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Review

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Review

Evaluation of Alternative Fuels for Sustainable Road Transportation

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Abstract: Human beings naturally move from one location to another in search of basic necessities. Road transportation is a low-cost, versatile, and widely accessible mode of transportation worldwide. However, using fossil-based (FB) fuels in transportation vehicles is inefficient, generates hazardous gases, and worsens environmental degradation. The current work assesses the application of clean fuels such as biofuels, natural gas, electricity, propane, and other emerging fuels to replace FB fuels in transport vehicles. Unlike FB fuels, the use of biohydrogen, biomethane, biodiesel, and bioethanol in transport vehicles resulted in emission reduction by 70 %, 63 %, 41 %, and 54 %, respectively, while electric vehicles lower maintenance costs, ensuring better engine performance, and better engine efficiency. The adoption of natural gas and propane as alternative fuels for transport vehicles is cost-effective, and promotes environmental sustainability. There is a need for targeted financial, infrastructural, and technical investments to further promote the application of these clean fuels for road transport application. The outcome of the study provides updated information and sensitizes automobile engineers, environmentalists, transport fleet operators, governments, and other stakeholders on the benefits derivable in the adoption of clean fuels as alternatives to FB fuels as transport vehicles fuel.

Keywords: alternative fuels; biofuels; electric vehicles; natural gas; road transportation.

1. Introduction

Humans are moving beings. One of the characteristics of a living human being is the ability to move from one point to another. People move from one location to the other to access better facilities, amenities, safety, and livelihoods. Road transportation is one of the most affordable, flexible, and easily accessible forms of transportation, globally. Though road transportation also allows for maximum traceability and door-to-door mobility, the system has resulted in adverse social and environmental impacts on the planet. Similarly, increased patronage of the road transport system has precipitated emissions of toxic gasses, deadly road accidents, and high consumption of fossil-based fuels. Also, the expansion of the road network has increased deforestation, bush burning, and disrupted terrestrial ecosystems, worldwide. Despite these drawbacks, the road transport system has developed and attracted more patronage in recent decades. Increased population growth, industrialization, socioeconomic development, and rising globalization have led to significant increments in road transportation, globally. The rising demand for goods and services, technological development, improved road infrastructure, enhanced sophistication in vehicles, and the use of artificial intelligence, the Internet of Things, and other innovative technologies have significantly transformed the road transport sector in recent years.

Movement by road transport is achieved through the use of different motorized vehicles such as cars, buses, trucks, motorcycles, bicycles, etc. which as available either as private or commercial vehicles. The total number of passenger cars and commercial vehicles increased from about 679 million and 247 million in 2006 to 288 million and 808 million in 2011, and further to 335 million and 947 million in 2015 (Figure 1) [1]. This is to provide for the increasing demand for mobility by road.

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Since most road transport vehicles are fuelled by FB fuels, emissions from the sector have increased considerably. Available data shows that the transport sector accounts for about 20 % of the global carbon dioxide (CO2) emission contributing 8.2 giga tonnes of CO2 (GtCO2) [2].

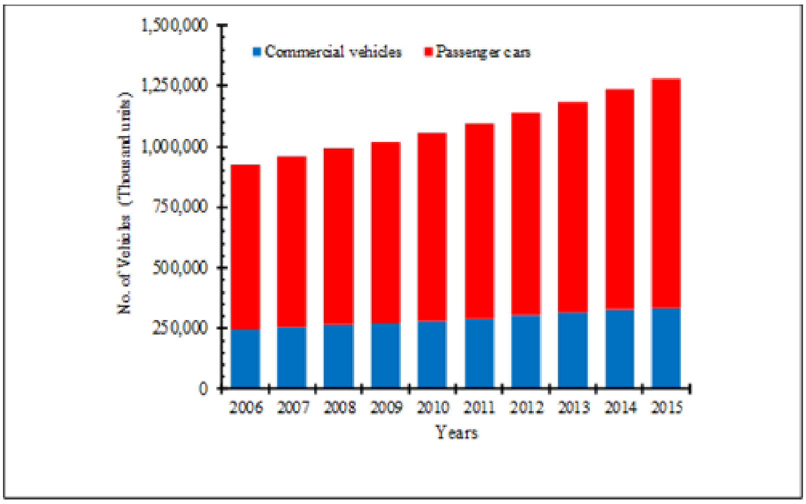

Figure 1. Number of passenger cars and commercial vehicles in the world (2006-2015).

