012, 939,914 in 2013, and 1,004,708 in 2014. This means almost a quarter million new vehicles and motorcycles were registered over those four years. Moreover, in the following four-year period, from 2015 to 2019, the number of registered vehicles and motorcycles increased yearly. In 2015, there were 1,352,980 registered vehicles and motorcycles. This number increased to 1,435,236 in 2016, 1,522,733 in 2017, 1,587,815 in 2018, and 1,655,700 in 2019. In total, 302,720 new cars and motorcycles were registered during that time. This indicated a 30% rise in vehicle numbers, which contributes to a higher rate of transportation-related GHG emissions, with private passenger vehicles, including taxis and motorcycles, accounting for nearly 99% of all the emissions in 2014, as reported by the World Resources Institute [3].

Researchers have investigated the effect of transportation-related carbon emissions using various experimental and modeling techniques, such as factor decomposition models, econometric models, and comprehensive models, due to their impact on health and human welfare [10–13]. This can be seen in the study conducted by Xia et al. [14], who assessed on-road vehicle emissions by identifying and targeting vehicles that emit excessive pollutants. Results suggest that combining on-road remote-sensing measurements and machine learning can improve vehicle emissions assessments. Similarly, Wang et al. [15] evaluated the potential environmental benefits of a large-scale transition to electric vehicles (EVs). This work provides new evidence to support a large-scale shift to EVs, which can help inform air pollution reduction and public health-policy decisions. Another study by Jiang et al., provides a new and comprehensive understanding of the spatial distribution of vehicle emissions from on-road vehicles [16]. Understanding this phenomenon could be used to develop more effective traffic-control strategies and improve air quality in urban areas. Coutinho et al. [17] examined the carbon emissions in the transportation sector in Amsterdam, Netherlands. The study found that implementing a demand-responsive transportation (DRT) system in Amsterdam resulted in lower mileage, operating costs, and GHG emissions per passenger compared to a regular bus line. Despite lower ridership, users rated the DRT system positively, with punctuality being a significant determinant of satisfaction. Another study by Lv et al., applied the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) and Geographically Weighted Regression (GWR) models to investigate the determinants of freight carbon emissions in China, as well as the effect of urbanization on carbon emissions from freight [18]. The results indicate that the total freight carbon emissions in China have increased significantly, with road freight contributing the most. Additionally, the findings show mixed effects of urbanization, including positive impacts on road and aviation transport emissions, as well as negative impacts on railway and waterway transport emissions in some provinces. Guo and Meng employed the Logarithmic Mean Divisia Index (LMDI) method to investigate the underlying causes of CO_2 emissions from the transportation sector in the Beijing–Tianjin–Hebei region of China [19]. The LMDI results indicated that transportation energy intensity and economic effects are the most significant contributing factors to increased carbon dioxide emissions. They also found that the effect of energy structure, freight turnover of unit industrial output, and industrialization contributed to reducing carbon dioxide emissions in the transport sector. Shabbir and Ahmad utilized the LEAP model to estimate the emissions of pollutants and energy consumption. They suggested policy measures to reduce emissions in two cities in Pakistan: Rawalpindi and Islamabad [20]. They found out that in the BAU scenario, where current trends were assumed to continue, the energy demand and emissions have increased dramatically. In the alternative scenarios, it has been demonstrated that energy consumption and pollution levels could be reduced by encouraging public transportation use and replacing diesel and gasoline vehicles with natural gas. Saisirirat et al., assessed the state of the biofuel industry in Ghana, evaluated the potential of biofuels in reducing greenhouse gas emissions from the road-transport sector, and discussed policy and regulatory frameworks required for the large-scale integration of biofuels in the transport sector [21]. The study revealed that integrating biofuels with vehicle electrification and using natural gas could reduce energy demand by 6.7% and 8.2% by 2030 and 7.4% and 7.8% by 2036, respectively, compared to the BAU scenario. It was also estimated that the alternative (ALT) and extreme (EXT) scenarios could reduce GHG emissions by 8.4% and 11.1% in 2030, as well as by 11% and 16.7% in 2036, respectively, compared to the BAU scenario. Raouz used LEAP software to analyze and investigate the Moroccan energy system and the effects of different actions on the energy and transport sector emissions. Using historical data, relevant forecasts, and assumptions, the researcher proposed and compared four future scenarios for energy demand, electricity generation, and greenhouse gas emissions [22]. The study revealed that Morocco's heavy reliance on fossil fuels and rising energy consumption pose significant challenges. However, if shale oil deposits are exploited and the new policy scenario is implemented, the country could generate 42% of its electricity from renewable sources by 2020. The study also stated that GHG mitigation could reduce greenhouse gas emissions by 50 million metric tons of CO_2 equivalents. Despite this, Morocco's legal and institutional situation hinders the sustained deployment of clean energy.

This paper uses the LEAP model to investigate different scenario analyses to study the relationship between road traffic, energy, and the environment, considering both data-driven and end-use energy perspectives in Qatar. The work presented in this paper can advance the field substantially. This is because it addresses a significant limitation in the existing literature. Moreover, it can be of interest to researchers, scholars, policy decision-makers, and the general public. They will benefit from the insights, methodologies, and recommendations presented in this study, which can guide in-depth research in the future, steer policy decisions, and contribute to advancing knowledge in this area.

2. Methods

2.1. The Modeling Framework

The Low-Emissions Analysis Platform (LEAP) is a software tool that supports energy planning, policy analysis, and climate change mitigation assessment. It was developed by the Stockholm Environment Institute (SEI) and is used by thousands of organizations in more than 190 countries [23]. It helps policymakers, energy planners, and analysts understand the energy sector and evaluate the impact of various energy policies and scenarios [24]. The flexible and user-friendly tool allows users to easily create and compare multiple energy scenarios and assess their environmental and economic impacts. Users of the platform include government agencies, academics, non-governmental organizations, consulting firms, and energy utilities at various scales, ranging from cities and states to national, regional, and global levels. LEAP offers a variety of analytical capabilities, including energy-system modeling, energy-efficiency analysis, renewable-energy analysis, and GHG analysis. Additionally, the software includes a technology-environment database (TED), which contains extensive technical, economic, and environmental information about a variety of technologies that were compiled from reliable sources, such as the Intergovernmental Panel on Climate Change (IPPC), the US Department of Energy (DOE), and the International Energy Agency (IEA) [25]. The IPPC was formed in 1988 by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) to supply scientific knowledge to governments at all levels of government to assist them in formulating climate policies [26]. However, the Department of Energy (DOE) is an agency of the United States government that promotes scientific and technological innovation in the energy sector and advances energy security [27]. The DOE handles many programs and initiatives, such as energy efficiency, renewable energy, nuclear safety, science, fossil energy, and environmental management. Similarly, IEA is dedicated to shaping a sustainable and secure energy future [28]. The organization provides authoritative analysis, data, policy recommendations, and solutions to safeguard energy security and assist the global transition to clean energy. TED can be used in a variety of ways with several different purposes. It can be used as a standalone tool or as part of LEAP to calculate the environmental loadings associated with the energy models. Overall, the LEAP tool provides several benefits, including low initial data requirements and intuitively presenting the outcomes [29]. The remarkable features of this tool, specifically the ability to integrate with diverse data sources such as national statistics and energy databases, make it a valuable tool for analyzing country-specific energy systems. Another important consideration in selecting LEAP in this work is that, to the best of our knowledge, prior studies in Qatar have not used it. As a result, there is an opportunity to investigate new approaches and methodologies that may not have been considered previously.

2.2. Data Collection

A wide range of data was collected to gather relevant information for this study, including vehicle types, fuel types, and mileage data obtained from WOQOD Vehicle Inspection (FAHES). WOQOD is Qatar's leading fuel distribution company, and FAHES is the only licensed company for inspecting vehicles, providing technically advanced inspections following road safety and pollution standards [30]. The data-collection process also includes relevant literature about the study. In addition, some statistical data were obtained from the Planning and Statistics Authority.

2.3. Model Structure

Figure 1 depicts that the LEAP model utilized in this paper is structured to solely examine road transportation, which is classified into three subcategories: light-duty vehicles (LDV), motorcycles, and heavy-duty vehicles (HDV). LDVs are categorized into private vehicles, such as saloon cars and 4×4s, as well as governmental and diplomatic vehicles, with 67,940 vehicles. The motorcycle category consists of only private motorcycles with 99 counts. Moreover, heavy-duty vehicles comprise public and private transportation (vehicles used for commercial purposes such as buses, trucks, and light commercial vehicles) with 21,114 vehicles. In addition, the figure shows that private vehicles are powered by gasoline and diesel, whereas governmental and diplomatic vehicles are powered solely by gasoline. For motorcycles, gasoline is used as fuel; public transportation runs on diesel, while private transportation uses diesel and gasoline.

2.4. Scenarios and Assumptions

LEAP Scenarios

A key LEAP component is the scenario analysis to describe how an energy system could develop over time in a specific social, economic, and governmental context [31]. Through LEAP, scenarios can be generated and evaluated based on factors such as energy demands, societal costs and benefits, and environmental consequences. In scenarios, users can explore a variety of hypothetical routes and discover what could happen if the change was executed. In order to minimize the need for data entry, scenarios are structured in a hierarchy such that when a scenario is created, it inherits expressions and data from the parent scenario.

