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Environmental Impact and Consequences of EU Car Fleet Development

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Abstract: This study analyzes the environmental impact of the EU car fleet and investigates the relationship between its age structure, motorization rate, the share of hybrid and electric vehicles, and carbon emission levels, considering both overall trends and regional variations based on population income. The methodology employed descriptive, comparative, and correlational analyses using recent data from European statistical and institutional sources. The findings indicate that despite the growing adoption of alternative-fuel vehicles (AFVs), the EU car fleet continues to age, and emissions show only a negligible reduction. Significant regional disparities were identified, with wealthier nations maintaining younger, more environmentally sustainable vehicle fleets. Furthermore, air pollution measured by carbon dioxide emissions was positively correlated with vehicle age and negatively correlated with both the share of AFVs and the proportion of newly registered vehicles. The research highlights the tension between the objectives of the circular economy and the crucial need for accelerated fleet modernization, proposing directions for advancing sustainable mobility and environmentally responsible consumer behavior.

Keywords: car fleet, CO_2 emissions, circular economy (CE), sustainable mobility, vehicle age, motorization rate, hybrid and electric vehicles

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1. Introduction

The responsible attitude of people toward the surrounding environment requires attention when satisfying unlimited needs with limited resources. This implies that material assets should be used for as long as they remain operationally suitable. However, a fundamental contradiction arises in this context because the use of such assets contributes to environmental pollution. Automobiles fall into this category because they often remain in use for a long time. On the other hand, their ecological footprint, expressed in terms of carbon dioxide emissions, fine particulate matter (PM), and other pollutants, is at a given point higher than that of modern means of transport powered by hybrid or fully electric engines.

The goal of the present research is to theoretically systemize the effects and empirically investigate the impact of the use of the EU car fleet on the environment, as well as to clarify the perspectives for the development of mobility in the context of sustainability and the circular economy (CE).

To achieve this goal, the study addresses the following key research questions:

- RQ1: What are the key effects of the car fleet that, according to the existing scientific literature, have the greatest impact on the environment and sustainability?
- RQ2: What is the correlation between the age of the car fleet and CO_2 emissions, and to what extent does the aging of the car fleet influence the negative ecological footprint in the EU?
- RQ3: Is the growth in the share of hybrid and alternative-fuel vehicles (HAFVs) among new registrations sufficient to achieve a significant reduction in CO_2 emissions in the overall EU car fleet?
- RQ4: What are the regional differences in the EU regarding the age of the car fleet, the degree of motorization, and carbon emissions, and how do they influence overall ecological goals?
- RQ5: What are the perspectives for the development of sustainable mobility and limiting the harmful effects of the condition and development of the car fleet in the EU?

The study is subject to the following limitations:

- It examines the strength of the relationship between the factors and CO_2 emissions, but not the respective causality;
- It measures environmental harm using the carbon dioxide indicator but omits many other resulting magnitudes which account for the ecological harm of automobiles, like PM and NO_x;
- It relies on fixed statistical data for a limited number of indicators, which may not capture the full range of factors or the sociodemographic characteristics of the countries studied;

– The lack of data for some indicators for Malta and Cyprus excludes these countries from the sample, leaving a total of 25 countries.
– The study period, from 2019 to 2024, was selected to capture the time of production and diffusion of vehicles with alternative powertrains, the introduction of stricter EU measures and environmental policies, the effects of the COVID-19 pandemic, and the subsequent economic and social changes. It also provides a sufficiently long six-year period for analyzing trends and relationships. Only the data on the average age of the vehicle fleet for 2024 are unavailable, which hinders the necessary calculations related to this indicator for that year.

2. Effects of Automobile Operation on the Environment

In contemporary society, vehicles have become an important means of meeting the daily needs of persons related to mobility, both of goods and passengers. The intensive development of transport is driven by the continuous expansion of the geographic range within which goods and people move, with the aim of maximizing access to goods and guaranteeing the right of every person to travel.

Globally, the mode of transport most widely used is road transport, which is logical given its main characteristics, particularly the flexibility in forming routes and accomplishing transport on the principle of "from door to door". It is important to note that "this principle determines the average door-to-door distance considered as the break-even distance" [1]. Alongside its advantages, automobile transport is known to have negative environmental impacts. This makes it necessary for the rolling stock, in the course of its exploitation, to be monitored during all phases of the product system, defined as "interlinked stages of a product system, from raw material acquisition or generation of natural resources to final disposal" [2]. What necessitates systematic observation is that, with advancing age, automobiles undergo changes in their main technical characteristics due to physical obsolescence, wear from prolonged use, and ongoing technological innovation, which is transforming transport by introducing vehicles powered by new energy systems.

In their product development, automobiles undergo a comparatively long life cycle (LC), characterized by peculiarities in the influence vehicles exert on the surrounding environment. Pennington et al. [3] and Sundin [4] defined life cycle assessment (LCA) as a method of accounting for the environmental impacts associated with a cradle-to-grave product or service. The full life cycle of a vehicle is a time interval which includes a sequence of processes, such as [5], and its study is of particular importance given the fact that "the automobile industry is said to be the largest manufacturing sector in the world and is one of the most resource-intensive of all major industrial systems" [6].

The full life cycle of a vehicle consists of a sequence of distinct stages, which are outlined below.

Raw material acquisition and pre-processing (including production of parts and components). At this stage, the negative impact is mainly associated with pollution from the extraction of natural raw materials used in automobile production, such as air and water pollution. High energy consumption and the destruction of entire ecosystems during the development and exploitation of deposits are also negative consequences. At this stage of the vehicle life cycle, Staniszewska et al. [7] identify the sources of negative impacts by linking them to the following: the source of electric power, which is usually coal or nuclear plant; the use of toxic chemicals and paints, which creates toxic waste; and the use of newly manufactured products at the expense of reclaimed or recycled elements.

Manufacturing. During production, automobile manufacturing plants emit CO_2, nitrogen oxides (NO_x), volatile organic compounds (VOCs), fine particulate matter, and other pollutants. In production terms, the focus has been on reducing paint-shop emissions, improving energy efficiency, and reducing waste [7].

Distribution. Traffic-related pollutants include NO, CO, CO_2, diesel-exhaust particles, fuel combustion, pollutants that arise from brake wear, tire wear, and resuspended particles (e.g., trace metals), as well as pollutants like ozone, NO_2, and secondary aerosol formed through physical and chemical processes [8].