The road transport sub-sector alone accounts for about 75 % of the CO_2 emission from the transport sector. This means that road transport generates 15 % of the total CO_2 emissions. Passenger vehicles comprising cars, buses, motorcycles, and taxis contributed 45.1 % while road freight (trucks, lorries, etc.) contributed 29.4 % of the total CO2 emissions (Figure 2) [3]. The United States, China, and India emitted 1 468.8 million metric tons of CO_2 (mmtCO_2), 748.4 mmtCO_2, and 277.5 mmtCO_2, respectively, to emerge the top three countries with the highest CO_2 emission from road transport in 2018 (Figure 3). The global CO_2 emission from the transport sector rose from 4100 MtCO_2 in 2000 to about 5800 MtCO_2 in 2020 and has been projected to become 5900 MtCO_2 in 2030. Despite the impact of emissions from road transportation, the global market share which was USD 1.07 trillion in 2015 rose to USD 3.4 Trillion in 2020 and has been estimated to rise to USD 4.7 Trillion in 2027 [4].

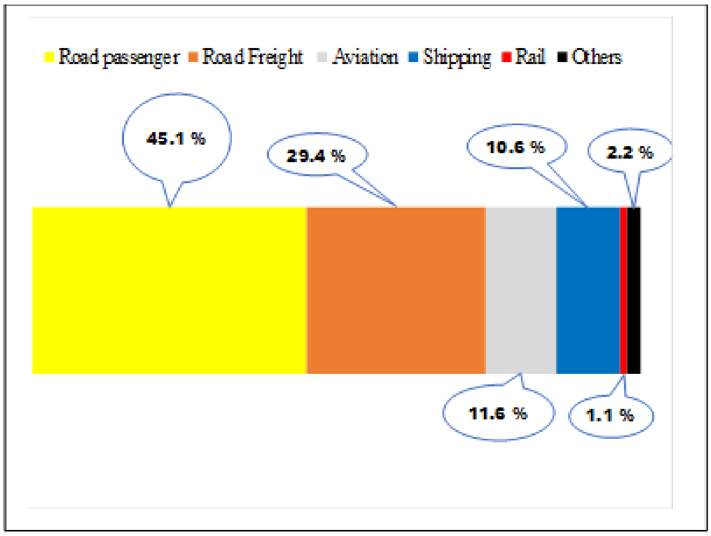

Figure 2. Share of global CO2 emission from the transport sector in 2018.

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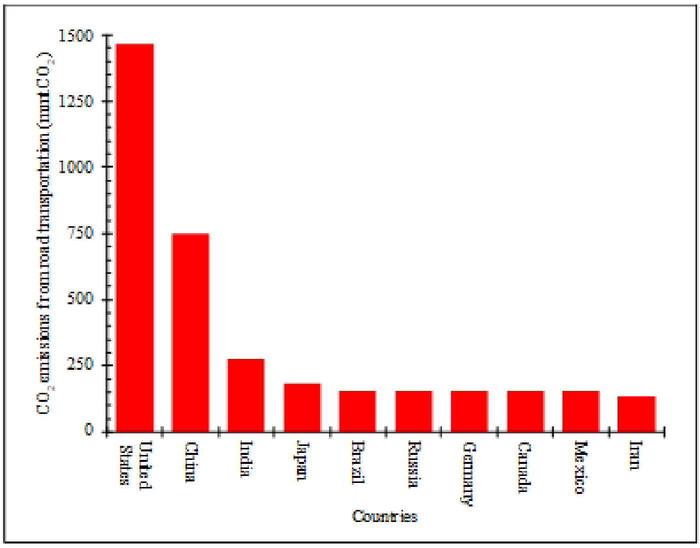

Figure 3. Top ten CO_2 emitters from road transportation in 2018.

Despite the contribution of road transportation to socioeconomic development, factors such as inadequate heavy-duty drivers, poor road infrastructure and maintenance, unsafe and crowded roads, and lack of enforcement of driving rules and policies are still militating against the growth of the sector. To curtail the environmental and health impacts of toxic emissions emanating from transport vehicles, there is a need to adopt sustainable road transportation strategies. Sustainable road transportation involves the movement of people, goods, and services from one point to the other without impacting the current and future generations. One of the strategies for ensuring strategies road transport system is to reduce emissions from transport vehicles. This can be achieved by adopting clean fuels as substitutes for the highly-polluting FB fuels in the road transportation sector. Various studies have been carried out to achieve CO2 emissions reduction in transport vehicles. The works of Li and Yu [5], Bu et al. [6], and Acar and Dincer [7] suggested the use of novel fuel combustion technologies, hybrid fuels, engine modifications, and other emissions mitigation strategies to attain net-zero emissions in transport engines. In their book, Di Blasio et al. [8] highlighted some clean and alternative fuels such as biodiesel, hydrogen, ethanol, biogas, etc. with the capacity to improve the performance, combustion, and emission characteristics of the automotive sector. The adoption of clean fuels to replace FB fuels in the transportation sector will improve combustion efficiency, reduce toxic emissions, and contribute to achieving sustainability, price reduction, efficiency, and ecologically friendly targets in the transportation system [9].

