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Article

Technical and environmental assessment of biofuel utilization in light and heavy vehicles: implications for carbon footprint reduction on high-traffic freeway

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ABSTRACT

The global imperative to reduce greenhouse gas (GHG) emissions necessitates urgent transitions in the transportation sector, which currently accounts for approximately 40% of global emissions. This study focuses on the potential of biofuels to serve as a sustainable alternative to fossil fuels within Iran's road freight transport sector, specifically along the North Tehran Freeway, a corridor characterized by heavy traffic and significant carbon emissions. Conducted over a one-year period from October 2022 to September 2023, this research calculates the carbon footprint of vehicles using gasoline and diesel, providing a detailed analysis of fuel consumption and resulting CO_2 emissions. The study highlights the feasibility of bioethanol and biodiesel, locally available in Iran, as practical substitutes for fossil fuels, particularly given the limited availability of electric vehicles (EVs) in the region. The findings reveal that gasoline dominates fuel consumption on the Tehran-North corridor, accounting for 86% of the total fuel use, thereby underscoring the urgent need for cleaner alternatives. This research contributes to the understanding of Iran's unique transportation challenges and offers practical solutions for reducing carbon emissions through biofuels. The study's granular approach, assessing emissions on a monthly basis, provides nuanced insights into seasonal and behavioral factors influencing fuel use, laying the groundwork for effective policy development aimed at transitioning Iran's transportation sector towards greater sustainability.

1. Introduction

The current level of unintentional greenhouse gas (GHG) emissions resulting from the burning of fossil fuels has reached a concerning point, necessitating immediate measures for prevention through the adoption of environmentally compatible climate policies. In 2015, the International Energy Agency developed a scenario for the future energy system aiming to restrict the rise in global average temperature to 2 degrees Celsius by 2050, later revised to 1.5 degrees Celsius [1]. Presently, the global transportation sector accounts for a quarter of total energy consumption and contributes around 40% of greenhouse gas emissions. With oil dominating the sector and fulfilling 90% of its fuel demand, the necessity for transitioning towards more sustainable energy sources is evident. Two pivotal transformations are crucial for decarbonizing transportation: the shift towards electricity, focusing on electric vehicles (EVs) and hydrogen fuel cell vehicles (HFCVs) for road transport, and the adoption of cleaner fuels like biofuels, hydrogen, and hydrogen-based fuels, especially in the aviation and maritime industries [2]. Incorporating biofuels into the energy mix emerges as a promising strategy to reduce carbon emissions and promote sustainability within the transportation sector. Biofuels, as renewable and easily accessible alternatives, offer a feasible means to diminish greenhouse gas emissions and lessen reliance on non-renewable fossil fuels. By embracing biofuels alongside other clean energy solutions, countries can advance towards their emission reduction objectives and facilitate the transition to a more environmentally conscious transportation infrastructure [3, 4]. One of the significant environmental challenges faced by Iran pertains to the production of 0.5 kg of carbon dioxide per US dollar of GDP, indicating one of the highest ratios of carbon dioxide production to GDP globally [5]. As a response, Iran pledged in the 2015 Paris Agreement to unconditionally reduce its greenhouse gas emissions by 4% by 2030 [6]. Given that the predominant use of fossil fuels in almost all motor vehicles in Iran makes transportation a primary contributor to carbon dioxide emissions, the imperative of transitioning to cleaner energy sources in Iran's transportation sector is twofold. Consequently, an essential step involves the assessment and comparison of the carbon footprint associated with renewable and non-renewable fuels within this sector. The North Tehran Freeway, known for its heavy traffic flow of various vehicles, presents a significant real-world challenge. We are undertaking the critical task of addressing the serious problem of high emissions in Iran by analyzing the carbon footprint along this route. This research not only evaluates the potential of biofuels as substitutes for fossil fuels to reduce carbon dioxide emissions but also aims to provide practical solutions for enhancing transportation sustainability. With bioethanol and biodiesel readily available in Iran and limited electric vehicle options due to production constraints, transitioning to biofuels emerges as a more feasible option over shifting from internal combustion engine (ICE) vehicles to electric ones. This comprehensive analysis lays the foundation for developing effective strategies to significantly reduce the carbon footprint in the transportation sector.

