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Simulation of the Progress of the Decarbonization Process in Poland's Road Transport Sector

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Abstract: In the years ahead, the majority of the EU member states will be implementing their energy and climate plans. These plans are aimed at fulfilling obligations related to the strategy for the Sustainable and Smart Mobility Strategy and the "Fit for 55" package. The European Commission has presented highly challenging proposals for the decarbonization of the transport sector through electrification and support for innovation. The decarbonization of transport will not be possible without cooperation and mutual understanding between manufacturers, suppliers, and customers, or without proper organization of the transport process itself. High-emission means of transport must be replaced with low-emission ones. In the EU, road transport generates 70% of all transport emissions. There are few scalable decarbonization opportunities in the transport sector. Various kinds of solutions should be promoted, yet at the same time, it is imperative to analyze the current situation and forecast desirable potential future outcomes. By employing optimization theory tools, specifically the SOLVER add-in—an Excel-based optimization tool—the optimum structure of the stock of road transport vehicles in Poland's commercial road transport sector was searched for. Several research hypotheses were formulated, primarily focusing on the potential for electric vehicles to reduce emissions significantly. These findings suggest a promising outlook for this transition, with particular implications for decision-makers in the field of shaping transport policy. As a result of the conducted analyses and simulations, the hypothesis—that the application of selected elements of optimization theory tools allows us to determine the optimum stock structure of the Polish road transport sector in terms of propulsion system type (emission performance) in the context of pollutant emission targets set for the sector resulting from the EU's climate policy targets, the European Green Deal, and the EU's transport policy in terms of decarbonization, taking into account determinants and constraints included in the analysis—was confirmed. An important finding and result is the statement that, in its current state, the Polish road transport sector is not ready for the challenges related to the new goals of climate policy, the European Green Deal, and EU transport policy in the context of decarbonization.

Keywords: decarbonization; road transport; emission performance; simulation; sustainable transport; EU climate policy; emission reduction

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1. Introduction

Reducing CO_2 emissions is a significant way to solve the problem of global warming, as CO_2 is the main component of greenhouse gases [1,2]. Transport plays an important role in the economy of a given country or region. However, at the same time, it is responsible for the high level of energy consumption due to its functioning. The energy demand of transport systems depends on the transport branch under examination and the type of transported cargo [3,4].

The Paris Agreement was signed by 195 countries at the 21st Conference of the Parties (or "COP21") to the United Nations Framework Convention on Climate Change (UNFCCC) at the end of 2015 [5,6], when 59 countries, accounting for 54% of the global carbon emissions, committed to zero carbon emissions by the middle of this century, including the

European Union, Japan, South Korea, Canada, the United Kingdom, the United States (by 2050), and China (by 2060) [7].

Understanding how carbon emissions have evolved through the urbanization process can help formulate effective countermeasures and, at the same time, ensure the high quality and efficiency of economic development while improving environmental quality [8]. EU climate policy has been consistently internationally leading but insufficient to meet climate targets. The deepening urgency of the climate crisis has led the EU to bolster its climate policy ambitions and toolbox over the last five years [9].

The overwhelming consensus of scientific opinion is that climate change in the form of global warming is real and driven by emissions of greenhouse gases caused by human activity [10–13]. The single most important greenhouse gas (GHG) is carbon dioxide, which is also the single most problematic GHG source, mostly emitted from the production and consumption of fossil fuels. Meanwhile, more than two-thirds of transport-related GHG emissions are from road transport. Therefore, motorized transport emissions have become a significant contributor to the global problem of GHG emissions that lead to climate change [14,15].

This study is an attempt to determine the target structure of the stock of Poland's road transport sector in terms of the type of propulsion system in the EU (and the required rate of replacing old vehicles with new generation vehicles) in relation to the targets set in EU climate policy for the reduction of the pollutant emissions generated by road transport by 2025, 2030, and 2035 using selected elements of optimization theory tools.

The specific problems covered by the study are the challenges related to the decarbonization of the road transport sector in Poland in the current situation.

The simulations performed in order to define the optimum structure of the stock of vehicles in road freight transport in Poland were intended to indicate whether it is possible to determine the optimum structure by means of the SOLVER tool and the GRG method. Even such a simple optimization tool managed to reveal that meeting two assumptions, i.e., staying within the values of investment outlays and meeting CO_2 emission targets, simultaneously in a given time horizon is non-viable. All simulations in the present study imply that if we intend to reach emission targets, we must choose between CO_2 emissions, overall transport performance, and total investment outlays. Consequently, my simulations imply that simultaneously meeting investment outlays and CO_2 emission targets within a given timeframe is unviable. Reaching emission targets requires either a greater financial outlay than expected, a significant reduction in transport performance, or accepting that CO_2 emission targets will not be met.

Commercial road transport (otherwise known as commercial road transport) is understood as transport in which transport services constitute the basic economic activity. This definition results directly from Art. 4 of the Act of 6 September 2001, on road transport. In point 1, it defines domestic road transport as "taking up and performing business activity in the field of transporting people or goods with motor vehicles registered in the country, which also includes vehicle combinations consisting of a motor vehicle and a trailer or semi-trailer, on the territory of the Republic of Poland, provided that the driving of the vehicle, the place of starting or ending the journey, and the road are located on the territory of the Republic of Poland. International transport is defined in a similar way, with the difference that the journey from the starting point to the destination takes place by crossing the border. It is also important in the aforementioned definition that it indicates that commercial transport is carried out with motor vehicles registered in the country.

Taking into account the fact that commercial road transport is an economic activity, entrepreneurs striving to optimize their financial results will choose the optimal types of vehicles, allowing for the transport of the maximum load weight at a time (one of the basic principles of transport technology). In other words, they use dedicated and properly selected vehicles for the transport task. We assume, however, that they do not use vehicles smaller than vehicles with a GVW of 3.5 t.

As a consequence, this study focuses on vehicles classified as trucks (i.e., for transporting goods, not people) in the GVW category up to 3.5 t and over 3.5 t. Vehicles intended for passenger transport have a different structure, which is characterized by a reduced passenger compartment (usually limited to two people) and an enlarged cargo compartment. Therefore, they are not technically adapted to transport people, which is also reflected in their approval and registration documents. However, when using national data sources, you can be sure that they concern vehicles that fall within the definition of commercial road transport in the aforementioned act.

This study aims to explore the feasibility of achieving decarbonization targets in Poland's road transport sector within existing financial constraints using optimization theory tools, as has been done in the rest of the article.

