Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal, 2025, 19(12), 81–90
https://doi.org/10.12913/22998624/209430
ISSN 2299-8624, License CC-BY 4.0

Received: 2025.07.01
Accepted: 2025.10.01
Published: 2025.11.01

Modelling trends in sustainable fuel consumption of compressed natural gas vehicles

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ABSTRACT

This paper focuses on modeling trends in the consumption of compressed natural gas (CNG) as a sustainable fuel in road transport and its comparison with traditional Diesel propulsion. The paper aims to assess the divergence between CNG and Diesel in terms of fuel efficiency and environmental impact, based on an analysis of historical consumption data from 2015 to 2020. The research uses time analysis and linear regression to predict consumption until 2030. The divergence method quantifies the difference in the rate of development between the two fuels, while bibliometric analysis points to research interest in topics such as emissions, combustion and alternative fuels. The results confirm a clear and growing divergence in consumption: CNG usage declined significantly from 5.2 to 4.5 kg per 100 km, while Diesel consumption dropped only slightly from 8.4 to 8.0 litres per 100 km. Prediction models suggest that by 2030, CNG vehicles will reach 3 kg/100 km, whereas Diesel vehicles will maintain levels above 7 litres. These findings indicate dynamic technological progress in CNG propulsion systems compared to the relative stagnation in Diesel efficiency. In parallel, bibliometric analysis reveals that CNG is a central theme in alternative fuel research, most notably in Asian countries such as India, Pakistan, and China, where urbanization and environmental pressures drive innovation. Keywords like "performance," "combustion," and "emissions" dominate the academic discourse, further reinforcing the fuel's relevance. The combination of empirical data and global research trends supports the conclusion that CNG represents not only a technologically and environmentally superior option, but also a research-backed pathway toward low-emission and cost-effective road transport.

Keywords: energy efficiency, consumption prediction, fuel divergence, ecological mobility, decarbonization of road transport.

INTRODUCTION

Growing concerns about climate change, dependence on fossil fuels and air pollution are fundamentally changing the mobility paradigm in the 21st century. The transport sector, which is responsible for a significant part of global greenhouse gas emissions, is forced to look for alternatives to traditional fuels. One of the most discussed alternatives is CNG, which is profiled as a technology with the potential to reduce emissions while ensuring stable operational performance. As reported by Prati et al. [1], CNG vehicles achieve significant reductions in nitrogen oxide (NO_x) and particulate matter (PM) emissions in real-world conditions compared to Diesel equivalents, while fuel consumption remains economically advantageous, especially in urban fleets.

From a fuel life cycle perspective, Van Mierlo et al. [2] point out that the use of CNG reduces total CO_2 emissions by up to 20–25%, with this difference increasing when biomethane is introduced into the distribution network. In addition to environmental aspects, CNG is also of interest from an energy security perspective, as highlighted by Debnath et al. [3] when comparing alternative fuels in developing economies. Their study shows that CNG offers resource flexibility, lower import costs and the possibility of local production, which also makes it attractive from the perspective of long-term energy strategies of countries.

Concurrently, the integration of digital technologies into transport infrastructure, intelligent fleet management systems, and energy distribution networks facilities advanced data-driven optimization, real-time monitoring, and predictive modelling of alternative fuel consumption, such as CNG, thereby reinforcing its strategic importance within intelligent and decarbonized mobility ecosystems.

Given the above-mentioned challenges and advantages of this technology, more and more research efforts are focused on analyzing consumption trends and predicting them in the context of diverging developments between CNG and Diesel. While some studies report a gradual convergence of performance and emissions between these fuels [4], others, especially from regions with developed transport systems, record a deepening divergence in favor of greener solutions. This research study therefore aims to identify and predict trends in CNG consumption compared to Diesel, as well as quantify the divergence between them in the years 2015 to 2030, to determine the environmental and operational efficiency of these propulsion systems.