2. Literature review

According to Pandey et al. [7], determining the comprehensive carbon footprint requires estimating and summing up the GHG emissions during the entire life cycle of a manufactured item. This life cycle encompasses all stages, from obtaining raw materials to final packaging, distribution, consumption, and disposition. This approach, known as cradle-to-grave analysis, provides a holistic view of inputs and outputs, including air pollutants, water usage, energy consumption, GHG emissions, and other relevant factors. Assessing the life cycle's environmental impact, costs, and benefits is often referred to as environmental life cycle assessment. To compute the carbon footprint, the GHG emissions released at each stage of the product's life cycle, referred to as GHG accounting, are estimated. Different methodologies exist for calculating the carbon footprint. Strutt et al. [8] have outlined three distinct domains to facilitate accurate calculations [9]. The first domain encompasses direct emissions, specifically those occurring at the calculation site. The second domain encompasses emissions associated with purchased energy. The third domain encompasses all indirect emissions, including those related to the transportation of goods, sold items, business travel, energy activities, product disposition, and other factors not accounted for in groups 1 and 2. Naturally, if all three domains are considered, the accuracy of the work will be higher. GHG data can be gathered by means of direct measurements on the spot in real time or estimated using emission factors and models. The selection of the most suitable approach depends on the purpose (mandatory, voluntary, or internal management), reliability, workability, expense, and scope. Emission factors and models are the favored and commonly utilized approaches [7]. To convert GHG data into equivalent carbon dioxide, conversion factors provided by the Intergovernmental Panel on Climate Change are employed [9].

Based on the study conducted by Murray et al. [10], a wide range of online calculators exist for carbon footprint calculations. Some of these calculators focus on estimating internal carbon footprints, while the rest estimate carbon footprints related to transportation, food, or related endeavors. Several studies have been conducted in the realm of calculating and comparing carbon footprints, specifically within the transportation sector. Girardi et al. [11] conducted a comparative assessment of the life cycle of an EV and a petrol-driven car in Italy, utilizing available data from the national power system regulations, electricity market laws, and the list of results from national reports. They focused on different scenarios for the years 2013 and 2030 to calculate both short-term and long-term impacts. The study revealed a reduction of over 40% in GHG emissions from EVs compared to ICEVs. Furthermore, Wu et al. [12] have focused on calculating and comparing the life cycle GHG emissions of EVs and petrol-driven cars. They utilized The China Automotive Life Cycle Database for the years 2010, 2014, and 2020. The results indicate that the potential for reducing emissions during the whole period of the life cycle can increase by 13.4% for EVs compared to petrol-driven cars by the year 2020. In another study, Leung et al. [13] investigated the impact of using biofuels in Hong Kong to reduce pollutant emissions in vehicles as well as carbon footprint. They demonstrated that the carbon dioxide emissions in the process of converting waste paper to ethanol can be reduced by 80% compared to the process of transporting waste paper to landfills [14].

