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EVALUATION OF THE EFFECTIVENESS OF INTEGRATING ELECTRIC VEHICLES INTO FLEET OPERATIONS

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Abstract:

This article presents an approach to decision-making for the implementation of electric passenger cars in enterprise fleets, considering both economic and environmental factors. The literature review is focused on fleet composition and the impacts of technological change. The paper examines practical aspects of introducing alternatively powered vehicles into corporate fleets and proposes a model for optimal fleet composition. The final section provides a case study on the adoption of electric vehicles (BEV, HEV) in selected fleets in Poland. The conclusion highlights key opportunities and constraints associated with integrating electric vehicles into fleet operations. The model proposed in the article incorporates Total Cost Ownership (TCO) of fleet and environmental criteria, as well as various forms of vehicle financing and the resulting limitations on vehicle mileage and duration of use, together with budget constraints and the discounting of cash flows over time. Importantly, vehicle depreciation and several other parameters are treated as nonlinear functions of multiple variables. As the research presented in the paper demonstrates, the introduction of electric vehicles into fleets is currently unprofitable in Poland, particularly for short-term use in company car fleets. The persistently higher purchase prices of such vehicles compared with internal combustion vehicles of a similar standard, combined with their substantially higher depreciation during the initial period of use, are not offset by lower operating costs. Electric vehicles gain an advantage only when environmental objectives are assigned a sufficiently high weighting. At the same time, over sufficiently long operating periods, the economic performance of electric vehicles may prove more favourable, although there remains considerable market uncertainty concerning price formation and the residual values of these vehicles.

Keywords: *low-emission vehicles, fleet management, fleet composition problem, environmental pollution, modelling, fleet electrification*

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1. Introduction

The rapid development of new low-emission vehicle propulsions is a key factor in shaping future transport solutions in both urban and non-urban areas, especially given the significant environmental impact of transport (Jacyna et al., 2021) – especially since it is one of the most effective instruments for internalising the external costs of transport (Wasiak et al., 2020). Strategic documents increasingly highlight the need to restrict the use of high-emission engines and to introduce mechanisms that encourage the uptake of low-emission powertrains, including electric ones (EV). Current plans announced by manufacturers also indicate substantial changes in the production share of low-emission vehicles, including all-electric (BEV[1]), hydrogen (FCEV[2]) and hybrid (HEV[1], PHEV[1]) vehicles. These trends are reflected in corporate fleets as well as in the private vehicle market, although the pace of change is considerably faster in company fleets for understandable reasons. Some companies that place strong emphasis on corporate social responsibility are becoming early adopters of electric vehicles. Their experience, particularly in the context of unstable economic and fiscal conditions, shows that the implementation of low-emission vehicles is a highly complex process that entails various risks.

From the perspective of introducing alternatively powered vehicles into fleets, it is essential to conduct a multifaceted assessment of their suitability for the intended purpose, as well as to evaluate the impact of these solutions on a company's economic performance and, ultimately, on the achievement of its environmental goals. With this in mind, the aim of this article is to discuss the practical aspects of implementing electric vehicles (EV) in corporate fleets and to present a formalized approach to decision-making related to their adoption.

This article presents the current state of knowledge on methods that support decision-making related to vehicle fleet composition, with particular emphasis on approaches that account for technological change, including alternative propulsion vehicles. It then discusses the practical aspects of implementing such vehicles in company fleets, drawing on the author's own experience. The paper also introduces a unique, formal approach to the decision-making process for enterprise fleet composition that includes vehicles with different propulsion systems and demonstrates its application to decisions regarding the adoption of all-electric and hybrid vehicles. The discussion of the results highlights the opportunities and challenges associated with integrating electric vehicles into corporate fleets.

2. Passenger car fleet composition: state of knowledge

Fleet composition primarily involves activities related to selecting vehicles that enable the execution of specific tasks at the required level and, of course, at the lowest possible cost. The increasingly common challenge of introducing alternatively powered vehicles into fleets is therefore one of the key elements of fleet composition. Given the wide range of options for acquiring and financing fleet vehicles, the issue of fleet composition is closely connected with decisions regarding vehicle financing methods and their operational lifetimes. It is also closely related to the assignment of vehicles to tasks. As a result, the decision-making process concerning fleet composition requires answers to the following questions:

- Which vehicles should be added to the fleet?
- Which vehicle financing methods should be selected?
- When should vehicles be introduced into the fleet and when should they be retired?
- Which vehicles should be assigned to specific tasks?

One of the first approaches to the fleet composition problem was Kirby's (1959) proposal of a homogeneous fleet composition model that considered the possibility of renting vehicles in the event of shortages in the company's own fleet. Similarly, the homogeneous fleet composition model proposed in (Ghiani et al., 2004) allowed for a shortage of vehicles, resulting in the need to rent them and eliminating the fixed costs associated with owning these vehicles, which was particularly relevant in the case of seasonal transport tasks. Loxton, Lin and Teo (2012), in addition to allowing for the rental of additional vehicles, also considered the uncertainty of tasks expected to be assigned to the fleet. The literature also includes

[1] US Department of Energy, Alternative Fuels Data Center. Electric Vehicles. Office of Energy Efficiency and Renewable Energy, Available online: https://afdc.energy.gov/vehicles/electric.
[2] US Department of Energy, Alternative Fuels Data Center. Hydrogen. Office of Energy Efficiency and Renewable Energy, Available online: https://afdc.energy.gov/fuels/hydrogen.

numerous models that combine the problems of fleet composition and transport routing, for example (Mardaneh et al., 2016).

As previously discussed, the fleet composition problem is closely related to the Fleet Replacement Problem (FRP). This problem involves determining a vehicle replacement plan that minimizes the total cost of owning and operating the fleet within a specified planning horizon. In practice, decisions in this area often result from internal company policies and adopted service standards such as vehicle age or mileage thresholds. Importantly, many vehicle replacement models assume that previously used vehicles are replaced with new vehicles of identical parameters (see, for example, (Enogwe et al., 2025), (Evans, 1989), (Malo et al., 2025)), which is rarely feasible in practice due to ongoing technological developments. For this reason, models that more accurately reflect real-world conditions have been proposed, allowing for the optimization of replacement plans that include the introduction of technically new vehicle types. Such models can therefore be applied to decision-making processes involving the introduction of EVs or other alternative propulsion systems into fleets.

Homogeneous vehicle replacement models developed with consideration for various conditions, including technological change, the interdependence between vehicle replacement decisions and their allocation to tasks, as well as different replacement policies and their proofs, have been described, among others, in (Bean et al., 1994; Hartman, 2001; Hartman and Murphy, 2006). Homogeneous vehicle replacement models have frequently been analysed as dynamic models that incorporate random variables, for example (Hartman, 2001).

The FRP problem applied to a heterogeneous vehicle fleet is referred to as the Parallel Fleet Replacement Problem (PFRP). The solution to the PFRP is a vehicle replacement schedule that achieves the optimal value resulting from the sum of capital expenditures for acquiring new vehicles, capital gains from retiring existing vehicles, and the change in the operating costs of new vehicles compared with existing ones (Parthanadee et al., 2012). Heterogeneous vehicle replacement models are characterized by the fact that decisions regarding the replacement of vehicles, including identical ones, are made individually rather than, as in homogeneous models, for predefined groups of vehicles, for example (Hartman (2020, 2004), Hartman and Ban (2002)).

The PFRP problem, which incorporates practical rules for vehicle replacement, user preferences, and the practice of replacing existing vehicles with Natural Gas Vehicles[3] (LPG or CNG), was formulated in (Parthanadee et al., 2012) as a linear integer programming problem. The findings presented in that study indicate that:

– purchasing new vehicles is not always the most economical option; in some cases, it may be more cost-effective to acquire used vehicles with relatively low mileage and age,
– replacing the oldest vehicles first, selecting homogeneous purchases in each period, and selling vehicles of the same age simultaneously are not necessarily optimal strategies, although they may appear cost-efficient,
– adopting an all-or-nothing strategy can be advantageous.