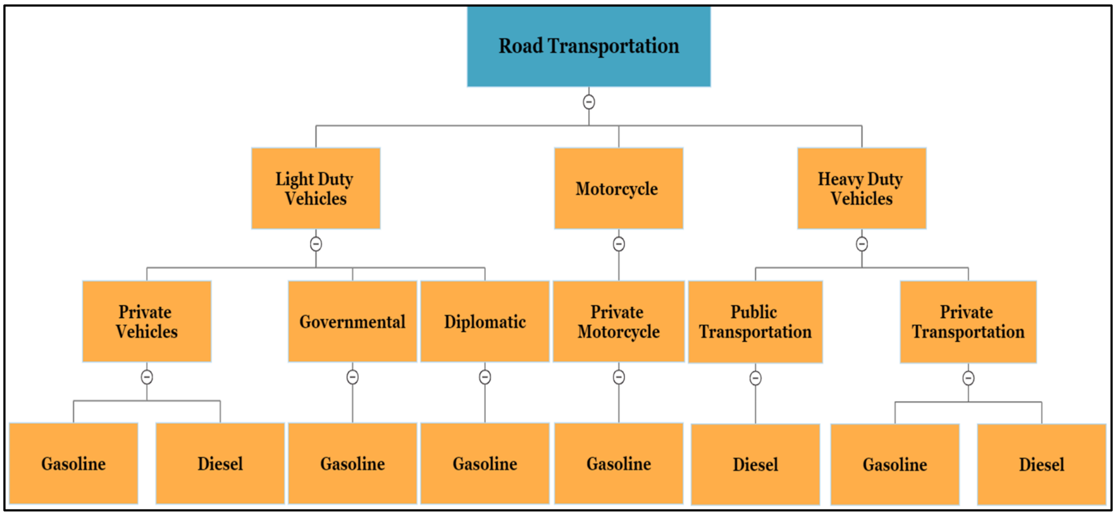

Figure 1. LEAP model illustration for road transport structure considered in this study.

This paper will employ the LEAP tool to implement three different scenarios. Each scenario "inherits" the conditions of the previous one. This includes the Historical, Business-as-Usual, and Public Transport scenarios. The latter is further divided into three sub-scenarios: fuel economy improvement, electrification of public transport, and the compressed natural gas fuel scenario for public transport. In this paper, 2017 was the base year (the first calculated year). The first scenario year considered is 2022; the end year (last year calculated) was 2050. Table 1 outlines the modeling periods.

Table 1. Modeling periods used for LEAP in this study.

Period	Timeline
Historical scenario	2017–2021
Future scenario	2022–2050

Historical Scenario

A historical scenario simulates past energy systems and conditions based on actual data and events. This scenario can help us understand past energy trends, challenges, and outcomes, as well as identify potential change drivers. To create a historical scenario in LEAP during the period 2017–2021, the following data were entered:

1. The total number of vehicle km traveled from 2017 to 2021: In 2017, the total number of vehicle km traveled was 2.34-billion km, while the distance traveled in 2018 was 1.91 billion. In 2019, there was a decrease, with the total vehicle km traveled reaching 1.85 billion. In 2020, there was a further decrease to 1.72 billion, and in 2021, the total vehicle km traveled reached 2.21 billion. Figure 2 demonstrates the total number of vehicle km traveled by all vehicles and motorcycles from 2017 to 2021.

2. The annual vehicle km traveled by light-duty vehicles, motorcycles, and heavy-duty vehicles from 2017 to 2021: In 2017, the LDVs had a share of vehicle km of 61.444%, whereas the motorcycles had a percent share of 0.007% and the HDVs had a share of 38.549%. In 2018, the LDVs, motorcycles, and HDV contributed 61.387, 0.007, and 38.606% of the total annual vehicle km traveled, respectively. In 2019, LDVs, motorcycles, and HDVs contributed 62.547, 0.006, and 37.447% of the yearly traveled distance, respectively. In 2020, the LDVs, motorcycles, and HDVs contributed 61.654, 0.008, and 38.338% of the total annual distance. In 2021, the percent share of the yearly traveled distance by LDVs decreased slightly to 61.105%. Moreover, there was a slight increase in motorcycles' percent share to 0.011%, while the HDVs' percent share was at 38.885% of the total annual distance traveled. Figure 3 and Table 2 present the

annual percentage of various vehicle types, including LDV, motorcycles, and HDV, from 2017 to 2021.

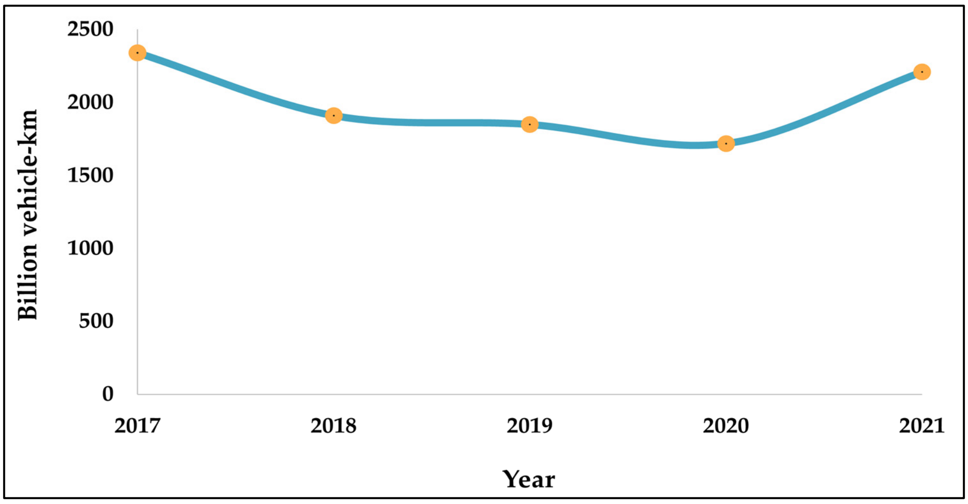

Figure 2. Annual kilometers traveled from 2017 to 2021 in Qatar (Historical scenario).

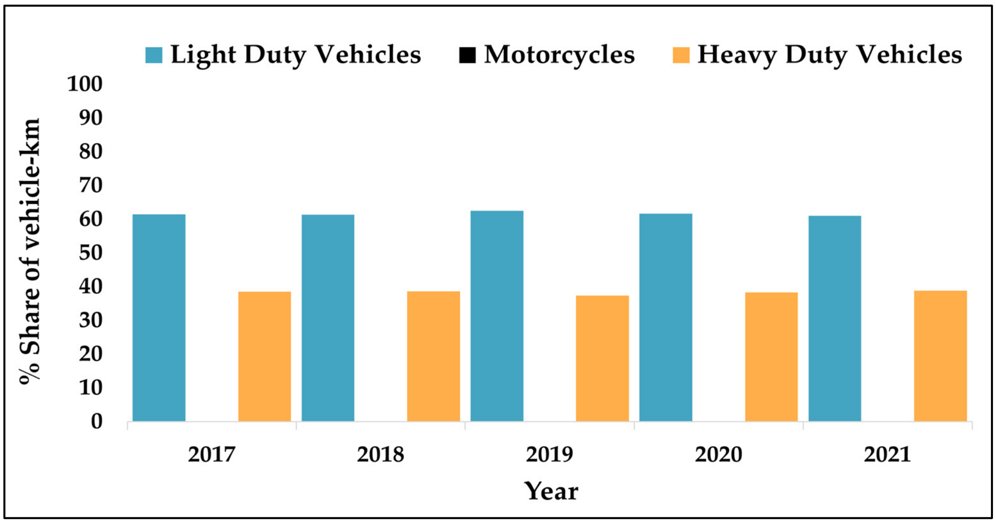

Figure 3. The annual traveled distance (km) percent share of LDV, motorcycles, and HDV from 2017 to 2021 in Qatar (historical scenario).

Table 2. The annual traveled distance percent shareof LDV, motorcycles, and HDV from 2017 to 2021 in Qatar (Historical scenario).

Branch	2017	2018	2019	2020	2021
LDV	61.444	61.387	62.547	61.654	61.105
Motorcycle	0.007	0.007	0.006	0.008	0.011
HDV	38.549	38.606	37.447	38.338	38.885

3. The annual percent share of fuel used per vehicle km traveled by light-duty vehicles, motorcycles, and heavy-duty vehicles from 2017 to 2021:
    - Light-duty vehicles: As shown in Table 3, for the LDV category, which includes private vehicles, governmental vehicles, and diplomatic vehicles, gasoline fuel was used in 99.96% of vehicle km traveled in LDV in 2017, while diesel was used in the rest. In 2018, gasoline accounted for 99.94%, while diesel accounted for 0.06%. In 2019, gasoline was used in 99.95% of the distance traveled, while

diesel accounted for a small percentage of 0.06%. In 2020, gasoline usage decreased slightly to 99.93%, while diesel usage increased slightly to 0.07%. As for 2021, gasoline continued to dominate fuel consumption at 99.95%, while diesel consumption decreased to 0.05%.

Table 3. The percent share of fuel used per vehicle km traveled by light-duty vehicles (Historical scenario).

Branch	2017	2018	2019	2020	2021
Gasoline	99.96	99.94	99.95	99.93	99.95
Diesel	0.04	0.06	0.06	0.07	0.05

- Motorcycles: Gasoline is the only used fuel in this category, which consists only of private motorcycles.
- Heavy-duty vehicles: In this category, which includes both public and private transportation, public transportation uses only diesel, while private transportation uses both gasoline and diesel. In 2017, gasoline accounted for 62.32% of the fuel used in private transportation, while diesel accounted for 37.68%. However, in 2018, gasoline usage increased to 64.39%, while diesel decreased to 35.61%. In 2019, the percent share of gasoline usage increased to 66.91, but diesel consumption decreased to 33.09%. In 2020, the percent share of gasoline slightly declined to 66.36%, while diesel usage increased to 33.64%. By 2021, the share of gasoline usage slightly increased to 66.41%, while diesel usage decreased to 33.59%. Figure 4 shows the percent share of fuel used per vehicle km traveled by private transportation.