THEORETICAL BACKGROUND

CNG is one of the main alternative fuels that has gained attention in recent years in both environmental policy and technological research. Due to its lower carbon footprint, lower costs and wide availability of natural gas in many countries, CNG appears to be an effective tool for decarbonizing road transport [5]. Compared to traditional fuels, it has lower CO_2, NO_x and PM emissions, making it a more sustainable form of mobility [6]. According to a study by Jain and Draexler [7], the use of CNG in public transport has the potential to reduce emissions by up to 35% compared to Diesel engines, especially in urban areas where the frequency of stops and starts is high. This trend is also supported by Jaworski et al. [8], who point out the advantage of lower air pollution and improved air quality in cities due to the higher spread of CNG buses.

The economic side of CNG technology was examined, for example, in the study of Sarkar et al. [9], who found that CNG operating costs are on average 25% lower than Diesel systems. This has a significant impact on the return on investment for urban businesses and transporters. In terms of technology development, research is focused on optimizing combustion and adapting hybrid systems to CNG, as demonstrated by the study by Mustafi and Agarwal [10], who propose integrated ignition and injection control to increase engine efficiency. The infrastructure aspect is also important, where according to Collantes and Melaina [11], the development of CNG stations is a key prerequisite for wider adoption of this technology, with countries such as India and Turkey experiencing a sharp increase in the number of CNG vehicles thanks to government support for infrastructure. When comparing the life cycle of vehicles including production, maintenance and disposal, CNG is shown to have a lower overall environmental impact than Diesel, as confirmed by Szumska [12] using the life cycle assessment (LCA) method.

It should also be emphasized that CNG technology is often considered as a transitional link between fossil fuels and fully emission-free alternatives such as hydrogen or electric propulsion [13]. For this reason, consumption models and their predictions are an important tool for the development of transport policies. Predictions based on consumption data from previous years, as well as the quantification of divergence between fuels, allow policymakers, municipalities or fleet operators to make data-based decisions [14]. In addition to technical and economic aspects, social acceptance is also important, as studied, for example, by Mohammed et al. [15], who found that in regions with higher environmental literacy and public support for decarbonization, the adaptation of CNG is significantly faster.

Summarizing these findings, it can be stated that CNG represents a technologically advanced, environmentally friendly and economically sustainable alternative in the current transport transition period. The consumption divergence between CNG and Diesel, which the study models, is therefore not just the result of random developments, but is firmly rooted in global technological, environmental and economic trends.

RESEARCH METHODOLOGY

The divergence calculation and prediction methodology were designed to quantify the development differences between two types of fuels (CNG and Diesel) in the context of their consumption and performance changes over time. In the first phase, historical fuel consumption data from 2015 to 2020 were analyzed in Google Colab research. These data were standardized per 100 kilometers and divided by fuel type, with CNG measured in kilograms and Diesel in liters. Based on these data, a time series was compiled that visualized the development of the consumption of individual fuels over the years. The divergence was then quantified as the difference between the CNG and Diesel consumption values in each year of the analyzed period 12/2015–06/2020. This difference was expressed both absolutely and relatively, and its development over time was monitored to determine whether the gap between the two types of propulsion is widening (divergence) or narrowing (convergence). To better understand the direction of this development, the trend of the difference was visualized in the form of overlapping consumption graphs, which allowed a clear representation of the points at which the differences between the technologies began to increase.

To predict fuel consumption until 2030, a linear regression model was implemented separately for each type of propulsion. The model used the time axis as the independent variable and historical consumption values as the dependent variable. Linear regression was selected due to its interpretability, computational efficiency, and suitability for modeling steady, incremental trends over a limited and relatively linear time window such as 2015–2020. It provides a transparent framework for projecting future values under the assumption of a constant rate of change, which aligns with observed empirical developments, particularly in the case of Diesel where changes are marginal, and linearity is evident. Alternative trend models, including polynomial and exponential regression, were considered during the modeling phase. Polynomial regression, while capable of capturing more complex nonlinear behavior, increases the risk of overfitting when applied to short or relatively stable datasets. Exponential regression, which assumes a constant percentage rate of change, is more suitable for modeling processes characterized by rapid growth or decay. However, these are conditions that are not consistently reflected in CNG or Diesel datasets. Furthermore, visual inspection of residuals and model fit metrics confirmed that linear regression achieved satisfactory explanatory power with minimal complexity, making it the most appropriate choice for medium-term forecasting in this context. The entire predictive process was further supported by a contextual bibliographic analysis that linked the numerical results with the scientific discourse in the field of fuel system development retrieved from Web of Science in 2025. In this way, methodological consistency was ensured between empirical trend analysis, predictive modeling, and research context, allowing the results to be interpreted not only from the perspective of performance and consumption, but also in the broader context of technological development and research priorities.