The problem of replacing a heterogeneous vehicle fleet under lower and upper budget constraints was described, among others, by Redmer (2016). He proposed optimizing vehicle replacement intervals by considering the discounted financial impact of these decisions. In addition, the problem of planning vehicle replacements under budget constraints was examined by, among others, Chand et al. (2000) and Keles and Hartman (2004). These studies also took into account the benefits arising from cumulative vehicle replacements. Ansaripoor and Oliveira (2018) presented research on the replacement of alternatively fuelled vehicles, incorporating flexible rental options and uncertainty in the economic environment, including prices, vehicle mileage and technological progress.

Vehicle replacement models also consider the possibility of introducing both new and used vehicles into a fleet (Parthanadee et al., 2012; Redmer, 2022). In case of alternatively powered vehicles, decisions related to charging infrastructure are also taken into account. For example, Bakker et al. (2025) proposed a model for optimising decisions concerning the purchase and salvaging of electric trucks, incorporating investments in charging infrastructure at depots as

[3] International Energy Agency. The Contribution of Natural Gas Vehicles to Sustainable Transport. 2010. Available online: https://www.iea.org/reports/the-contribution-of-natural-gas-vehicles-to-sustainable-transport

well as the use of public fast chargers for long-distance transport.

Many other models addressing random factors have also been described in the literature. Uncertainty in demand and fuel prices was incorporated into the vehicle replacement model proposed by Zheng and Chen (2018). Dynamic fleet replacement planning under task uncertainty was examined, among others, by Gkochari (2015) and Jeon and Yeo (2017). Stochastic and simulation models of vehicle replacement planning have also been developed, incorporating variables such as CO_2 emission costs, fuel prices, vehicle mileage and fuel consumption as random factors, for example (Ansaripoor et al., 2014). Furthermore, the literature includes fleet replacement models that account for vehicle failure rates, for example (Rust, 1987).

Models for replacing vehicles and other fixed assets that account for technological developments, including the introduction of alternative fuel vehicles, have also been examined by Bean et al. (1994), Büyüktahtakın and Hartman (2016), Hritonenko and Yatsenko (2012), Jinxing et al. (2024), Kleindorfer et al. (2012) and Wang et al. (2013), among others. These studies note that technological changes can both accelerate vehicle replacement and delay it, particularly when more advanced solutions are expected to become available on the market in the near future.

In addition to widely used single-criteria approaches to vehicle fleet composition, the literature includes several multi-criteria approaches that can be applied to this problem, such as the MAJA method (Jacyna, 2022), ELECTRE (Roy and Bouyssau, 1993) and the point-based method (Jacyna and Wasiak, 2015). Multi-criteria decision support methods applied to equipment replacement have also been discussed by González et al. (2005), Hartman (2004) and Sarache Castro et al. (2009).

In both single-criteria and multi-criteria approaches, vehicle operating costs, defined in various ways, play a key role. It is worth noting that fleet composition models described in the literature are mostly based on fixed and variable operating costs. A recent development in this area is the inclusion of the Total Cost of Ownership (TCO) and the discounting of costs. According to the definition by Gartner Inc. (Ellram, 2002), the Total Cost of Ownership represents the total cost of acquiring, installing, using, maintaining and ultimately disposing of an asset within a company over a specified period. In the case of a fleet vehicle, this includes all costs associated with its purchase and operation from its entry into service to its retirement. The issue of TCO has been widely discussed in the literature, including by Ellram (2002), Malo et al. (2025), Mazur and Wasiak (2018) and Noorbakhsh et al. (2019) , as well as in studies on alternatively powered vehicles (Jinxing et al. 2024; Palmer et al., 2018). The literature also contains numerous studies on the impact of fleet electrification on environmental pollution, both for individual vehicles (Zamasz et al., 2021) and public transport (Jinxing et al. 2024; Ribeiro and Mendes, 2022; Tang et al., 2021), as well as for municipal fleets (Bieda et al., 2023). These models often incorporate constraints related to allowable emission levels in subsequent periods.

Despite the extensive literature on various approaches to vehicle fleet composition, there is no model that simultaneously incorporates decisions on introducing and retiring vehicles different from those currently in use, selecting vehicle financing methods, and allocating vehicles to tasks, while also accounting for functional relationships that reflect the Total Cost of Ownership. The model proposed in (Mazur, 2023) addressed this gap for a Rent-a-Car company. This paper, however, proposes a reduction in computational complexity and a generalization of that model so it can be applied to the fleets of other types of companies.

3. Practical aspects of implementing alternative drive vehicles into passenger car fleets

With their rapid development, increasing market penetration and growing environmental relevance, alternative fuel vehicles are becoming increasingly popular. Given the fast pace at which these vehicles are being introduced to the market, numerous questions arise regarding their implementation in passenger car fleets. Key issues include the availability of charging infrastructure for EVs and the amount of electricity required for fleet operation. As the automotive industry continues to innovate and enhance vehicle technologies, the balance between profitability and financial benefits for end users is beginning to shift.

The introduction of alternative fuel vehicles into passenger car fleets represents an important step toward sustainable transport and requires a holistic approach that considers technical, economic, social and environmental factors. It is closely linked to a variety of practical challenges, including charging infrastructure and fleet management, as well as the environmental awareness and engagement of vehicle users, all of which play a critical role in the success of such initiatives.

Key aspects in the decision-making process for implementing alternatively powered vehicles into a fleet include:

1. Analysing the availability of various propulsion technologies on the market and selecting those that best meet the fleet's requirements.
2. Assessing the availability of technical solutions, such as charging infrastructure, including the possibility of charging vehicles at the workplace, the potential to conclude agreements with public charging station operators, the accessibility of alternative fuel refuelling points, and the feasibility of developing in-house charging infrastructure.
3. Evaluating purchase costs, Total Cost of Ownership, tax incentives and subsidies available for alternatively powered vehicles compared with conventional combustion vehicles.
4. Training users in the operation and effective use of alternatively powered vehicles and associated technologies.
5. Using monitoring software that enables tracking energy consumption, monitoring vehicle condition and scheduling regular maintenance.
6. Applying route planning software that considers the availability of charging stations or alternative refuelling points to avoid range limitations, reduce costs and energy consumption, improve business travel efficiency and vehicle performance, and enhance environmental benefits and financial savings.
7. Introducing incentive programs for users, such as awards for energy savings and competitions promoting environmentally friendly driving behaviour.
8. Implementing integrated solutions, including intelligent transportation systems, that can improve fleet efficiency, reduce environmental impact and support the monitoring and analysis of fuel savings and operating costs to assess return on investment.
9. Conducting awareness campaigns for vehicle users about the environmental impact of alternatively powered fleets, as part of the company's sustainable fleet strategy.
10. Ensuring familiarity with local and national regulations regarding alternatively powered vehicles to prevent legal issues.
11. Developing a long-term plan for the implementation of alternatively powered vehicles that accounts for technological advancements, changes in availability and infrastructure development, in order to adapt the fleet to future needs and opportunities.

In this context, a key aspect of implementing alternative fuel vehicles in fleets is securing acceptance from the end users of these vehicles. This applies both to corporate fleets and to companies offering rental services. It is therefore essential to identify the needs and preferences of vehicle users and, when necessary, to take steps to shape these preferences in line with company policy.

Another important issue is the analysis of market opportunities and the company's internal capabilities for ensuring the required driving ranges of alternative fuel vehicles. It is crucial to identify available alternative fuel stations and electric vehicle charging locations, as well as to assess the company's capacity to develop its own alternative fuel or electric charging infrastructure. It is also worth considering the feasibility of refuelling or charging vehicles at users' homes or at other regular destinations.

When considering the introduction of alternatively powered vehicles into a fleet, it is essential to assess the impact this decision will have on business costs. A thorough analysis of the Total Cost of Ownership should be carried out, taking into account access to charging and refuelling infrastructure, as well as all costs related to vehicle operation, financing and purchase. Legislative incentives for users of alternatively powered vehicles are also important, such as higher spending limits for vehicles whose depreciation can be included in operating costs or subsidies for the purchase of such vehicles. In Poland, for instance, if a subsidy was obtained under the "Mój Elektryk" (My Electric-one) program (applications closed on January 31, 2025), the monthly financing payment taking into account the residual value proposed by the financing provider could be the same as or even lower than for a comparable conventionally powered vehicle.