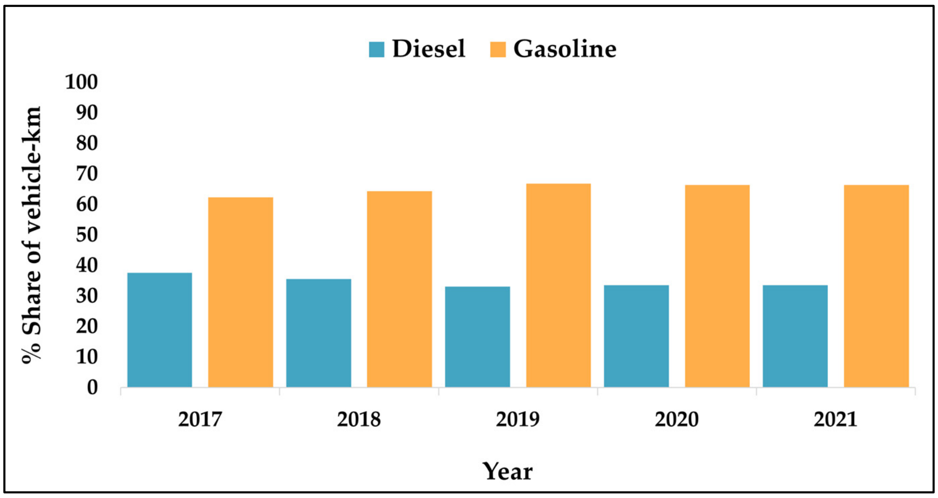

Figure 4. Fuel percent share of private transportation from 2017 to 2021 in Qatar (Historical scenario).

4. The energy intensity in liters per vehicle km: The energy intensity was 0.11 L per vehicle kilometer for private, governmental, and diplomatic vehicles, 0.13 for motorcycles, 0.10 for public transportation, and 0.13 for private vehicles.
5. The annual percent share of light-duty vehicle subcategories, including private, governmental, and diplomatic vehicles: As can be seen in Table 4, private vehicles are the most popular form of transportation, with a utilization rate of 99.91% in 2017, 99.93% in 2018, 99.92% in 2019, 99.94% in 2020, and 99.95% in 2021.

Table 4. The percent share of private, governmental, and diplomatic vehicles from 2017 to 2021 in Qatar (Historical scenario).

Branch	2017	2018	2019	2020	2021
Private Vehicles	99.919	99.932	99.928	99.940	99.953
Governmental	0.001	0.004	0.005	0.005	0.004
Diplomatic	0.080	0.064	0.069	0.055	0.043

6. The annual percent share of motorcycles: Motorcycles accounted for 0.007% of the total share in 2017, which remained unchanged in 2018. It fell in 2019 but rose again in 2020, reaching 0.008%. By 2021, it had increased to 0.011%. Figure 5 below shows the percentage share that private motorcycles held from 2017 to 2021.

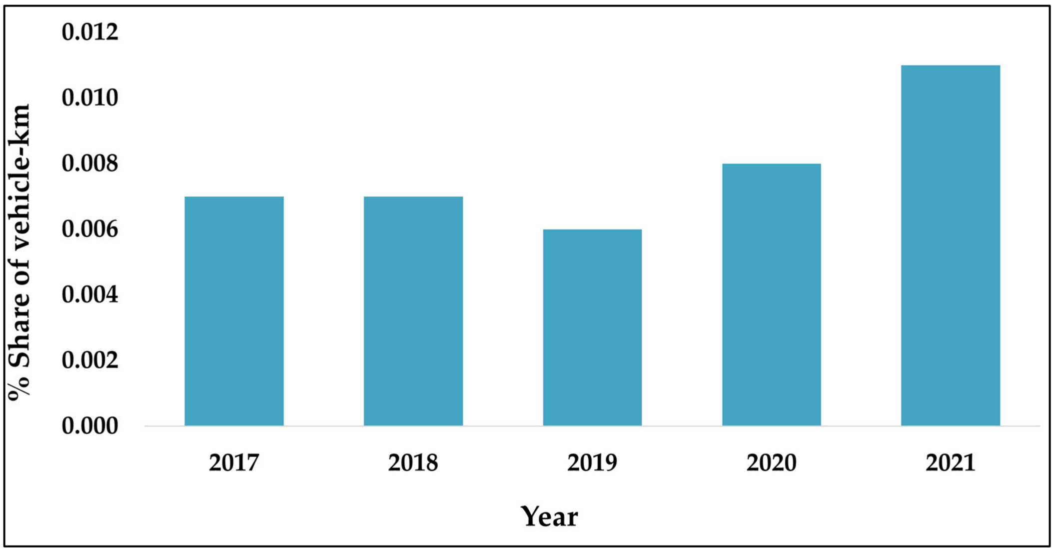

Figure 5. The annual percent share of motorcycles from 2017 to 2021 in Qatar (Historical scenario).

7. The annual percentage share of the heavy-duty vehicle category: This is divided into two sub-categories: public and private transportation. Between 2017 and 2021, private transportation dominated the market, with a percentage share of 98.66% in 2017 and 98.53% in 2020 and 2021. However, it is worth mentioning that public transportation has seen slight growth when its percentage share increased from 1.34% in 2017 to 1.83% in 2019, then declined to 1.47% in 2020 and remained unchanged in 2021. Table 5 shows the percentage share of vehicle km traveled by public and private transportation, with private transportation accounting for the majority of vehicle kilometers.

Table 5. The percentage share of vehicle km traveled annually by public and private transport from 2017 to 2021 (Historical scenario).

Branch	2017	2018	2019	2020	2021
Public Transportation	1.34	1.59	1.83	1.47	1.47
Private Transportation	98.66	98.41	98.17	98.53	98.53

Business-As-Usual Scenario (BAU)

After creating a model based on past activity and related emissions, it becomes feasible to forecast the potential future evolution of transportation and the associated emissions. This scenario serves as a reference point for comparison with alternative scenarios and policy options. The baseline scenario is usually developed using historical data and projections of future trends. However, an assumption was used in the BAU scenario as per the following: It was assumed that there would be a 10% growth rate in vehicle count, which means that the number of vehicle km traveled on roads will increase by 10% annually as well.The data displayed are used with the growth function to estimate the total vehicle km traveled between 2022 (the first future scenario) and 2050 (the end year). Growth functions are mathematical models that predict the future growth of a variable based on specific assumptions and growth rates. Our study used 10% per year as the growth rate to estimate the future value of vehicle km. According to the results, vehicle km traveled shall increase significantly over time, from 3.24 billion in 2025 to 35.06 billion in 2050, as presented in Figures 6 and 7 below.

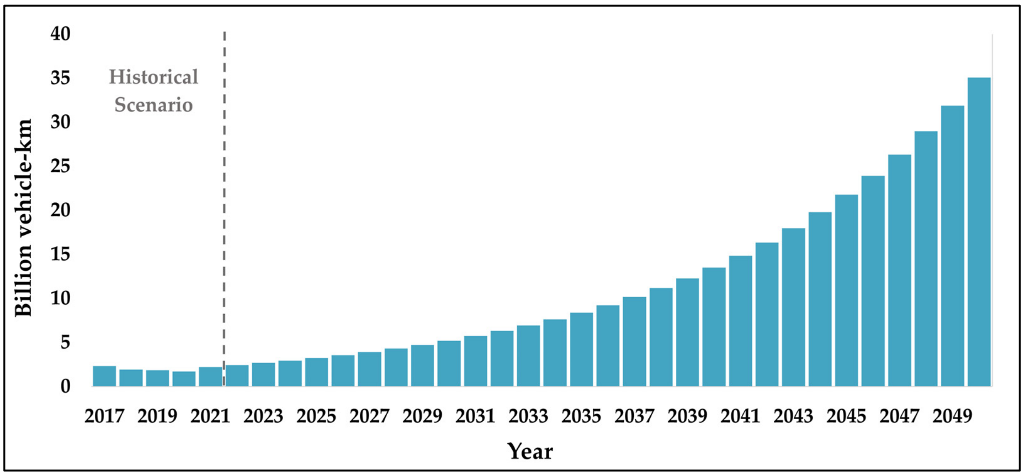

Figure 6. Total vehicle km based on the assumption of a 10% growth rate (BAU scenario).

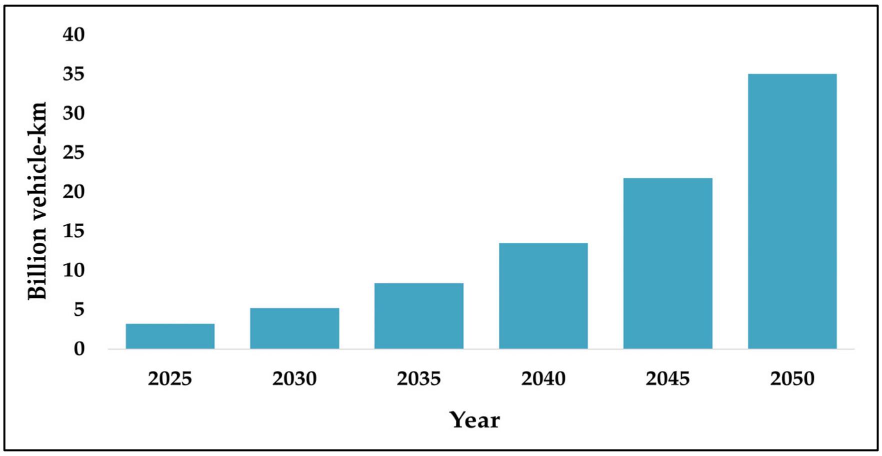

Figure 7. Total vehicle km (billion vehicle kms) based on the assumption of a 10% growth rate, with results presented every five years.

Although the actual percentage increase is about 28.4% in 2021 relative to 2020 data, an assumption of a 10% increase is adopted since it is more realistic considering that major infrastructure projects have been accomplished in the country.

Public Transport Scenario (PUB)

All over the world, when it comes to road transportation, private vehicles dominate daily travel behavior [32]. According to [33], the inhabitants of affluent cities prefer to travel by private vehicle. Qatar is an excellent example of this, having one of the Middle East's highest per-capita vehicle ownership rates. Most people rely on private cars, and as the population grows, so does the number of private vehicles. Based on [34], the total population in Qatar at the end of February 2023 was 2,982,631. Thus, with this population, more people will require transportation, and more vehicles will be on the road. The result is an increase in the sources of carbon emissions and other pollutants that contribute to climate change and air pollution. Therefore, it is crucial to encourage public transportation as it can decrease emissions, reduce traffic, and conserve energy. This is because buses, for example, have a higher occupancy rate when compared to private vehicles, which can lead to a reduction in the number of vehicles on the road. As a result, in this scenario, as in the paper [20], the following assumptions were made:

1. The growth rate of public transportation would increase by 1%. As seen in Figures 8 and 9, in 2025, the percent share of vehicle km traveled will be 1.53, rising to 1.6 in 2030, 1.69 in 2035, 1.77 in 2040, 1.86 in 2045, and 1.96 in 2050.
2. The growth rate of private vehicles would decrease by 1%. As depicted in Figures 10 and 11, in 2025, the percent share of vehicle km traveled will be 96, declining to 91.3 in 2030, 86.8 in 2035, 82.6 in 2040, 78.5 in 2045, and 74.7 in 2050.