Therefore, Poland's road transport sector is faced with a classic decision dilemma wherein the search for an optimum solution means compromise. In the context of defining the optimal structure of the stock of vehicles in Poland's (commercial) road transport sector, the SOLVER tool successfully performs its task, allowing us to determine the optimum vehicle stock structure in terms of propulsion system types within the set assumptions as well as within the constraint. What is problematic, however, is that it is capable of satisfying only one constraint instead of two. This means that Poland's road transport sector is confronted with a serious challenge. Both previous analyses [16–18] and simulations allow us to conclude that the Polish road transport sector is not prepared for the required energy transformation. What is more, reaching new decarbonization targets also appears impossible at the current financing level.

2. Materials and Methods

The present study employs the SOLVER tool and the GRG non-linear optimization method, a generalization of the RGM (Renormalization Group Method). The GRG (Generalized Reduced Gradient) is an iterative method implemented in SOLVER based on an implementation of the GRG algorithm code proposed by L. Landson and published in 1975. The GRG method enables finding local solutions to models with low convexity.

SOLVER is a Microsoft Excel add-in capable of solving single-criterion optimization tasks with up to 200 variables. SOLVER works with the so-called "objective cell", which can be defined as a formula. This means that we can work with a mathematical model and that the work should begin by entering the model in a worksheet. From the perspective of SOLVER, the model consists of several components. The first is an objective cell (target function)—a cell in the worksheet model that, once the SOLVER is applied, is expected to assume the minimum or maximum value or a value set as a real number. The other is variable cells (decision variables)—cells containing sought values, changed iteratively, and substituted by SOLVER for the target function until the optimum solution is found. The next are constraint cells (which can be used in relation to the values of the objective cell and variable cells)—for entering constraints, a formula in a worksheet cell the value of which must be within specific limits or reach target values.

The estimation of measurement data was done using the MS Excel spreadsheet program and the generalized reduce gradient method offered by the MS SOLVER analysis tool. The SOLVER add-in is capable of analyzing linear, non-linear, integer, and binary optimization problems and is suitable for this type of issue [19–21].

The present article is not aimed at describing optimization methods and models; rather, it presents an application of the above-described tool in a specific situation, i.e., searching for the optimum structure of the stock of vehicles in Poland's commercial road transport sector.

The study makes use of numerical data as well as self-contained documents.

As for numerical data, they were retrieved from a commercial source (SAMAR) and from generally available collections of statistical information: domestic (Central Statistical Office, GUS) and European (EUROSTAT). Due to their form, subject, scope, and high reliability (being a compilation of multiple sources), the data obtained from SAMAR were treated as the basis for statistical analyses.

The information available in the SAMAR database under a subscription offering access to selected sections of periodic reports included data contained in the so-called "Park" database. In practice, the reports contain the following information: number of vehicles, type of propulsion, age, and corresponding data on the structure and changes in the size of each group in comparison to the year preceding.

The advantages of the data source, which were the above reports, certainly include the fact that they were created on the basis of consolidation and analysis of data available in the Central Statistical Office and in CEPiK. According to the information provided by SAMAR, these data are corrected and real data, i.e., taking into account the real state (closest to real) of the vehicle stock in Poland. While preparing its reports, SAMAR eliminated the biggest disadvantage of the data contained in CEPiK: the possibility of a large number of not-updated records—i.e., vehicles appearing in the registers that are not actually in operation. Due to these advantages, the data from these sources was used as is.

Accessed under subscription, SAMAR reports for the years 2010 to 2019 were complete. They were usually available in the form of collective reports and reports for three main categories of vehicles: buses, trucks, and passenger cars.

It was decided that the data accessed from SAMAR should constitute the basis for the present analyses and that the remaining sources should only provide supplementary information.

Numerical data from EUROSTAT largely overlapped with domestic data. In many areas, however, the available data included data previously unpublished by GUS. Thus, EUROSTAT data perfectly complimented information that had already been retrieved and collected. Generally, they were a valuable source of information in the context of cutting CO_2 emissions. In this area, EUROSTAT data were the main and basic source of all data on collective emissions of greenhouse gases and pollutants at the domestic level.

Data from SAMAR as well as industry magazines and reports are embedded in public statistics. SAMAR is a leading non-state automotive market research center in Poland. The value of his studies is mainly related to the scope of the analyses he presents in his reports as well as their embedding in current trends and events occurring on the automotive market in Poland. In terms of data on registration or the condition of the transport fleet, SAMAR relies on CEPiK data (public statistics). Partial data from CEPiK are the basis for some GUS (and then Eurostat) information. Therefore, the primary source of data is the CEPiK databases. The reliability and consistency of the data presented by SAMAR and the Central Statistical Office are thus analogous. These data differ only in the degree of "granulation" or the degree of processing in the course of the analysis (i.e., given dynamics or a more extensively developed structure). The advantage of SAMAR over the Central Statistical Office as a data source is its timeliness—SAMAR prepares its reports more frequently than the Central Statistical Office regarding the state of the vehicle database in the country.

3. Results

Variant B of the simulation assumes an equal share of vehicles in transport performance, determined on the basis of vehicle structure by propulsion type. Electric vehicles are preferred since they are presented as the only "zero-emission" vehicles heavily promoted and supported by manufacturers. Currently, there is less focus on the remaining technologies due to the maturity of the technologies themselves as well as relevant energy carrier stations. As a consequence, in the structure of total emissions determined, the level of emissions attributable to electric vehicles according to mean emissions for 2019 (i.e., the number of vehicles in the structure multiplied by relevant emissions) lowers the total. Meanwhile, vehicles categorized as "alternative" sources belonging to the "other" subgroup are treated as zero-emission vehicles (0 g CO_2).

3.1. Remarks and Assumptions

This study omits the full CO_2 emission cycle approach, which also includes emissions generated in vehicle manufacturing or supplying fuel for these vehicles. The approach would severely complicate not only the calculations themselves but also the model of

the objective function and constitute a significant obstacle to the application of the main method employed in this study, i.e., elements of the optimization theory and the SOLVER tool. Another argument is the disproportionate effort and cost of retrieving the required information and data for performing such calculations.

When determining the objective function, more specifically its linear equation, it is necessary to select the representative unit of the objective. In the present study, units currently used in the measurement of CO_2 emissions, i.e., units of weight, appear to be a natural choice. In the context of the subject of the analysis, a problematic issue is how to relate the units of measure for CO_2 emissions to units expressing the measure of actual road freight transport performance. A natural choice would be to convert CO_2 emissions to the total distance covered by vehicles in the aforementioned group. The problem, however, is the availability of such detailed information.

Available data indicative of transport performed by commercial vehicles as part of haulage globally for a given year can be accessed in official statistics in the form of transport performance expressed in tonne-kilometers (Tkm). The unit is used in the official measurements of transport performance, and its reference to CO_2 emissions does not raise any objections on the part of manufacturers or entrepreneurs in the industry [22]. A similar method for measuring compliance with the required standards is also presented in Article 8 of Regulation (EU) 2019/1242.

