



Monitoring and Identification of Carbon Footprint Changes for Selected Fuels on the Example of the Koszalin-Kołobrzeg-Białogard Functional Area

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Abstract: This article presents changes in the carbon footprint generated by vehicles using different types of fuel (gasoline, diesel, liquefied petroleum gas) in the Koszalin–Kolobrzeg–Białogard Functional Area (KKBOF) with projections up to 2055. The study is based on historical data from 2019–2023 and forecasts of the number of vehicles until 2055. The research aims to monitor the carbon footprint generated by vehicles using various types of fuel (gasoline, diesel, liquefied petroleum gas) in KKBOF from 2019 to 2023 and to identify changes up to 2055 in implementing sustainable transport policies in the region. The results confirm that gasoline-powered vehicles generate the highest carbon footprint, and this gap is expected to widen by 2055. The highest rate of CO₂ emission growth has been observed in highly urbanized areas, particularly in the Koszalin city district, where the projected average annual increase in emissions from gasoline-powered vehicles is 0.64 tons, compared to 0.37 tons for diesel and 0.10 tons for liquefied petroleum gas. The study highlights the need for comprehensive CO₂ reduction strategies in the transport sector, including developing the Mobility as a Service model and infrastructure for low-emission vehicles. Action is essential in urban areas where emission-related problems are most severe. The findings of this study can serve as a basis for shaping transport policies aligned with the goals of sustainable development and the European Green Deal.

Keywords: sustainable development, carbon footprint, KKBOF, transport, CO₂ emissions

1. Introduction

Sustainable development is a concept of socio-economic growth that aims to meet present needs without compromising the ability of future generations to meet their own needs (Silvestre & Țîrcă 2019). It is based on three main pillars: environmental, social, and economic. The ecological aspect is particularly significant, encompassing protecting natural resources, biodiversity, and efforts to mitigate climate change (Burchard-Dziubińska et al. 2014). One of the key indicators of human impact on the environment is the emission of greenhouse gases, especially carbon dioxide (CO₂) (Cenkier 2024, Balogh & Jámor 2017, Gabryelewicz et al. 2021). Industry (Lenort et al. 2019) and transport are important elements in this.

In the context of CO₂ emissions, particular attention should be given to the transport sector, which accounts for 21% of global carbon dioxide emissions, making it the most emissive sector in many developed countries. Europe and North America have historically contributed the most to emissions from this sector (Gis 2017, Nocera & Cavallaro 2014).

The European Union, recognizing the need to combat environmental degradation, has adopted an ambitious strategy known as the European Green Deal. Its goal is to transform the EU into a modern, resource-efficient, and competitive economy that will achieve climate neutrality by 2050. This is a highly ambitious task, particularly with the continuous increase in registrations of used, high-emission vehicles (Sobolewski 2019, Bayer & Aklın 2020, Ziemacki 2021).

The established goals will only be achieved by applying all available tools, including promotional and informational campaigns, regulatory and legislative measures, financial support, and fiscal incentives. Decreased demand for transport (e.g., through teleworking), improved vehicle efficiency, and the development of zero-emission technologies can reduce greenhouse gas emissions (Racoceanu 2021).

In the transport sector, there are several main pathways to decarbonization. The first is transport electrification, which, however, requires significant changes in infrastructure and the electricity production system (Brdulak & Pawlak 2022). Another solution is biofuels, an alternative to traditional fossil fuels (Kupczyk et al. 2017). The third pathway is hydrogen utilization, which, as a future fuel, could complement or even replace electric propulsion by offering a better range and shorter refueling times (Ściażko et al. 2018).



Hydrogen is already used in public transportation, including buses and trains, particularly on non-electrified routes. Initiatives such as H2Accelerate aim to introduce hydrogen-powered trucks on a large scale to the European market. Each of these solutions has its own balance of advantages and disadvantages, as well as costs and benefits (Filina-Dawidowicz et al. 2024). However, technological advancements offer the potential to reduce production costs and address current technical challenges (Pyza et al. 2022).