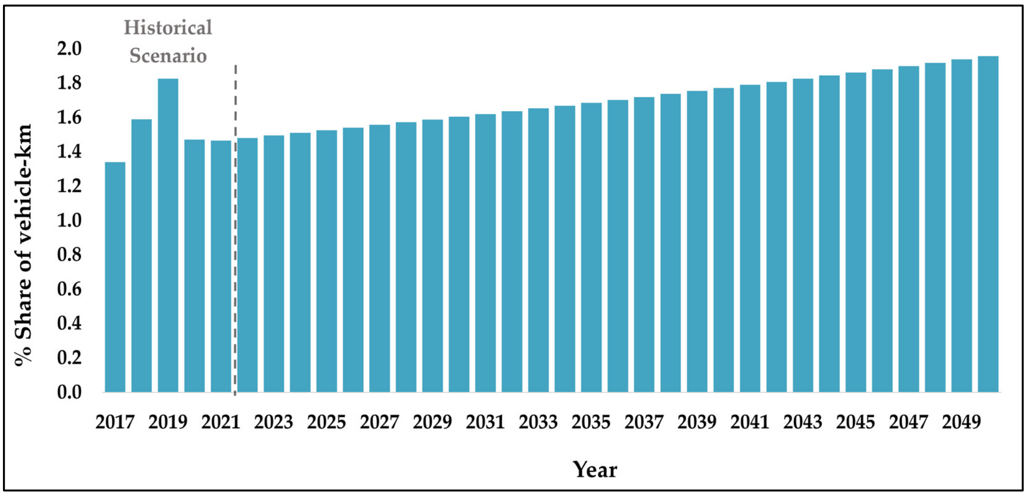

Figure 8. The annual percent share of vehicle km traveled in Qatar with an assumption of a 1% increase in public transportation (public transport scenario).

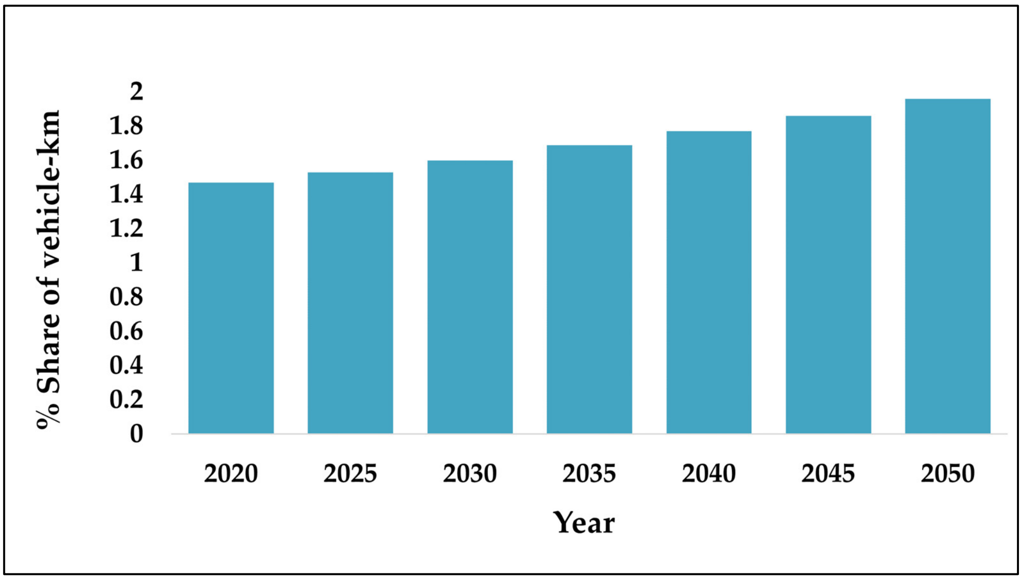

Figure 9. The annual percent share of vehicle km traveled in Qatar with an assumption of a 1% increase in public transportation for every five years from 2020 to 2050.

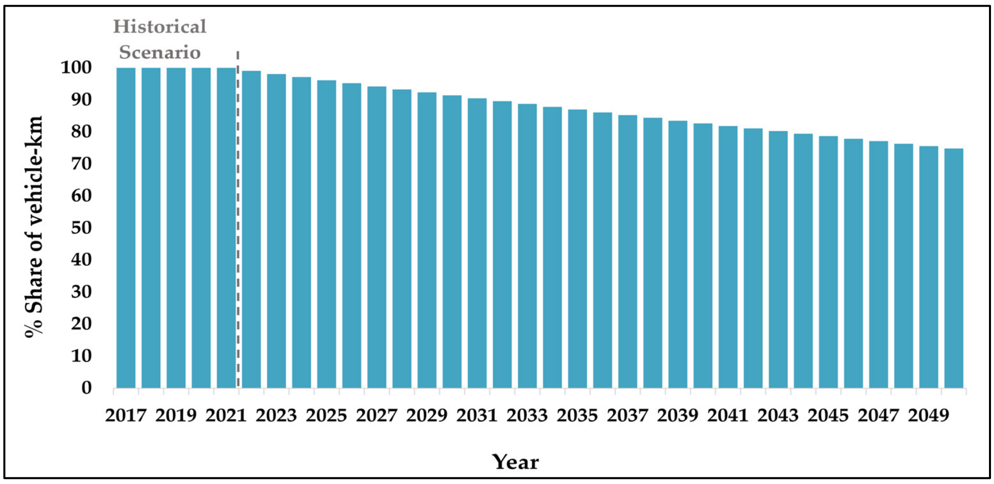

Figure 10. The percent share of vehicle km traveled in Qatar with an assumption of a 1% decrease in private vehicles (public transport scenario).

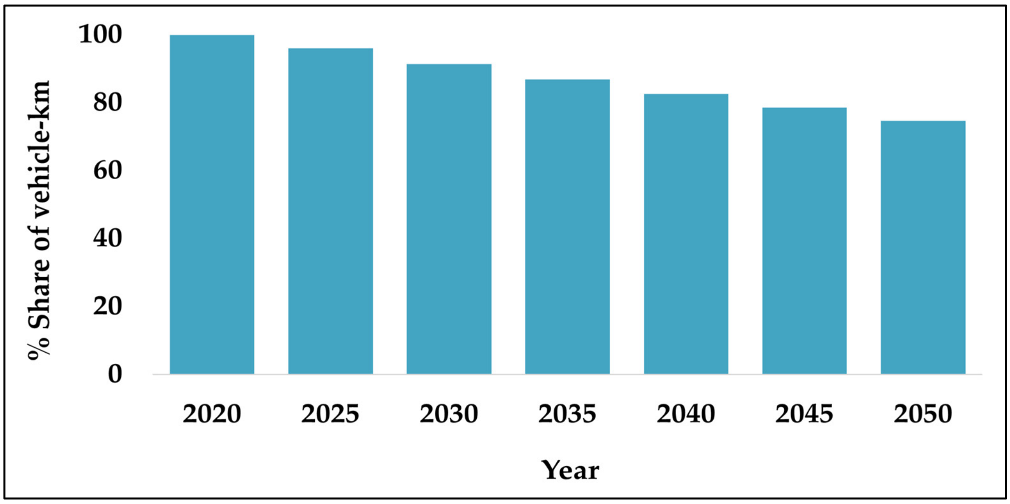

Figure 11. The annual percent share of vehicle km traveled in Qatar with an assumption of a 1% decrease in private vehicles for every five years from 2020 to 2050.

Fuel Economy Improvement Scenario

The fuel economy improvement scenario is a sub-scenario within the public transport scenario. The vehicle's fuel economy is the amount of fuel consumed per kilometer traveled [29]. In Qatar, the Ministry of Economy and Commerce has requested that all vehicle agents and dealers display fuel efficiency labels beginning in 2017 [35]. The label determines the fuel efficiency of the vehicle using fuel economy measures. The purpose for showing these labels is to raise consumer awareness about the energy efficiency of each vehicle, enabling them to make informed decisions about the vehicle they purchase and how to reduce their fuel consumption. Since the country has recently taken steps to improve the fuel economy of private vehicles, an improvement in the fuel economy of public transportation vehicles will be implemented in this scenario. This is because public transportation uses fuel rates on a large scale. Consequently, even minor improvements in the fuel economy can result in substantial fuel cost savings and an overall reduction in greenhouse gases. The improvement in this scenario can be modeled by reducing the liters of fuel consumed per distance traveled, eventually improving fuel efficiency. To make the reduction, we used the "interp" function. The "interp" function can be utilized to determine a value for a specific year by using the linear interpolation of a time series of year/value pairs [36]. To model the scenario, the following assumptions were made:

1. There will be a 10% improvement by 2030: The year 2030 was selected in order to align with Qatar's 2030 Vision, by which the country aims to promote sustainable practices and reduce its carbon footprint. Moreover, the year 2030 also represents a significant milestone because it marks the year when the sustainable development goals (SDGs) of the United Nations are expected to be achieved. A 10% improvement was chosen as a reasonable goal that could be achieved without significantly disrupting the existing systems.
2. There will be a 20% improvement by 2040: 2040 was chosen because it is considered a midpoint between 2030 and 2050, representing significant milestones in the global action to combat climate change. By selecting this year, we will be able to ensure that progress toward these objectives has been achieved. The 20% improvement was chosen for this year in order to gradually increase the efforts while maintaining a realistic and achievable target.
3. There will be a 30% improvement in 2050: The year 2050 was chosen due to its significance as a critical long-term goal for sustainable development and climate action. An excellent example is the net-zero goal, which many countries strive towards by 2050. Net zero means reducing GHG emissions to the absolute lowest possible level, with the remaining emissions being re-absorbed by the oceans and forests [37]. This year's 30% increase was chosen to accelerate our progress while maintaining a balance of ambition and feasibility.