Use stage. This stage is characterized by a very large influence on air pollution, especially with the increasing length of vehicle use. According to Sundar et al., "Automobiles are serious global threat for increase in global warming due to emission of carbon dioxide gas. Over the past century, there are many factors which produce an effect of automobile emissions on global warming such as fuel used, road gradient, increasing vehicle age, payload, cold starts, and maintenance condition of the vehicle" [9].

End of life (including product recovery or recycling). At this stage, the used vehicle is sent to a specialized facility with the necessary technology and modern equipment for further processing.

Some authors supplement the life cycle of an automobile by adding the development stage, which is connected with marketing and the development of technical specifications for a new vehicle; development of construction documentation, production and testing of a prototype and pilot series (project preparation for production); and development of technological documentation [10].

Other authors present the life cycle of any industrial product in a generalized manner, considering that "the typical life of any industrial product begins with the extraction and processing of its raw materials, then its manufacturing, distribution, use, and lastly its end-of-life stage" [11].

Miner et al. [12] examine some effects of automobile use, dividing them conditionally into three groups: externalities of cars and automobility, harms to people and society, and harms to the environment. Each group is stratified into specific consequences (Table 1).

Table 1. Environmental and social externalities of car use and their relevance to EU fleet sustainability

Main category	Specific effects	Illustrative environmental or social outcomes
Externalities of cars and automobility	– Crashes and traffic incidents – Intentional violence (road rage, crime) – Air pollution (PM, ozone, lead) – Sedentary travel and loss of physical activity – Excessive consumption of space, time, and resources – Carbon emissions and resource extraction	– Road fatalities and injuries – Public-health costs from air pollution – Congestion and land-use pressure – GHG accumulation and climate forcing
Harms to people and society	– Deaths, injuries, assaults – Terrorism and war linked to energy dependence – Ill health (physical, mental, behavioral) – Social isolation and reduced communication	– Increased mortality and morbidity – Psychological stress and inequality – Diminished social cohesion
Harms to the environment	– Climate change – Loss of wildlife and biodiversity – Habitat destruction and fragmentation – More frequent and severe natural disaster	– Ecosystem degradation; – Reduced resilience of natural systems; – Long-term environmental instability

Source: based on [12]

The authors distinguish three groups of effects associated with automobile use: externalities, social harms, and environmental harms. For this study, the focus is on environmental damages, with the main concerns being climate change, loss of wildlife and biodiversity, habitat destruction and fragmentation, and more frequent and severe natural disasters.

Direct consequences for the surrounding environment of the use of automobiles are evident in relation to several key areas, described below.

Pollution, including particulate matter (PM), ozone, and lead. Particulate matter describes tiny pieces of solid or liquid matter in the atmosphere. The main sources in urban areas are diesel-engine road vehicles (DERV), industrial, public, commercial, and residential combustion. Particulate matter is categorized based on size: PM10: particles with a diameter of 10 μm or less, which can enter the respiratory system and cause health issues. PM2.5: Fine particles with a diameter of 2.5 μm or less, which can penetrate deep into the lungs and bloodstream, posing significant health risks. The PM2.5 fraction is part of the PM10 fraction [13]. The adverse health effects of exposure to elevated concentrations of air pollutants, in particular ozone, particulate matter with aerodynamic diameters less than 10 μm (PM10) and less than 2.5 μm (PM2.5), sulfur dioxide, nitrogen dioxide, carbon monoxide, and lead, are well known [14]. The long-term reliance on automobiles leads to technological obsolescence and threatens air quality, as their outdated powertrain cannot achieve the minimal pollution levels characteristic of new hydrogen or electric vehicles. In contemporary conditions, automobiles rely not only on of internal combustion engines (ICEs) but also on new-generation powertrain systems that use lithium-ion batteries, which require urgent attention for disposal, as they contain toxic substances that, if improperly treated, can lead to irreversible processes affecting the planet's climate.

Climate change. Climate change, partly driven by road transport and requiring preventive measures, calls for monitoring harmful emissions and limiting vehicle use, as the common problem of climate change and transport is actually part of a much larger challenge of sustainable development [15]. To mitigate this negative influence, specific limitations, such as emission limits, territorial restrictions, and defined time windows, should be introduced for older vehicles (both for natural and legal persons). This ensures that cars in an advanced phase of the life cycle are used only when absolutely necessary, achieving a dual effect: providing the owner with a reliable means of transportation while simultaneously limiting the unfavorable environmental impact of these automobiles.

Carbon emissions. Emissions mean the release of greenhouse gases and/or their precursors into the atmosphere over a specified area and period of time. Carbon dioxide (CO_2) emissions stem from the burning of fossil fuels and the manufacture of cement; they include CO_2 produced during the combustion of solid, liquid, and gaseous fuels as well as gas flaring [13]. To limit this pollution, efforts are focused on reducing the use of older vehicles (in an advanced stage of their life cycle) in the goods transport segment by categorizing them based on harmful emissions and establishing road taxes and motor vehicle ownership taxes that directly correlate with the car's age and ecological classification. In this way, automobile transport is prepared to achieve the so-called Fit for 55 goal, which represents an EU plan to reduce greenhouse gas (GHG) emissions by at least 55% by 2030 compared to 1990 levels [16].

Resource extraction. In the automobile industry, for example, metals such as platinum group metals (PGMs), rare earth elements (REEs), indium, or gallium are used in catalysts, electronics, batteries, electric motors, and LED headlights. As a result of this broader technological development, today's products show a significantly greater degree of material diversity and complexity [17, 18].

Consumption of resources. In theory and practice, it is assumed that automobile production is a material-intensive industry and that the long-term use of motor vehicles represents a possible means of meeting transportation needs at relatively lower maintenance costs than that of producing a new tangible asset. This can be viewed as a serious advantage for those vehicles which are distinguished by a comparatively long exploitation period, especially with adequate maintenance and systematic audit of their technical condition. While these measures cannot ensure full compliance with current environmental standards established by legislation and defining the maximum permissible emissions of harmful gases and particulate matter, such as those specified in the Euro 6 [19, 20] and Euro 7 [21] regulations, they nevertheless provide an opportunity to extend the operational lifespan of the vehicle.

The new regulation will replace the current Euro 6 regulation for passenger cars and vans (Regulation (EC) No 715/2007) [19], and the Euro VI regulation for trucks and buses (Regulation (EC) No 595/2009) [20]. It is important to note the main difference between the two standards: Euro 7 extends the lifetime requirements compared to Euro 6/VI and introduces the concept of an "additional lifetime" beyond the "main lifetime." During the additional lifetime, emission limits of gaseous pollutants are adjusted using a durability multiplier [21]. This fact is favorable for vehicles across different classes in terms of the extended duration and mileage requirements introduced in the new standards. Regarding pollutant emission limits, the required parameters are largely maintained at levels comparable to Euro 6, with more stringent requirements applying to heavy-duty vehicles.