Additionally, implementing innovative monitoring systems, such as (Grunt et al. 2022), enables the optimization of chemical raw material transportation management, indirectly contributing to reducing the carbon footprint through more efficient resource utilization and minimizing losses during transportation and storage. Integrating advanced platforms, such as the Multi-domain, Autonomous Measurement Buoy offers valuable opportunities to enhance environmental monitoring systems. These platforms extend beyond their immediate domain by providing comprehensive real-time data on water quality through indicators like temperature, pH, and turbidity (Błażejowski et al. 2024). Their adaptability and scalability could inspire similar innovative approaches in reducing the carbon footprint, as seen in sectors like transport, where systemic monitoring is crucial for managing resources efficiently and achieving sustainability objectives.

All the aforementioned measures undertaken in the transport sector directly impact the carbon footprint. This environmental indicator emerged in the early 21st century in response to the need for monitoring and controlling greenhouse gas emissions. The concept originates from the broader notion of the ecological footprint and belongs to the footprint family of indicators used to assess environmental pressure (Kulczycka & Wernicka 2015).

The definition of carbon footprint has evolved over the years. Initially, it focused solely on CO₂ emissions, but a broader approach has since become dominant, incorporating other greenhouse gases. According to the international standard ISO 14067:2018, the carbon footprint is the sum of greenhouse gas emissions and removals expressed in carbon dioxide equivalent (CO₂e). In addition to CO₂, it includes methane (CH₄), nitrous oxide (N₂O), fluorinated industrial gases (HFCs, PFCs), and sulfur hexafluoride (SF₆) (Zarczuk 2021). A Global Warming Potential (GWP) index is determined for these gases, allowing comparisons of their climate impact relative to CO₂ (Śleszyński 2021). The GWP value indicates how strongly a given gas contributes to climate warming over a century compared to carbon dioxide. This study focuses specifically on CO₂ emissions, which can be calculated using the following formula (Schaefer 2014):

$$CF_{\text{Transport}}(\text{kgCO}_2\text{e}) = \text{Distance travel (km)} \cdot \text{Fuel consumption rate} \left(\frac{\text{km}}{\text{l}} \right) \cdot EF \frac{\text{kgCO}_2\text{e}}{\text{l}} \quad (1)$$

where:

$CF_{\text{Transport}}$ – Carbon Footprint.

Distance traveled (km) – Distance covered (in kilometers).

Fuel consumption rate (km/l) – fuel used per distance (liters per kilometer).

EF (kg CO₂e/l) – Emission factor (kilograms of CO₂ equivalent per liter).

The carbon footprint plays a fundamental role in sustainable development, with its consequences particularly evident in the environmental dimension. The rising emission of greenhouse gases accelerates climate change, manifesting in a range of negative phenomena. The increased frequency of extreme weather events, such as droughts, floods, and hurricanes, is a direct consequence of a growing carbon footprint. These events lead to significant ecosystem degradation and loss of biodiversity. The acidification of oceans is particularly concerning, caused by the absorption of excess carbon dioxide from the atmosphere, which has a catastrophic impact on marine ecosystems, including coral reefs and marine organisms with calcareous skeletons. Climate change driven by high carbon footprints also contributes to soil degradation and the reduction of arable land (Frączek & Śleszyński 2016). This process is hazardous because of the growing global population and the need to ensure food security. Additionally, changes in precipitation patterns and temperature affect the natural vegetation cycles of plants, potentially leading to significant disruptions in agricultural production (Adamiec & Jarosz-Krzemińska 2022). Recycling of waste, particularly recycling of vehicles, is an important process (Chamier-Gliszczyński & Krzyżynski 2005).