RESULTS AND DISCUSSION

This chapter presents the key findings of the study through a combination of environmental, bibliometric, and consumption trend analyses. First, it compares the emission profiles and consumption dynamics of CNG and Diesel fuels, highlighting the environmental advantages of CNG. The second part provides a bibliometric perspective on how CNG-related research is thematically and geographically distributed. Finally, the chapter examines historical consumption trends and offers a prediction model outlining the expected divergence in the use of CNG and Diesel fuels by 2030. Together, these sections provide a comprehensive understanding of both the practical and scientific dimensions of CNG in the context of sustainable transport.

Environmental and consumption trends of CNG and Diesel fuels in transport

In recent years, energy consumption patterns in the transportation sector have undergone significant shifts. A comparative analysis of fuel types reveals notable trends in the use of alternative and conventional fuels. CNG consumption showed a systematic decrease, while Diesel recorded only a slight decrease.

Figure 1 provides a comprehensive graphical comparison of the emissions of four major pollutants produced during the operation of CNG and Diesel-powered vehicles. The emission categories included in the analysis are CO_2, NO_x, sulfur dioxide (SO_2) and particulate matter (PM). The first graph in the upper left corner shows that CNG produces significantly less CO_2 – around 110 grams per kilometer, while Diesel vehicles emit up to 248 grams. This difference underlines the potential of CNG to reduce the carbon footprint, which is a key factor in the fight against climate change. In the upper right graph, we see an even more significant difference for nitrogen oxides – CNG reaches a value of around 58 $mg.km^{-1}$, while Diesel reaches up to 960 $mg.km^{-1}$. NO_x emissions are a major problem for air quality, especially in urban areas, where they contribute to respiratory diseases. The lower part of the graph shows the differences in sulfur and particulate emissions. For SO_2, CNG emissions are practically negligible (0.0017 $g.km^{-1}$), while Diesel reaches values of over 0.13 $g.km^{-1}$. This confirms that natural gas is a practically sulfur-free fuel, which has a positive impact on acid rain and infrastructure corrosion. The last graph on the bottom right shows PM emissions, where Diesel again reaches ten times higher values than CNG. PM are particularly dangerous pollution components because they penetrate the lungs and bloodstream and are classified as carcinogenic. Overall, this graph clearly demonstrates that CNG has a significantly more favorable environmental profile than Diesel in terms of emissions. It is not only about reducing greenhouse gases, but also about eliminating local pollutants that have a direct impact on the health of residents. In the context of sustainable transport and reducing emissions in cities, CNG appears to be a much cleaner and more sensible alternative.

A synthesis of key findings from the quantitative and bibliographic analysis was conducted to identify developmental differences in fuel consumption and understand how these trends are reflected in the scientific literature. Based on historical data collected between 2015 and 2020, the development of CNG and Diesel consumption was analyzed, focusing on the rate of change, differences in efficiency and environmental impact. This approach is in line with research findings by authors such as Martins and Brito [16], who have shown that CNG has lower emissions, and a favorable power-to-consumption ratio compared to traditional fuels. Similarly, Khan et al. [17] emphasize in their studies that CNG represents a beneficial path for developing countries to reduce environmental burden without the need for an immediate transition to electromobility.

The results were visualized through graphs showing the development of consumption and the divergence between propulsion systems. These outputs also served as a basis for the construction of a prediction model, which allows estimating the development of consumption up to 2030.