Holmatov et al. [15] evaluated the environmental impact of transportation using vehicles fueled by renewable sources. This evaluation encompassed three aspects: land footprint, carbon footprint, and water footprint. Their findings showed that, compared to gasoline-powered vehicles, EVs exhibited a 96% reduction in emissions in a bio-electricity scenario and a 100% reduction in a solar electricity scenario. Vehicles running on 20% biodiesel blend (B20) fuel had 12% lower emissions, while HFCVs showed 100% lower emissions. However, it is important to note that these vehicles had a significantly larger water footprint than conventional gasoline vehicles. The pioneering aspect of this study resides in the computation and scrutiny of the carbon emissions profile for a heavily traversed roadway in Iran on a monthly and yearly cadence, marking a novel endeavor in this domain. Furthermore, the research entails appraising the viability of biofuels as feasible substitutes for traditional fossil fuels with the aim of curbing carbon dioxide emissions. Previous studies on carbon emissions and biofuels have been conducted in different geographic and economic contexts, often focusing on developed countries or regions with advanced renewable energy infrastructure. This article fills the gap by providing detailed, localized data on carbon emissions specific to the Tehran-North corridor, offering insights into a region with unique challenges such as heavy reliance on fossil fuels and limited biofuel production infrastructure. The study uniquely emphasizes the potential of biofuels as a sustainable alternative in Iran's transportation sector, where the adoption of EVs is limited. While biofuels have been extensively studied globally, their application and feasibility within Iran's road freight transport context have not been thoroughly explored. This research provides valuable data and analysis that could inform future policy decisions and industrial strategies in Iran and similar regions. Unlike many previous studies that provide a snapshot or annual average of emissions, this article offers a granular analysis of fuel consumption and emissions on a monthly basis. This temporal detail helps to identify patterns in fuel use and emissions that are influenced by seasonal changes, travel behaviors, and other factors, providing a more nuanced understanding of the challenges and opportunities for emission reduction. The study goes beyond theoretical assessments by applying findings to a specific, heavily trafficked roadway in Iran. This practical approach ensures that the research has immediate relevance and applicability, offering tangible solutions for reducing the carbon footprint in Iran's transportation sector. Overall, the article contributes to the body of knowledge on sustainable transportation by addressing critical gaps in data and analysis for Iran, providing a pathway for practical, region-specific strategies to reduce greenhouse gas emissions through the adoption of biofuels.

3. Methodology

Iran's biofuel production mainly involves bioethanol and biodiesel, but production volumes are relatively low. The agricultural residues and waste that could serve as feedstock are often not fully utilized, primarily due to logistical issues and a lack of infrastructure. The adoption of biofuels in road freight transport in Iran is limited, reflecting broader challenges within the biofuel industry. The transportation sector in Iran heavily relies on fossil fuels, particularly diesel, due to the country's abundant oil resources and subsidies that keep fuel prices low. This reliance on fossil fuels contributes significantly to carbon emissions, particularly in the road freight transport sector, which is a major consumer of diesel. The potential for biofuels to serve as a more sustainable alternative to diesel in road freight transport is significant, especially considering the increasing pressure to address climate change and reduce dependency on fossil fuels. To justify the focus on reducing carbon emissions through the adoption of biofuels in road freight transport, it is essential to highlight the environmental benefits of biofuels, such as lower greenhouse gas emissions compared to conventional diesel. The development of the biofuel industry could also have economic benefits, including job creation in rural areas, reduced dependency on oil, and improved energy security. While Iran's biofuel industry is still underdeveloped, there is a significant opportunity to expand biofuel production and use in road freight transport to reduce carbon emissions. Focusing on biofuels could not only help mitigate the environmental impact of the transportation sector but also promote sustainable economic growth by leveraging the country's agricultural resources and reducing reliance on fossil fuels. This study, conducted over a one-year period in 2023, focused on investigating carbon dioxide (CO_2) emissions due to their significant impact on the road transport sector in Iran. The decision to concentrate on CO_2 was driven by its predominant role in contributing to the environmental challenges faced by the transportation sector. One of the critical reasons for this focus on CO_2 is its considerable contribution to the overall greenhouse gas emissions in Iran's road transport sector, making it a key target for emission reduction strategies. CO_2 emissions are a major concern globally, and in Iran, the road transport sector is a significant source of these emissions, which underscores the importance of addressing this pollutant to mitigate climate change and its associated impacts. Additionally, the study encountered challenges in accessing reliable data on other greenhouse gases, such as nitrogen oxides (NO_x) and sulfur oxides (SO_x), and their emission contributions across different types of vehicles in Iran. This limitation in data availability made it difficult to conduct a comprehensive analysis of all greenhouse gases, leading to a specific focus on CO_2. Policymakers and researchers need to carefully weigh these strengths and limitations when considering biofuels as part of a broader strategy for sustainable energy and climate change mitigation. Sustainable practices, technological advancements, and comprehensive lifecycle assessments are essential to maximizing the benefits of biofuels while minimizing their environmental impact. In this study, the calculation of carbon dioxide emissions is conducted using an analytical approach. For this purpose, traffic data on the Tehran-North freeway has been extracted from the website of the National Road Management Center [16]. Additionally, Figure 1 displays the map of this route.