In a broader socio-economic context, the consequences of a high carbon footprint translate into health issues related to air pollution, climate-induced migration, and rising costs of adapting to changing environmental conditions. The transition toward a low-emission economy has become necessary, particularly in the transport sector, which remains one of the significant sources of greenhouse gas emissions.

Therefore, actions to reduce the carbon footprint are crucial for maintaining ecological balance and ensuring that future generations can meet their needs. This requires systemic changes in how the economy and society operate, with a particular focus on developing low-emission technologies and shifts in consumption patterns.

Only a comprehensive approach to the issue of greenhouse gas emissions can ensure the effective achievement of sustainable development goals and the protection of the natural environment for future generations.

This study aims to monitor the carbon footprint generated by vehicles using different types of fuel (gasoline, diesel, and liquefied petroleum gas) in the Koszalin–Kolobrzeg–Bialogard Functional Area (KKBOF) during the period 2019–2023 and to identify changes projected until 2055 in the context of implementing sustainable transport development policies. The main research problem is formulated as the following question: To what extent does the type of fuel used in road transport within KKBOF generate the highest carbon footprint, and how will this relationship evolve until 2055, considering the need to balance economic development with environmental protection? In response to this research problem, the following hypotheses have been formulated:

- [H1] Gasoline-powered vehicles generate the highest carbon footprint among the analyzed fuel types in KKBOF.
- [H2] This disparity will continue to widen until 2055 due to gasoline's higher CO₂ emission factor.
- [H3] A more significant increase in gasoline-powered vehicles is projected than in diesel and liquefied petroleum gas (LPG) vehicles, negatively impacting achieving sustainable development goals in KKBOF.

2. Research Methodology and Materials Used

The study is based on statistical data on the number of vehicles by fuel type from 2019 to 2023, obtained from the Local Data Bank of the Central Statistical Office of Poland (GUS). The analysis includes emission factors for each fuel type, expressed as kg CO₂ per liter (for fuels):

1. Gasoline – 2.31 kg CO₂/liter.
2. Diesel – 2.68 kg CO₂/liter.
3. LPG – 1.51 kg CO₂/liter.

Additionally, the following values for average annual fuel consumption per passenger car were adopted (<https://www.gov.pl/attachment/c75185bb-89c3-4fc5-a0a3-fc2ee7680bf9>):

1. Gasoline (Petrol) – 1,200 liters per year per vehicle.
2. Diesel Fuel – 1,500 liters per year per vehicle.
3. Liquefied Petroleum Gas (LPG) – 1,100 liters per year per vehicle.

Based on this, the annual mileage (in km) for each fuel type was calculated using the following formula:

$$\text{Annual mileage (km)} = \frac{\text{Annual consumption (litre)}}{\text{Fuel consumption rate } (\frac{l}{km})} \cdot 100 \quad (2)$$

Moreover, the following results were obtained:

1. Gasoline (Petrol) – 17,143 km.
2. Diesel Fuel – 25,000 km.
3. Liquefied Petroleum Gas (LPG) – 14,667 km.

The scope of the study covers the KKBOF area, incorporating historical data from 2019–2023 and projections up to 2055, focusing on CO₂ emissions from road transport, categorized by fuel type. The following assumptions were adopted: constant emission factors throughout the forecast period, maintenance of current trends in the fuel structure of the vehicle fleet, linear growth in the number of vehicles, and variation in CO₂ emissions depending on the degree of urbanization of the area.

3. Results

Table 1 presents data on the number of vehicles using each fuel type in KKBOF from 2019 to 2023 to calculate the carbon footprint for each fuel type.

Then a forecast of the number of vehicles until 2055 was made (Table 2), according to the formulas:

$$CAGR = \left(\frac{End}{Start} \right)^{\frac{1}{n}} - 1 \quad (3)$$

$$\text{Forecast} = \text{final value} \cdot (1 + CAGR)^n \quad (4)$$

where:

CAGR (Compound Annual Growth Rate) – The annualized growth rate over a specified period.

End – Final value at the end of the period.