It is also worth noting that in short-term rental companies, EVs are typically classified in a higher revenue category due to their higher purchase price. As a result, these vehicles can generate higher daily rental rates, which translates into greater profitability for this segment.

4. Passenger car fleet composition model

4.1. Assumptions and general form of the model

The model proposed in this article, unlike the one described in (Mazur, 2023), addresses situations in which the selection of specific vehicle models to meet known demand has already been determined. Assuming that this demand can be met with vehicles possessing specific functional characteristics, the fleet composition decision problem is simplified to decisions concerning the following:

- Which vehicle models should be introduced into the fleet within each demand category?
- Which financing methods should be selected for each vehicle?
- How long should each vehicle be operated within the fleet?

Because this model does not account for decisions regarding vehicle releases at subsequent points in time, nor for vehicle occupancy or breakdowns within these time units, the planning unit can be set to one month. It is also worth noting that although the proposed model is heterogeneous, a homogeneous group of vehicles can always be represented as a single vehicle, provided that all vehicles in the group operate under similar conditions and that decisions concerning their purchase and resale are made collectively. This approach significantly reduces the computational complexity of the problem, particularly for fleets consisting of several hundred vehicles or more.

In constructing the model, it was assumed that the company's need categories and the corresponding vehicle demand volumes within these $\mathbf{ZP}$ categories were known, as were the $\mathbf{SP}$ vehicle models that met the requirements identified for each category. It was also assumed that the available vehicle financing methods and their $\mathbf{MF}$ characteristics were known, and that specific principles for $\mathbf{DW}$ fleet composition had been adopted, expressed through a set of constraints and decision-making criteria. Importantly, decisions regarding fleet composition refer to a defined planning period ($\boldsymbol{T}$) and to a specific organizational unit with particular $\boldsymbol{CP}$ characteristics. In this approach, the passenger car fleet composition model can be formally expressed as follows:

$$\mathbf{MKFS} = \langle \boldsymbol{T}, \boldsymbol{CP}, \mathbf{MF}, \mathbf{SP}, \mathbf{ZP}, \mathbf{DW} \rangle$$

4.2. Model parameters

Due to the nature of the problem and the structure of the decision-making model, the parameters it contains relate to the planning period, company characteristics, identified tasks, and the vehicles and financing methods used. The general model parameters and company characteristics include: the set $\boldsymbol{T}$ of unit numbers for the planning period ($\boldsymbol{T} = \{1, 2, \dots, t, \dots T\}$), the fleet budget $B(t)$ in each unit (PLN), and the required fleet utilization factor U^{min}. The company characteristics $\boldsymbol{CP}$ incorporated into the model include: the binary parameter $wo(t)$, which is equal to 1 when the cost of tire replacement and storage is incurred in unit t, the cost of in-house fleet management $KZ(wf)$ as a function of the fleet size wf (PLN per month), and the annual cost of equity kw (% per year). It was assumed that other company characteristics affecting the values of the model parameters are accounted for directly during their identification.

The $\mathbf{MF}$ vehicle financing methods were incorporated into the model by defining a set $\boldsymbol{M}$ of financing method[4] numbers ($\boldsymbol{M} = \{1, \dots, m, \dots M\}$) and specifying, for each method, the following parameters: the obtained discount R_m (percent of the vehicle value), the financing period N_m (months), the initial payment O_m (percent of the vehicle value), the monthly payment r_m (percent of the vehicle value), the vehicle buyout amount RV_m (percent of the vehicle value), and the binary parameter Wd_m, which is equal to 1 when the vehicle is bought back after the financing period. The interest portion of the monthly payment $o_m(tf) \equiv o_{m,tf}(N_m, O_m, r_m, RV_m)$ in month tf of the financing period was also included (percent of the vehicle value), as well as the cost of external financing $kd_m \equiv kd_m(N_m, O_m, r_m, RV_m)$ (percent per year), total mileage limit P_m (km per financing period) specified in the contract, the parameter αu_m, interpreted as the reduction in vehicle insurance costs associated with financing through a given method and equal to 1 when the financing includes an insurance service, the parameter αs_m, interpreted as the reduction in inspection and mechanical repair costs associated with a given financing method and equal to 1 when financing includes inspection and

[4] There are at least 18 forms of vehicle financing available on the Polish market, including operational leasing with an initial payment and low residual value, loans with an initial payment and high buyout, and medium-term rental. Moreover, when considering any specific financing option, it is always necessary to negotiate or determine its detailed parameters.

mechanical repair services, the binary parameter αo_m, interpreted as the reduction in tire replacement and servicing costs when the financing includes such services, the binary parameter αz_m, equal to 1 when financing is combined with fleet management services, and the parameter αn_m, interpreted as the reduction in bodywork and paintwork repair costs when the vehicle is financed using a specific method.

According to the previous assumptions, the demand for **ZP** vehicles is described by a set $\boldsymbol{W}$ of need categories for vehicle users[5] ($\boldsymbol{W} = \{1, \dots, w, \dots W\}$), the required number of vehicles $V_w(t)$ (units), and the average vehicle mileage $P_w(t)$ (km) identified for these categories and for each unit t of the planning period. **SP** vehicles were represented by defining: a set $\boldsymbol{V}$ of their identifiers ($\boldsymbol{V} = \{1, \dots, v, \dots V\}$), a set $\boldsymbol{VO}$ of identifiers of currently used vehicles, a set $\boldsymbol{VP}$ of identifiers of vehicles that may be introduced into the fleet, and for each vehicle: a set $\boldsymbol{W}(v)$ of need categories that it can satisfy, the current period of use DT_v (months), the current mileage DL_v (km), the net list price wk_v (PLN), the net price of additional equipment wd_v (PLN), the set $\boldsymbol{M}_v$ of available financing methods, the forecast residual value $RV_v(ST_v(t), SL_v(t))$ as a function of cumulative age $ST_v(t)$ and mileage $SL_v(t)$ (PLN), the registration cost $Kr_v(m)$ as a function of the financing method m (PLN), the average costs of mechanical repairs, technical inspections and check-ups $Km_v(ST_v(t), SL_v(t))$ as a function of cumulative age $ST_v(t)$ and mileage $SL_v(t)$ (PLN), the mileage limit between subsequent mechanical repairs and inspections Lg_v (km), the net price of a set of tires Co_v (PLN), the mileage limit between subsequent tire replacements Lo_v (km), the cost of tire replacement and storage Ko_v (PLN per replacement), the average monthly cost of bodywork and paintwork repairs not covered by AC insurance Kb_v (PLN/month), the annual insurance cost $Ku_v(ST_v(t), SL_v(t), m)$ as a function of cumulative age $ST_v(t)$, mileage $SL_v(t)$ and financing method m (PLN/year), the annual cost of the insurance purchased immediately before the analysis period Kuo_v (PLN/year), the net price of fuel or propulsion energy cp_v (PLN/l or PLN/kWh), the average specific fuel or energy consumption zp_v (l/km or kWh/km), the average cost of consumables Kip_v (PLN/km), the expected costs of remarketing and preparation for resale $Krm_v(T_v)$ as a function of useful life T_v (PLN), the average specific CO_2 emission ec_v (g/km), and the average specific energy consumption ze_v (kJ/km).

4.3. Problem statement

The model includes the following binary decision variables: $x_v(t)$, which equals 1 when vehicle v is to be introduced into the fleet in unit $t$of the planning period, $x_{v,m}$, which equals 1 when vehicle v is to be financed using method m, $y_v(t)$, which equals 1 when vehicle v is to be withdrawn from the fleet in unit t, $z_v(t)$, which equals 1 when vehicle v is to be operated in the fleet in unit t, and $z_{v,w}(t)$, which equals 1 when vehicle v is to be assigned to need category w in unit t.