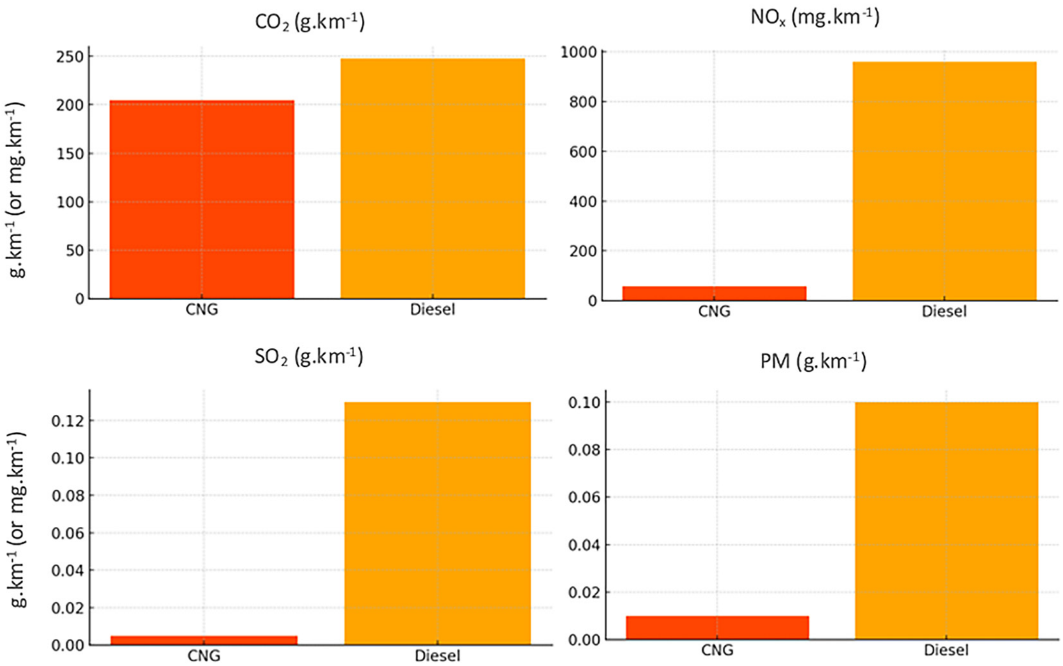

Figure 1. Emission comparison by fuel type CNG vs. Diesel. Author's own data processing conducted in Google Colab

The trend estimates follow the models published in the studies of Wainberg et al. [18] and Jahirul et al. [19], which show that the decrease in CNG consumption is most pronounced in the case of public transport and light commercial vehicles.

Bibliometric analysis of CNG research on thematic focus and international collaboration

An essential part of the research is also the interpretation of bibliometric data, which complement the empirical part with information on the most frequently researched concepts, the geographical focus of research and the direction of scientific attention. According to findings of Yao et al. [20], the research on CNG technologies is geographically concentrated mainly in Asia, with India, Pakistan and China among the most active researchers in the field of alternative fuels. The results thus show how CNG is profiled not only as a technologically efficient, but also as a research-supported alternative in the field of sustainable transport.

Figure 2 shows a visualization of the density of key research terms in the form of a so-called heatmap of research keywords. This is the output of a bibliometric analysis that serves to identify the most frequent and thematically related terms in academic publications. The density and color of the areas indicate the intensity of occurrence of a specific term. Yellow and green clusters represent the most frequently used terms, while blue to dark blue areas have a significantly lower incidence.

The center of the map is dominated by terms such as "CNG", "performance", "combustion" and "emissions", which form the core of research interest in the field of fuel systems and combustion. These terms are closely linked to the assessment of the efficiency and environmental impacts of alternative fuels, such as compressed natural gas. Around them are terms such as "hydrogen", "diesel-engine", "gasoline", or "combustion characteristics", which indicates that the analysis covers a wide range of fuels and propulsion technologies from traditional to new and renewable alternatives. In the lower and left part of the map, less common but relevant terms such as "life-cycle assessment", "injection timing", or "si engine" are found, which point to additional technical and evaluation aspects of the research, such as injection timing or life-cycle carbon footprint assessment.