1.1. Motivation, Aim, and Structure

The subject of alternative fuels for transport vehicles is one of the strategies for achieving net-zero emissions, ensuring energy security, and a sustainable environment. The contributions of the road transportation sector to global social, economic, and industrial developments demand that adequate attention and resources be devoted to the sector. Despite the importance of this sector, it is debatable whether enough research has been conducted in the research domain to present updated information to different stakeholders. The need to fill this obvious gas forms the motivation for the current intervention.

This study aims to convey up-to-date information on the various clean fuel options available for road transport vehicles to recommend and select the best among them. The objective is to examine the utilization of various renewable and clean fuel options for sustainable road transport vehicles. The current study gives an overview, the benefits, and drawbacks of biofuels (biodiesel, bioethanol, biohydrogen, biomethane, etc.), electricity, natural gas, and other emerging fuels with the potential to replace FB fuels as transport engine fuels. The structure of this contribution includes an introduction, a global road transportation system, clean fuels for road transportation, implications,

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challenges, and opportunities in the clean fuel for transport vehicles, and a conclusion. The scope of the study is restricted to an overview and assessment of the various clean and renewable fuel options for transport vehicles. The production techniques, techno-economic, and performance evaluation of these fuels are outside the scope of this work. The result of this assessment will enlighten stakeholders and enrich scholarship by updating the available information in the research domain to stimulate further studies.

2. The Global Road Transportation System

Riding horses and oxen was the first known means of road transportation. During this era, a coverage of 25 kilometres per day was considered a good journey. By 1839, the use of bicycles with pedals which was a great improvement in the riding of animals became prominent. The first petrol-driven car designed and constructed by a German engineer, Karl Benz was introduced in 1886. The car had three wheels and seats for two people and could travel 13 km/h. The introduction of internal combustion engines to the road transportation system in the late 19th century was followed by the deployment of cars, buses, and trucks and the construction of networks of roads. Figure 4 shows a typical FB fuel vehicle. The introduction of innovative technologies has led to the use of fast-speed cars, electric cars, hybrid cars, self-driving vehicles, and drones [10].

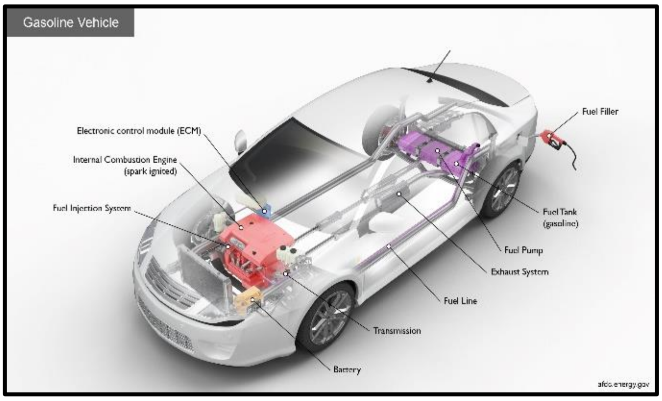

Figure 4. Gasoline vehicle [11].

In terms of the road network, the global road network for road transportation has reached about 64,285,009 km. The United States has the largest road network of 6.58 million km while the United Arab Emirates is reputed to have the best road network, globally. Table 1 shows the top 10 countries with the largest road network and their respective road density. The United Arab Emirates, Finland, Switzerland, The Netherlands, and France are the countries with the best roads, worldwide.

Table 1. Top ten countries with the largest road network.

Country	Total road length (km)	Density (km/100 km^2)
United States	6,803,479	69
India	6,372,613	194
China	5,198,000	54
Brazil	2,000,000	23
Russia	1,529,373	9
France	1,053,215	191
Canada	1,042,300	10
Australia	873,573	11
Mexico	817,596	42
South Africa	750,000	61

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The passenger vehicles have been dominated by FB fuels, especially petrol, and diesel. However due to meeting stringent emission regulations and reducing dependence on FB fuels, some countries have started using electric, plug-in, hybrid, and other alternative fuel vehicles in recent years [12]. As of 2019, petrol and diesel fuels still dominated the fuel supply for passenger vehicles in some countries (Figure 5). It can be observed that the share of petrol used for passenger vehicles is higher in 2019 than in 2015 for all the countries. Similarly, the share of non-FB fuels such as electric, plug-in, and hybrid vehicles increased in 2019 when compared with 2015 [13]. This shows increased penetration of electric, plug-in, hybrid, and alternative fuel vehicles in those countries.