By choosing 2030, 2040, and 2050, we can align our efforts with global targets and milestones, contribute to the achievement of sustainability, and assist in creating a roadmap for long-term planning and implementation. Figure 12 shows a gradual reduction over time in energy intensity, indicating that the vehicle consumes less energy for every vehicle kilometer traveled.

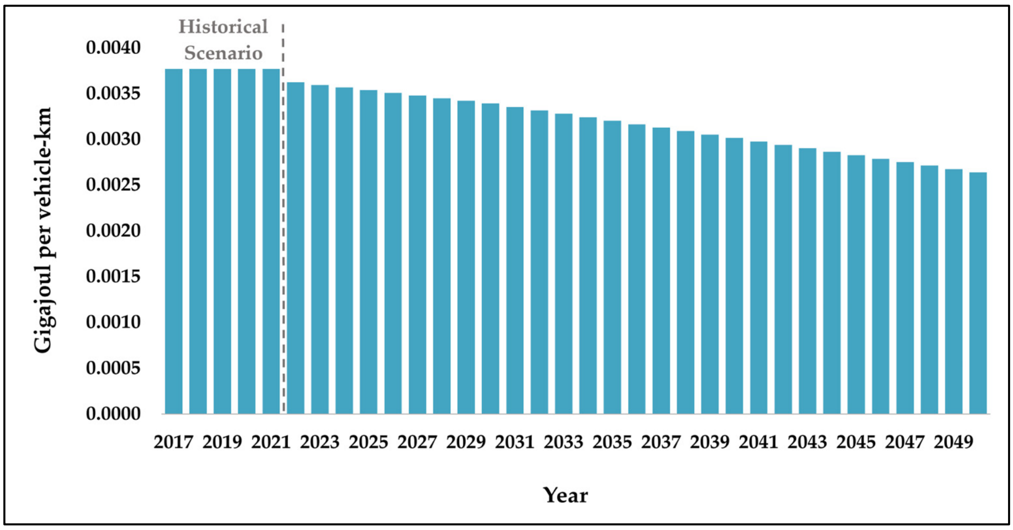

Figure 12. The gradual reduction in energy intensity when the improvements are implemented for public transportation (fuel-economy scenario).

Compressed Natural Gas Scenario of Public Transportation (CNG)

The compressed natural gas scenario is a sub-scenario within the public transport scenario. According to references [4,38], Qatar is attempting to reduce its carbon footprint. These steps include, but are not limited to, using compressed natural gas as fuel in the transport sector and launching a project to promote sustainable transport in the country through electric vehicles. To accomplish this, WOQOOD, Qatar Energy (formerly known as Qatar Petroleum (QP)), and Mowasalat (Qatar's leading transportation service provider) have begun to use compressed natural gas (CNG) for transportation. CNG has several potential advantages, especially when it comes to reducing noise and air emissions [39]. It is considered an environmentally friendly fuel because it cuts down on emissions of carbon monoxide (CO), carbon dioxide (CO_2), and nitrous oxides (N_2O), which are hazardous to human health and contribute to climate change. Thus, prioritizing using compressed natural gas as the primary fuel for public transportation in the country can lead to significant benefits, mainly if it is used as a long-term solution.

Electrification of Public Transportation

The electrification of public transportation is another sub-scenario within the public transport scenario. Electric vehicles have the potential to be beneficial to cities in several ways. This technology, for example, produces lower noise-emission levels, has a relatively simple construction process, and has better environmental performance [40]. It has better environmental performance because electric vehicles produce almost no emissions, including greenhouse gases, fine dust, and nitrogen oxide. Therefore, it is locally emission-free [41]. In Qatar, in preparation for the 2022 World Cup, the country made significant investments in order to improve its transportation infrastructure and reduce its carbon footprint. A total of 25% of the public buses in the country were replaced with electric buses for use during the tournament [42]. Considering the many advantages electric buses provide, including reduced emissions and improved operational efficiency, it is worth exploring and examining the potential findings of a long-term switch from diesel buses to electric ones and the impact this could have on public health, the environment, and urban transportation sustainability as a whole.

3. Results and Discussion

3.1. Baseline Scenario

Figure 13 and Table 6 depict the total GHG emissions from road transportation under the baseline scenario based on the 100-year global warming potential (GWP). The GWP of a GHG is an indication of how much warming is caused over time by a gas [43]. For GWP, carbon dioxide (CO_2) has an index value of 1, whereas the GWP for all other greenhouse gases is determined by the amount of warming they generate compared to CO_2. It can be depicted from the results that when no improvements are assumed, the total GHG emissions will build up 6,498,030 metric tons of carbon equivalent between 2020 and 2050. Carbon dioxide will account for the highest total GHG emissions, comprising 6433 thousand metric tons. This result is not surprising since, compared to other studies, carbon emissions tend to be higher than other emissions, and the study conducted by Xiurui et al. [44] is one example. Methane marks the second highest GHG emission with 50,240 metric tons of carbon equivalent, followed by nitrous oxide, which will reach 14,780 metric tons of carbon equivalent in 2050.

Table 6. Total GHG emissions from road transportation under the baseline scenario, measured in thousand metric tons of carbon equivalent.

GHG	2020	2025	2030	2035	2040	2045	2050	Total
Carbon Dioxide	124.37	234.14	377.09	607.30	978.07	1575.19	2536.85	6433.00
Methane	0.97	1.83	2.95	4.74	7.64	12.30	19.81	50.24
Nitrous Oxide	0.29	0.54	0.87	1.40	2.25	3.62	5.83	14.78
Total	125.63	236.51	380.90	613.44	987.95	1591.11	2562.50	6498.03

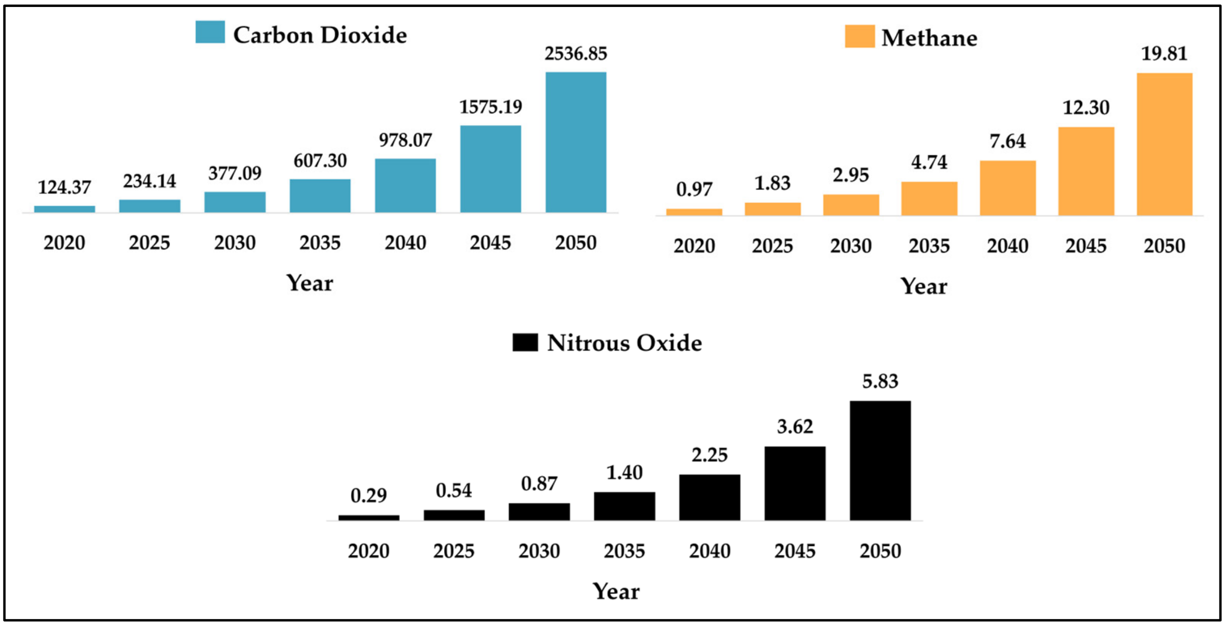

Figure 13. Total GHG emissions from road transportation under the baseline scenario, measured in thousand metric tons of carbon equivalent using a 100-year GWP.

The quantity of such emissions in a country like Qatar underscores the need for effective measures to mitigate their adverse effects. Several factors can be responsible for this continuous increase in emissions, including population growth and economic development.

Figure 14 and Table 7 show the GHG emissions from LDVs under the baseline scenario based on the 100-year GWP. LDVs are the most significant contributors to GHG emissions compared to motorcycles and HDVs. They are responsible for 57.69% of total emissions in this scenario, with CO_2 emitting the most compared to other greenhouse gases. This is because in Qatar, private vehicles, which fall under the category of light-duty vehicles, are the most commonly used means of transportation. This trend can be attributed to consumer preferences that favor LDVs over motorcycles and HDVs. Thus, the government should take different measures to control their registration. One of the policies could be limiting the number of vehicles registered each year, such as in Singapore and Shanghai [20]. Additionally, in the baseline scenario, where no actions are taken to reduce emissions, Qatar has limited use of public transportation. Thus, people are more likely to drive their vehicles, resulting in increased emissions. However, the occupancy rate of private vehicles is usually low, generating higher emissions per passenger.

Table 7. GHG emissions from LDVs under the baseline scenario, measured in thousand metric tons of carbon equivalent.