Overall, Figure 2 shows that the topic of CNG is a central research axis in the field of internal combustion engine and alternative fuels research, and is often studied in relation to performance, emissions and comparison with other types of fuels such as hydrogen, Diesel or biofuels. This map thus offers an overview of how research focuses are thematically interconnected and where the greatest interest of the scientific community is concentrated.

Figure 2. Heatmap of researched keywords from various scientific studies

Figure 3 shows a visualization focused on research collaborations focused on emissions, alternative fuels, or specifically CNG fuel research. Each node represents a country and the lines between them show co-authorship links between scientists or institutions in that country. The thickness and color of the lines express the intensity of collaboration, while the size of the nodes represents the number of publications or the country's involvement in research. It is clear from the figure that India and Pakistan are among the two most important research nodes in this area. India has extensive connections with countries such as Vietnam, Lithuania, Poland, Malaysia, Indonesia, and China, which points to its strong research background and active collaborations within Asia and parts of Europe. India's importance can be explained by its growing energy consumption, high dependence on imported fossil fuels, and efforts to diversify its propulsion sources, including CNG as an environmentally friendly alternative for public transport. Pakistan emerges as the second dominant hub, linked to countries such as China, Saudi Arabia, Brunei, Algeria, Scotland, France and Brazil. This country likely has a research hub or international program that integrates developing countries from Asia, Africa and even Europe.

Given its environmental challenges, urbanization and dependence on energy imports, Pakistan has a strong incentive to explore alternative fuels to reduce emissions and increase energy security. China, although not the largest hub, is a significant bridge between India, Pakistan and Saudi Arabia, which may be related to its global role in alternative fuel vehicle technology and component manufacturing. Countries such as Vietnam, Lithuania, Iraq and Malaysia act as smaller but active research hubs that can be partners in joint projects or provide regional data or test platforms. Overall, the map of international collaboration reveals a strong research dynamic in Asia, where most of the dominant players in the development and study of alternative fuels are located. This is due to a combination of demographic pressure, urbanization challenges, insufficient infrastructure, and at the same time the strategic need to address emissions and energy efficiency in the context of emerging economies. These countries publish the most in this area because they are directly affected by the problems that alternative fuels like CNG help to solve, both in terms of emissions and in terms of economics and sustainable development.

Divergence and prediction of the development of CNG and Diesel fuel consumption

Based on the above overview of international research activity, it can be concluded that countries with a high level of urbanization and environmental challenges are naturally becoming leaders in the development of alternative fuels and reducing emissions from transport. This geographical dynamic of research also reflects the practical need to address issues related to growing fuel consumption, air pollution and unsustainable dependence on oil. It is in this context that we continue with the analytical part of the study, in which we focus on the divergence and