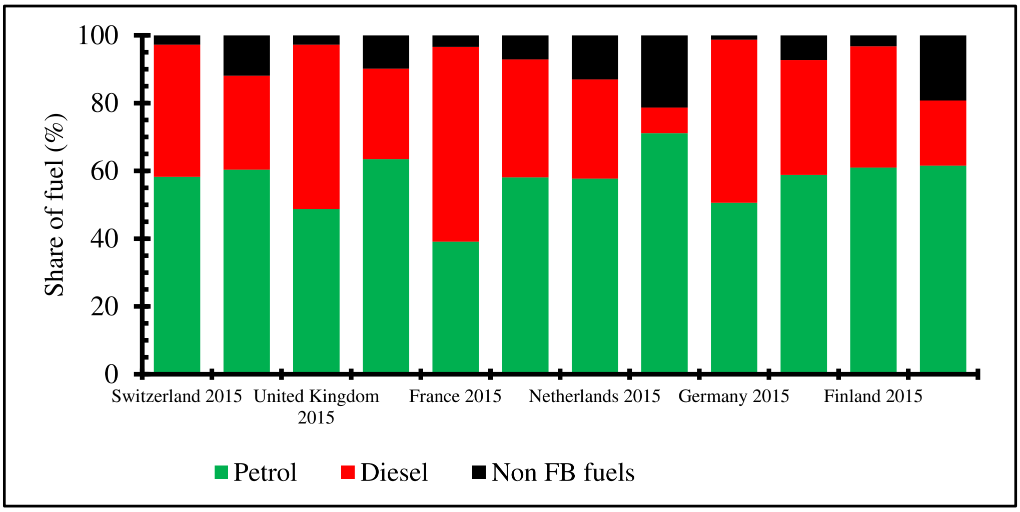

Figure 5. share of petrol and diesel fuels in passenger vehicles in selected countries for 2015 and 2019.

3. Clean Fuels for Road Transportation

To reduce the dependence of road vehicles on petrol and diesel fuels, clean fuels such as biofuels, hydrogen, electricity, propane, natural gas, and other emerging fuels are being gradually introduced to the mix.

3.1. Biofuels

Biofuels are liquid or gaseous renewable fuels derived from plant, agricultural wastes, animal fats, vegetable oil, algae material, or other similar organic matters. Biofuels are considered clean fuels since their application generates little or no dangerous emissions. The demand for biofuels has increased significantly in recent decades necessitating many countries and organizations to invest in their production and utilization [14]. The generation of biofuels from waste and other non-edible feedstocks makes it cost-effective and environmentally friendly. Biofuel generation also contributes to sanitation and is a feasible avenue for waste disposal and management. The utilization of biofuels for power generation and as fuel for internal combustion engines (ICEs) lowers tail-pipe emissions, and environmental degradation, and reduces the importation of FB fuels [15]. Popular examples of biofuels include biodiesel, bioethanol, biomethane, biohydrogen, and renewable diesel. Figure 6 shows the fuel system of a typical biodiesel vehicle. Table 2 compares the five major examples of biofuels.

The use of biodiesel, bioethanol, biomethane, biohydrogen, renewable diesel, and other biofuels to power transport vehicles has been tested and found to be economical, beneficial, and better than the use of petrol and diesel fuels. For example, Puricelli et al. [16] reported that the use of biohydrogen, biomethane, biodiesel, and bioethanol in transport vehicles resulted in emission reduction by 70 %, 63 %, 41 %, and 54 % respectively, when compared with petrol and diesel fuels. A similar investigation by Panoutsou et al. [17] and Dias et al. [18] reported that the replacement of petrol and diesel fuels with biofuels helps to improve engine performance, reduces nitrogen oxides (NOx) and particulate matter emissions, decarbonize the transport sector, and improved the

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efficiency of the vehicles. The fuel consumption and environmental assessment of biofuels in transport vehicles in Ethiopia reported that the use of bioethanol produced from sugarcane molasses saves 83 % fossil energy and reduces GHG emissions by 39 % while biodiesel generated from jatropha ensures 77 % energy savings and reduction of tailpipe GHG emissions by 79 % [19]. The application of biodiesel as an alternative fuel for vehicles in India [20], bioethanol in Poland and Brazil [21], biomethane in Sweden [22], and biohydrogen in the West Midlands region of England [23] reduces GHG emissions, contributes to air quality, and ensures return on investments.

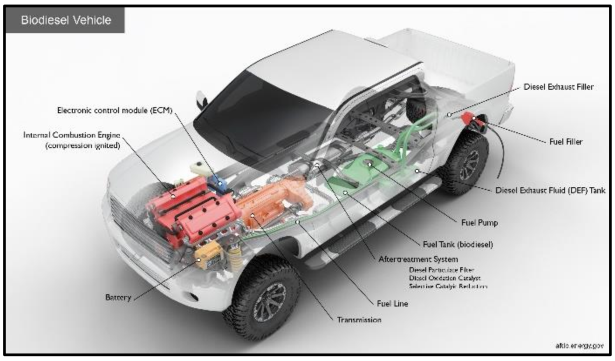

Figure 6. Biodiesel vehicle [24].