In summary, the automobile fleet has significant environmental impacts across all stages of its life cycle. While ecological problems provoke scientific interest in reducing humanity's negative imprint, significant potential lies in the exploitation of automobiles in an advanced stage of their life cycle. These vehicles represent a paradox: they conflict with air quality principles, yet they fall within the scope of the circular-economy model. This model extends the product life cycle, postponing the need for energy-intensive new production (thereby reducing the carbon footprint and resource dependency). Furthermore, it increases mobility and makes automobiles more accessible to lower-income consumers, integrating more participants into the circular market.

The role of automobiles in long-term use is directly connected to the pursuit of sustainable development, where meeting the needs of the present generation should not compromise the ability of future generations to meet their own needs. This, in turn, requires society to create, to a large extent, a closed loop of material flows [22].

3. Methodology

In line with the goal set in the introduction, the present research analyzes the levels and changes in a series of indicators from 2019 to 2024 for the 25 EU member states included in the sample, as well as by region, based on population purchasing power.

The study examines indicators of the car fleet and CO_2 air pollution, such as:

- newly registered cars and the total size of the car fleet (overall and per 1,000 inhabitants);
- the share of hybrid and alternative fuel vehicles (HAVFs) in new car registrations and in the total car fleet;
- the average age of the car fleet;
- average carbon dioxide CO_2 emissions [g/km].

Official statistical data are drawn from Eurostat. Data on the average age of the car fleet and CO_2 emissions were obtained from the European Automobile

Manufacturers' Association (ACEA), which in turn draws its data from the European Environment Agency (EEA). In addition, normative and policy-related data from the European Commission, including materials related to the Fit for 55 program [20] and Regulation (EU) 2024/1257 of the European Parliament [21], are used.

The following hypotheses are tested in this study:

- H1: In line with trends in car fleet development, new car registrations, vehicle penetration, and the motorization rate are increasing, the role of HAFVs is expanding, while the car fleet is aging.
- H2: Significant regional differences exist in the flow and stock of the car fleet in the EU, where the wealthier countries have a more sustainable car fleet.
- H3: In Bulgaria, traditionally, the purchase of used automobiles is preferred, and only a small proportion of these vehicles meet environmental and safety standards.
- H4: Across the EU CO_2 emissions decrease, although unevenly over time and across countries.
- H5: A strong positive relationship exists between air pollution in terms of CO_2 emissions and parameters like the size and age of the car fleet, as well as the degree of motorization.
- H6: A strong negative relationship is expected between air pollution and the share of HAFVs, both in new registrations and in the overall car fleet.

From a geographical perspective, the study covers data for 25 European countries (EU member states excluding Malta and Cyprus, for which data are unavailable). From a regional perspective, the countries are grouped according to purchasing power parity (PPP). This classification divides the EU countries into three groups [23]:

- Region I: More developed regions (GDP per capita above 100% of the EU-27 average). Countries: Belgium, Denmark, Germany, Ireland, France, Luxembourg, the Netherlands, Austria, Finland, and Sweden.
- Region II: Transition regions (GDP per capita between 75% and 100% of the EU-27 average). Countries: Czechia, Estonia, Greece, Spain, Italy, Hungary, Poland, Portugal, Slovenia, and Slovakia.
- Region III: Less developed regions (GDP per capita below 75% of the EU-27 average). Countries: Bulgaria, Croatia, Latvia, Lithuania, and Romania.

For testing the hypotheses, the methods of descriptive, comparative, and correlational analysis were applied, more specifically:

- The trends in the development of the individual car fleet indicators over a six-year period are analyzed using annual growth rates and compound annual growth rates (CAGR).[1] To provide a deeper analysis of the COVID-19 pandemic's impact, the CAGR for the post-pandemic period (2021–2024) is calculated. This analysis supports the verification of hypotheses H1–H4.

[1] Data for the "average car fleet age" indicator for 2024 are unavailable, and the calculations therefore cover a five-year period.

– Examining automobile fleet indicators by region makes it possible to assess whether income disparities influence more environmentally responsible behavior. In order to determine the degree of structural inequality among the indicators across regions, and to test H2, the integrated coefficient of inequality (ICI) is calculated using Formula (1) [24]:

$$ICI = \sqrt{1 - \frac{20{,}000}{10{,}000 + \sum_{i=1}^{k} d_{it}^2}} \quad (1)$$

where: d_{it} denotes the indicator's share of region i at time t, and k denotes the number of regions. The closer the coefficient is to 1, the greater the differences in the distribution of the given measure between regions. To assess the unevenness of the regional structure over the entire period, the geometric mean of the ICI was calculated.

The strength and direction of the relationship between car fleet development, as measured by selected indicators, and environmental pollution in terms of CO_2 emissions are examined using the non-parametric Spearman's rank correlation coefficient (ρ). The findings of the correlation analysis confirm Hypotheses H5 and H6.

Through the applied methodology, the present research links the state and development of mobility and the automobile fleet in the EU with the general goal of European strategy and policy directed toward sustainable development and CE. The convenience of personal mobility for European citizens is assessed in light of its impact on the surrounding environment and the ethical implications of consumer behavior for future generations.

4. Results and Discussion

Analysis of the state of the EU car fleet for the period 2019–2024 reveals a complex interrelation between its growth, the transition to innovative technologies, and consumer demand, which jointly influence the environment.

The data indicate three distinct trends in the development of the new passenger car market over the period 2019–2024. New car registrations in the EU exhibit an overall downward trend, driven primarily by the sharp decline in 2020 (−23.5%) associated with the COVID-19 pandemic (Table 2).

Total new car registrations declined sharply in 2020 and continued to decrease until 2022. A partial recovery is observed in 2023–2024. Despite this improvement, the overall trend remains negative, as indicated by a CAGR of −3.5%. In 2024, registrations are still 2.5 million units below the initial level. When excluding the anomalous year 2020, the trend turns positive, with a CAGR of 2.1%. A similar pattern is evident in new car registrations per 1,000 inhabitants. The indicator decreased from 30 units in 2019 to 21 in 2022, then stabilized at 24 in 2023–2024. The overall CAGR is negative (−3.6%), but becomes positive (2.2%) when 2020 is excluded. This confirms a moderate recovery in underlying demand.