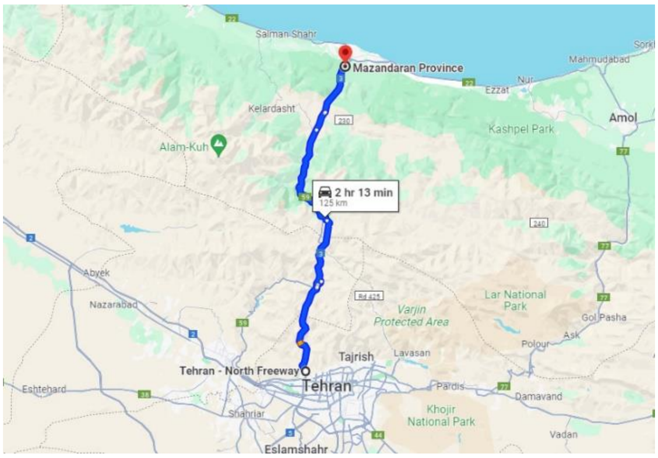

Figure 1. North Tehran freeway map

To determine the carbon footprint, the first step involves calculating the distance covered [17].

$$S = l \times n \quad (1)$$

Where S represents the distance covered in kilometers, l denotes the length of the road in kilometers, and n represents the number of vehicles. By utilizing the computed distance traveled, the total fuel consumption can be determined using the following Equation (2) [17]:

$$C_{tot} = S \times C_e \quad (2)$$

In Equation (2), C_{tot} represents the total fuel consumption in liters, and C_e represents the vehicle's energy consumption per kilometer in liters. Table 1 displays the default values for energy consumption for various vehicle types. These quantities are calculated based on an assumed average lifespan of 20 years for each vehicle in Iran, taking into account the expert opinions in the field.

Table 1. The default energy consumption values for various vehicle types

Vehicle type	Energy consumption value (liter/km)
Class 1 (Cars and pick-up trucks)	0.11
Class 2 (Mini trucks and minibuses)	0.22
Class 3 (Normal trucks less than 10 meters and 3 axles)	0.38
Class 4 (Buses)	0.45
Class 5 (Trailers and carriers above 3 axles)	0.7

Then, the values obtained for the total fuel consumption are utilized to compute the amount of energy consumption (E_c) in liters with the help of Equation (3)[17]:

$$E_c = C_{tot} \times F \quad (3)$$

The calculation of the energy consumption value is performed by converting the fuel consumption using the energy content (F). The unit of energy content is gigajoules per liter, and its values, which are based on the type of fuel consumed, are specified in Table 2 for diesel and gasoline.

Table 2. Energy content values for gasoline and diesel

Fuel type	Energy content (GJ/L)	Reference
Gasoline	0.03466	[18]
Diesel	0.03868	[18]

Then, using equation (4), the emission value (E_m) is calculated by multiplying the energy consumption value by the emission factor (*FF*). The unit of the emission factor is tons of carbon dioxide per terajoule [17].

$$E_m = E_c \times FF \quad (4)$$

The values of the emission factors for the fuels used are provided in Table 3.

Table 3. Emission factor values for the fuels used

Fuel type	Emission factor (tCO_2/TJ)	Reference
Gasoline	69.3	[19]
Diesel	74.1	[19]

4. Results and discussion

4.1 Calculating the carbon footprint of consumed gasoline and diesel fuel

In light of the limitations imposed by the COVID-19 pandemic, calculations have been conducted for one year following the lifting of restrictions. Specifically, the period considered spans from October 2022 to September 2023. The initial step involved calculating the volume of gasoline and diesel consumed in liters for various vehicle classes. Gasoline was used as fuel for Class 1 vehicles, whereas diesel was used for other classes. Table 4 illustrates the fuel consumption for different vehicle classes throughout the designated one-year period.