Table 2. Comparison of various types of biofuels [25].

Types of biofuels	Description	Methods of production	Areas of applications	Benefits	Drawbacks
Biodiesel	Liquid biofuel contains long-chain fatty acid esters and is usually produced from vegetable oils wastes.	• Transesterification • Pyrolysis • Micro Emulsion • Superfluid/Supercritical	• Power generation • ICEs fuel • Fuel for heavy-duty construction equipment and agricultural machinery • Feedstock for green diesel	• Cost-effective • Environmentally friendly • Safe and non-toxic • Renewable and biodegradable • Emits less carbon and other GHGs • High combustion efficiency in ICEs • Can be used without engine modifications • Compatible with FB fuel storage and transport facilities	• Emits more NOx • Some of the feedstocks conflict with the food chain • Some feedstocks need to be cultivated • Can deteriorate in storage • Clogging of fuel filter and fuel lines
Bioethanol	Liquid biofuel is produced from the fermentation of natural materials, plant derivatives, or wastes.	Fermentation	• ICEs fuel • Power generation • Fuel for heavy-duty construction equipment and agricultural machinery	• Cost-effective • Contributes to waste management • Enhances sanitation. • Less emission of GHGs • minimizes air pollution	• Impact food security • Scarce feedstock • Needs ethical approval
Biomethane	Gaseous biofuel is generated from the upgrading and removal of CO_2 and other impurities from biogas.	Anaerobic digestion	• ICEs fuel • Electricity generation • Space heating • Fuel for power plants • Industrial applications	• Low production cost • Waste conversion to fuel • Low carbon emission • Environmentally sustainable	• Emission of GHG • Contributes to global warming • Emission of methane

				• Generation of fertilizer • Waste management	
Biohydrogen	Advanced biofuel produced from biomass through biological and thermochemical processes	• Gasification • Fermentation • Biophotolysis • Microbial electrolysis, • Pyrolysis	• Transportation fuel • Electricity generation • Food and beverage industries • Pharmaceutical industries	• Clean and non-toxic • High energy content • Renewable and non-polluting • Odourless and safe	• Relatively expensive • Technical and infrastructure demanding • Difficulty in storage and transport
Renewable diesel	Liquid biofuel consists of a blend of straight-chain and branched paraffin hydrocarbons within the C15–C18 range.	• Hydrogenation • Hydrotreating • Hydroprocessing • Hydrodeoxygenation	• Power generation • ICEs fuel • Industrial applications • Turbine fuel • Can be used as bio-jet fuel for aviation	• Lower water footprint • Supplemental fuel for turbines. • Renewable and biodegradable • Highly sustainable • Reduced emission	• Expensive production process • Not widely used

3.2. *Electricity*

Electricity can be used as an alternative to petrol and diesel fuels to power transport vehicles. Such vehicles powered with electricity are called electric vehicles (EVs) which can be battery-electric vehicles (BEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), or fuel cell electric vehicles (FCEVs). Electricity can be generated from solar, wind, hydropower, or other renewable sources. The BEVs operate entirely in electric mode with no engine parts. The energy requirement is supplied from the rechargeable batteries which are charged at 150-400 miles' intervals. The HEVs use both fuel and an electric motor to drive the car. The batteries gain energy through regenerative braking when the vehicle accelerates. The PHEVs have both ICE and electric motors to drive the car. The engine provides power for the car when the batteries are depleted. The FCEVs use fuel cell which converts the energy stored as hydrogen to electricity to power the vehicle [26]. The EVs can be charged at intervals at privately owned charging stations or in public charging stations located in shopping centres, garages, hotels, etc. Figure 7 shows a typical PHEV.

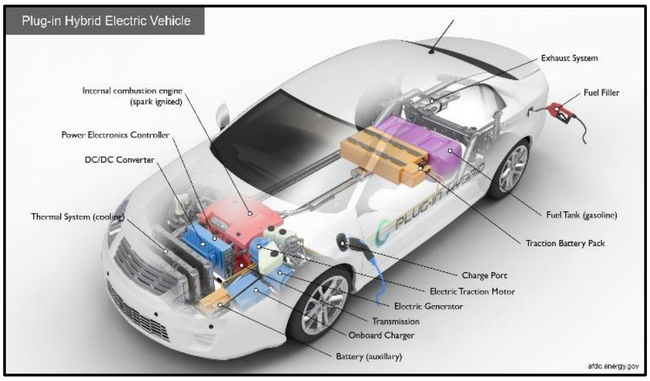

Figure 7. Plug-in hybrid electric vehicle [27].