In order to add an economic dimension to the simulation, it was also necessary to relate the changes in the structure of vehicles (in terms of the type of propulsion) to economic quantities, which in this study included the cost of marketing new vehicles with a specific type of propulsion. Therefore, it was essential to assume the value required to make the investment. In the present study, it was defined as an initial payment made when financing the lease of commercial vehicles. Having reviewed offers for new commercial vehicles (tractor units) from several lessors, it was found that for the model (generic) vehicle SCANIA 500S, with a purchase price of approx. PLN 600,000, the initial payment amounted to approx. PLN 120,000 [23]. Taking this value as a departure point, initial payments for other types of propulsion were estimated and presented in Table 1 below.

Table 1. Estimated cost of commissioning 1 vehicle with a specific type of propulsion [thousand PLN].

Non-Hybrid Gasoline	**100**	**Bioethanol**	**110**
Hybrid gasoline	140	Electric	180
Non-hybrid diesel	120	LPG	130
Hybrid diesel	140	CNG	130
BIO-diesel	130	LNG	130
		Other	140

Source: own elaboration based on data from SAMAR reports.

Assuming that the value reported for transport performance in 2020 is an effect of the pandemic (−12.2% y/y) and a constant increase starts in 2021 at the annual rate of 4%. Consequently, in 2025, transport performance is reported at 422,169 million Tkm, and in 2030, the value will increase to 513,633 million Tkm, reaching 624,913 million Tkm in 2035 (Table 2).

The above assumptions concerning transport performance in the subsequent years constitute the baseline variant.

Future revenue and profit in the transport sector were estimated on the basis of fixed assumptions with regard to the sector's growth rate. Specifically, it is expected that in 2021–2025, the revenue growth rate will be 2% y/y, in 2026–2031, it will be 4%, and in 2032–2035, it will reach 5%. It was also assumed that in the whole period from 2021–2035, the profitability would amount to 2.5% (see Table 3 below).

Table 2. Estimated transport performance in the commercial road transport sector—baseline variant for the years 2021–2035 [million Tkm].

Year	2019	2020	2021	2022	2023	2024	2025
Transport performance	395,311	346,992	360,872	375,307	390,319	405,932	422,169
Year			2026	2027	2028	2029	2030
Transport performance			439,056	456,618	474,883	493,878	513,633
Year			2031	2032	2033	2034	2035
Transport performance			534,178	555,545	577,767	600,878	624,913

Source: own elaboration based on data from GUS.

Table 3. Forecast transport performance in the commercial road transport sector—baseline variant for the years 2021–2035 [million PLN].

Year	2019	2020	2021	2022	2023	2024	2025
Passengers	10,397	9151	9334	9521	9711	9905	10,103
Goods	133,129	134,136	138,160	142,305	146,574	150,971	155,500
Total	143,526	143,287	147,494	151,825	156,285	160,876	165,603
Aggregated revenue							925,370
Financial result	4376	1980	3687	3796	3907	4022	4140
Profitability	3.0%	1.4%	2.5%	2.5%	2.5%	2.5%	2.5%
Aggregated financial result							25,908
Year			2026	2027	2028	2029	2030
Passengers			10,508	10,928	11,365	11,820	12,292
Goods			160,165	164,970	169,919	175,017	180,267
Total			170,673	175,898	181,284	186,836	192,560
Aggregated revenue							1,832,621
Financial result			4267	4397	4532	4671	4814
Profitability			2.5%	2.5%	2.5%	2.5%	2.5%
Aggregated financial result							48589
Year			2031	2032	2033	2034	2035
Passengers			12,784	13,423	14,094	14,799	15,539
Goods			185,675	191,245	196,983	202,892	208,979
Total			198,459	204,669	211,077	217,691	224,518
Aggregated revenue							2,889,036
Financial result			4961	5117	5277	5442	5613
Profitability			2.5%	2.5%	2.5%	2.5%	2.5%
Aggregated financial result							75,000

Source: own elaboration based on data from GUS.

In 2025, aggregated transport sector revenue will amount to PLN 925,370 million, which, with profitability at 2.5%, means a net financial result of PLN 25,908 million (aggregated amount). This is the maximum amount that the businesses in the sector will be able to allocate to vehicle fleet upgrades, obviously assuming (as in the baseline variant) that they wish to spend their entire profits in this way.

In 2030, aggregated transport sector revenue will be PLN 1,832,621 million, which, with profitability at 2.5%, means a net financial result of PLN 48,589 million (aggregated amount).

In 2035, aggregated transport sector revenue will amount to PLN 2,889,036 million, which, with profitability at 2.5%, means a net financial result of PLN 75,000 million (aggregated amount).

The above calculations constitute the baseline variant, which will be modified in subsequent iterations of the simulation.

3.2. 2025 Horizon

The first simulation for the 2025 horizon was carried out with baseline assumptions and code-named 2025_B. The constraints in the first simulation are outlined in Table 4 below.

Table 4. Constraints and the objective function for simulation 2025_B.

Constraints				Objective Function	
	Type	**Value**	**Unit**		
Total emissions	≤	16,607,813	t CO_2	Total calculated emissions	
Total expenses	≤	25,907,890	thousand PLN	Value	Unit
Transport performance	≤	422,169	million Tkm	16,607,813	t CO_2
Mean transport performance per vehicle		0.099			
Electric vehicles	≥	2590	each		
Non-hybrid gasoline	≤	625,050			
Non-hybrid diesel	≤	2,892,771			

Source: own elaboration based on data from SAMAR reports.

SOLVER fails to find an optimum solution based on the above-listed constraints, i.e., it does not meet the total emission limit (see Table 5 below). With thus defined constraints, SOLVER is unable to determine values using the linear method (LP simplex) or the evolutionary method (which is in line with expectations, as the problem does not have a linear character due to the way in which the intermediate calculations are constructed). Meanwhile, when using the non-linear method (GRG), SOLVER displays a message on failure to satisfy all constraints and generates a structure as shown in the table below (non-compliance with total transport performance assumptions).

Table 5. Structure and remaining values generated in simulation 2025_B.

	2025	**Structure**	**Difference Relative to 2019**	**Total Cost**	**Possible Transport Performance**	**Calculated Emissions**
Non-hybrid gasoline	296,283	14.813%	−328,767	0	29,274	1,902,808
Hybrid gasoline	30	0.000%	0	1	3	133
Non-hybrid diesel	2,525,469	68.415%	−304,302	0	249,526	15,720,153
Hybrid diesel	5	0.000%	−202	0	0	23
BIO-diesel	36	0.001%	5	659	4	143
Bioethanol	3	0.000%	−10	0	0	17
Electric	143,235	3.441%	140,645	25,316,171	14,152	−1,015,498
LPG	8	4.277%	−176,987	0	1	35
CNG	0	0.091%	0	0	0	0
LNG	0	0.070%	0	0	0	0
Other	370,499	8.892%	4222	591,059	36,607	0
TOTAL	3,335,568		−665,396	25,907,890	329,567	16,607,813

Source: own elaboration based on data from SAMAR reports.