Table 4. The amount of fuel consumed by different types of vehicles

Vehicle type	Fuel consumption value (million liters)
Class 1 (Cars and pick-up trucks)	118.07
Class 2 (Mini trucks and minibuses)	8.29
Class 3 (Normal trucks less than 10 meters and 3 axles)	4.03
Class 4 (Buses)	2.59
Class 5 (Trailers and carriers above 3 axles)	3.83

It can be observed that during the one-year period under investigation, a total of over 118 million liters of gasoline and over 18.7 million liters of diesel were consumed on the Tehran-North corridor. This indicates that gasoline accounts for approximately 86% of the total fuel consumption on this route. Despite the fact that the energy consumption in Class 1 vehicles is significantly lower compared to other vehicle classes, the total fuel consumption of Class 1 vehicles is much higher due to the significantly larger number of vehicles in this class. It is also observed that in diesel-powered vehicles, Class 2 vehicles, namely mini-trucks and minibuses, despite their lower energy consumption, have allocated the highest fuel consumption to themselves due to their larger numbers. In the second step, the monthly fuel consumption in liters has been calculated. Figure 2 illustrates the monthly consumption of gasoline and diesel separately, in millions of liters, from October 2022 to September 2023. It is observed that during the warm and moderate months of the year, there is a significant increase in fuel consumption, with the gasoline and diesel consumption in these months being almost twice as much as the colder months. The highest gasoline consumption occurs during the summer months when intercity travel is at their peak. During these months, over fifty million liters of gasoline are consumed in total. In October, a 31% decrease in consumption compared to the previous month is observed, with the most significant factors being the start of the school year and a noticeable drop in temperature, leading to a significant decrease in intercity travel. This decrease in consumption continues with the decrease in temperature to the point that the lowest fuel consumption is also related to the coldest months of the year, namely January and February when intercity travel reaches its minimum due to severe cold weather.

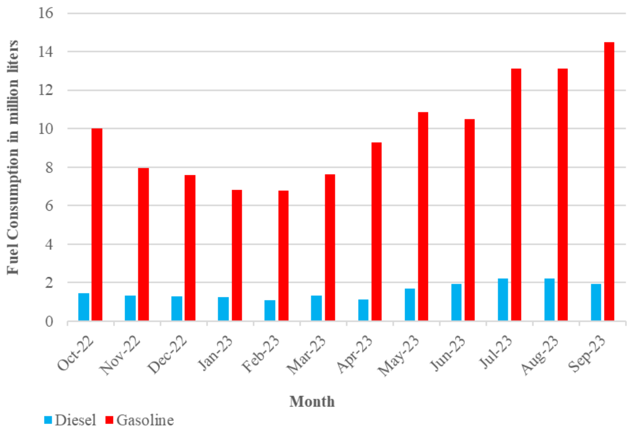

Figure 2. The amount of fuel consumed

The highest amount of diesel consumption is also observed in the summer season, particularly during the months of July and August, where approximately 2.2 million liters of diesel are consumed in each of these months. Unlike gasoline, the reason why the peak diesel consumption is not in August is because truck drivers tend to go on vacation and have less work engagement during that month. The lowest diesel consumption, around one million liters, occurs in the months of February and April. It appears that the cold weather in February and the partial closure of the month due to the New Year holiday in April contribute to this situation. Then, the carbon dioxide footprint has been calculated. The total amount of carbon dioxide released throughout the year is 337.3 million liters, with 84% of it, which is equivalent to 283.6 million liters, coming from burning gasoline and the remaining 16%, which is 53.7 million liters, resulting from burning diesel. The monthly carbon dioxide emissions in terms of million liters are shown in Figure 3. As expected, the pattern of carbon dioxide emissions follows a similar trend to the fuel consumption pattern, and during the hot months of the year, with a significant increase in traffic and fuel consumption, the emissions also show a noticeable rise. In fact, the emissions resulting from burning gasoline in September are more than double the emissions in the months of January and February. The emissions resulting from burning diesel also follow a similar pattern, with the emissions in the month of September being more than double the emissions in the months of January and February.

4.2 Calculating the impact of replacing fossil fuels with biofuels

In this stage, the calculations were again performed using the conversion and emission factors specific to biofuels. Diesel vehicles can use biodiesel, while gasoline vehicles can use bioethanol. Therefore, the calculations assumed using these fuels instead of fossil fuels. Table 5 displays the energy content and emission factor of pure biofuels, including corn ethanol and palm biodiesel. Subsequently, the values related to conventional biofuels, which include E5, E10, B5, B10, and B20, are calculated using the data in Tables 2,3 and 5. Table 6 presents the energy content and emission factor of these fuel variants. Since the use of B100, E100, and E85 requires modifications to the vehicle system and the addition of special filters, the calculations for these fuels were ignored.