GHG	2020	2025	2030	2035	2040	2045	2050	Total
Carbon Dioxide	72.38	134.94	217.32	349.99	563.67	907.79	1462.01	3708.09
Methane	0.63	1.18	1.90	3.06	4.93	7.94	12.79	32.43
Nitrous Oxide	0.17	0.31	0.50	0.81	1.31	2.11	3.39	8.60
Total	73.18	136.43	219.72	353.87	569.90	917.84	1478.18	3749.12

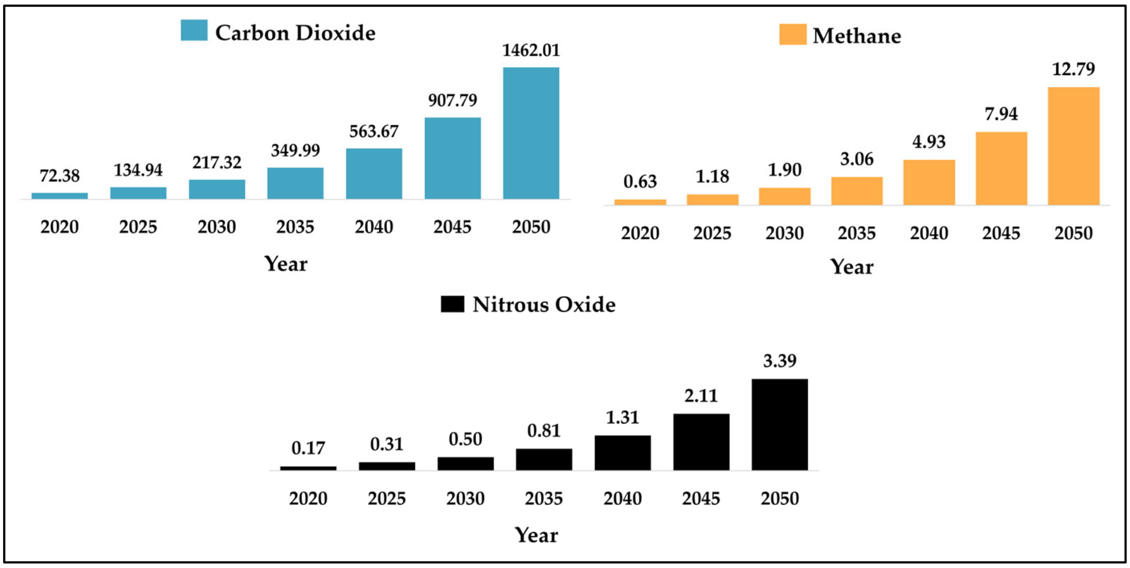

Figure 14. GHG emissions from LDVs under the baseline scenario, measured in thousand metric tons of carbon equivalent using a 100-year GWP.

Figure 15 and Table 8 illustrate motorcycle GHG emissions based on the 100 GWP under the baseline scenario. It is evident by the below results that motorcycle emissions are considered low compared to LDVs and HDVs. They are responsible for 0.012% of total emissions. Motorcycles' most significant emissions value derives from carbon dioxide, with 784.4 metric tons of carbon equivalent, followed by methane with 0.0069 and nitrous oxide with 0.0018. The low emission level can be attributed to the fact that only private motorcycles were examined in this study. If additional types of motorcycles had been considered, GHG emission amounts might have been higher. Another reason for having low emissions in this category can be justified by the fact that motorcycles tend to be smaller and lighter than LDVs and HDVs. This means they have less mass to move, necessitating less fuel and lower emissions.

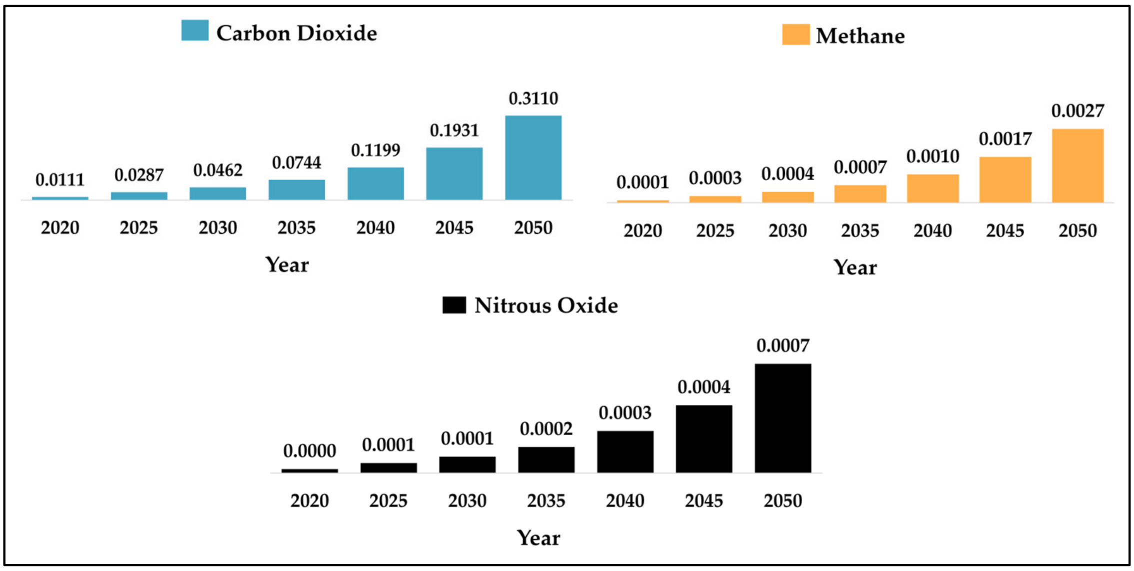

Figure 15. GHG emissions from motorcycles under the baseline scenario, measured in thousand metric tons of carbon equivalent using 100-year GWP.

Table 8. GHG emissions resulting from motorcycles under the baseline scenario, measured in thousand metric tons of carbon equivalent.

GHG	2020	2025	2030	2035	2040	2045	2050	Total
Carbon Dioxide	0.0111	0.0287	0.0462	0.0744	0.1199	0.1931	0.3110	0.7844
Methane	0.0001	0.0003	0.0004	0.0007	0.0010	0.0017	0.0027	0.0069
Nitrous Oxide	0.0000	0.0001	0.0001	0.0002	0.0003	0.0004	0.0007	0.0018
Total	0.0112	0.0290	0.0467	0.0753	0.1212	0.1952	0.3144	0.7931

Figure 16 and Table 9 show how much greenhouse gases do HDVs produce under the baseline scenario based on the 100-year GWP. This category ranks second in terms of emissions after the LDVs and accounts for 42.29% of the total emissions in this scenario. Moreover, carbon dioxide emissions are higher than methane and nitrogen oxide. By 2050, carbon dioxide emissions will reach 1,074,540 metric tons of carbon equivalent and account for 2724.13 thousand metric tons of the total emissions in this category. Considering that these emissions are only produced by road transportation, they are incredibly high, reaching levels that can be compared to those of much larger countries. The fact that Qatar's emissions from road transportation are so high is a significant concern for climate change. Hence, the country's governmental policies must be amended to reduce its emissions to achieve its climate goals.

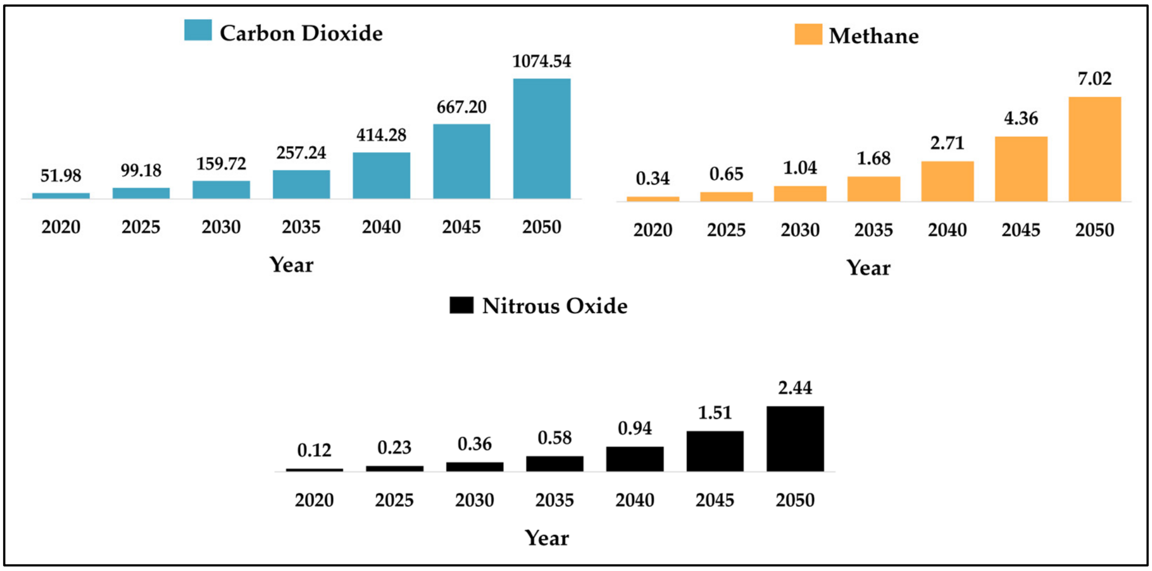

Figure 16. GHG emissions from HDVs under the baseline scenario, measured in thousand metric tons of carbon equivalent using 100-year GWP.

Table 9. GHG emissions resulting from HDVs under the baseline scenario, measured in thousand metric tons of carbon equivalent.

GHG	2020	2025	2030	2035	2040	2045	2050	Total
Carbon Dioxide	51.98	99.18	159.72	257.24	414.28	667.20	1074.54	2724.13
Methane	0.34	0.65	1.04	1.68	2.71	4.36	7.02	17.80
Nitrous Oxide	0.12	0.23	0.36	0.58	0.94	1.51	2.44	6.18
Total	52.43	100.05	161.13	259.50	417.93	673.08	1084.00	2748.11

3.2. Public Transportation Scenario

Earlier, it was mentioned that in this scenario, a 1% increase in the growth rate in public transportation and a 1% decrease in growth in private vehicle rate would be assumed. Reducing the use of private vehicles and increasing the dependence on public transportation will result in a total reduction of GHG by 2050. This is shown in Figure 17 and Table 10. According to our results, the total GHG emissions are expected to reach 5,757,560 metric tons of carbon equivalent. This is equivalent to a 163.13% reduction in GHG emissions compared to the baseline emission levels. It is clear from the amount of reduction that the proposed scenario is effective in reducing greenhouse gas emissions. This suggests that the country would expect more reductions if higher assumptions were made. The other positive aspect is that Shabbir and Ahmad studied NOx, SO_2, and PM_{10} emissions using the same scenario [20]. All these gases were reduced the most in this scenario compared to the others, indicating that this scenario will have a significant environmental impact regardless of the emitted gas under evaluation.