In this simulation variant, a total of 1,475,664 vehicles were decommissioned, mainly gasoline and diesel vehicles, along with nearly all gas-fueled ones. At the same time, 144,872 vehicles, mostly electric ones, were placed in service.

The above-described solution is not entirely satisfactory due to its failure to meet all constraints simultaneously. Therefore, it seems justified to leave out one of the constraints, i.e., the constraint concerning the total cost of the proposed changes in structure.

By modifying constraints so as to enable SOLVER to minimize total emissions, we also receive a message on failure to meet all constraints at the same time. This prompted the author to abandon the constraint imposed on the amount of investment outlays. Accordingly, we arrive at simulation 2025_B_E, which maintains the CO_2 emission level (see Table 6 below) and transport performance constraints (requiring at least the assumed level to be met).

Table 6. Constraints and the objective function for simulation 2025_B_E.

Constraints				Objective Function	
	Type	**Value**	**Unit**		
Total emissions	≤	16,607,813	t CO_2	Total calculated emissions	
Transport performance	≥	422,169	million Tkm	Value	Unit
Mean transport performance per vehicle		0.099		16,607,813	t CO_2
Electric vehicles	≥	2590	each		
Non-hybrid gasoline	≤	625,050			
Non-hybrid diesel	≤	2,892,771			

Source: own elaboration based on data from SAMAR reports.

The use of the non-linear method (GRG) allows SOLVER to find the optimum solution while complying with all of the above constraints. The generated structure is presented in Table 7 below.

Table 7. Structure and remaining values generated in simulation 2025_B_E.

	2025	**Structure**	**Difference Relative to 2019**	**Total Cost**	**Possible Transport Performance**	**Calculated Emissions**
Non-hybrid gasoline	553,093	12.851%	−71,957	0	54,648	3,552,107
Hybrid gasoline	0	0.000%	−30	0	0	0
Non-hybrid diesel	2,576,048	59.852%	−253,723	0	254,524	16,034,993
Hybrid diesel	0	0.000%	−207	0	0	0
BIO-diesel	0	0.000%	−31	0	0	0
Bioethanol	0	0.000%	−13	0	0	0
Electric	585,954	13.614%	583,364	105,005,516	57,895	−3,219,513
LPG	56,543	1.314%	−120,452	0	5587	240,226
CNG	0	0.000%	0	0	0	0
LNG	0	0.000%	0	0	0	0
Other	532,356	12.369%	166,079	23,251,121	52,599	0
TOTAL	4,303,995		303,031	128,256,637	425,252	16,607,813

Source: own elaboration based on data from SAMAR reports.

In this simulation variant, a total of 446,413 vehicles were decommissioned, mainly vehicles with diesel and gasoline engines, as well as a substantial number (120,452) of gas-fueled ones. At the same time, the stock of vehicles was expanded by 1,052,474 vehicles, mostly electric ones. In total, the number of vehicles increased by 303,031.

Simulation 2025_B_N involves making slight modifications to the previous variant by leaving out the possible transport performance constraint in favor of the constraint related to investment outlays. This means constraints, as presented in Table 8 below.

Table 8. Constraints and the objective function for simulation 2025_B_N.

Constraints				Objective Function	
	Type	**Value**	**Unit**		
Total emissions	≤	16,607,813	t CO_2	Total calculated emissions	
Total expenses	≤	25,907,890	thousand PLN	Value	Unit
Mean transport performance per vehicle		0.099		16,607,813	t CO_2
Electric vehicles	≥	2590	each		
Non-hybrid gasoline	≤	625,050			
Non-hybrid diesel	≤	2,892,771			

Source: own elaboration based on data from SAMAR reports.

The use of the non-linear method (GRG) allows SOLVER to find the optimum solution while complying with all of the above constraints. The generated structure is presented in Table 9 below.

Table 9. Structure and remaining values generated in simulation 2025_B_N.

	2025	**Structure**	**Difference Relative to 2019**	**Total Cost**	**Possible Transport Performance**	**Calculated Emissions**
Non-hybrid gaosline	305,960	9.222%	−319,090	0	30,230	1,964,955
Hybrid gasoline	0	0.000%	−30	0	0	0
Non-hybrid diesel	2,520,178	75.959%	−309,593	0	249,004	15,687,223
Hybrid diesel	0	0.000%	−207	0	0	0
BIO-diesel	0	0.000%	−31	0	0	0
Bioethanol	0	0.000%	−13	0	0	0
Electric	146,523	4.416%	143,933	25,907,890	14,477	−1,044,366
LPG	0	0.000%	−176,995	0	0	0
CNG	0	0.000%	0	0	0	0
LNG	0	0.000%	0	0	0	0
Other	345,144	10.403%	−21,133	0	34,102	0
TOTAL	3,317,805		−683,159	25,907,890	327,812	16,607,813

Source: own elaboration based on data from SAMAR reports.

In this simulation variant, a total of 827,092 gasoline and diesel vehicles were decommissioned, along with all gas-fueled vehicles. At the same time, 143,933 vehicles, mostly electric ones, were placed in service. In total, the number of vehicles increased by 683,159.

3.3. 2030 Horizon

The first simulation for the 2030 horizon was carried out with baseline assumptions and code-named 2030_B. The constraints in the first simulation were outlined in the table below. SOLVER fails to find an optimum solution based on the above-listed constraints, thus failing to stay within the total emission limit (see Table 10 below).

Table 10. Constraints and the objective function for simulation 2030_B.

Constraints				Objective Function	
	Type	**Value**	**Unit**		
Total emissions	≤	11,071,876	t CO_2	Total calculated emissions	
Total expenses	≤	48,589,150	thousand PLN	Value	Unit
Transport performance	≤	513,633	million Tkm	11,071,876	t CO_2
Mean transport performance per vehicle		0.099			
Electric vehicles	≥	2590	each		
Non-hybrid gasoline	≤	625,050			
Non-hybrid diesel	≤	2,892,771			

Source: own elaboration based on data from SAMAR reports.

With the constraints formulated above, when using the non-linear method (GRG), SOLVER displays a message on failure to satisfy all constraints and generates a structure as shown in Table 11 below (non-compliance with total transport performance assumptions).

Table 11. Structure and remaining values generated in simulation 2030_B.