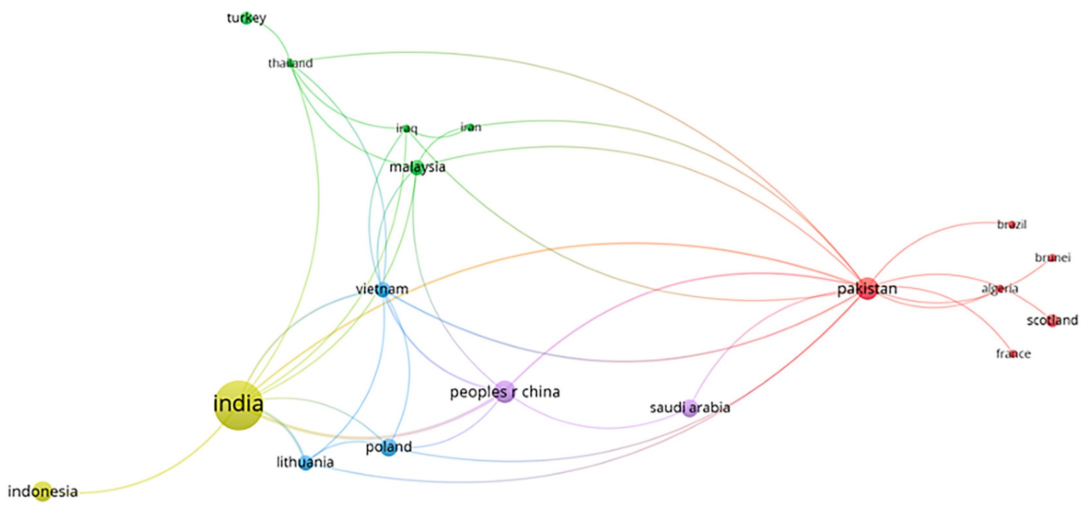

Figure 3. Map of international cooperation between countries in the field of CNG research and alternative fuels

prediction of the development of CNG and Diesel fuel consumption. While in the previous chapters the attention was focused on general research trends and countries involved in the development of solutions, the following part brings a quantitative analysis based on real data on consumption, emissions and vehicle performance obtained within the project Ecological Pumping Integrated Center (EPIC) for the monitored period 12/2015 – 06/2020 [21]. The aim is to identify how the efficiency of these two types of drives changes over time, and whether their technological convergence is approaching (convergence) or whether the differences are deepening (divergence). This analysis will not only allow us to understand the current state, but also to estimate future developments up to 2030 using trend models. Thanks to this, we can formulate recommendations for fleet renewal strategies, energy policy and ecological optimization of road transport.

Figure 4 visually shows the development of fuel consumption of two different types of vehicles (CNG and Diesel). The analyzed development in the monitored period shows a significant divergence, i.e. the distancing of CNG and Diesel consumption. While the consumption of Diesel vehicles in the period 2015–2020 is decreasing slightly from approximately 8.4 liters per 100 kilometers in 2015 to 8.0 liters in 2020, the consumption of CNG vehicles is decreasing at a more significant rate, from approximately 5.2 kg per 100 kilometers to 4.5 kg. This difference indicates that CNG-powered vehicles are becoming more efficient from year to year, while the improvement in Diesel vehicles is only moderate and practically stagnant. The analysis shows that CNG not only maintains lower consumption than Diesel over the course of five years, but also deepens this difference. The divergence between these two types of fuel is evidence of technological progress in the use of natural gas as a fuel, which is not only more environmentally friendly but also more energy efficient.

This development also supports the environmental and economic benefits of switching to CNG in the field of transport, especially in the public and municipal sectors.

Figure 5 shows the projected development of fuel consumption for CNG and Diesel vehicles over a ten-year period. The visualization also includes historical data from 2015 to 2020, which serve as a starting point for the prediction model. While historical data is shown as solid lines, the expected future development is shown as dashed lines, which separate the real past from the modeled future. Historical values show that Diesel consumption is decreasing slightly, but the rate of this decrease is very gradual. In contrast, CNG consumption not only has a lower starting value, but also decreases much more significantly. The prediction further amplifies this difference. While Diesel will maintain its consumption above 7 liters per 100 kilometers in 2030, CNG should, according to the trend, drop to 3 kg for the same distance. This development indicates that natural gas combustion technology is undergoing faster innovation, which is reflected in ever lower consumption. Such an improvement has a direct impact on the economy of operation, as lower consumption at a stable fuel price means lower costs. At the same time, it shows that in the coming years the transition to CNG will become increasingly attractive