Table 2. New car registrations tendencies in the EU, 2019–2024

Indicator	2019	2020	2021	2022	2023	2024
New car registrations [thousand units]	13,215	10,116	9,866	9,343	10,633	10,701
GR (new car registrations) [%]	1.7	−23.5	−2.5	−5.3	13.8	0.6
New car registrations per 1,000 inhabitants [units]	30	23	22	21	24	24
GR (new car registrations per 1,000 inhabitants) [%]	2.0	−23.6	−2.2	−5.3	13.4	0.3
Share of HAFVs in new car registrations [%]	9.3	21.5	39.5	46.8	50.4	53.4
GR (share of HAFVs in new car registrations) [%]	40.8	131.0	84.3	18.3	7.6	6.0

HAFVs – hybrid and alternative-fuel vehicles; GR – growth rate.

Source: authors' calculations based on Eurostat [25–29] and ACEA [30–35]

In contrast, the share of HAFVs in new car registrations demonstrates strong and sustained growth, increasing from 9.3% in 2019 to 53.4% in 2024. Although growth rates show a decelerating trend after 2021, they remain consistently positive. The high CAGR of 33.8% (and 7.8% when excluding 2020) indicates a structural transformation towards alternative fuel vehicles.

Overall, the results highlight a divergence between declining market volume and a rapidly evolving market structure, characterized by the increasing penetration of alternative fuel vehicles.

Table 3 reveal persistent regional asymmetries in both the structure and intensity of new car registrations over the period 2019–2024, alongside a pronounced but uneven technological transition toward HAFVs. The distribution of newly registered cars by region remains highly concentrated, with Region I consistently dominating at around 60% of total registrations, followed by Region II with approximately 35–38%, while Region III retains only a marginal share of about 2–3%. The average ICI for this indicator is approximately 0.5, reflecting a relatively high and stable degree of structural concentration and confirming the leading role of Region I in shaping overall market dynamics.

When the analysis shifts to the intensity of registrations per 1,000 inhabitants, regional disparities appear less pronounced but remain significant. The average ICI of 0.3 suggests a comparatively more balanced distribution across regions; however, notable differences persist. In Region I, approximately 29 new cars per 1,000 inhabitants are registered on average, whereas in Region III this level is nearly four times lower, reflecting disparities in purchasing power, economic development, and market maturity.

Table 3. Regional development and structural inequality in new car registrations, 2019–2024

Indicator	Region	2019	2020	2021	2022	2023	2024
Share of newly registered cars by region [%]	I	61.2	63.1	61.1	62.1	61.2	59.6
	II	36.5	34.6	36.6	35.4	36.3	37.7
	III	2.3	2.3	2.3	2.5	2.6	2.7
ICI (share of newly registered cars)	ICI	0.5	0.5	0.5	0.5	0.5	0.4
New car registrations per 1,000 inhabitants by region [units]	I	37.6	29.6	27.9	26.7	29.8	29.1
	II	24.8	17.9	18.6	17.1	19.9	20.7
	III	8.7	6.9	6.5	6.9	8	8.4
ICI (registrations per 1,000 inhabitants)	ICI	0.3	0.3	0.3	0.3	0.3	0.3
Share of HAFVs in new car registrations by region [%]	I	64.5	75.8	66	66.8	64.9	63.5
	II	34.1	22.6	32.3	31.1	32.9	34.4
	III	1.4	1.7	1.8	2.1	2.2	2.1
ICI (HAFVs share)	ICI	0.5	0.6	0.5	0.5	0.5	0.5

ICI – integrated coefficient of inequality.

Source: authors' calculations based on Eurostat [25–29] and ACEA [30–35]

At the same time, the diffusion of HAFVs demonstrates both strong growth and considerable regional concentration. Although the overall share of HAFVs in new registrations increases substantially over time, their distribution remains uneven. The average ICI of around 0.5 indicates a pronounced structural imbalance, with Region I accounting for the majority of HAFV uptake, reaching 63.5% in 2024. This suggests that the adoption of alternative technologies is strongly associated with the economic and infrastructural advantages of more developed regions.

A comparative analysis of ICI values across the examined indicators reveals that structural inequality is more pronounced in relative shares, including HAFVs, than in intensity-based indicators. This suggests that, although access to vehicle ownership is gradually becoming more balanced across regions, market dynamics and technological transformation continue to evolve unevenly. In summary, significant regional disparities persist, with the wealthiest region dominating new car registrations (ICI ≈ 0.5). While adjusting for population reduces the observed inequality, it remains substantial. At the same time, despite the overall decline in total registrations, the results point to a clear structural shift toward HAFVs, concentrated primarily in economically advanced regions, indicating that the transition toward sustainable mobility in the EU is spatially uneven and continues to reinforce existing regional imbalances.

The analysis of the EU car fleet for 2019–2024 indicates a steady but moderate upward trend in key quantitative indicators (Table 4).

Table 4. Dynamics of the EU car fleet: key indicators, 2019–2024

Indicator	2019	2020	2021	2022	2023	2024
Car fleet [thousand units]	244,850	247,656	250,247	252,612	256,130	259,278
GR (car fleet) [%]	2.2	1.5	1.4	1.3	1.8	1.6
Motorization rate [units per 1,000 inhabitants]	515	524	531	535	542	550
GR (motorization rate) [%]	2.3	1.7	1.4	0.6	1.4	1.5
Share of HAFVs in car fleet [%]	3.7	4.5	5.9	7.5	9.2	9.6
GR (share of HAFVs in car fleet) [%]	14.5	22.6	31.2	26.0	23.2	4.5
Average age of car fleet [years]	11.5	11.8	12.0	12.3	12.5	N/A
GR (average age of car fleet) [%]	6.5	2.6	1.7	2.5	1.6	N/A

GR – growth rate; N/A – not applicable.

Source: authors’ calculations based on Eurostat [25–29] and ACEA [30–35]

The total number of passenger cars increased from 244.9 million to 259.3 million units, supported by relatively stable annual growth rates despite slight post-2019 deceleration. The CAGR reaches 1.0%, or 0.9% when excluding 2020, confirming that the expansion is stable and not driven by short-term fluctuations. A similar pattern is observed in the motorization rate, which rises from 515 to 550 vehicles per 1,000 inhabitants. This reflects a gradual increase in car ownership and sustained demand for personal mobility. The corresponding CAGR of 1.1% (0.9% excluding 2020) further suggests a mature and steadily developing market.

In contrast, the share of HAFVs shows significantly stronger dynamics, increasing from 3.7 to 9.6%. High annual growth rates, especially between 2020 and 2023, indicate accelerated adoption of cleaner technologies. The CAGR of 17.3% (12.9% excluding 2020) highlights a clear structural shift, although the slowdown to 4.5% in 2024 signals the beginning of stabilization.