	2030	**Structure**	**Difference Relative to 2019**	**Total Cost**	**Possible Transport Performance**	**Calculated Emissions**
Non-hybrid gasoline	0	0.000%	−625,050	0	0	0
Hybrid gasoline	23	0.001%	−7	0	2	102
Non-hybrid diesel	2,219,359	77.647%	−610,412	0	219,281	13,814,730
Hybrid diesel	17	0.001%	−190	0	2	82
BIO-diesel	29	0.001%	−2	0	3	116
Bioethanol	10	0.000%	−3	0	1	56
Electric	272,530	9.535%	269,940	48,589,150	26,927	−2,743,319
LPG	26	0.001%	−176,969	0	3	109
CNG	0	0.000%	0	0	0	0
LNG	0	0.000%	0	0	0	0
Other	366,273	12.815%	−4	0	36,189	0
TOTAL	2,858,267		−1,142,697	48,589,150	282,408	11,071,876

Source: own elaboration based on data from SAMAR reports.

In this simulation variant, a total of 1,412,637 vehicles were decommissioned: all gasoline vehicles and parts of diesel vehicles, along with nearly all gas-fueled vehicles. At the same time, 269,940 vehicles, mostly electric ones, were placed in service. Still, the above-described solution is not entirely satisfactory due to its failure to meet all constraints simultaneously. Therefore, it seems justified to leave out one of the constraints—i.e., the constraint concerning the total cost of the proposed changes in structure.

By leaving out the investment outlay constraint, we obtain simulation 2030_B_E, which maintains the CO_2 emission level (see Table 12 below) and transport performance constraints (requiring at least the assumed level to be met).

Table 12. Constraints and the objective function for simulation 2030_B_E.

Constraints				Objective Function	
	Type	**Value**	**Unit**		
Total emissions	=	11,071,876	t CO_2	Total calculated emissions	
Transport performance	≥	513,633	million Tkm	Value	Unit
Mean transport performance per vehicle		0.099		11,071,876	t CO_2
Electric vehicles	≥	2590	each		
Non-hybrid gasoline	≤	625,050			
Non-hybrid diesel	≤	2,892,771			

Source: own elaboration based on data from SAMAR reports.

The use of the non-linear method (GRG) allows SOLVER to find the (locally) optimum solution while complying with all of the above constraints. The generated structure is presented in Table 13 below.

Table 13. Structure and remaining values generated in simulation 2030_B_E.

	2030	**Structure**	**Difference Relative to 2019**	**Total Cost**	**Possible Transport Performance**	**Calculated Emissions**
Non-hybrid gasoline	625,050	11.744%	0	0	61,757	4,014,231
Hybrid gasoline	0	0.000%	−30	0	0	0
Non-hybrid diesel	2,429,234	45.644%	−400,537	0	240,018	15,121,129
Hybrid diesel	0	0.000%	−207	0	0	0
BIO-diesel	0	0.000%	−31	0	0	0
Bioethanol	0	0.000%	−13	0	0	0
Electric	1,491,568	28.026%	1,488,978	268,016,086	147,373	−8,063,484
LPG	0	0.000%	−176,995	0	0	0
CNG	0	0.000%	0	0	0	0
LNG	0	0.000%	0	0	0	0
Other	776,278	14.586%	410,001	57,400,181	76,699	0
TOTAL	625,050		1,321,167	325,416,266	525,847	11,071,876

Source: own elaboration based on data from SAMAR reports.

In this simulation variant, a total of 577,813 vehicles, mainly diesel and nearly all gas-fueled ones, were decommissioned. Meanwhile, the stock of vehicles was expanded by 1,898,980 electric vehicles. Overall, the number of vehicles increased by 1,321,167.

Simulation 2030_B_N involves making modifications to the previous variant by abandoning the possible transport performance constraint in favor of the investment outlays constraint. This means constraints, as presented in Table 14 below.

Table 14. Constraints and the objective function for simulation 2030_B_N.

Constraints				Objective Function	
	Type	**Value**	**Unit**		
Total emissions	=	11,071,876	t CO_2	Total calculated emissions	
Total expenses	≤	48,589,150	thousand PLN	Value	Unit
Mean transport performance per vehicle		0.099		11,071,876	t CO_2
Electric vehicles	≥	2590	each		
Non-hybrid gasoline	≤	625,050			
Non-hybrid diesel	≤	2,892,771			

Source: own elaboration based on data from SAMAR reports.

The use of the non-linear method (GRG) allows SOLVER to find the optimum solution while complying with all of the above constraints. The generated structure is presented in Table 15 below.

Table 15. Structure and remaining values generated in simulation 2030_B_N.

	2030	Structure	Difference Relative to 2019	Total Cost	Possible Transport Performance	Calculated Emissions
Non-hybrid gasoline	530	0.019%	−624,520	0	52	3404
Hybrid gasoline	0	0.000%	−30	0	0	0
Non-hybrid diesel	2,223,431	78.592%	−606,340	0	219,684	13,840,076
Hybrid diesel	0	0.000%	−207	0	0	0
BIO-diesel	0	0.000%	−31	0	0	0
Bioethanol	0	0.000%	−13	0	0	0
Electric	272,530	9.633%	269,940	48,589,150	26,927	−2,771,603
LPG	0	0.000%	−176,995	0	0	0
CNG	0	0.000%	0	0	0	0
LNG	0	0.000%	0	0	0	0
Other	332,607	11.757%	−33,670	0	32,863	0
TOTAL	2,829,098		−1,171,866	48,589,150	279,526	11,071,876

Source: own elaboration based on data from SAMAR reports.

In this simulation variant, a total of 1,441,806 vehicles were decommissioned, mainly gasoline and diesel vehicles along with all gas-fueled ones. At the same time, 269,940 vehicles, mostly electric ones, were placed in service. The total number of vehicles rose by 1,171,866.

3.4. 2035 Horizon

The first simulation for the 2035 horizon was carried out with baseline assumptions and code-named 2035_B. The constraints in the first simulation were as shown in the table below. SOLVER fails to find an optimum solution based on the above-listed constraints, thus failing to comply with the total emission limit (see Table 16 below).

Table 16. Constraints and the objective function for simulation 2035_B.

Constraints				Objective Function	
	Type	Value	Unit		
Total emissions	≤	7,750,313	t CO_2	Total calculated emissions	
Total expenses	≤	74,999,521	thousand PLN	Value	Unit
Transport performance	≤	624,913	million Tkm	7,750,313	t CO_2
Mean transport performance per vehicle		0.099			
Electric vehicles	≥	2590	each		
Non-hybrid gasoline	≤	625,050			
Non-hybrid diesel	≤	2,892,771			

Source: own elaboration based on data from SAMAR reports.