Start – Initial value at the beginning of the period.

n – Number of years in the forecast period.

Table 1. Number of vehicles by fuel type in KKBOF in the years 2019-2023

	Petrol				Diesel fuel				Liquefied petroleum gas			
	1*	2*	3*	4*	1	2	3	4	1	2	3	4
2019	32,242	25,091	20,352	14,522	18,445	15,298	14,097	8,393	6,763	6,059	6,287	4,223
2020	33,068	25,558	20,894	14,817	19,095	15,713	14,704	8,904	6,904	6,127	6,393	4,285
2021	33,789	26,360	21,608	15,172	19,487	16,343	15,419	9,319	6,939	6,140	6,497	4,304
2022	34,211	26,861	22,227	15,442	19,452	16,665	15,824	9,534	7,037	6,188	6,498	4,282
2023	35,082	27,394	22,443	15,697	19,900	17,066	16,088	9,813	7,164	6,240	6,558	4,316

Source: Own study based on bdl.stat.gov.pl

1* Koszalin City District

2* Kolobrzeg District

3* Koszalin District

4* Bialogard District

Table 2. Projected number of vehicles by fuel type in KKBOF until 2055

District	Fuel	Dec 30	Dec 35	Dec 40	Dec 45	Dec 50	Dec 55
Koszalin City District	Petrol	37,816	39,726	40,735	42,195	43,655	45,114
	Diesel Fuel	21,647	22,226	22,806	23,385	23,965	24,544
	Liquefied petroleum gas	7,421	7,679	7,936	8,193	8,451	8,708
Kolobrzeg District	Petrol	28,192	29,340	30,488	31,636	32,784	33,932
	Diesel Fuel	18,313	18,798	19,284	1,977	20,256	21
	Liquefied petroleum gas	6,498	6,705	6,912	7,119	7,325	7,532
Koszalin District	Petrol	24,195	25,161	26,126	27,091	28,057	29,022
	Diesel Fuel	17,322	17,801	18,281	1,876	1,924	1,972
	Liquefied petroleum gas	6,758	6,968	7,178	7,387	7,597	7,807
Bialogard District	Petrol	16,897	17,573	18,249	18,926	19,602	20,278
	Diesel Fuel	10,634	10,940	11,247	11,553	1,186	12,166
	Liquefied petroleum gas	4,469	4,609	4,749	4,889	5,029	5,169

Source: own study.

The number of vehicles in individual districts shows a clear upward trend in 2030-2055. In Koszalin City District, the number of vehicles powered by gasoline increased by 19.3%, and those powered by diesel by 13.4%. LPG-powered vehicles record an increase of 17.3%. A similar pattern is visible in Kolobrzeg District, where the number of gasoline vehicles grows by 20.3%, and those powered by diesel by 14.7%. For LPG-powered vehicles, the increase is 15.9%. In Koszalin District, the number of gasoline-powered vehicles increased by 19.9%, and those powered by diesel by 13.8%. LPG-powered vehicles record an increase of 15.5%. Bialogard District shows a 20% increase in gasoline-powered vehicles, while diesel-powered vehicles increase by 14.4%. The increase in LPG-powered vehicles is 15.6%.