To simplify the formal notation, the following auxiliary variables related to vehicles were also included: the period of operation in the fleet T_v (months), the vehicle age $ST_v(t)$ at unit t of the planning period (months), the mileage accumulated in the fleet L_v (km), the mileage $L_v(t)$ in unit $t$of the planning period (km), the cumulative mileage $SL_v(t)$ up to unit t (km), and the vehicle value adjusted for the financing method WP_v (PLN), as well as the following auxiliary variables related to units $t$of the planning period were included: the cost of vehicle registration $RE(t)$ (PLN), the costs of servicing, tire maintenance and bodywork or paintwork repairs not covered by third-party liability insurance $SO(t)$ (PLN), the cost of vehicle insurance $UK(t)$ (PLN), the costs of fuel or energy consumption and operating fluids $PE(t)$ (PLN), the cost of remarketing and resale $RM(t)$ (PLN), fleet management costs $ZF(t)$ (PLN), depreciation-related cash flows $UW(t)$ (PLN), vehicle financing costs $KF(t)$ (PLN), and the Total Cost of Ownership (owning and operating) the fleet $TCO(t)$ (PLN).

The following constraints relate to: task execution (1), the feasibility of performing tasks based on vehicle availability (2), mileage limits (3), limitations on the period of vehicle use resulting from the chosen financing method (4) and (5), the condition of the fleet at the beginning of the analysis period (6) and (7), changes in fleet status in subsequent periods

[5] Need categories can be defined by considering the minimum requirements of vehicle users regarding the vehicle class and specific parameters, such as the number of seats.

(8) and (9), the periods of vehicle operation (10), vehicle age in subsequent units of the planning period (11) and (12), vehicle mileage in individual units of the planning period (13), cumulative mileage (14) and (15), total mileage over the entire operating period in the fleet (16), the selection of financing methods (17), the vehicle value after discount for each financing method (18), compliance with the required fleet utilization level (19), and budget constraints (20).

Auxiliary conditions were also formalized to account for the costs of vehicle registration (21) and (22), servicing, bodywork and paintwork repairs, and tire-related expenses not covered by comprehensive insurance (23), motor insurance (24)-(26), consumption of operating fluids and fuel or energy (27), remarketing and preparation of vehicles for resale (28), the cost of maintaining the vehicle management system (29), vehicle depreciation (30)-(32), and vehicle financing (33).

$$\forall t\in \boldsymbol{T}\ \ \forall w\in \boldsymbol{W}\quad \sum_{v\in \boldsymbol{V}:w\in \boldsymbol{W}(v)} z_{v,w}(t)=V_w(t) \tag{1}$$

$$\forall t\in \boldsymbol{T}\ \ \forall v\in \boldsymbol{V}\ \ \sum_{w\in \boldsymbol{W}} z_{v,w}(t)\le z_v(t) \tag{2}$$

$$\forall v\in \boldsymbol{V}\ \ \forall t\in \boldsymbol{T}: ST_v(t)\le \sum_{m\in \boldsymbol{M}_v} x_{v,m}\cdot N_m \quad z_v(t)\cdot SL_v(t)\le \sum_{m\in \boldsymbol{M}_v} x_{v,m}\cdot P_m \tag{3}$$

$$\forall v\in \boldsymbol{V}\quad T_v\ge \left(\sum_{m\in \boldsymbol{M}_v} x_{v,m}\cdot N_m - DT_v\right)\cdot (1-z_v(T)) \tag{4}$$

$$\forall v\in \boldsymbol{V}\ \ \forall t\in \boldsymbol{T}\quad \sum_{m\in \boldsymbol{M}_v} x_{v,m}\cdot N_m \ge z_v(t)\cdot ST_v(t)\cdot \left(1-\sum_{m\in \boldsymbol{M}_v} x_{v,m}\cdot Wd_m\right) \tag{5}$$

$$\forall v\in \boldsymbol{VO}\ \ z_v(0)=1 \tag{6}$$

$$\forall v\in \boldsymbol{VP}\ \ z_v(0)=0 \tag{7}$$

$$\forall v\in \boldsymbol{V}\ \ z_v(1)=z_v(0)+x_v(1) \tag{8}$$

$$\forall t\in \boldsymbol{T}\ \{1\}\ \forall v\in \boldsymbol{V}\ \ z_v(t)=z_v(t-1)+x_v(t)-y_v(t) \tag{9}$$

$$\forall v\in \boldsymbol{V}\ \ T_v=DT_v+\max\left\{T\cdot z_v(T);\sum_{t\in \boldsymbol{T}} t\cdot y_v(t)\right\}-\sum_{t\in \boldsymbol{T}}(t-1)\cdot x_v(t) \tag{10}$$

$$\forall v\in \boldsymbol{V}\ \ ST_v(0)=DT_v \tag{11}$$

$$\forall v\in \boldsymbol{V}\ \ \forall t\in \boldsymbol{T}\ \ ST_v(t)=(DT_v+t)\cdot z_v(t)-\sum_{t'=1}^{t}(t'-1)\cdot x_v(t') \tag{12}$$

$$\forall v\in \boldsymbol{V}\ \ \forall t\in \boldsymbol{T}\ \ L_v(t)=\sum_{w\in \boldsymbol{W}} P_w(t)\cdot z_{v,w}(t) \tag{13}$$

$$\forall v\in \boldsymbol{V}\ \ SL_v(0)=DL_v \tag{14}$$

$$\forall v \in \boldsymbol{V} \ \forall t \in \boldsymbol{T} \ SL_v(t) = DL_v + \sum_{t'=1}^{t} L_v(t') \tag{15}$$

$$\forall v \in \boldsymbol{V} \ L_v = DL_v + \sum_{t \in \boldsymbol{T}} L_v(t) \tag{16}$$

$$\forall v \in \boldsymbol{V} \ \sum_{m \in \boldsymbol{M}_v} x_{v,m} = 1 \tag{17}$$

$$\forall v \in \boldsymbol{V} \ WP_v = (wk_v + wd_v) \cdot \left(1 - \sum_{m \in \boldsymbol{M}_v} x_{v,m} \cdot R_m\right) \tag{18}$$

$$\frac{\sum_{t \in \boldsymbol{T}} \sum_{w \in \boldsymbol{W}} \sum_{v \in \boldsymbol{V}} z_{v,w}(t)}{\sum_{t \in \boldsymbol{T}} \sum_{v \in \boldsymbol{V}} z_v(t)} \geq U^{min} \tag{19}$$

$$\begin{gathered}\forall t \in \boldsymbol{T} \backslash \{\mathrm{T}\} \ B(t) \geq \sum_{v \in \boldsymbol{V}} \sum_{m \in \boldsymbol{M}_v : ST_v(t)=1} x_{v,m} \cdot O_m \cdot WP_v + \sum_{v \in \boldsymbol{V}} z_v(t) \cdot \sum_{m \in \boldsymbol{M}_v : ST_v(t) \leq N_m} x_{v,m} \cdot r_m \cdot WP_v \\ + \sum_{v \in \boldsymbol{V}} \sum_{m \in \boldsymbol{M}_v : ST_v(t)=N_m} x_{v,m} \cdot Wd_m \cdot RV_m \cdot WP_v - \sum_{v \in \boldsymbol{V}} RV_v\big(ST_v(t), SL_v(t)\big) \cdot y_v(t) + RE(t-1) + SO(t) \\ + UK(t-1) + PE(t) + RM(t) + ZF(t)\end{gathered} \tag{20}$$

$$\forall t \in \{0\} \cup \boldsymbol{T} \backslash \{T\} \ RE(t) = \sum_{v \in \boldsymbol{V}} x_v(t+1) \cdot \sum_{m \in \boldsymbol{M}_v} x_{v,m} \cdot Kr_v(m) \tag{21}$$