At the same time, the average age of the car fleet rises from 11.5 to 12.5 years (no data for 2024), indicating ongoing ageing. The CAGR of 1.7% (1.4% excluding 2020) suggests that fleet renewal remains relatively slow despite increasing HAFVs penetration.

The comparison of these trends reveals a divergence between quantitative growth and structural transformation. While fleet size and motorization expand moderately, the transition towards alternative fuel vehicles progresses much faster, alongside a continued ageing of the vehicle stock.

The regional dynamics of car fleet characteristics over the period 2019–2024 reveal clearly distinguishable patterns in the regional structure (Fig. 1).

The results reveal a high degree of structural stability in the regional composition of the car fleet, with Region I consistently dominating, followed by Region II, while Region III maintains a small but gradually increasing share (Fig. 1a). This persistent configuration is confirmed by the ICI, which remains constant at 0.4 throughout the entire period, indicating enduring regional disparities. A similar pattern is observed in the diffusion of hybrid and alternative fuel vehicles, where growth is evident across all regions but remains strongly concentrated in economically more advanced ones (Fig. 1c). Despite the upward trend, the overall penetration of HAFVs remains limited, reaching only 9.6% in 2024. The unchanged ICI (0.4; geometric mean 0.4) further highlights that the transition toward environmentally friendly technologies is spatially uneven and reinforces existing structural imbalances.

In contrast, intensity-based indicators exhibit a more balanced and convergent pattern. The motorization rate increases steadily across all regions, with only marginal differences between them and a slight lead of Region II over Region I (Fig. 1b), suggesting that vehicle ownership is relatively evenly distributed. This is supported by the low ICI values (0.1, declining to 0.0 in 2024; geometric mean 0.1). Similarly, the average age of the car fleet shows a gradual upward trend, accompanied by a modest reduction in regional disparities (Fig. 1d). Although Region III continues to exhibit the oldest vehicles, the decline in ICI from 0.2 to 0.1 (geometric mean 0.1) indicates a limited convergence in fleet ageing. Overall, the findings suggest that while access to car ownership is relatively homogeneous across regions, structural aspects of the fleet – particularly composition and technological adoption – remain uneven and resistant to convergence.

Unlike the volatility observed in new car registrations, the overall car fleet demonstrates high inertia in its evolution. Adjusting for population size does not substantially alter this trend, as motorization levels remain relatively high and stable, suggesting that car ownership is already widespread across regions.

The current market situation confirms that the diffusion of innovative and eco-friendly technologies within the car fleet is slow, largely due to the long economic life of vehicles and conservative consumer behavior. Although HAFVs exhibit strong growth rates, their overall share remains relatively low, highlighting a discrepancy between the rapid transformation of new car markets and the gradual renewal of the existing fleet.

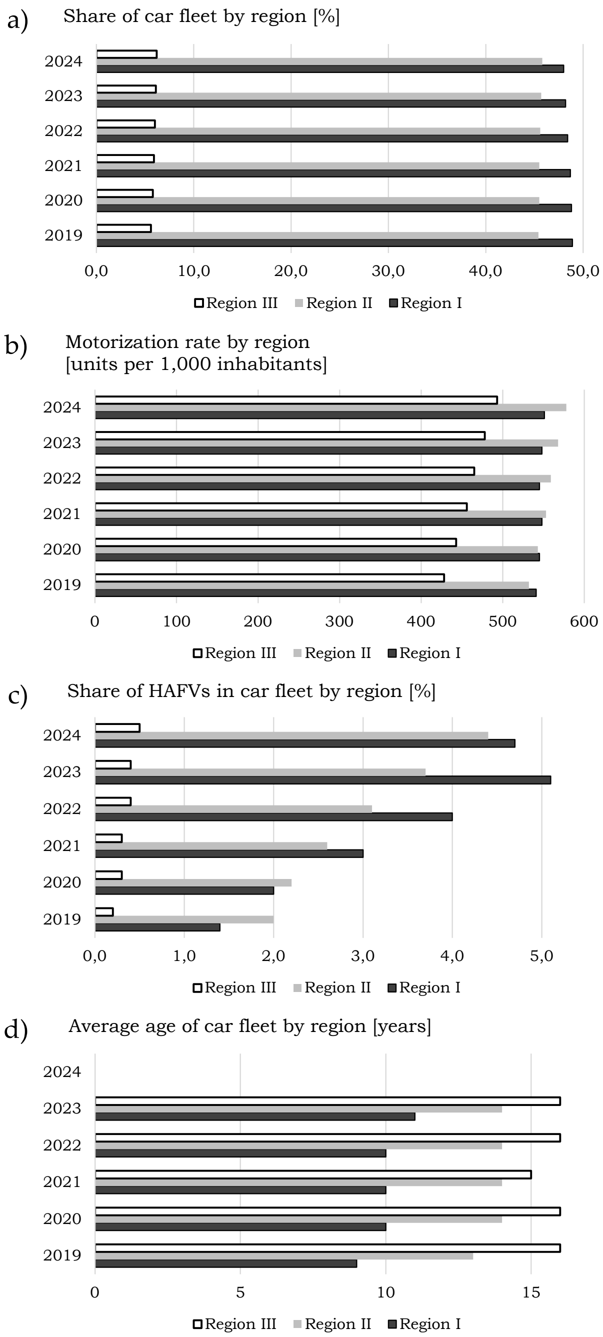

Fig. 1. Regional dynamics of car fleet composition, motorization rate, HAFV penetration, and average fleet age in the EU, 2019–2024

Source: authors' calculations based on ACEA [30–35]

This conclusion is supported by the increasing average age of the fleet, indicating delayed replacement of older vehicles. Combined with the decline in new car registrations, this suggests that the transition toward newer and more technologically advanced vehicles is slow and uneven across regions. Inequality remains more pronounced in structural indicators – such as fleet composition and HAFV shares – while it is lower and declining in intensity-based indicators, including motorization rate and fleet age, implying relatively balanced access to car ownership but uneven progress toward sustainable mobility.

The growth of the car fleet mirrors improved financial capacity among Europeans, allowing households to own more than one personal vehicle, reflecting a demand for convenience and mobility, while also suggesting a preference for older cars and a degree of skepticism toward entirely new ones. The combination of an expanding fleet and its simultaneous aging highlights a gap between the EU's sustainable mobility strategies and actual consumer behavior. New vehicles offer enhanced safety features and a lower ecological footprint, yet their market penetration remains limited and insufficient.