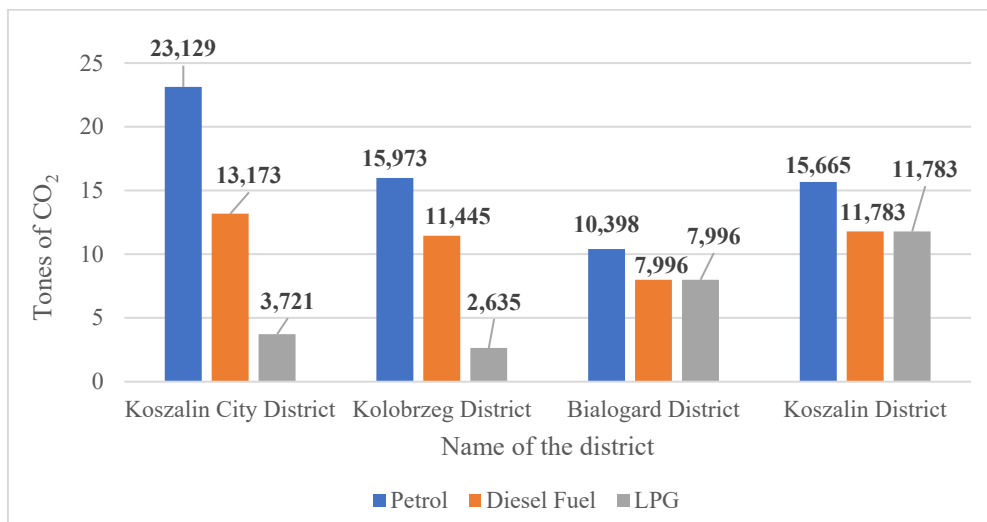
The increasing number of vehicles powered by different fuel types in individual districts indicates growing environmental pressure regarding carbon footprint emissions. The dominant share of gasoline-powered vehicles, which show the highest percentage growth, may significantly impact emission levels, considering the higher carbon footprint of this fuel than others. The stable, though slightly slower, increases in the number of diesel- and LPG-powered vehicles will also contribute to total emissions. The carbon footprint figures, calculated according to formula (1), are presented in Table 3.

Table 3. Carbon footprint for each fuel type (tons of CO₂)

	Fuel	2019	2020	2021	2022	2023	2030	2035	2040	2045	2050	2055
Koszalin City District	Petrol	58,035	59,556	60,865	61,569	6,308	68,018	7,047	73,276	75,905	78,535	81,164
	Diesel Fuel	39,073	40,467	41,268	41,195	42,171	45,865	47,142	48,418	49,694	5,097	52,246
	Liquefied Petroleum Gas	1,207	12,313	12,363	12,531	12,764	1,347	13,934	14,398	14,862	15,326	15,791
Kolobrzeg District	Petrol	4,516	46,065	47,521	48,412	4,935	50,809	52,838	54,866	56,895	58,924	60,953
	Diesel Fuel	3,241	3,331	34,637	35,315	36,155	38,776	39,822	40,869	41,864	4,286	43,855
	Liquefied Petroleum Gas	10,804	10,925	10,948	11,041	11,133	11,596	11,965	12,333	12,702	1,307	13,439
Koszalin District	Petrol	366	37,594	38,893	4,005	40,459	43,568	45,308	47,048	48,787	50,526	52,265
	Diesel Fuel	29,884	31,118	32,624	33,468	34,036	36,647	37,654	38,662	39,664	40,665	41,667
	Liquefied Petroleum Gas	11,564	11,758	11,948	11,948	1,206	12,429	12,819	13,209	13,599	13,988	14,378
Bialogard District	Petrol	261	26,633	27,262	27,732	28,235	3,039	31,612	32,833	34,055	35,276	36,498
	Diesel Fuel	17,788	18,879	19,746	20,179	20,794	22,522	23,171	2,382	24,474	25,129	25,784
	Liquefied Petroleum Gas	777	7,871	7,909	7,872	7,938	8,215	8,466	8,716	8,962	9,208	9,454

Source: own study.

Figure 1 presents the changes in carbon dioxide (CO₂) emissions in 2055 compared to 2019, and Figure 2 presents the average annual carbon dioxide (CO₂) emissions increase.

**Fig. 1.** Difference in CO₂ emissions between 2055 and 2019

Source: own study.