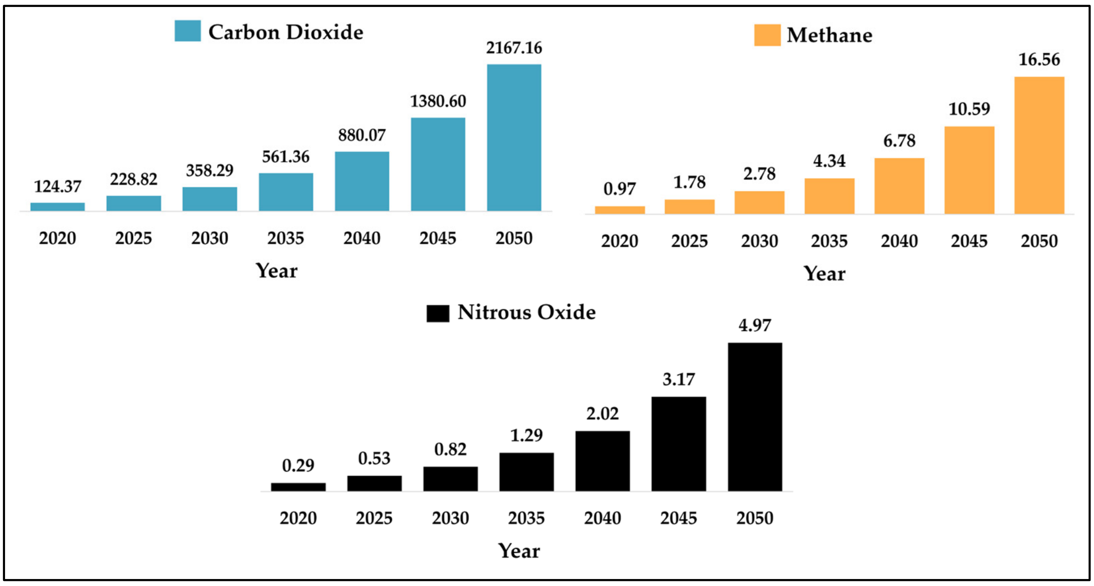

Figure 17. GHG emissions from the public transport scenario, measured in thousand metric tons of carbon equivalent using 100-year GWP.

Table 10. GHG emissions from public transport scenario, measured in thousand metric tons carbon equivalent.

GHG	2020	2025	2030	2035	2040	2045	2050	Total
Carbon Dioxide	124.37	228.82	358.29	561.36	880.07	1380.60	2167.16	5700.68
Methane	0.97	1.78	2.78	4.34	6.78	10.59	16.56	43.79
Nitrous Oxide	0.29	0.53	0.82	1.29	2.02	3.17	4.97	13.09
Total	125.63	231.13	361.89	566.99	888.87	1394.36	2188.69	5757.56

Figure 18 and Table 11 depict the LDVs' GHG emissions under the public transport scenario based on the 100-year GWP. Due to the reduction in the private vehicle growth rate in this scenario, it was evident that emissions from LDVs would be reduced compared to emissions from LDVs in the baseline scenario. The difference between the emission levels between the two scenarios is estimated to reach 739,980 metric tons of carbon equivalent, corresponding to a 267.91% reduction in emissions. The drop that can be achieved shows how crucial it is to find alternatives to the high reliance on private vehicles to reduce the country's transport emissions.

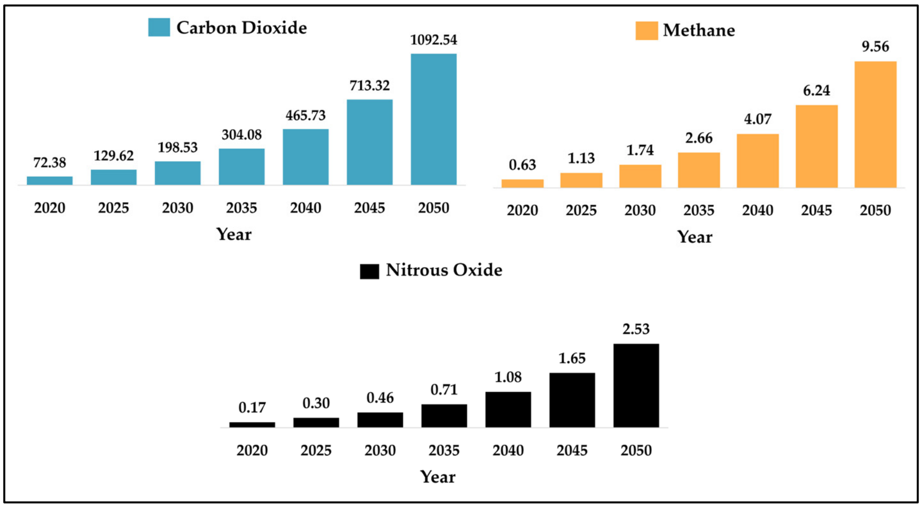

Figure 18. GHG emissions from LDVs under the public transport scenario, measured in thousand metric tons carbon equivalent using 100-year GWP.

Table 11. GHG emissions from LDVs under the public transport scenario, measured in thousand metric tons carbon equivalent.

GHG	2020	2025	2030	2035	2040	2045	2050	Total
Carbon Dioxide	72.38	129.62	198.53	304.08	465.73	713.32	1092.54	2976.21
Methane	0.63	1.13	1.74	2.66	4.07	6.24	9.56	26.03
Nitrous Oxide	0.17	0.30	0.46	0.71	1.08	1.65	2.53	6.90
Total	73.18	131.06	200.73	307.44	470.88	721.22	1104.63	3009.14

Figure 19 and Table 12 show the motorcycle GHG emissions from road transportation under the public transportation scenario. According to the results, there has been no change in emissions compared to the baseline scenario. This is because the improvement made in this scenario does not impact motorcycles. Thus, greenhouse gas emissions will reach 79,310 metric tons by 2050, with carbon dioxide representing the highest emissions.

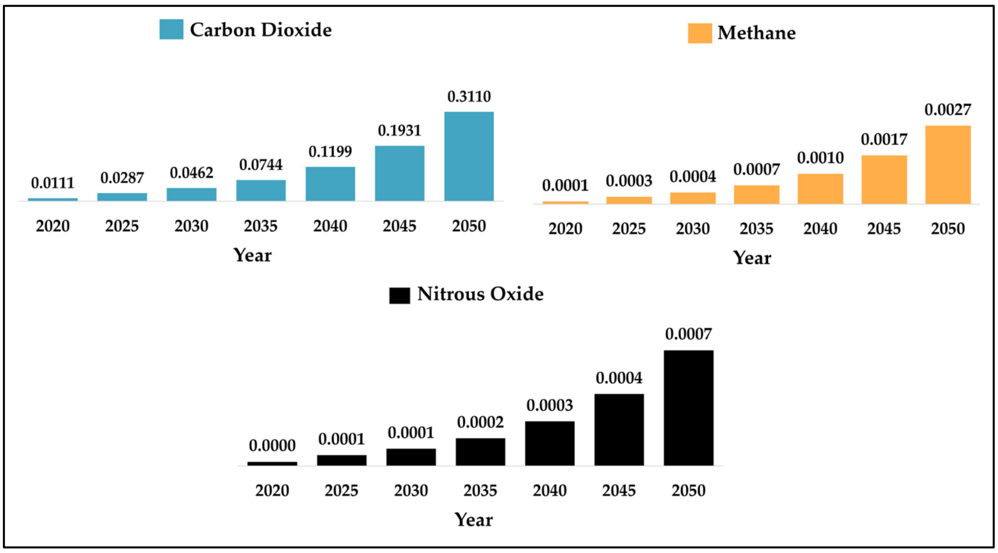

Figure 19. GHG emissions from motorcycles under the public transport scenario, measured in thousand metric tons of carbon equivalent using 100-year GWP.

Table 12. GHG emissions resulting from motorcycles under the public transport scenario, measured in thousand metric tons of carbon equivalent.

GHG	2020	2025	2030	2035	2040	2045	2050	Total
Carbon Dioxide	0.0111	0.0287	0.0462	0.0744	0.1199	0.1931	0.3110	0.7844
Methane	0.0001	0.0003	0.0004	0.0007	0.0010	0.0017	0.0027	0.0069
Nitrous Oxide	0.0000	0.0001	0.0001	0.0002	0.0003	0.0004	0.0007	0.0018
Total	0.0112	0.0290	0.0467	0.0753	0.1212	0.1952	0.3144	0.7931

The GHG emissions from HDVs in the public transport scenario are depicted in Figure 20 and Table 13, based on the 100-year GWP. In this scenario, the total emissions will reach 2,747,620 metric tons of carbon equivalent, of which carbon dioxide will account for 2,723,690, methane for 17,760, and nitrous oxide for 6,180. The expected emission rates from this scenario are almost similar to those projected from the baseline scenario.

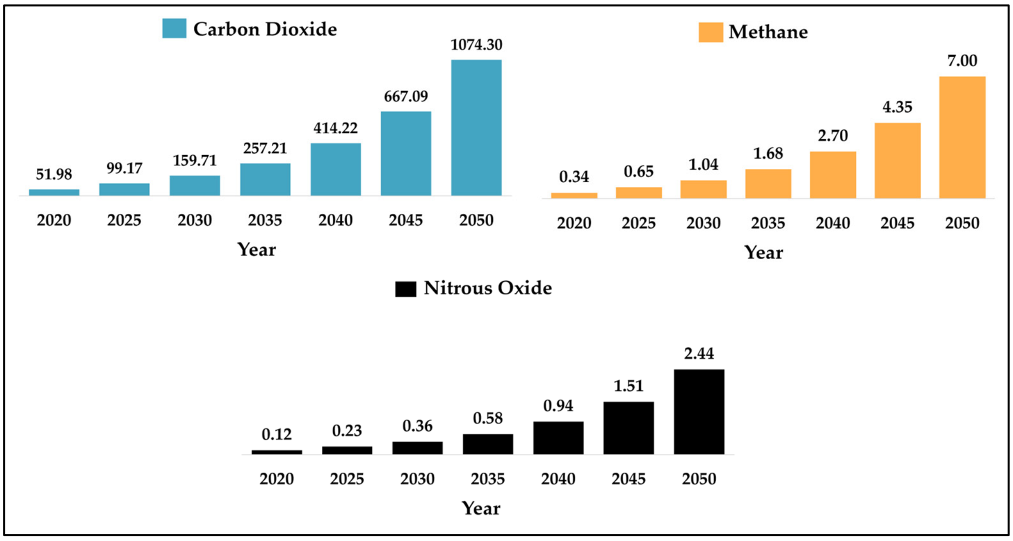

Figure 20. GHG emissions from HDVs under the public transport scenario, measured in thousand metric tons of carbon equivalent using 100-year GWP.