The European population is not rushing to change their cars, relying on the greater financial accessibility of older cars, the time-tested qualities of internal combustion engine (ICE) vehicles, the still poorly developed infrastructure for charging electric vehicles, or sentimental attachment to older vehicles. This conclusion can be drawn both from the results of the present study and from the findings of EY (2025), which indicate that approximately half of global car buyers now intend to choose ICE vehicles, as demand for electric vehicles softens due to range anxiety, insufficient charging infrastructure, geopolitical concerns, and high service costs [36]. ACEA also highlights the problem of insufficient numbers of charging stations, noting that they need to be eight times as numerous and more evenly distributed across the EU's regions [37]. Even within the category of AFVs, hybrids predominate, allowing the use of the ICE alongside the additional capabilities and power of electrification. In this way, the benefits of contemporary technologies are diluted by the inertia of already-produced cars, whose prolonged operational life maintains their accumulated CO_2 emissions.

The ecological consequences of car fleet development are reflected in CO_2 emission levels. Overall, CO_2 emissions decreased by 2.1% over the period; however, excluding the anomalous year 2020, when transport demand declined during the pandemic, emissions increased at an average annual rate of 0.4% (CAGR 2021–2024). Following the COVID-19 pandemic, newly registered automobiles decreased by 23.5%, while the total number of vehicles and the degree of motorization continued to grow. CO_2 emissions initially decreased by 12%, then increased by 7.8% in 2021, decreased again, and rose by 1.3% in 2024. This trend does not align with the overall market development. The composition and rate of fleet renewal, rather than market volume, are crucial to emission levels. Although emissions decrease at times, the reductions are insufficient to meet sustainability goals related to ecological protection and population well-being.

The reduction in emissions is primarily due to substantially lower levels in the first region compared to the others (Fig. 2).

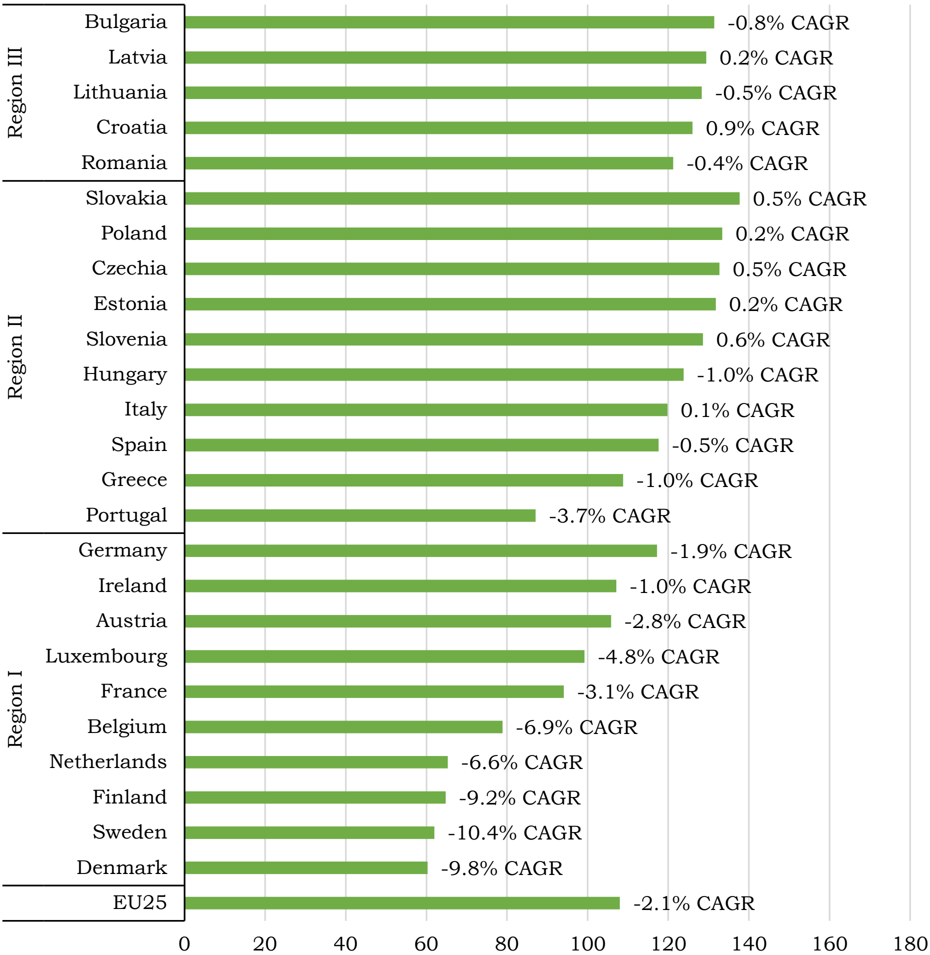

Fig. 2. Regional differences in CO_2 emissions among EU-25, 2019–2024

Source: authors' calculations based on ACEA [30–35]

A larger car fleet in more populous countries does not lead to significant disparities in carbon footprint or vehicle age, reflecting more efficient use and sustainable behavior among consumers in these countries, which also have a higher GDP per capita. Income emerges as the main driver of the ecological transition in the EU car fleet, with wealthier regions (Region I) characterized by significantly younger, more environmentally friendly, and less polluting vehicles.

According to Figure 2, the countries of Western and Northern Europe (which often fall into Region I) report a substantial reduction in carbon intensity. Due to higher incomes, political incentives, developed infrastructure, and cultural identity, decarbonization in these countries has progressed significantly. This is especially true given that the total number of passenger cars in these countries is higher because of their larger populations. In Central and Eastern Europe, these trends are reversed or significantly less pronounced. Countries such as Slovakia, Poland, Czechia, Estonia, and Bulgaria are much more dependent on importing cheaper second-hand automobiles, which ultimately hinders efforts to reduce overall CO_2 emissions and undermines the positive effects of technological progress in countries like Sweden, Denmark, Finland, and others.

Population income plays an essential role in environmentally responsible behavior. In regional terms, significant differences are observed across almost all indicators except the motorization rate, the average age of the car fleet, and CO_2 emission levels. In developed European economies, domestic car production and higher consumer purchasing power drive the adoption of innovative and alternatively powered vehicles. This accessibility leads to a significantly lower average age of the car fleet in countries like Germany, Sweden, and Finland compared to lower-income nations such as Bulgaria and Romania.