The analysis of carbon footprint emission trends from 2019 to 2055 for selected districts of the West Pomeranian Voivodeship shows a systematic increase in CO₂ emissions across all examined fuel categories. In the Koszalin City District, which exhibits the highest growth dynamics, a total increase of 23,129 tons in CO₂ emissions from gasoline-powered vehicles was projected between 2019 and 2055, translating to an average annual increase of 0.64 tons. For diesel vehicles in the same district, emissions are projected to increase by 13,173 tons of CO₂ over the same period, with an average annual growth of 0.37 tons. In comparison, emissions from LPG-powered vehicles are expected to rise by 3,721 tons of CO₂, resulting in an average annual increase of 0.10 tons.

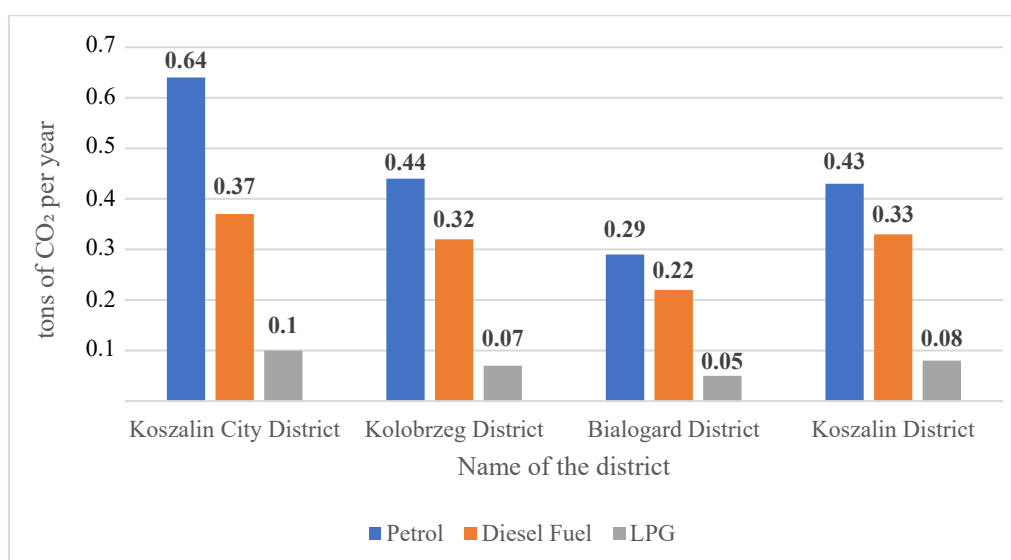


Fig. 2. The projected average annual increase in CO₂ emissions (2019-2055)

Source: own study.

In Kolobrzeg District, the upward trend is also evident, although less intense than in Koszalin. CO₂ emissions from gasoline-powered vehicles increased by 15,793 tons (average of 0.44 tons per year), from diesel vehicles by 11,445 tons (average of 0.32 tons per year), and from LPG-powered vehicles by 2,635 tons (average of 0.07 tons per year).

Bialogard District shows the lowest growth dynamics among the examined administrative units. The increase in CO₂ emissions from gasoline-powered vehicles amounted to 10,398 tons (an average of 0.29 tons per year), from diesel vehicles to 7,996 tons (an average of 0.22 tons per year), and from LPG-powered vehicles to 1,684 tons (an average of 0.05 tons per year).

In the Koszalin District, an increase in CO₂ emissions from gasoline-powered vehicles of 15,665 tons (an average of 0.43 tons per year), from diesel vehicles of 11,783 tons (an average of 0.33 tons per year), and LPG-powered vehicles of 2,814 tons (an average of 0.08 tons per year) was observed.

Monitoring and identifying changes indicate a significant correlation between the degree of urbanization and CO₂ emission levels. More urbanized areas, such as Koszalin City and Kolobrzeg District, exhibit significantly higher emission increases than areas with lower population density. In all analyzed districts, the highest emission values are associated with gasoline-powered vehicles, while LPG-powered vehicles generate the smallest increase in the carbon footprint. The observed trends suggest the need for effective CO₂ emission reduction strategies in the transport sector, particularly in urban areas with a high concentration of vehicle traffic.