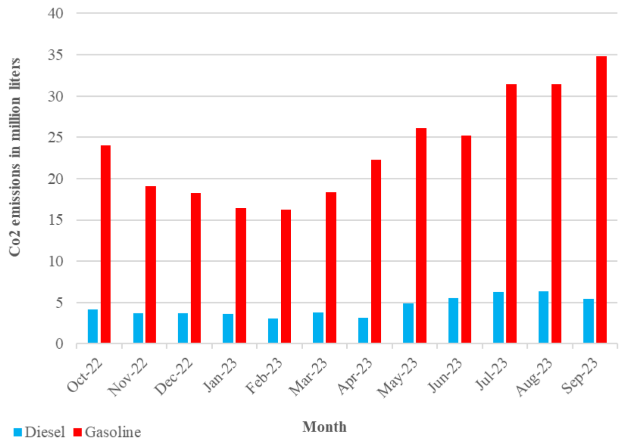

Figure 3. Monthly CO_2 emissions

Table 5. Values of energy content and emission factor of pure biodiesel and bio gasoline

Fuel type	Energy content (GJ/L)	Emission factor (tCO_2/TJ)	Reference
B100	0.03393	33.19	[20]
E100	0.021	18.53	[21]

Table 6. Values of energy content and emission factors of conventional biofuels

Fuel type	Energy content (GJ/L)	Emission factor (tCO_2/TJ)
B5	0.03844	72.05
B10	0.03821	70.01
B20	0.03773	65.92
E5	0.03398	66.76
E10	0.03329	64.22

The emission levels from various combinations of biofuels have been initially calculated. Figure 4 displays the monthly emissions of gasoline, E5, and E10. It is evident that although the consumption patterns are similar, the emission levels decrease as the concentration of bioethanol in the blend increases.

Figure 5 compares the emissions of these three fuels over the course of one year. The reduction in carbon dioxide emissions when using E5 is over 11.9 million liters, indicating a decrease of 4.19%. Additionally, the reduction in carbon dioxide emissions when using E10 is over 23.8 million liters, indicating a decrease of 8.39%. In the next step, the carbon dioxide emissions from biodiesel blends of 5%, 10%, and 20% have been calculated.

Figure 6 displays the monthly emissions of diesel fuel, B5, B10, and B20. It can be observed that the consumption patterns are similar, but as the concentration of biodiesel in the blend increases, the emission levels decrease.

In Figure 7, the emissions of these three fuels have also been compared over the course of one year. The reduction in CO_2 emissions when using a 5% biodiesel blend is approximately 1.63 million liters, indicating a decrease of 3.04%. Additionally, the reduction in carbon dioxide emissions when using a 10% biodiesel blend is over 3.26 million liters, indicating a decline of 6.08%. The capacity for emission reduction with a 20% biodiesel blend is over 6.5 million liters, representing a reduction of 12.15%.

Through the calculations conducted on the replacement of gasoline and diesel with biofuels, it has been determined that we can achieve a minimum reduction of 13.5 million liters, equivalent to 4.01%, and a maximum reduction of 30.3 million liters, equivalent to 8.98%, in carbon dioxide footprint. The minimum scenario corresponds to the substitution of E5 and B5, while the maximum scenario involves the substitution of E10 and B20.