Table 13. GHG emissions resulting from HDVs under the public transport scenario, measured in thousand metric tons of carbon equivalent.

GHG	2020	2025	2030	2035	2040	2045	2050	Total
Carbon Dioxide	51.98	99.17	159.71	257.21	414.22	667.09	1074.30	2723.69
Methane	0.34	0.65	1.04	1.68	2.70	4.35	7.00	17.76
Nitrous Oxide	0.12	0.23	0.36	0.58	0.94	1.51	2.44	6.18
Total	52.43	100.05	161.12	259.47	417.87	672.95	1083.79	2747.62

Tables 14 and 15 compare the total reductions in emissions from the public transport scenario with the baseline starting in 2020 and continuing every five years until 2050. It was found that the total reduction of emissions measured in metric tons of carbon equivalent will reach 740,470, which is equivalent to 163.13%.

Table 14. The reduction in emissions from the public transport scenario to the baseline scenario, measured in thousand metric tons of carbon equivalent.

GHG	2020	2025	2030	2035	2040	2045	2050	Total
Carbon Dioxide	-	−5.31	−18.79	−45.94	−97.99	−194.58	−369.69	−732.32
Methane	-	−0.04	−0.16	−0.40	−0.86	−1.71	−3.25	−6.44
Nitrous Oxide	-	−0.01	−0.04	−0.10	−0.22	−0.45	−0.85	−1.69
Total	-	−5.37	−19.00	−46.45	−99.08	−196.74	−373.80	−740.47

Table 15. The percentage reduction in emissions from the public transport scenario to the baseline scenario between 2020 and 2050.

GHG	2020	2025	2030	2035	2040	2045	2050	Total
Carbon Dioxide	0%	2.27%	4.99%	7.56%	10.02%	12.35%	14.57%	51.77%
Methane	0%	2.73%	5.76%	8.44%	11.26%	13.90%	16.41%	58.50%
Nitrous Oxide	0%	1.85%	5.75%	7.86%	10.22%	12.43%	14.75%	52.86%
Total	0%	6.86%	16.50%	23.86%	31.50%	38.69%	45.73%	163.13%

Fuel Economy Improvement Scenario

It was previously assumed that fuel economy will improve by 10% in 2030, 20% in 2040, and 30% in 2050. Therefore, Tables 16 and 17 demonstrate that fuel efficiency improvements will reduce emissions compared to the baseline scenario. The total GHG emissions from 2020 to 2050 will be reduced by 751,890metric tons of carbon equivalents, which is a reduction of 164.08%.

Table 16. The amount of reduction in emissions from the fuel economy scenario to the baseline scenario, measured in thousand metric tons of carbon equivalent.

GHG	2020	2025	2030	2035	2040	2045	2050	Total
Carbon Dioxide	-	−5.4063	−19.0402	−46.5636	−99.3973	−197.5563	−375.7312	−743.695
Methane	-	−0.0469	−0.1658	−0.4055	−0.8654	−1.7193	−3.2685	−6.4714
Nitrous Oxide	-	−0.0125	−0.0441	−0.1079	−0.2304	−0.4579	−0.8709	−1.7239
Total	-	−5.4658	−19.2502	−47.0771	−100.4931	−199.7336	−379.8706	−751.8903

Table 17. The percentage reduction in emissions from the fuel economy scenario to the baseline scenario between 2020 and 2050.

GHG	2020	2025	2030	2035	2040	2045	2050	Total
Carbon Dioxide	0%	2.31%	5.05%	7.67%	10.16%	12.54%	14.81%	52.54%
Methane	0%	2.56%	5.63%	8.55%	11.33%	13.98%	16.50%	58.55%
Nitrous Oxide	0%	2.32%	5.09%	7.74%	10.25%	12.65%	14.94%	52.99%
Total	0%	7.20%	15.77%	23.95%	31.74%	39.17%	46.25%	164.08%

In contrast, Tables 18 and 19 show a decrease in emissions under the fuel economy scenario compared to the public transport scenario. This comparison illustrates that the total emission reduction will be 11,416 metric tons of carbon equivalent, which represents a reduction of 1.93%. The decrease in the first case is much higher than in the second. This is because, in the first case, the assumption is that the country has taken no action when comparing fuel economy with the baseline. On the other hand, in the second case, fuel economy is compared with public transport, which has already been improved. Although the reduction is considered low, it can still have a significant impact on reducing emissions in the country and can prove to be an effective measure in the future.

Table 18. The amount of reduction in emissions from the fuel economy scenario to the public transport scenario, measured in thousand metric tons of carbon equivalent.

GHG	2020	2025	2030	2035	2040	2045	2050	Total
Carbon Dioxide	-	−0.0891	−0.2451	−0.6223	−1.4044	−2.9715	−6.0357	−11.3681
Methane	-	−0.0002	−0.0005	−0.0013	−0.0029	−0.0061	−0.0124	−0.0233
Nitrous Oxide	-	−0.0002	−0.0005	−0.0014	−0.0030	−0.0064	−0.0131	−0.0247
Total	-	−0.0895	−0.2461	−0.6249	−1.4103	−2.9840	−6.0612	−11.4160

Table 19. The percentage reduction in emissions from the use of fuel economy option in the public transport scenario between 2020 and 2050.

GHG	2020	2025	2030	2035	2040	2045	2050	Total
Carbon Dioxide	0%	0.04%	0.07%	0.11%	0.16%	0.22%	0.28%	0.87%
Methane	0%	0.01%	0.02%	0.03%	0.04%	0.06%	0.07%	0.23%
Nitrous Oxide	0%	0.04%	0.06%	0.11%	0.15%	0.21%	0.26%	0.82%
Total	0%	0.09%	0.15%	0.25%	0.35%	0.48%	0.62%	1.93%

4. Conclusions and Recommendations

The population growth in Qatar has led to a corresponding rise in traffic. This resulted in a significant increase in greenhouse gas emissions. In Qatar, these emissions derive primarily from the transportation industry. This makes it one of the key sectors to focus on for emission reduction. Considering the critical role the transportation sector plays in reducing emissions, this study was conducted in line with the country’s strong commitment to environmental priorities. This is mainly because of the need for more research in Qatar. To conduct this study, LEAP was used as a forecasting tool for the country’s GHG emissions. This was done by considering three scenarios and their corresponding sub-scenarios. The main scenarios are (1) The historical scenario; (2) The business-as-usual scenario; and (3) The public transport scenario. The third main scenario has been further investigated considering three sub-scenarios, namely (i) Fuel economy improvement; (ii) Electrification of public transportation; and (iii) Using compressed natural gas.

Due to LEAP’s ability to assist in analyzing and facilitating various scenarios, it has been identified as an invaluable tool for investigating the different cases outlined in the study. LEAP in this study brings about great insights because it has never been used in the literature that studies this part of the world. The tool is a crucial part of this research paper, as it estimates actual emissions and projects future emissions using real traffic data from the traffic department. The findings would contribute significantly to the literature since the study this research tackles is the first ever conducted in Qatar.

Based on the results of the LEAP model, the following can be concluded; (1) CO_2 emissions were the highest in all scenarios that were considered; (2) The baseline scenario predicts that the total GHG emissions will add 6,498,030 metric tons of carbon equivalents by 2050; (3) The LDV category is responsible for 57.69% of the total emissions in the baseline scenario; (4) By implementing the public transport scenario, total GHG emissions will be reduced by 163.13% compared to baseline; (5) LDVs in the public transport scenario will emit 267.91% less GHG emissions than LDVs in the baseline scenario; (6) The fuel economy scenario will result in 164.08% reduction in emissions compared to the baseline; and (7) Fuel economy will reduce emissions by 1.93% compared to the public transport scenario.

By understanding current trends and forecasting the future, Qatar can implement policies that promote sustainable transportation practices, reduce greenhouse gas emissions, and mitigate adverse environmental impacts.

Based on the findings of this study, specific actions are recommended for decision-makers; (1) Recognize LEAP as a valuable and essential tool for informing energy planning and policy decisions in Qatar; (2) Invest in expanding and improving the public transportation system; (3) Provide incentives, such as discounts, to public transportation users; (4) Launch campaigns to raise public awareness of public transportation's environmental and health benefits; (5) Train drivers on how to use efficient driving techniques to minimize emissions, such as avoiding unnecessary acceleration and braking; and (6) Reduce the number of empty miles traveled by public transportation agencies by optimizing their routes and schedules, thereby reducing the amount of energy wasted and the number of emissions generated.

There are some limitations to this study, which should be acknowledged. One of the limitations is regarding data. Due to the unique context of the study conducted in Qatar, several data elements could not be readily accessed or were not directly available. However, data requirements were augmented by adapting data from other countries and using global databases to ensure the thoroughness and comprehensiveness of conducted analysis, such as energy intensity.

Since this study focuses on road transportation, future researchers can use LEAP to investigate the emissions associated with other modes of transportation, such as airplanes and ships. The tool can also forecast the country's emissions from various industries, such as energy and manufacturing. This will benefit and improve existing literature while expanding our understanding of emission forecasting. More importantly, it would enable Qatar to strategically allocate resources and investments while setting realistic and achievable emission reduction targets.

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