4. Conclusions and Discussion

The study successfully achieved its research objective by providing a detailed identification and analysis of changes in the carbon footprint generated by vehicles using different fuel types in KKBOF. The empirical analyses, based on historical data from 2019-2023 and projections until 2055, enabled the assessment of the current state of CO₂ emissions and the forecasting of future trends in this area. The results fully confirmed the research hypothesis in response to the research question concerning identifying the fuel type generating the highest carbon footprint and the forecast of its changes. It was demonstrated that gasoline-powered vehicles generate the highest carbon footprint, and this disparity will systematically increase until 2055, posing a significant challenge to achieving the sustainable development goals in the studied region.

The analysis revealed an apparent variation in the carbon footprint across different fuel types and districts within KKBOF. A particularly significant finding was the correlation between the population density of the areas and CO₂ emissions. In more densely populated urban districts, especially in Koszalin City District, the highest growth dynamics of the carbon footprint were observed, with a projected average annual increase in CO₂ emissions from gasoline-powered vehicles reaching 0.64 tons. This value significantly exceeds the emissions generated by diesel-powered vehicles (0.37 tons/year) and LPG-powered vehicles (0.10 tons/year).

An important methodological aspect of the study was the adoption of specific research assumptions, which also represent its limitations. The assumption of constant emission factors throughout the forecast

period and the linear growth in the number of vehicles, while allowing for creating a coherent predictive model, may not fully reflect future technological and regulatory changes.

In reality, dynamic advancements in vehicle technology are expected, which could impact emission levels and potential shifts in the fuel composition of the vehicle fleet, especially in the context of the development of electromobility and other alternative propulsion sources.

The results indicate the necessity of taking decisive action in transport policy, particularly in highly urbanized areas. In the context of achieving the European Green Deal goals and striving for climate neutrality, implementing comprehensive CO₂ emission reduction strategies in the transport sector appears essential. These strategies should consider both technological and behavioral aspects, including promoting more environmentally friendly transportation options and changes in mobility patterns among residents.

The study opens up opportunities for future scientific research directions. Expanding the scope of analysis to include the potential for reducing the carbon footprint through the development of alternative transportation modes, such as electromobility and shared transport, would be particularly valuable. Another important area for further research could be an in-depth analysis of the socio-economic factors influencing the transition toward low-emission solutions, considering residents' willingness to change transportation behaviors and the barriers to such a transition.

Another potential research direction could be a comparative analysis with other functional areas of similar characteristics, which would allow for identifying best practices in carbon footprint reduction in transport. A valuable extension would also include the impact of planned investments in transport infrastructure and changes in local and regional transport policies on the carbon footprint levels in future analyses.

In connection with the research results obtained, it seems reasonable to formulate the following recommendations for the local and regional authorities of KKBOF. Above all, developing and implementing a comprehensive strategy for CO₂ emission reduction in the transport sector is necessary, with particular emphasis on heavily urbanized areas. This strategy should include the development of infrastructure for low-emission vehicles, including electric vehicle charging stations and CNG/LNG gas refueling points.

Local authorities should also consider introducing low-emission zones in city centers, especially in Koszalin and Kolobrzeg, where the emission problem is most severe. Infrastructure and regulatory measures should be accompanied by intensive educational and informational campaigns, increasing residents' awareness of the impact of their transportation choices on the natural environment.

In the long term, it is necessary to strive to create an integrated mobility management system in the region, promoting sustainable mobility (Chamier-Gliszczyński 2012, Chamier-Gliszczyński 2016), considering both residents' transportation needs and environmental goals. Such a system should use modern information technologies to optimize transportation flows and reduce unnecessary car traffic. In terms of spatial planning, adopting the principle of Transit Oriented Development is key, as it will allow for the systematic reduction of residents' dependence on individual transport. It is also important to support the development of bicycle and pedestrian infrastructure as an alternative to short-distance transport.

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