With the constraints formulated above, when using the non-linear method (GRG), the tool displays a message on failure to satisfy all constraints and generates a structure as shown in Table 17 below (non-compliance with total transport performance assumptions).

Table 17. Structure and remaining values generated in simulation 2035_B.

	2035	Structure	Difference Relative to 2019	Total Cost	Possible Transport Performance	Calculated Emissions
Non-hybrid gasoline	134,299	4.096%	−490,751	0	13,269	862,504
Hybrid gasoline	12	0.000%	−18	0	1	53
Non-hybrid diesel	2,359,117	71.946%	−470,654	0	233,090	14,684,672
Hybrid diesel	17	0.001%	−190	0	2	82
BIO-diesel	18	0.001%	−13	0	2	73
Bioethanol	15	0.000%	2	177	1	79
Electric	419,248	12.786%	416,658	74,998,417	41,423	−4,475,666
LPG	18	0.001%	−176,977	0	2	78
CNG	0	0.000%	0	0	0	0
LNG	0	0.000%	0	0	0	0
Other	366,284	11.170%	7	927	36,190	0
TOTAL	3,279,028		−721,936	74,999,521	323,981	11,071,876

Source: own elaboration based on data from SAMAR reports.

In this simulation variant, a total of 1,138,603 vehicles were decommissioned, mainly gasoline and diesel vehicles along with nearly all gas-fueled ones. Meanwhile, 416,666 vehicles, mostly electric ones, were placed in service. Still, the solution is not entirely satisfactory due to its failure to meet all constraints simultaneously. Therefore, it seems justified to leave out one of the constraints—one concerning the total cost of the proposed changes in structure.

In order to modify the constraints, the condition concerning the amount of investment outlays was ignored. Accordingly, we arrive at simulation 2035_B_E, which maintains the CO_2 emission level (see Table 18 below) and transport performance constraints (requiring at least the assumed level to be met).

Table 18. Constraints and the objective function for simulation 2035_B_E.

Constraints				Objective Function	
	Type	Value	Unit		
Total emissions	≤	7,750,313	t CO_2	Total calculated emissions	
Transport performance	≥	624,913	million Tkm	Value	Unit
Mean transport performance per vehicle		0.099		7,750,313	t CO_2
Electric vehicles	≥	2590	each		
Non-hybrid gasoline	≤	625,050			
Non-hybrid diesel	≤	2,892,771			

Source: own elaboration based on data from SAMAR reports.

The use of the non-linear method (GRG) allows SOLVER to find the optimum solution while complying with all of the above constraints. The generated structure is presented in Table 19 below.

In this simulation variant, a total of 604,677 vehicles were decommissioned, mainly diesel and gasoline vehicles as well as some LPG-fueled vehicles. At the same time, the stock of vehicles was expanded by 2,963,703 vehicles, mostly electric ones. Overall, the number of vehicles increased by 2,359,026.

Table 19. Structure and remaining values generated in simulation 2035_B_E.

	2035	Structure	Difference Relative to 2019	Total Cost	Possible Transport Performance	Calculated Emissions
Non-hybrid gasoline	363,602	5.717%	−261,448	0	35,925	2,335,144
Hybrid gasoline	149,021	2.343%	148,991	20,858,777	14,724	662,575
Non-hybrid diesel	2,521,770	39.651%	−308,001	0	249,161	15,697,129
Hybrid diesel	130,993	2.060%	130,786	18,310,076	12,943	647,132
BIO-diesel	130,887	2.058%	130,856	17,011,230	12,932	517,285
Bioethanol	131,047	2.060%	131,034	14,413,694	12,948	712,136
Electric	2,040,281	32.080%	2,037,691	366,784,400	201,588	−11,229,629
LPG	141,767	2.229%	−35,228	0	14,007	602,307
CNG	128,206	2.016%	128,206	16,666,844	12,667	544,694
LNG	137,247	2.158%	137,247	17,842,096	13,561	583,103
Other	485,169	7.628%	118,892	16,644,915	47,937	0
TOTAL	6,359,990		2,359,026	488,532,033	628,392	11,071,876

Source: own elaboration based on data from SAMAR reports.

Simulation 2035_B_N involves making slight modifications to the previous variant by leaving out the possible transport performance constraint in favor of the constraint related to investment outlays. This means constraints, as presented in Table 20 below.

Table 20. Constraints and the objective function for simulation 2035_B_N.

Constraints				Objective Function	
	Type	Value	Unit		
Total emissions	≤	7,750,313	t CO_2	Total calculated emissions	
Total expenses	≤	74,999,521	thousand PLN	Value	Unit
Mean transport performance per vehicle		0.099		7,750,313	t CO_2
Electric vehicles	≥	2590	each		
Non-hybrid gasoline	≤	625,050			
Non-hybrid diesel	≤	2,892,771			

Source: own elaboration based on data from SAMAR reports.

The use of the non-linear method (GRG) allows SOLVER to find the optimum solution while complying with all of the above constraints. The generated structure is presented in Table 21 below.

Table 21. Structure and remaining values generated in simulation 2035_B_N.

	2035	Structure	Difference Relative to 2019	Total Cost	Possible Transport Performance	Calculated Emissions
Non-hybrid gasoline	140,207	4.310%	−484,843	0	13,853	900,445
Hybrid gasoline	0	0.000%	−30	0	0	0
Non-hybrid diesel	2,358,870	72.516%	−470,901	0	233,066	14,683,136
Hybrid diesel	0	0.000%	−207	0	0	0
BIO-diesel	0	0.000%	−31	0	0	0
Bioethanol	0	0.000%	−13	0	0	0
Electric	419,254	12.889%	416,664	74,999,521	41,424	−4,511,704

Table 21. *Cont.*

	2035	Structure	Difference Relative to 2019	Total Cost	Possible Transport Performance	Calculated Emissions
LPG	0	0.000%	−176,995	0	0	0
CNG	0	0.000%	0	0	0	0
LNG	0	0.000%	0	0	0	0
Other	334,552	10.285%	−31,725	0	33,055	0
TOTAL	3,252,883		−748,081	74,999,521	321,398	11,071,876

Source: own elaboration based on data from SAMAR reports.

In this simulation variant, a total of 1,164,745 vehicles were decommissioned, mainly gasoline and diesel ones, along with all gas-fueled vehicles. At the same time, 416,664 vehicles, mostly electric ones, were placed in service. In total, the number of vehicles increased by 748,081.

4. Discussion

4.1. Model 2025

Simulation 2025_B shows that meeting emission standards using the assumed investment outlays is not possible with the assumed transport performance level. Satisfying the emission standard with the assumed investment outlays means that possible transport performance could be decreased below the assumed level (by 21.9%).