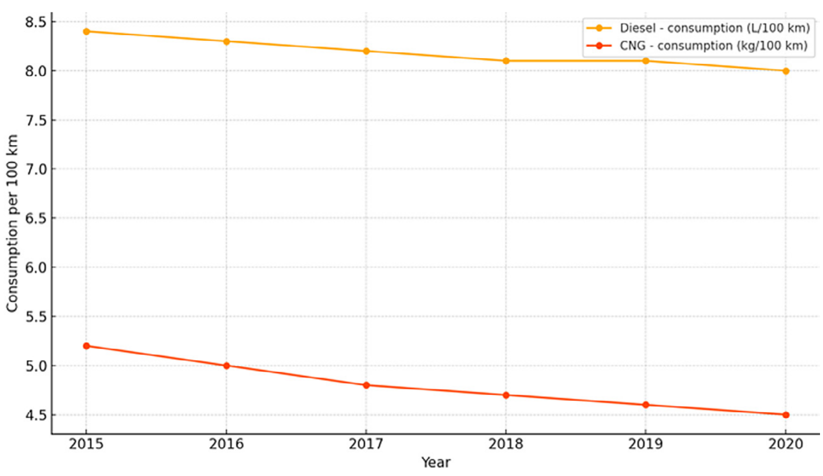

Figure 4. Consumption divergence between CNG and Diesel (2015–2020)

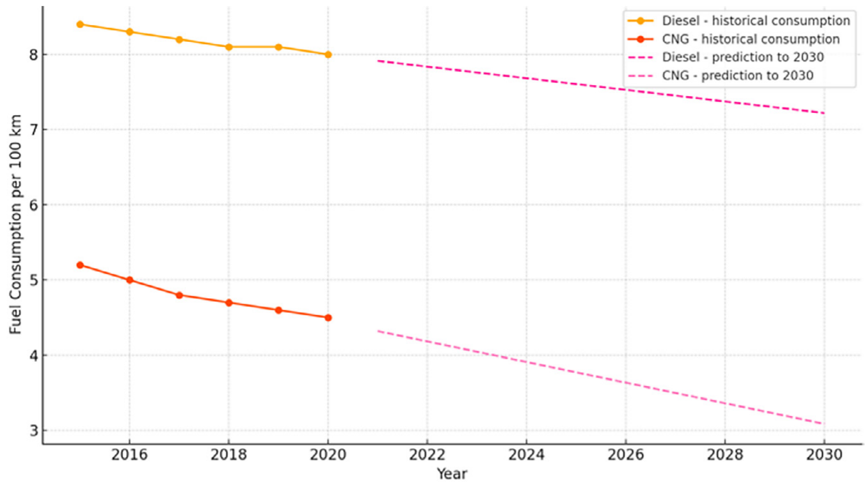

Figure 5. Fuel consumption prediction CNG and Diesel (2021–2030)

not only from an ecological, but also from a practical and financial point of view. The figure visually underlines the increasing efficiency and convenience of CNG as the transport fuel of the future.

These findings have significant practical implications, particularly for policy-makers, municipal planners, and fleet managers seeking effective strategies for reducing transport-related emissions. The clear environmental advantage of CNG over Diesel, especially in terms of nitrogen oxides, particulate matter, and sulphur dioxide emissions, positions CNG as a viable transitional solution in urban and regional transport systems where full electrification is not yet feasible. The bibliometric analysis also highlights geographic disparities in research attention, indicating where institutional knowledge and technological capacity are most concentrated. This insight can help guide international cooperation and technology transfer, particularly to regions with high pollution burdens but limited infrastructure for alternative fuels. From an investment perspective, the historical and predictive consumption trends suggest that while Diesel still dominates in some sectors, the window of opportunity for scaling up CNG-powered fleets remains open, especially in countries experiencing rapid urbanization and growing public transport needs. Strategic investments into CNG refuelling infrastructure and vehicle conversion programs (supported by targeted policy incentives) could accelerate adoption and generate measurable environmental benefits in the near term. Moreover, governments and municipalities could use these insights to prioritize funding schemes, tax policies, and procurement strategies in favour of cleaner propulsion systems. For example, integrating life-cycle emissions data and bibliometric evidence into cost-benefit analyses can strengthen the case for CNG-powered buses or utility vehicles as cost-effective solutions with immediate public health benefits. In summary, the results of this study are not only academically relevant but also actionable. They provide a data-driven foundation for evidence-based decisions in transport policy, urban planning, and sustainable investment, emphasizing the role of CNG as a strategic bridge toward a low-emission transport future.