$$RE(T) = 0 \tag{22}$$

$$\begin{gathered}\forall t \in \boldsymbol{T} \ SO(t) = \sum_{v \in \boldsymbol{V}} Km_v\big(ST_v(t), SL_v(t)\big) \cdot \left[\left\lfloor \frac{SL_v(t)}{Lg_v} \right\rfloor - \left\lfloor \frac{SL_v(t-1)}{Lg_v} \right\rfloor\right] \cdot \sum_{m \in \boldsymbol{M}_v} x_{v,m} \cdot (1 - \alpha s_m) \\ + \sum_{v \in \boldsymbol{V}} \left[Ko_v \cdot wo(t) + Co_v \cdot \left[\left\lfloor \frac{SL_v(t)}{Lo_v} \right\rfloor - \left\lfloor \frac{SL_v(t-1)}{Lo_v} \right\rfloor\right]\right] \cdot \sum_{m \in \boldsymbol{M}_v} x_{v,m} \cdot (1 - \alpha o_m) \\ + \sum_{v \in \boldsymbol{V}} Kb_v \cdot z_v(t) \cdot \sum_{m \in \boldsymbol{M}_v} x_{v,m} \cdot (1 - \alpha n_m)\end{gathered} \tag{23}$$

$$UK(0) = \sum_{v \in \boldsymbol{V} : \frac{ST_v(1)-1}{12} = \left\lfloor \frac{ST_v(1)-1}{12} \right\rfloor} \sum_{m \in \boldsymbol{M}_v} Ku_v(ST_v(0), SL_v(0), m) \cdot x_{v,m} \cdot (1 - \alpha u_m) \tag{24}$$

$$\begin{gathered}\forall t \in \boldsymbol{T} \backslash \{\mathrm{T}\} \ UK(t) = \sum_{v \in \boldsymbol{V} : \frac{ST_v(t+1)-1}{12} = \left\lfloor \frac{ST_v(t+1)-1}{12} \right\rfloor} \sum_{m \in \boldsymbol{M}_v} Ku_v(ST_v(t), SL_v(t), m) \cdot x_{v,m} \cdot (1 - \alpha u_m) \\ - \sum_{v \in \boldsymbol{V} : t < 12 \cdot \varphi} y_v(t) \cdot [1 - \varphi] \cdot Kuo_v - \sum_{v \in \boldsymbol{V} : t > 12 \cdot \varphi \ \wedge \ \frac{ST_v(t)}{12} \neq \left\lfloor \frac{ST_v(t)}{12} \right\rfloor} y_v(t) \cdot [1 - \varphi] \\ \cdot \textstyle\sum_{m \in \boldsymbol{M}_v} Ku_v(ST_v(t - \varphi \cdot 12), SL_v(t - \varphi \cdot 12), m) \cdot x_{v,m} \cdot (1 - \alpha u_m); \ \text{where:} \ \varphi = \frac{ST_v(t)}{12} - \left\lfloor \frac{ST_v(t)}{12} \right\rfloor\end{gathered} \tag{25}$$

$$UK(T) = -\sum_{v\in\boldsymbol{V}:T<12\cdot\varphi1} y_v(T)\cdot[1-\varphi1]\cdot Kuo_v - \sum_{v\in\boldsymbol{V}:T>12\cdot\varphi1 \wedge \frac{ST_v(T)}{12}\neq\left\lfloor\frac{ST_v(T)}{12}\right\rfloor} y_v(T)\cdot[1-\varphi1] \cdot \sum_{m\in\boldsymbol{M}_v} Ku_v(ST_v(T-\varphi1\cdot 12), SL_v(T-\varphi1\cdot 12), m)\cdot x_{v,m}\cdot(1-\alpha u_m);\ \text{where: } \varphi1 = \frac{ST_v(T)}{12} - \left\lfloor\frac{ST_v(T)}{12}\right\rfloor \tag{26}$$

$$\forall t\in\boldsymbol{T}\ \ PE(t) = \sum_{v\in\boldsymbol{V}} (cp_v\cdot zp_v + Kip_v)\cdot L_v(t) \tag{27}$$

$$\forall t\in\boldsymbol{T}\ \ RM(t) = \sum_{v\in\boldsymbol{V}} y_v(t)\cdot \sum_{m\in\boldsymbol{M}_v} x_{v,m}\cdot Wd_m\cdot Krm_v(T_v) \tag{28}$$

$$\forall t\in\boldsymbol{T}\ \ ZF(t) = KZ\left(\sum_{v\in\boldsymbol{V}}\left[z_v(t)\cdot\left(1-\sum_{m\in\boldsymbol{M}_v} x_{v,m}\cdot\alpha z_m\right)\right]\right) \tag{29}$$

$$UW(0) = \sum_{v\in\boldsymbol{VO}} (WP_v - RV_v(DT_v, DL_v)) + \sum_{v\in\boldsymbol{V}} WP_v\cdot x_v(1) \tag{30}$$

$$\forall t\in\boldsymbol{T}\setminus\{T\}\ \ UW(t) = \sum_{v\in\boldsymbol{V}} (WP_v\cdot x_v(t+1) - RV_v(ST_v(t), SL_v(t))\cdot y_v(t)) \tag{31}$$

$$UW(T) = \sum_{v\in\boldsymbol{V}} (RV_v(ST_v(T), SL_v(T))\cdot z_v(T)) + \sum_{v\in\boldsymbol{V}} (z_v(T) - y_v(T))\cdot \sum_{m\in\boldsymbol{M}_v} x_{v,m}\cdot Wd_m\cdot Krm_v(T_v) \tag{32}$$

$$\forall t\in\boldsymbol{T}\ \ KF(t) = \sum_{v\in\boldsymbol{V}} z_v(t)\cdot WP_v \sum_{m\in\boldsymbol{M}_v:ST_v(t)\leq N_m} x_{v,m}\cdot o_m(ST_v(t)) \tag{33}$$

Finally, restrictions on the type of decision variables (34)-(38) were taken into account.

$$\forall t\in\boldsymbol{T}\ \ \forall v\in\boldsymbol{V}\ \ \forall w\in\boldsymbol{W}\ \ z_{v,w}(t)\in\{0,1\} \tag{34}$$

$$\forall t\in\boldsymbol{T}\ \ \forall v\in\boldsymbol{V}\ \ x_v(t)\in\{0,1\} \tag{35}$$

$$\forall t\in\boldsymbol{T}\ \ \forall v\in\boldsymbol{V}\ \ y_v(t)\in\{0,1\} \tag{36}$$

$$\forall t\in\boldsymbol{T}\ \ \forall v\in\boldsymbol{V}\ \ z_v(t)\in\{0,1\} \tag{37}$$

$$\forall v\in\boldsymbol{V}\ \ \forall m\in\boldsymbol{M}_v\ \ x_{v,m}\in\{0,1\} \tag{38}$$

Given the simplified approach to mapping vehicle demand, the economic decision-making criteria include the undiscounted or discounted Total Cost of Ownership the vehicles in the fleet, while the environmental criteria include total CO_2 emissions and total energy consumption. In accordance with the previously introduced formalism, the costs $TCO(t)$ in period t resulting from owning and operating the fleet are expressed as follows:

$$\forall t\in\boldsymbol{T}\ TCO(t) = UW(t) + KF(t) + RE(t) + SO(t) + UK(t) + PE(t) + RM(t) + ZF(t) \tag{39}$$

The criterion of the undiscounted Total Cost of Ownership a vehicle fleet is defined as follows:

$$TCO = \sum_{t=0}^{T} TCO(t) \longrightarrow \min \tag{40}$$

In the case of the discounted cost criterion, the key issue is to take into account the weighted average cost of capital $WAC(t)$. This cost is a function of the cost of equity and the cost of debt, which depends on the financing methods considered, as well as the capital structure, which is formally expressed as follows:

$$\forall t \in \boldsymbol{T}\ WAC(t) = \left(1 - \frac{KO(t)}{CK(t)}\right) \cdot \frac{kw}{12} + \frac{KO(t)}{CK(t)} \cdot \frac{ko(t)}{12} \cdot (1 - CIT) \quad (41)$$

The parameter CIT in relation (41) represents the corporate income tax rate, which is equal to 19%, while the parameters defining the total capital $CK(t)$, the total external capital $KO(t)$ at the beginning of the period, and the cost of external capital $ko(t)$ for individual months of the analysis period are determined as (42), (43), (44).