Simulation 2025_B_E shows that meeting emission standards and the assumed possible transport performance level (0.07% above the assumption) would require investment outlays 495% in excess of the original assumptions.

Simulation 2025_B_N demonstrates that satisfying both emission standards and the assumed investment outlays would allow building a stock of vehicles capable of ensuring transport performance at a level of 78% of the expected value (22% below the assumption).

4.2. Model 2030

Simulation 2030_B also shows that meeting emission standards using the assumed investment outlays is non-viable at the assumed transport performance level. Satisfying the emission standard with the assumed investment outlays means that possible transport performance could be brought down below the assumed level (by 45%).

In Simulation 2030_B_E, we also see that meeting emission standards and the assumed possible transport performance level (1.6% above the assumption) would require investment outlays 687.9% in excess of the initial assumptions.

Simulation 2030_B_N demonstrates that satisfying both emission standards and the assumed investment outlays would allow building a stock of vehicles capable of ensuring transport performance at a level of 54.4% of the expected value (45.6% below the assumption).

4.3. Model 2035

Simulation 2035_B shows that meeting emission standards with the assumed investment outlays is impossible at the assumed transport performance level. Satisfying the emission standard at the assumed investment outlays means that possible transport performance could be decreased below the assumed level (by 48.2%).

Simulation 2035_B_E shows that meeting emission standards and the assumed possible transport performance level (0.6% above the assumption) would require investment outlays exceeding the original assumptions by 651.4%.

Simulation 2035_B_N demonstrates that satisfying emission standards as well as the assumed investment outlays would allow building a stock of vehicles capable of ensuring transport performance at a level of 51.4% of the expected value (48.6% below the assumption).

5. Conclusions

Many researchers used the MS Excel Solver computer program to calculate the model and perform the simulation, solving it as a non-linear programming optimization task [24–27]. The optimization models that are built are implemented in Microsoft Excel's module "Solver" in order to process the calculations [28–30]. The task of optimizing non-linear programming is the basis for developing correct conclusions that provide many practical implications in the decision-making process [31,32].

The assumed goals of the study were achieved, as a result of which the main findings were developed. One of the scenarios that awaits the Polish road transport sector in the near future. Firstly, charging penalties for failure to meet the CO_2 emission targets burdens the financial results of transport companies even more, limiting their ability to modernize their fleet. Secondly, the limitation of the possible transport performance means a decrease in the share in the EU transport market, a decrease in revenues, and a decrease in the scale of operations. At the same time, the oldest means of transport are gradually being phased out and replaced with new, zero-emission ones. Thirdly, relying on external financial mechanisms to support the transformation and modernization of the fleet of vehicles.

The use of the GRG method underlying the SOLVER tool in the context of this study is directly related to the considerations carried out in it. One of the objectives of the study is an attempt to determine the target structure of the rolling stock of the Polish transport sector in terms of the type of drive in connection with the objectives of reducing emissions of pollutants generated by road transport resulting from the EU climate policy. In this context, a local solution according to the GRG method will be a structure of drives for the Polish transport fleet so as to achieve emission goals. The problem, however, is the need to take constraints into account. Constraint conditions place limits on the changes that the GRG algorithm can make to the drive structure. The use of the SOLVER tool will therefore allow for taking these limitations into account when striving for the GRG algorithm to optimize one of the parameters, the total emission. It is the total emissions of the rolling stock that are directly related to the pollution reduction target of the EU policy guidelines.

In all perspectives (horizons), series B allowed us to reach a fairly balanced structure in the simulations. Nevertheless, a key problem is that staying within all three constraints is impossible, as demonstrated by the message displayed by SOLVER. B-series simulations are therefore inferior to B_N-series simulations, where the constraint imposed was the amount of investment outlays. Accordingly, B-series simulations are provided for informational purposes only.

The application of the SOLVER tool and the non-linear method (GRG) enabled us to determine the optimal structure in terms of propulsion types, albeit within only one of all relevant constraints. Hence, the tool is suitable only for relatively simple optimization problems. Although its usefulness is limited, it can be used in hypothetical considerations. As a tool, SOLVER does not permit the user to carry out any form of forecasting. In the above-described application, its reliance on a number of assumptions is its main shortcoming. Consequently, simulations involving a time horizon of more than 5 years are tainted by significant error resulting from the (in)correctness of such assumptions. SOLVER may be used as part of an auxiliary procedure in the process of optimizing structures built on the basis of advanced results, complex environmental factor prediction models, and constraints.

The adopted limiting conditions could not be fully met. Thus, the simulation was not completely successful (half of the assumptions). As a consequence, variants of this model were created: the B_N model (abandonment of the limiting condition—possible transport performance) and the B_E model (abandonment of the limiting condition—maximum amount of investment outlays).

As a consequence, the B_E model variant is a model that ignores the determined level of profits of the entire transport sector (which determines the level of investments in rolling stock that can be covered). The B_E model suggests that capital expenditure is not a constraint, so it implicitly assumes the existence of strong and readily available support for

companies in the sector to invest in vehicle replacement. It also assumes that the rolling stock will allow for a certain level of transport performance.

On the other hand, the B_N model ignores the assumption regarding the transport performance possible while retaining the investment outlays as a limiting condition. Thus, it shows what the transport performance (possible to perform) should look like with specific investment outlays for the replacement of rolling stock while maintaining the target emission sums.

Transport performance is an important element of all simulations, as it reflects the potential of the Polish transport sector, i.e., real transport capacity. As shown by the differences in the simulation results of the B_N and B_E models, this one differs significantly depending on the adopted constraints.

In the context of defining the optimum structure of the stock of vehicles in Poland's (commercial) transport sector, the SOLVER tool successfully performs its task, allowing the author to determine the optimum vehicle stock structure by propulsion system type within set assumptions as well as within the constraint.

Pollutants emitted by road vehicles, from the point of view of many legal regulations, are understood as CO_2 emissions and/or nitrogen oxides (NOx). In this study, air pollution is understood as the main source of CO_2 emissions. CO_2 emissions are the main element of the EU's climate goals. On the other hand, when emission standards for combustion vehicles are mentioned—EURO standards—both CO_2 and NOx emissions are understood (which are precisely specified in the given standard). In practice, it should be remembered that pollutant emissions related to the operation of combustion vehicles on public roads include not only CO_2 and NOx emissions (which were previously regulated by EURO standards), but also dust emissions from brake pads or tires. Negotiations and discussions regarding EURO 7, which may also cover pollution in the form of particulate matter from, among others, tire operations, are still underway. The simplification used in this study (equating "pollutants" with "CO_2 emissions") results from the very purpose of the development.

An analysis of all simulations allowed the author to draw some important conclusions.