The example of Bulgaria, which has the lowest GDP per capita of all member states and, correspondingly, one of the highest CO_2 levels, is illustrative in this regard (Fig. 3). The country is ranked 22nd in the number of registered cars and 25th per capita, with only 7 new cars per 1,000 people compared to an EU average of 24. Petrol automobiles account for 76% of new registrations, and HAFVs account for barely 8%. The country also maintains the oldest car fleet, with over 60% of imported used cars being more than ten years old. These peculiarities stem, on the one hand, from income inequalities, which push those wishing to purchase a higher-end personal vehicle to the second-hand car market. On the other hand, developments in the Bulgarian car market may also reflect public skepticism toward new technologies, insufficient infrastructure to support their use, and a view of the car primarily as a means of transport that can continue to be used as long as it fulfills its basic function. These distinctive features lead to a continuing and ever-increasing dependence on the import of used cars, accompanied by high carbon emissions, a refusal to adopt additional road safety measures, and a refusal to offer product warranties.

The dominance of used cars, which is proclaimed by the CE's reuse strategy, also represents its main paradox. Extending the life cycle of vehicles increases resource efficiency, as it postpones the need for new production and the harmful emissions associated with it, and also reduces the demand for materials such as steel, aluminum, and rare-earth elements. At the same time, however, this prolongs reliance on obsolete technologies that emit high levels of CO_2, NO_x, and fine particulate matter [38]. Thus, the ecological benefits of reuse go hand in hand with deteriorating air quality, underscoring the necessity for integrated policies combining circular-economy logic with accelerated car-fleet renewal and the transition to clean energy.

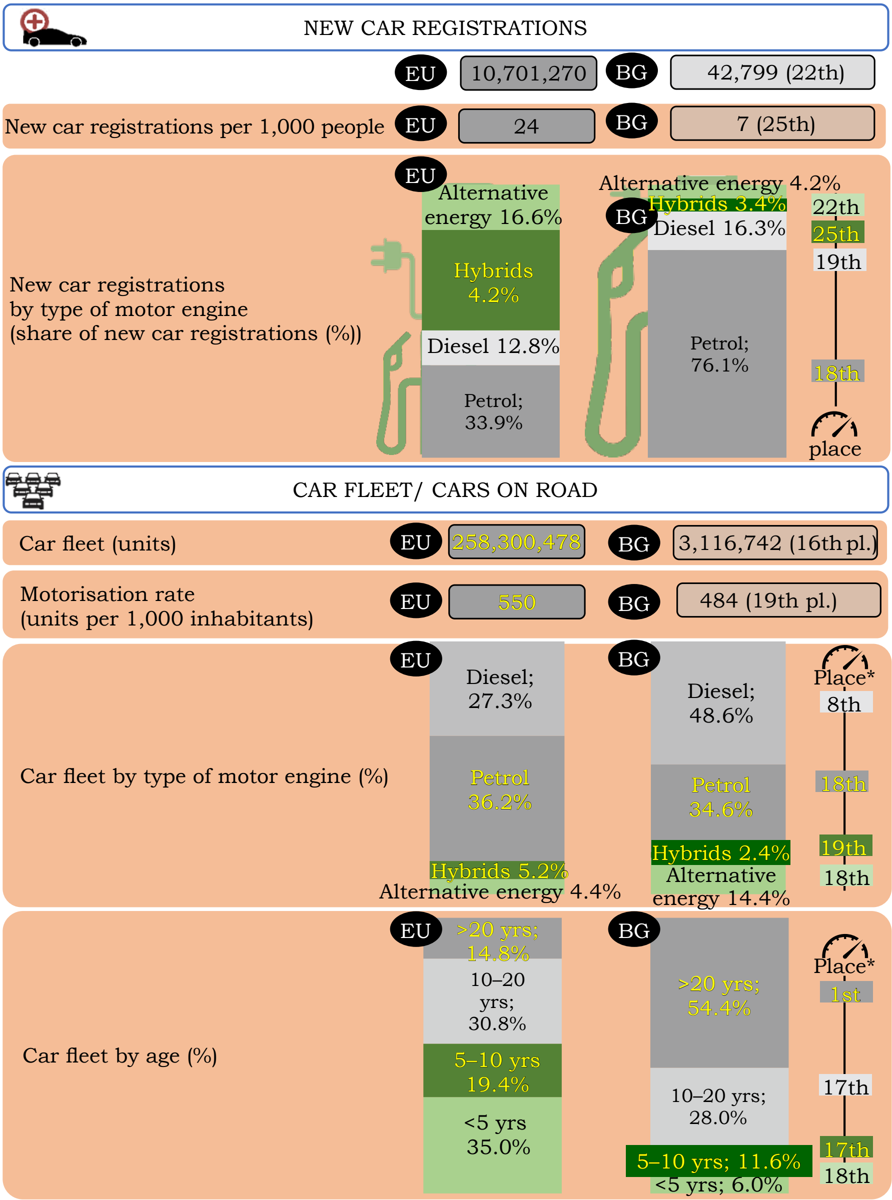

Fig. 3. Bulgarian and EU car fleet condition in 2024[2]

Source: authors' calculations based on Eurostat [25–29] and ACEA [30–35]

[2] When interpreting Bulgaria's position in the rankings by engine type and vehicle age, the limitations of the available data should be taken into account: information on alternative fuel cars is available for 23 member states, petrol and diesel cars for 21, and data on the age structure (under 5 years, 5–10 years, 10–20 years) for 18 countries. Only 17 countries provide data for cars over 20 years old.

The correlation analysis (Fig. 4) further quantitatively confirms these relationships. A strong positive and statistically significant relationship is observed between the average age of the car fleet, and CO_2 emissions during 5 out of the 6 years studied (Spearman's $\rho > 0.6$, $p < 0.05$). An older car fleet, which is predominantly replenished by the second-hand car market, contributes to a negative ecological footprint. The paradox associated with the reuse and re-commercialization of this type of product is evident. At the current stage of technological development, the secondary car market does not improve the environment; on the contrary, it worsens it.