CONCLUSIONS

The results of the quantitative analyses confirm a clear trend in favor of CNG fuel, not only in terms of consumption, but also in terms of environmental efficiency. The divergence between CNG and Diesel technologies has deepened over the years 2015 to 2020, with prediction models indicating a continuation of this trend until 2030. Diesel consumption is decreasing only slightly, while CNG consumption is decreasing significantly faster, thus increasing the technological and ecological advantage of this fuel.

These findings within the divergence analysis are also fully consistent with the findings of bibliometric analyses. The keyword density and network cooperation between countries show that research on CNG, its emissions and performance parameters is among the frequently researched areas, especially in countries with increasing urbanization and environmental challenges. Countries such as India, Pakistan, China and Malaysia play a key role in shaping research trends, confirming that the divergence between propulsion systems has not only a technological but also a geopolitical dimension. At the same time, the visualizations confirm that CNG is a core concept within thematic classifications in the field of sustainable transport, which further strengthens its importance as a promising fuel of the future. While Diesel engine technologies have reached a certain level of technological stagnation, the development of CNG propulsion is recording dynamic progress, which is reflected not only in the reduction of consumption, but also in the overall improvement of the environmental footprint.

The divergence that was observed between 2015 and 2020 will deepen even further according to the models by 2030. While Diesel vehicles will maintain relatively stable consumption, CNG vehicles will move towards higher energy efficiency thanks to innovations, combustion optimization and infrastructure development. This development supports not only environmental sustainability, but also economic rationality of operation, which is crucial especially for the public sector and commercial transport, where fuel costs play a significant role. Given the current direction of policies to reduce emissions and increase energy security, CNG appears to be one of the most realistic bridges between traditional fossil and future emission-free solutions. The results obtained thus confirm that the divergent development between CNG and Diesel is not just a temporary phenomenon, but a reflection of deeper technological and systemic shifts that will shape the nature of transport in the next decade.

However, several limitations of the current study should be acknowledged. First, the predictive model is based solely on linear regression applied to historical data from 2015 to 2020, a relatively short period that may not fully capture nonlinear market or technological changes. Excluding external variables such as fuel prices, policy changes, or global supply chain disruptions may affect the accuracy of long-term forecasts. Furthermore, while bibliometric analysis offers valuable context, it does not account for the quality or impact of individual studies. However, it does reflect their frequency and co-occurrence. These limitations can be addressed in future research by incorporating more sophisticated forecasting techniques such as multivariate regression, AutoRegressive Integrated Moving Average (ARIMA) models, or machine learning approaches that allow for the integration of external economic, legislative, and technological variables. Furthermore, a larger dataset covering a longer time period and more vehicle categories (e.g., heavy-duty, hybrid, or dual-fuel vehicles) could improve the granularity and robustness of future models. The bibliometric scope could be extended to include an analysis of the impact of citations, funding sources and institutional affiliation to better understand the factors influencing research intensity. Also, comparative studies involving other alternative fuels (e.g. hydrogen, bio-CNG or electric propulsion) could offer a more holistic view of future transport trajectories and their environmental consequences in the future. In summary, by combining the results of predictive modelling and bibliographic analyses, it can be concluded that consumption developments and research trends are mutually supportive. However, practical observations from the field are in line with academic trends, which increases the credibility of the conclusions of this study. CNG therefore appears to be not only an efficient but also a research-based route to low-emission and cost-effective transport. Nevertheless, further interdisciplinary research is necessary to capture the complex interaction between technology, policy, infrastructure and user behaviour that will ultimately determine the future of sustainable mobility.

Acknowledgements

This research paper is a partial output of the project VEGA 1/0713/24 Digital economy as a key challenge for the transformation of enterprises in Slovakia financed by the Ministry of Education, Research, Development and Youth of the Slovak Republic, KEGA 032EU-4-2024 Creation of an education model for increasing the skills of students of a non-programming university in the field of using artificial intelligence tools to support business and entrepreneurship, and Project of Young Researchers and PhD Students A-25-107/3020-14 The use of unconventional methods in marketing and the possibility of improving them through artificial intelligence.

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