Achieving CO_2 emission targets for Poland's transport sector within all of the analyzed time horizons (2025, 2030, and 2035) requires financial outlays in amounts higher than might potentially be available. Transport companies that want to satisfy the estimated demand for transport performance may be unable to incur the cost of the investment even with the aid of leasing. Thus, they would have to be supported by other financial sources, preferably with the least negative effect on their financial results.

Meeting CO_2 emission targets for Poland's road transport sector is possible in each of the analyzed time horizons, albeit it requires substantial investment outlays or a reduction in transport performance capabilities.

In all successful simulations, an attempt to determine the optimum structure anticipated the elimination of a considerable number of diesel and gasoline vehicles in favor of electric ones. The calculation model on which the simulations were based, like the mechanisms governing setting emission standards for vehicle manufacturers, favors electric vehicles.

In all simulations, LPG-fueled vehicles were partly or totally eliminated (they were only present in the structure for 2019). This is due to a number of factors. First, it is a consequence of the assumed pattern of CO_2 emissions for CO_2 emission calculation purposes for the optimized structure. The pattern foresaw that emissions generated by such vehicles would be higher than for biodiesel and similar to hybrid diesel vehicles. Therefore, they would not constitute the best alternative to other types of propulsion. Another question is the way in which the constraints were formulated—more specifically, the absence of constraints with regard to the reduction of the number of vehicles featuring this particular type of propulsion. This results from the approach in which the fastest path to pollutant reduction is sought, with intermediate solutions being far less desirable.

Vehicles defined as "other" in the CO_2 emission categories generated 0 g CO_2/km. As regards optimization mechanisms, they would not be beneficial enough, as reflected by

their relatively minor change in terms of the share in the structure of all propulsion systems in the stock of vehicles in all versions of the simulation.

The best and most effective path to meeting CO_2 emission targets involves upgrading to electric vehicles or increasing the overall proportion of zero-emission vehicles.

In accordance with the simulations, financial resources are the key constraint and obstacle to achieving CO_2 emission targets within all time horizons. Simulations and analyses were considered in isolation from many environmental factors, including the availability of electric vehicles with desirable parameters within the assumed price range.

This study is of great importance in the context of further planned and implemented actions under Poland's climate policy. Institutions responsible for decisions in this area, on the basis of such analyses as this one, should make necessary adjustments to already developed plans to make them realistic and achievable. The article is not exhaustive, but it is a good start. Comparative analyses between different countries on the progress of decarbonization in road transport or attempts to construct simulation models using other, more advanced tools such as Matlab/Simulink [33–37] would be worth considering. It therefore seems necessary to continue research as part of subsequent research projects because such in-depth analyses will allow for confirmation or refutation of the theses presented in this article and possibly improve the tools used.

The limitation of SOLVER in this application is related to the reliance on a number of assumptions that result from the very construction of the simulations carried out. The GRG algorithm (and therefore the SOLVER) require a clear formulation of constraints in the form of one value (for each condition). The aim of the research conducted was not to forecast all the elements that make up the values determining the above-mentioned limiting conditions. Thus, they were established "ad hoc" based on an analysis of the current state. This means that these assumptions over a horizon longer than 5 years are themselves subject to a high risk of error. Thus, the model results themselves "inherit" this error. It is worth emphasizing, however, that each forecasting method is associated with a certain level of acceptable error and a degree of variability in the forecasted values. In the present case, the aim was not to make such detailed forecasts. Thus, when interpreting the results, it should be remembered that this is only a simulation and not a forecast. This means that the results of the simulations cannot be the basis for making decisions. However, they can be the basis for formulating conclusions and assumptions about the possible directions of future development. More importantly, in the context of the purpose of the study, they can be the basis for verifying the formulated hypotheses because they do not refer to forecasting future states of the environment. They only focus on identifying the current state and future challenges. Thus, it is possible to formulate assessments of the current situation and further perspectives when the current environmental conditions do not change. To a large extent, they are an introduction and an invitation to discuss current problems and directions for future actions in the context of the drive structure of the fleet of vehicles in the transport sector in Poland and in the context of the objectives of the EU climate policy.

Undoubtedly, the obtained results and conclusions formulated on the basis of the conducted analyses are an introduction to the discussion on the direction and method of action in order to achieve the goals of the new EU policy in the field of reducing the emissions of the domestic transport sector. The simulations carried out show the scale of the problem, giving an overview of the type and nature of the challenges faced by the Polish transport sector. At present, there is a lack of specific information that would allow for alternative ways of approaching the problem. On the one hand, the technology related to the "clean" or "cleaner" alternative drive to the currently used internal combustion engines is still developing. There are ideas of synthetic fuels or the conversion of internal combustion engines to hydrogen fuels. On the other hand, the political discussion is still going on, and alternative technologies are an element of it; which of them will be considered "green" is still unknown. This directly determines the cost of the entire transformation. It is also not known how the plans related to the modernization of infrastructure, which are crucial in the context of electric cars, will be implemented in practice. The method of

implementing these largest investments (e.g., the construction of new factories) remains a question mark.

It seems, therefore, that the next step should be a two-track study—technological, economic, and legal. These groups of factors will determine both the conditions in which the transformation will take place and its dynamics. Future analyses should therefore include an analysis of the current state of technology in the field of alternative means of propulsion for motor vehicles, together with calculations and forecasts regarding the costs of implementing such technologies. In addition, the direction, plans, and financing of the modernization of road infrastructure need to be analyzed. Another important aspect will be the analysis of current executive regulations related to the implementation of climate policy objectives. At the moment, all these elements are still in a highly undetermined state, which makes their study difficult. The implementation of the above research will allow us to take up the challenge of trying to forecast individual elements of the environment in which the transformation will take place.

Stabilization of the legal and technological environment will allow the use of more complex forecasting methods and tools. Conditions will also be created for creating new scenarios for the development of events in accordance with, for example, selected technological paths. It is also possible that, thanks to the combination of the above-mentioned methods and optimization methods, it will be possible to determine the effective mix of these paths.

This simulation study is an invitation to discuss the transformation of the structure of the main resources of the Polish transport sector in the context of the challenges of the coming years and decades. The method used in the study is one of many research tools that can be used in this field of research. The GRG method and the SOLVER tool take a relatively narrow approach to the issue. The simulations carried out show this quite vividly. However, it is a useful tool in the context of the conducted considerations. However, everything indicates that when conducting research in a more in-depth way, using only the optimization approach may be insufficient. Future researchers are therefore faced with the challenge of selecting additional tools and exploring alternative research paths to the ones presented in the study. This is due to the very essence of the subject of the study. The applied method will therefore be used in future research, but the procedure itself needs to be supplemented with earlier steps in the context of a broader assessment of the future states of key environmental factors.

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