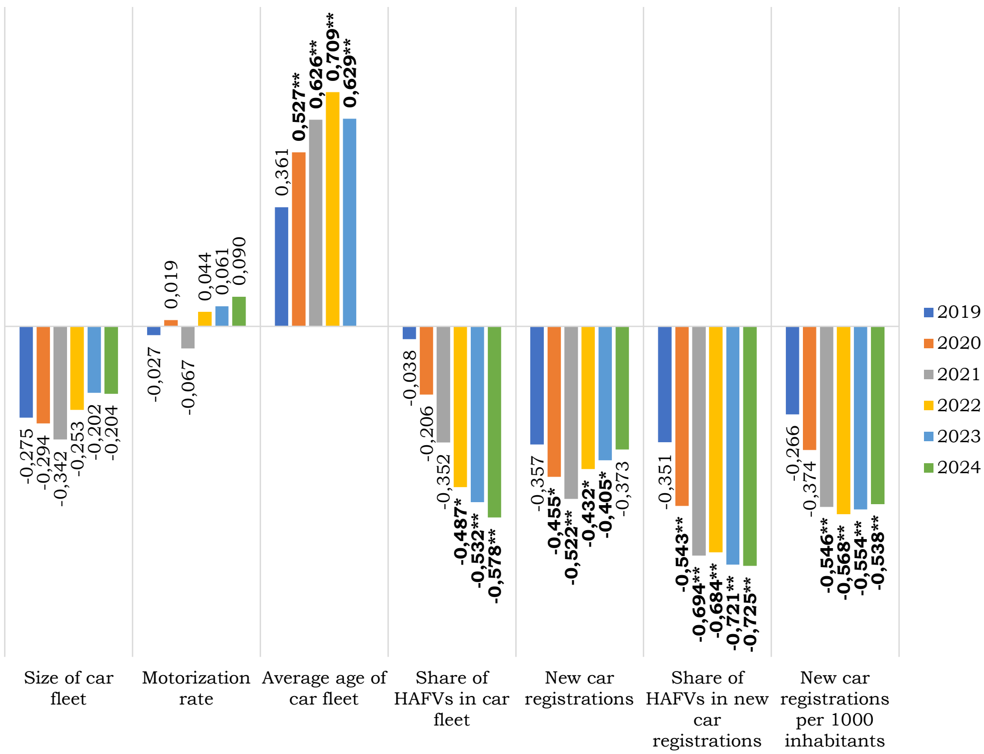

Fig. 4. Correlation between CO_2 emissions and key fleet indicators, 2019–2024.
Values marked with "*" indicate correlation significant at the 0.05 level (2-tailed), and values marked with "**" indicate correlation significant at the 0.01 level (2-tailed)

Source: authors' calculations based on Eurostat [25–29] and ACEA [30–35]

On the other hand, lower carbon emissions can be achieved by increasing the density of newly registered automobiles and by purchasing those powered by alternative or supplementary ICE energy sources. These steps would also reduce the average age of the car fleet – a positive direction with a proven environmentally friendly footprint. It is precisely the renewal of the car fleet and the increase in HAFVs, when balanced with consumer behavior and the desire for mobility and convenience of a personal vehicle, that constitute a source of sustainability for the European car market and a key direction for its development.

For the moment, the prolonged exploitation of ICE vehicles, rather than the extension of the life cycle of HAFVs (which are not sufficiently widespread), is both an ecological problem and a factor shaping the future development of the car fleet. The following can be considered elements of the solutions in the field of sustainable mobility:

- Promotion of the purchase of new automobiles with innovative powertrains and safety systems.
- Implementation of a CE reuse strategy to extend the lifespan of electric vehicles through warranty and post-warranty maintenance, as well as re-commercialization or buyback by car dealers.
- Introduction and enforcement of stricter emission and durability standards for automobiles under Euro 6 and Euro 7.
- Differentiated taxation according to the age and ecological class of the automobile. As of 2024, 11 of the 27 EU member states offer tax incentives covering the acquisition, ownership, and provision of company cars [35].
- Zoning of urban access based on vehicle carbon footprint, whereby more desirable areas are accessible only to newer, lower-emission vehicles.
- Targeted subsidies for the purchase of electric vehicles, as already implemented in several countries. In 2024, 19 of the 27 EU member states were implementing initiatives aimed at promoting the adoption of electric vehicles [35].
- Building and expansion of fast and easily accessible infrastructure for charging and servicing AFVs (such initiatives are indicated by 13 of the 27 EU member states [35]).
- Increasing the cost of owning ICE vehicles through higher excise duties on fuel.
- Strategies for the scrapping of end-of-life vehicles (ELVs), involving the precise determination of when a vehicle can be considered end-of-life, prevention of its export, clear rules for its handover, and the possibility of recycling 85% of its materials for reintegration into the production of new vehicles [39]. On the one hand, this will reduce the risk of pollution and resource loss; on the other hand, it will help decrease dependence on raw material imports, improve the quality of recycled material and protect the environment.
- Creating greater awareness and trust among the more conservative segments of society about the qualities of new cars and narrowing the green gap in consumer behavior.

Environmentally responsible consumer behavior is not driven solely by financial motivation but is shaped by cultural, social, and personal reasons, which may run counter to the ecological needs of society. More flexible business strategies aimed at replacing used cars with additional payments toward new ones, intensive advertising of the ecological benefits and technologies used in new cars, social influence in favor of purchase from the primary car market, and diverse income-adjusted installment strategies could create good prospects for promoting norms of sustainable development and behavior in Central and Eastern European countries. Currently, technological development and innovation outpace Europeans' psychological and practical readiness to reorient their behavior toward sustainable automobile transport.

5. Conclusion

The study confirms that the car fleet has a strong impact on carbon dioxide (CO_2) emissions, which, together with particulate matter and nitrogen oxides (NO_x), serve as key indicators of air pollution, with vehicle age and income identified as the main determinants impeding the fleet's sustainable development. Despite the explosive growth of newly registered personal vehicles powered by alternatives to the ICE, especially in richer European regions, the share of these technologies in the overall car fleet is low. Their favorable influence on the environment remains limited, and the dissemination and adoption of new technologies among consumers remain problematic. Serious regional imbalances exacerbate this effect in countries with lower purchasing power, particularly in Bulgaria, where a preference for older automobiles and an affinity for the secondary car market for various reasons impede the development of sustainable mobility and road safety. From this perspective, a paradox is also evident between the CE model and the need to accelerate the decommissioning of older automobiles. The prospects for reducing the harm associated with preferred personal transport lie in a combination of measures: promoting new cars powered by alternative fuels, extending their operational life, and developing mechanisms that increase consumers' financial capacity and trust in new vehicles. Through these measures, accelerated renewal of car fleets and reduced regional disparities among EU member states can be achieved.

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CRediT Author Contribution

Y. H.: conceptualization, data curation, investigation, writing – original draft preparation, methodology, validation, formal analysis, writing – review and editing, visualization, supervision.

D. Zh.: writing – original draft preparation, investigation, writing – review and editing, supervision.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The datasets supporting the findings of this study are publicly available and derived from open-access repositories maintained by the European Automobile Manufacturers' Association (ACEA) and Eurostat, as well as from official documents of the European Commission and the European Union (EU Official Journal). All data used in the analysis are publicly accessible and have been aggregated at the country level to ensure comparability across EU member states. No proprietary or confidential data were used.

Use of Generative AI and AI-Assisted Technologies

No generative AI or AI-assisted technologies were employed in the preparation of this manuscript.

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