The use of electricity in transport vehicles is environmentally friendly and the vehicles do not emit any pollutants. There is no need for fuel in most EVs and in the case of HEVs, the cost of fuel is drastically reduced. reduce the cost of fuel significantly. EVs require little or no maintenance since there are fewer parts when compared with ICEs. Other benefits of EVs include better performance,

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more enjoyable driving, lower running costs, tax benefits, and incentives [28]. However, there are cost and infrastructural challenges associated with EVs, particularly in low-income countries. Also, the disposal and management of used batteries are still challenging and expensive [29]. The use of electricity to drive transport vehicles has gained traction and has become more acceptable in recent decades. This is due to the benefits of zero-emission, energy security, return on investment, and improved efficiency. Reports of EV use for road transportation in various jurisdictions including Lithuanian [30], China [28], Norway [31], United Kingdom [32], and Sub-Saharan Africa [33] show that it contributes to zero-emission and decarbonization, promotes energy saving, aids renewable energy integration, and contributes towards environmental sustainability.

3.3. *Natural gas*

Natural gas is a domestically generated gaseous fuel for cooking, electric power generation, fuel for ICEs, and as feedstock for chemical products. Natural gas is a clean, odourless, and highly flammable gaseous mixture of hydrocarbon, mainly methane and ethane, and occurs as compressed natural gas (CNG) and liquefied natural gas (LNG). CNG is synthesized by compacting natural gas to less than 1 % of its volume at normal atmospheric pressure. On the other hand, LNG is a product of the liquefaction of natural gas at low temperatures to become mainly methane in liquid form with a small percentage of other hydrocarbons. The global production of natural gas increased from 3.26 trillion cubic meters in 2011 to about 4.04 trillion cubic meters in 2021, with the United States, Russia, and Iran dominating the market [34].

Natural gas is more cost-effective, reliable environmentally friendly and burns cleaner than FB fuels. LNG is easy to transport and has versatile applications for electric power generation, cooking, heating, and as vehicle fuel. During combustion, natural gas emits less CO2 and other GHGs when compared with FB fuels. The storage process and infrastructure of natural gas are relatively expensive and its application contributes to methane leaks and environmental pollution. Since natural gas is highly flammable and combustible, careless handling and storage can cause fire outbreaks. Unlike the gasoline vehicle, the fuel tank is replaced by a tank containing compressed natural gas and a metal tube or flexible hole connecting the tank to the combustion chamber (Figure 8).

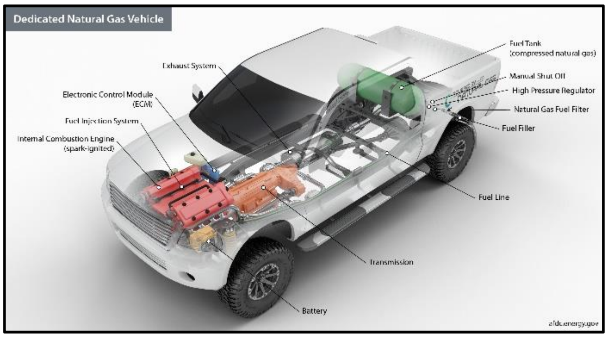

Figure 8. Natural gas vehicles [35].

The work of Ogden et al. [36], Quiros et al. [37], and Khan et al. [38] tested natural gas as a transportation fuel to replace diesel and petrol fuels for ICEs. The results of their tests showed that natural gas offers economic, technical, environmental, and safety benefits over the use of petrol or gasoline fuel for transport vehicles. For example, transport vehicles fuelled with compressed natural gas emitted less CO2, methane, and nitrous oxide when compared with FB fuel vehicles. The use of natural gas as a substitute fuel for traditional vehicle fuels yielded about 9–17% reduction in GHG emissions and contributed to environmental sustainability in China [39]. Similar studies by Likhanov and Rossokhin [40], Warguła et al. [41], Abdullah and Anwar [42], and Dyr et al. [43] on the use of compressed natural gas as an alternative fuel for public transport vehicles across various jurisdictions showed the performance, effectiveness, efficiency, and practicability of the new fuel. The adoption of natural gas as an alternative fuel for transport vehicles ensures net-zero emissions and contributes to environmental sustainability.

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3.4. . Propane

Propane is a three-carbon alkane (C3H8) colourless, odourless gas commonly called liquefied petroleum gas (LPG). It is mainly used for water heating, cooking, refrigerant, clothes drying, raw materials in plastic making industries, and as fuel for ICEs [25]. Propane is usually stored under pressure in liquid form but turns into a gaseous state when the pressure is released. Due to its high octane rating, LPG is an efficient fuel for spark ignition (SI) engines. LPG possesses high energy content, good burning qualities, and is comparatively low-cost. When released into the environment, LPG does not pollute the air nor contaminate the aquatic and terrestrial habitats. The use of LPG in ICE does not impact human health, ensures fuel economy and good engine performance, and reduces the consumption of FB fuels [41].