$$\forall t \in \boldsymbol{T}\ CK(t) = \sum_{v \in \boldsymbol{V}} RV_v(ST_v(t), SL_v(t)) \cdot z_v(t) \quad (42)$$

$$\forall t \in \boldsymbol{T}\ KO(t) = \sum_{v \in \boldsymbol{V}} WP_v \cdot z_v(t) \cdot \sum_{m \in \boldsymbol{M}_v : ST_v(t) \leq N_m} x_{v,m} \cdot \left[RV_m + \sum_{t'=t}^{N_m} (r_m - o_m(t'))\right] \quad (43)$$

$$\forall t \in \boldsymbol{T}\ ko(t) = \frac{1}{KO(t)} \cdot \sum_{v \in \boldsymbol{V}} WP_v \cdot z_v(t) \cdot \sum_{m \in \boldsymbol{M}_v : ST_v(t) \leq N_m} x_{v,m} \cdot kd_m \cdot \left[RV_m + \sum_{t'=t}^{N_m} (r_m - o_m(t'))\right] \quad (44)$$

When actual costs incurred during the analysis period are discounted, the criterion for the company's Net Total Fleet Costs is expressed as follows:

$$NTCO = \sum_{t=0}^{T} \frac{TCO(t)}{(1 + WAC(t))^t} \longrightarrow \min \quad (45)$$

The criterion for total CO_2 emissions and the criterion for total energy consumption are expressed as follows:

$$EC = \sum_{v \in \boldsymbol{V}} ec_v \cdot \sum_{t \in \boldsymbol{T}} L_v(t) \longrightarrow min \quad (46)$$

$$ZE = \sum_{v \in \boldsymbol{V}} ze_v \cdot \sum_{t \in \boldsymbol{T}} L_v(t) \longrightarrow \min \quad (47)$$

The fleet composition assessment criteria included in the model may be considered separately or jointly through a multi-criteria approach.

5. Case study

5.1. Input data

The proposed model was applied to solve the decision-making problem of composing a small fleet of four to five vehicles, taking into account average annual mileage levels of 20 000, 30 000 and 40 000 km. The analyses did not include budget constraints or minimum fleet utilization requirements. It was assumed that only all-season tires would be used. The annual cost of equity k_W was set at 15%, and the corporate income tax rate at 19%. The cost of managing a fleet of four to five vehicles was assumed to be PLN 5 000 (part-time).

The analyses considered six vehicle financing methods ($\boldsymbol{M} = \{1, 2, 3, 4, 5, 6\}$), with the first three parameterized for combustion vehicles (FFV) or PHEVs and the last three for BEVs. Methods 1 and 4 represent equity financing, methods 2 and 5 correspond to operating leasing with an initial payment and low residual value, and methods 3 and 6 correspond to operating leasing with an initial payment and high residual value. The parameters of these financing methods are summarized in table 1.

The analysis period covers 36 months, and vehicle demand was defined based on two categories of needs ($\boldsymbol{W} = \{1, 2\}$). For the first category, two vehicles are required during the initial 12 months and three vehicles during the subsequent 24 months. For the second category, two vehicles are required throughout the entire analysis period. The projected monthly mileage for the vehicles, based on average annual values of 20 000 km, 30 000 km or 40 000 km, is shown in fig. 1.

Accordingly, the case study considered a fleet of four vehicles in the first year of analysis and five vehicles in the subsequent two years. It was assumed that at the beginning of the analysis period, the company would retire all previously operated vehicles and make decisions regarding the introduction of new vehicles identical in type to those previously used, that is, combustion engine vehicles, hybrids or electric vehicles, along with the choice of financing method for each vehicle.

Table 1. Selected parameters of the vehicle financing methods included in the analysis

Parameter	Method 1	Method 2	Method 3	Method 4	Method 5	Method 6
R_m	10%	12%	12%	20%	22%	22%
N_m	0	24	24	0	24	24
O_m	100%	10%	10%	100%	10%	10%
r_m	0,00%	3,71%	2,20%	0,00%	3,71%	2,58%
RV_m	0,0%	21,0%	60,0%	0,0%	21,0%	50,0%
Wd_m	1	1	0	1	1	0
kd_m	0,00%	7,871%	7,802%	0,00%	7,871%	7,819%
P_m	999 999	999 999	80 000	999 999	999 999	80 000
αu_m	0	0,15	0,15	0	0,15	0,15
αs_m	0	0,10	0,10	0	0,10	0,10
αo_m	0	0,10	0,10	0	0,10	0,10
αz_m	0	0	0	0	0	0
αn_m	0	0,10	0,10	0	0,10	0,10

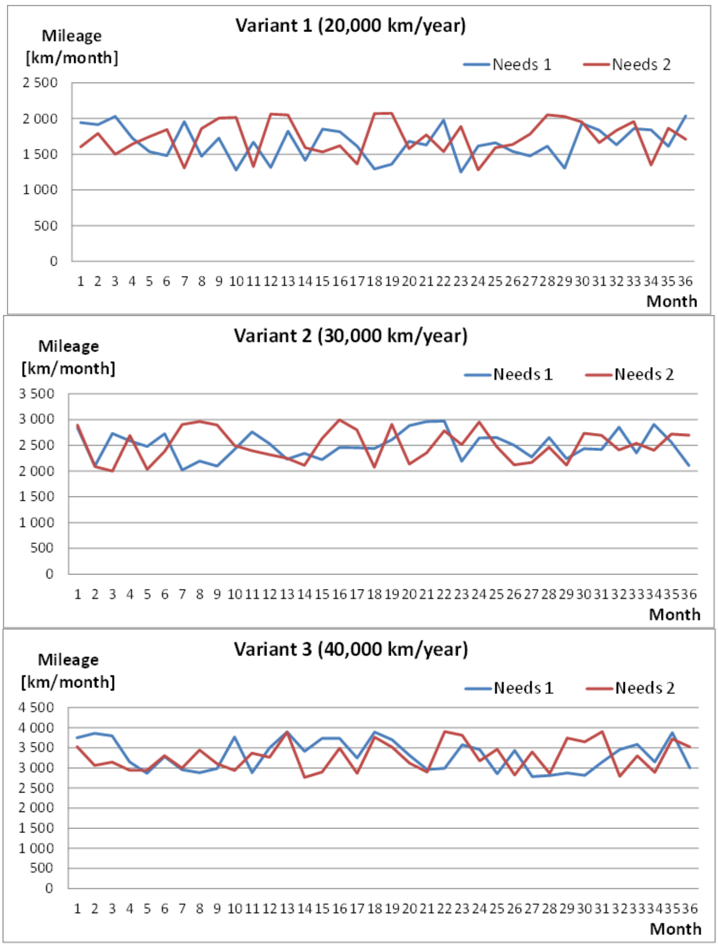

Fig. 1. Forecasted monthly vehicle mileage in variant terms

The analyses included a total of six vehicle models: two gasoline-powered vehicles, two PHEVs and two BEVs electric. For each type of propulsion, one lower-class vehicle, which could be used exclusively to satisfy the transport needs of the first category, and one higher-class vehicle, which could meet the needs of both categories, were considered. Additionally, taking into account the possibility of replacing each vehicle up to three times (with a minimum annual operating period assumed), a set of 72 vehicle options was obtained.

Selected parameters of the vehicles included in the analysis are presented in table 2. Their residual values and maintenance and repair costs are shown in fig. 2 and 3. Annual insurance costs for combustion and PHEVs were assumed to be 3.0% of the vehicle value plus PLN 800, while for BEVs the premium was set at 4.5% of the vehicle value plus PLN 700.

5.2. Results

The composition of the fleet was evaluated based on the three previously defined variants of fleet task size and the following five criteria:

– minimizing TCO,
– minimizing NTCO,
– minimizing CO_2 emissions (EC),
– minimizing energy consumption (ZE),
– maximizing the sum of weighted normalized NTCO (weight 0,8), normalized CO_2 emissions (weight 0,15), and normalized energy consumption (weight 0,05).

The results obtained for each analysis variant are summarized in table 3.