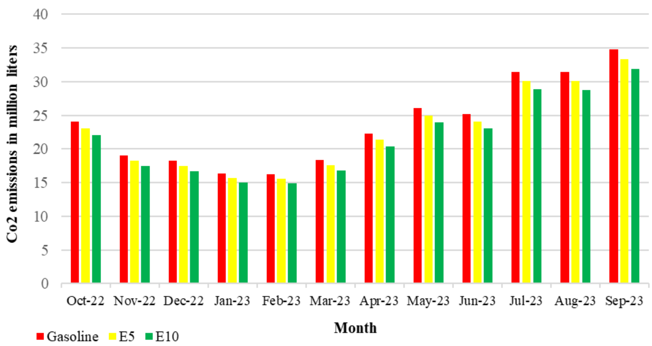

Figure 4. The monthly emissions of gasoline, E5, and E10

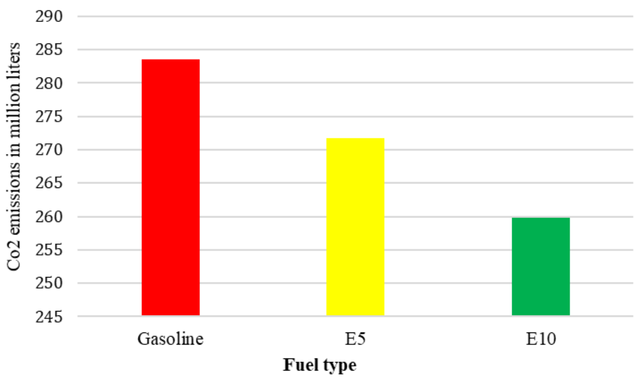

Figure 5. Comparing the carbon footprint of gasoline, E5, and E10 over a year

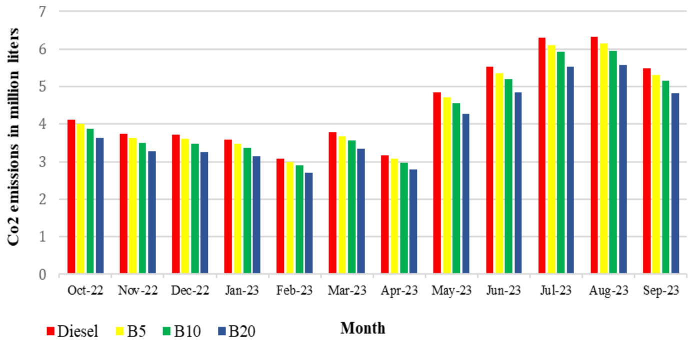

Figure 6. The monthly emissions of diesel, B5, B10, and B20

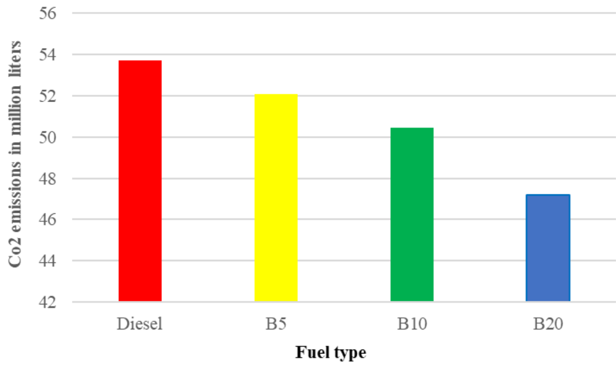

Figure 7. Comparing the carbon footprint of diesel, B5, B10 and B20 over a year

5. Conclusions

The analysis of fuel consumption and CO_2 emissions along the Tehran-North axis over a one-year duration has yielded significant findings. Notably, gasoline constitutes the major share, accounting for approximately 86% of the total fuel consumed on this route. While individual passenger vehicles exhibit lower energy consumption, their sheer volume renders them influential contributors to overall fuel consumption. Furthermore, the study reveals a distinct seasonal pattern, indicating substantially higher fuel consumption during warmer months, particularly at the peak of intercity travel, compared to colder months. Correspondingly, CO_2 emissions align with the fuel consumption patterns, with an excess of 337 million liters of CO_2 produced on this axis, of which 84% is attributed to gasoline combustion. To assess the potential impacts of biofuels, computational modeling was employed to simulate complete substitution scenarios, whereby gasoline and diesel were replaced entirely by bio-gasoline and biodiesel at lower blend percentages. The results estimated a range for annual carbon footprint reduction from a minimum of 13.5 million liters (equivalent to 4.01%) to a maximum of 30.3 million liters (equivalent to 8.98%). These findings underscore the potential of biofuels in mitigating CO_2 emissions within the transportation sector. Nevertheless, challenges associated with the utilization of biofuel blends, including the need for vehicle modifications to accommodate higher blend percentages, must be considered.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the authors.

Conflict of interest

The authors declare no potential conflict of interest.

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