Propane has been used as an alternative fuel for vans, school buses, commercial transport vehicles, and other heavy-duty vehicles. Propane can be used as the sole fuel for transport vehicles (dedicated fuel) or used in conjunction with gasoline (bi-fuel), thus allowing for greater flexibility and choice [44]. Figure 9 shows a dedicated propane vehicle. Propane has low carbon content and low oil contamination characteristics thereby contributing to longer engine life. Propane-powered vehicles are effective in a cold climate because the mixture of propane and air enters the combustion chamber in the gaseous state [45].

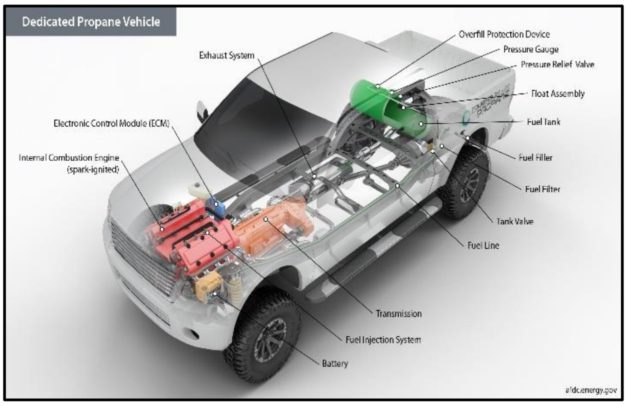

Figure 9. Propane vehicle [46].

Previous studies by Raslavičius et al. [47], Synák et al. [48], and Kim et al. [49] on the applicability of LPG as an alternative fuel for transport vehicles revealed the effectiveness of LPG from performance, economic, and safety points of view. The use of LPG in SI and CI transport vehicles also emitted less particulate matter, NOx, CO2, and toxic gases when compared with FB fuels. Similar tests conducted in Ghana [50], Korea [51], India [52], and other jurisdictions indicated that LPG is a sustainable and environmentally friendly alternative fuel for transport vehicles.

3.5. *Emerging fuels*

Currently, new fuels are being developed and tested for possible use as alternative fuels for transport vehicles. Some of the emerging fuels include biobutanol, dimethyl ether (DME), methanol, and other renewable hydrocarbon biofuels. Table 3 presents the description and potential benefits of using these emerging fuels for transport vehicles. The application of biobutanol as an alternative fuel for transport vehicles was investigated by Pugazhendhi et al. [53], Yusoff et al. [54], and Szulczyk and Cheema [55] revealed reduced emissions, better engine performance, better economic feasibility, and improved engine durability across varying testing conditions. The use of DME was also tested and found to be a practicable and feasible alternative to FB fuels. DME influences the reduction in GHG emissions, better engine performance, and guarantees a return on investments when used to power transport vehicles [56, 57].

Table 3. Description and benefits of emerging fuels for transport vehicles.

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Emerging fuels	Description	Benefits as ICE fuel
Biobutanol	• Butanol made from the fermentation of corn and biomass feedstocks • Immiscible with water • High calorific value = 29.2 MJ/L • Melting point = −89.5 °C • Boiling point = 117.2 °C • Flash point = 36 °C • Self-ignition temperature = 340 °C.	• Higher energy content • Lower Reid vapor pressure • Improved energy security • Generation of fewer emissions • Allows more transport options
Dimethyl ether	• Produced from biomass, methanol, fossil fuels, and synthetic gas • No carbon-to-carbon bonds • Colourless and non-toxic • Highly flammable • Cetane number = 55-60 • Boiling point - = - 25 °C • Lower heating value= 28 MJ/Kg • Self-ignition temperature = 325 °C • Flash point = -42 °C	• High cetane number • No particulate matter emissions • Good energy efficiency
Methanol	• Produced by steam-reforming natural gas to create a synthesis gas and then methanol and water vapour. • Clear and colourless • Highly flammable and volatile • Higher heating value = 22.9 MJ/Kg • Lower heating value = 20.1MJ/Kg • Boiling point = 64.96 °C	• Lower production costs • Lower risk of flammability • Improved energy security
Renewable hydrocarbon biofuels	• Produced from lipids, cellulosic materials, energy crops, and other biomass	• Engine and infrastructure compatibility • Increased energy security • Reduced emissions of GHGs • More flexibility

4. Implications, Challenges, and Prospects

The use of FB fuels to power ICEs is expensive, inefficient, emits toxic gases, leads to engine wear, and generates noise. Economically, FB fuels are imported, impact the macroeconomic sector, and constitute a drainpipe in the foreign exchange of most countries. The process of extraction, refining, transportation, and storage of petrol and diesel fuels is expensive and requires skilled personnel and machinery. The numerous challenges and environmental impact of running transport vehicles on FB fuels necessitate the search for alternative fuels.