Due to the exclusion of vehicles previously used in the fleet and the resulting lack of data on their condition, the fleet composition plans generated in the study assume the use of identical vehicles to meet the needs of each category. While both cost-based criteria identify PHEVs as the most favourable option for the first category of transport needs at an average annual mileage of 40 000 km, and combustion engine vehicles as optimal for the remaining categories and mileage levels, both environmental criteria indicate BEVs as the best choice for the analysed fleet, regardless of mileage or transport need category. It can also be observed that the optimal operating periods obtained under the cost criteria are long, typically three years in nearly all cases. However, operating periods do not affect the environmental criteria, as it was assumed that over a three-year horizon, any deterioration in vehicle condition would not significantly influence fuel or energy consumption.

Table 2. Selected parameters of the vehicles included in the analysis

Parameter	Vehicles 1–9	Vehicles 10–24	Vehicles 25–33	Vehicles 34–48	Vehicles 49–57	Vehicles 58–72
Propulsion	FFV	FFV	PHEV	PHEV	BEV	BEV
$\boldsymbol{W}(v)$	{1}	{1,2}	{1}	{1,2}	{1}	{1,2}
DT_v	0	0	0	0	0	0
DL_v	0	0	0	0	0	0
wk_v	74 065	91 870	94 634	104 878	122 764	168 293
wd_v	0	0	0	0	0	0
$\boldsymbol{M}_v$	{1,2,3}	{1,2,3}	{1,2,3}	{1,2,3}	{4,5,6}	{4,5,6}
$Kr_v(m)$	160 / 340 / 0	160 / 340 / 0	160 / 340 / 0	160 / 340 / 0	160 / 340 / 0	160 / 340 / 0
Lg_v	15 000	15 000	20 000	15 000	40 000	30 000
Co_v	1 278	950	1 180	950	769	2 277
Lo_v	65 000	65 000	50 000	65 000	65 000	80 000
Ko_v	0	0	0	0	0	0
Kb_v	250	333	250	333	500	583
Kuo_v	0	0	0	0	0	0
cp_v	4,846	4,846	4,846	4,846	1,248	1,248
zp_v	0,056	0,059	0,048	0,046	0,143	0,166
Kip_v	40	40	40	40	40	40
ec_v	125,00	133,00	108,00	103,00	85,37	99,10
ze_v	1 792,0	1 888,0	1 536,0	1 456,0	514,8	597,6