The implication of using alternative fuels such as biofuels, electricity, natural gas, propane, biobutanol, diethyl ether, and other emerging renewable fuels as transport vehicles include better engine performance, reduced maintenance cost, and a significant reduction in CO2, CHGs, and other toxic tailpipe emissions. Electric vehicles are environmentally friendly, emits no toxic gases, and requires fewer engine parts and low maintenance cost. The use of natural gas and propane contributes to gas utilization for energy generation and the emission of fewer pollutants. Generally, the adoption of clean, renewable, and non-polluting fuels as an alternative fuel for road transport vehicles ensures better engine performance and contributes to renewable energy integration, energy security, energy diversification, and environmental sustainability.

However, there are obvious challenges militating against the fuel realization of the benefits of the adoption of these alternative fuels in the road transportation sector. The use of unblended

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biofuel results in increased fuel consumption but lower engine performance and efficiency compared to FB fuels. Biodiesel has low calorific values and its application in ICEs precipitates higher NOx emissions causing power drops and might require engine modifications. During storage, biodiesel, bioethanol, biobutanol, and other biofuels deteriorate and their quality becomes susceptible and compromised. The feedstock of most biofuels conflicts with the food chain triggering food vs fuel debates and exacerbating food security.

There is a need for tank replacement and other engine modifications to convert permits ICEs run on natural gas. There is a huge investment in transport and storage facilities, safety gadgets, and other infrastructural requirements to integrate natural gas into transport fuel systems. The high cost of electric vehicles, inadequate charging facilities, and environmental impacts on the disposal of used batteries need to be holistically addressed. There is inadequate awareness and education on the safety requirements for the use of LPG, CNG, and LNG as transport vehicle fuel. Methane, a constituent of LPG is hazardous, a GHG, and a major contributor to the formation of ground-level ozone and impacts human health.

The prospect of biofuels as a substitute fuel in transport vehicles is bright and promising going by the need for more effective ICEs, strict emission regulations, and enhanced renewable energy integration. The world is moving towards renewable energy utilization and great resources are been mobilized to achieve it. As countries continue to implement and enforce emission regulations, the use of biofuels, natural gas, and other clean hydrocarbon fuels in transport vehicles will continue to attract researchers' interest and attention.

5. Conclusions

Access to effective and safe road transportation is one of the metrics for measuring the quality of life and a major contributor to socioeconomic development. The use of FB fuels as primary energy sources for transport vehicles has been ineffective, impacted air quality, and exacerbated environmental degradation. Besides, the process of refining, transporting, and storage of petrol and diesel fuels is expensive, hazardous, and requires huge technical and infrastructural outlay. This has necessitated the conduct of research and development of clean and non-polluting fuels to replace FB fuels.

This study assesses and recommends the application of biofuels, electricity, natural gas, propane, and other emerging fuels as alternative fuels for sustainable road transportation. The adoption of these alternative fuels is cost-effective, reduces the emission of CO2, NOx, particulate matter, and other GHGs, mitigates environmental degradation, and contributes to renewable energy integration. When electricity generated from solar energy, and other renewable energy sources are used to power transport vehicles, there is no emission and low maintenance cost, the vehicle lasts longer, and guarantees a more pleasurable motoring experience. Though natural gas and propane are prone to sluggish combustion processes and contribute to more methane in the atmosphere, the overall advantages outweigh the identified shortcomings.

Going forward, more collaborative and multidisciplinary research is needed to fine-tune the raw materials, production process, storage, and utilization avenues for biofuels. The high production cost and increased emission of NOx from biodiesel fuel should be addressed to find a lasting solution. The blending of CNG, LPG, and LNG with hydrogen and other gaseous fuels will improve their combustion efficiency, and energy content, and eliminate other drawbacks associated with the fuels. there is a need for more research and funding into the production and utilization of emerging fuels including biobutanol, DME, methanol, and other renewable hydrocarbon biofuels. The use of novel technologies such as smart metering, robotic technology, artificial intelligence, etc., and relevant statistical and optimization techniques should be adapted in the research and testing of these fuels.

The government should launch aggressive mobilization and sensitization campaigns to activate consumers' interests in the benefits of the utilization of these fuels on transport vehicles. Policies and legislation allowing tax reliefs and other incentives should be introduced and enforced to encourage the production and utilization of biofuels, natural gas, and other clean alternatives for transport

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vehicle applications. The government should invest in the production of electric vehicles as a way to bring down the exorbitant cost and other discouraging issues around their massive utilization.

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