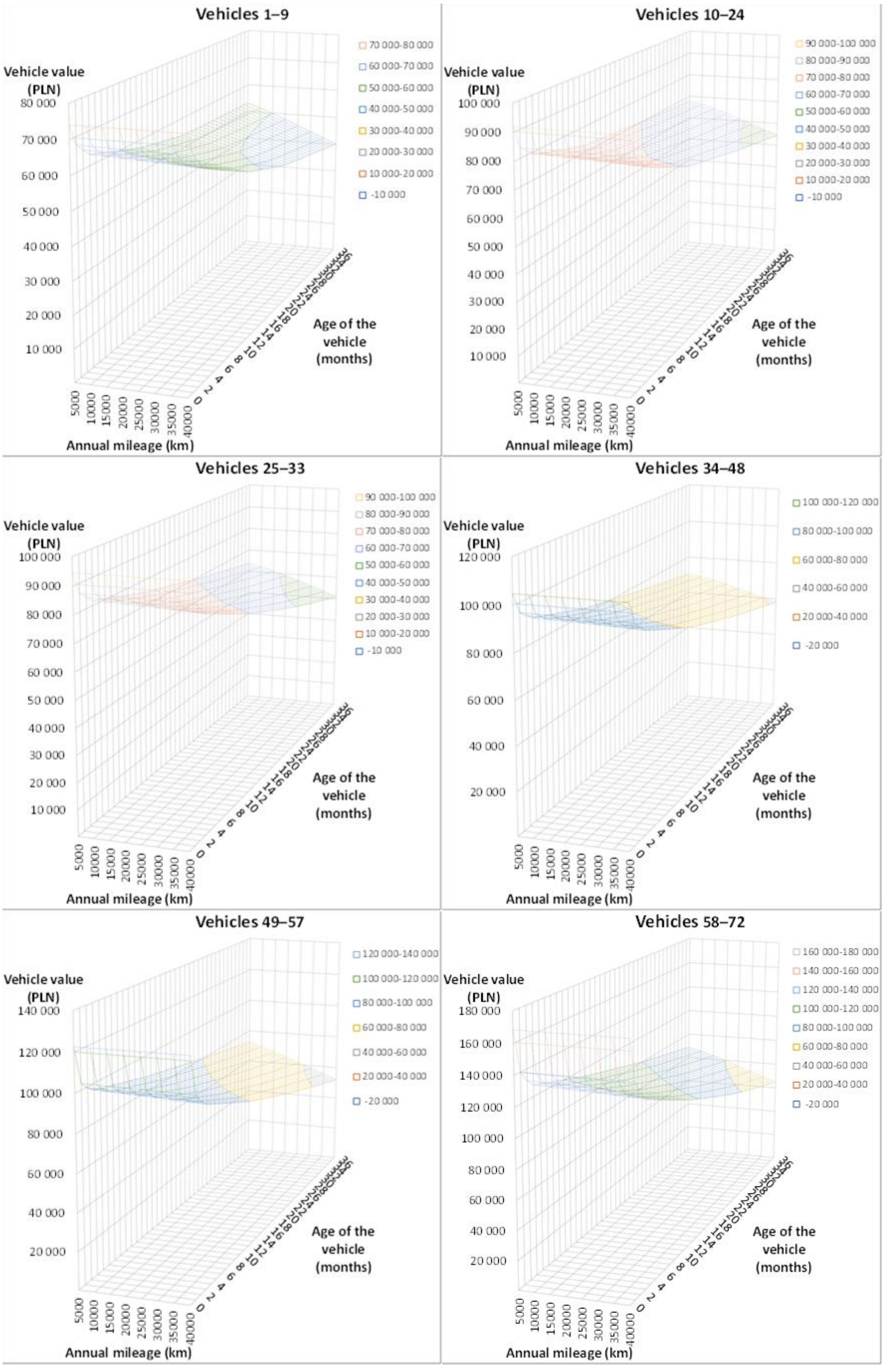

Fig. 2. Residual value of vehicles as a function of their age and annual mileage

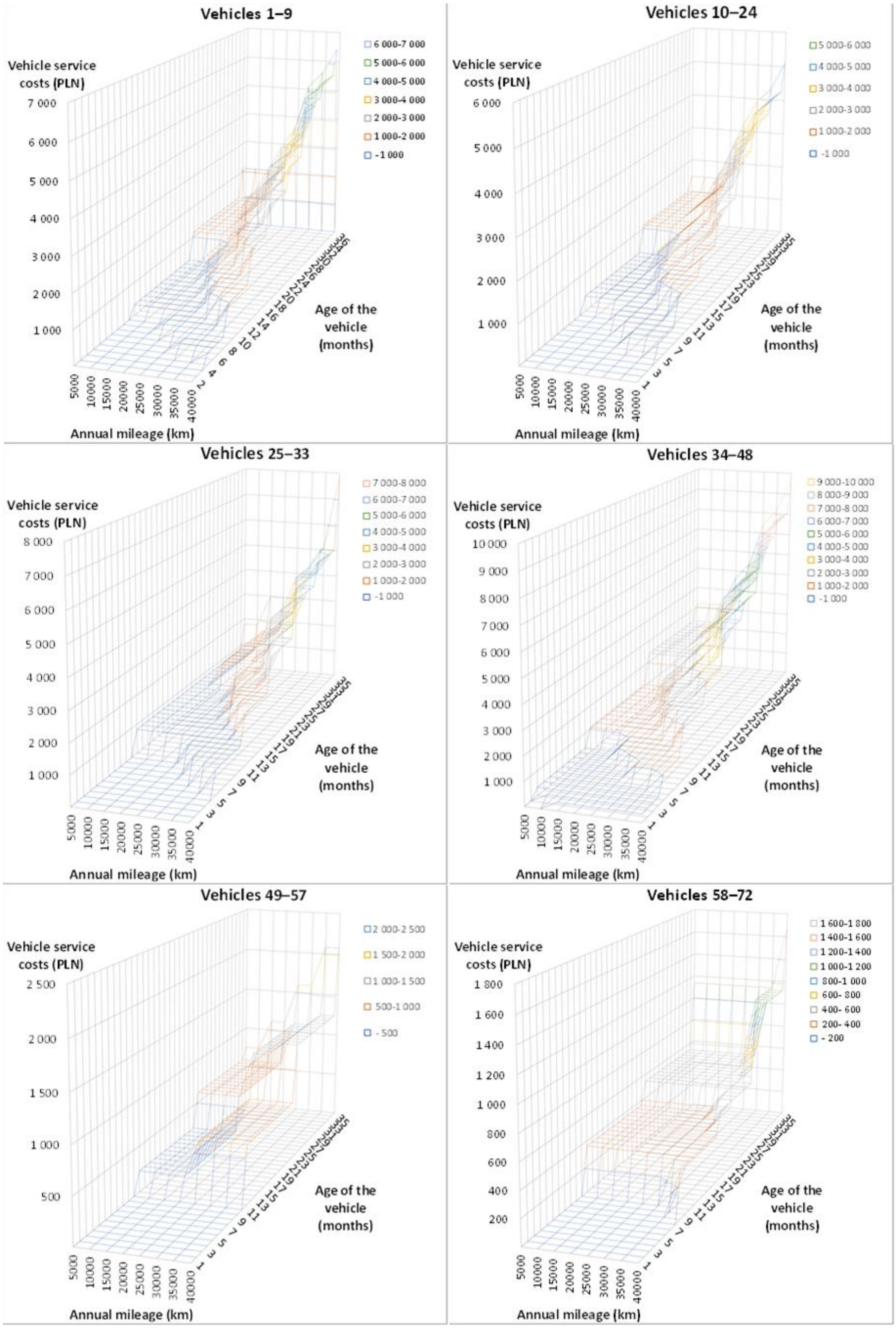

Fig. 3. The value of vehicle technical maintenance as a function of age and annual mileage

The final criterion – considered the most important – shows that, in the analysed case, for the first category of transport needs and for average annual mileage of 30 000 or 40 000 km, BEVs should be introduced, with an operating period of three years. In all other cases, combustion engine vehicles would represent the better option, given the adopted weighting of the criteria.
To illustrate the differences in total fleet costs for vehicles with different drive types, the developed model was used to optimize vehicle operating periods and financing methods separately for BEVs, PHEVs, and combustion engine vehicles. These analyses considered an average annual vehicle mileage of 30 000 km. For all drive types, cash purchase was the optimal financing option, and the optimal operating period was 35 or 36 months. A comparison of the costs obtained for optimal fleet composition solutions, taking into account vehicles with specific drive types, is presented in table 4.
As noted above, the analysed fleet results indicate that choosing BEVsunder current conditions is generally not economically viable. The main reason is the recent and substantial decline in the residual values of BEVs, which have decreased by several to several dozen percentage points more than those of conventional vehicles (see fig. 2). Combined with the still considerably higher purchase prices of BEVs, this places them at a significant disadvantage compared with vehicles using other types of drivetrains. In addition, insurance for BEVs remains typically more expensive than insurance for comparable conventional or PHEVs.
Regardless of the scenario analysed, financing vehicle purchases with a company's own funds proved to be the most effective option according to economic criteria. For environmental criteria, the financing method is irrelevant, provided that the optimal operating period is not shorter than the financing period and, under the adopted simplifying assumptions, does not exceed three years, since within such a period the vehicle's environmental impact is not significantly affected by its age.

Table 3. Comparison of optimization results for three variants of average annual vehicle mileage

Needs	Parameter	Minimization				Maximizing the sum of weighted normalized NTCO, EC and ZE
		TCO	NTCO	EC	ZE	
Average annual mileage: 20 000 km/year						
1	Vehicles	1, 2, 3	1, 2, 3	49, 50, 51	49, 50, 51	1, 2, 3
	Financing method	1	1	4, 5, 6	4, 5, 6	1
	Service life	36	36	unlimited[1)]	unlimited[1)]	36
2	Vehicles	10, 11	10, 11	58, 59	58, 59	10, 11
	Financing method	1	1	4, 5, 6	4, 5, 6	1
	Service life	33	36	unlimited[1)]	unlimited[1)]	36
Average annual mileage: 30 000 km/year						
1	Vehicles	1, 2, 3	1, 2, 3	49, 50, 51	49, 50, 51	49, 50, 51
	Financing method	1	1	4, 5, 6	4, 5, 6	4
	Service life	35	36	unlimited[1)]	unlimited[1)]	36
2	Vehicles	10, 11	10, 11	58, 59	58, 59	10, 11
	Financing method	1	1	4, 5, 6	4, 5, 6	1
	Service life	35	35	unlimited[1)]	unlimited[1)]	35
Average annual mileage: 40 000 km/year						
1	Vehicles	25, 26, 27	1, 2, 3	49, 50, 51	49, 50, 51	49, 50, 51
	Financing method	1	1	4, 5, 6	4, 5, 6	4
	Service life	23	36	unlimited[1)]	unlimited[1)]	36
2	Vehicles	10, 11	10, 11	58, 59	58, 59	10, 11
	Financing method	1	1	4, 5, 6	4, 5, 6	1
	Service life	31	36	unlimited[1)]	unlimited[1)]	36

1) Limited only by financing method.

Table 4. Comparison of the effects of implementing vehicles with different drive types into the fleet for an average annual vehicle mileage of 30 000 km – financing methods and optimal operating periods

Criterion	**Propulsion**		
	FFV	**PHEV**	**BEV**
TCO (PLN)	497 714	521 918	588 570
NTCO (PLN)	495 352	532 622	620 091
EC (g)	53 993 942	44 503 342	38 366 506
ZE (kJ)	770 688 192	631 333 984	231 355 814
Cost type (PLN)			
Vehicle impairment	**49 963**	66 605	**139 994**
Vehicle financing	0	0	0
Vehicle registration	800	800	800
Service and tires	56 406	**78 948**	**14 374**
Paint and body repairs	**48 000**	48 000	**90 000**
Vehicle insurance	**39 078**	45 199	**76 432**
Fuel/Energy and other fluid consumption	**123 420**	102 318	**86 921**
Remarketing	0	0	0
Fleet management	180 048	180 048	180 048

It is also worth noting that the relatively low attractiveness of external vehicle financing, despite the inclusion of an additional 2% leasing discount, is undoubtedly related to the assumption that no budget constraints were applied in the analyses. The company was assumed to have sufficient cash available, which in practice, especially when purchasing a dozen or more vehicles, may not be the case. Under such circumstances, external financing may become a more appealing option.

A comparison of the optimal solution obtained for an average annual mileage of 30 000 km with the option of financing the same vehicles through leasing with a low buyout is presented in table 5. As the comparison shows, although leasing is approximately 5,7% more expensive according to the NTCO criterion for the parameters considered, it reduces the required maximum monthly budget by more than 80%.

When analysing this issue, it is important to emphasize that it is multifaceted and complex, requiring the consideration of numerous parameters whose values may change in response to shifts in the social, economic and political environment in which a company operates. Therefore, before implementing any specific solution, comprehensive sensitivity analyses should always be carried out, considering various scenarios of energy price fluctuations, fuel price changes and potential variations in vehicle residual values.

6. Conclusions

The primary motivation for implementing alternative-propulsion vehicles has always been environmental protection. Economic arguments in favour of these vehicles include lower electricity costs compared with fuel costs for conventional vehicles, as well as simpler construction, which in turn reduces the costs of periodic inspections. However, the analysed decision problem shows that, at present, there are several cost components that significantly outweigh the savings in maintenance and fuel or energy consumption. The most significant of these is vehicle depreciation. In addition, repair expenses and insurance costs negatively affect the economic attractiveness of BEVs.

It is also important to consider the maximum three-year vehicle service life assumed in the analysed case. As the service life is extended to four or five years, if such an operating period is optimal for a given fleet, the advantage of conventional vehicles diminishes. This is because the decline in residual value becomes less pronounced in later years of operation, while the savings resulting from lower energy costs accumulate over the extended service life.

Table 5. Comparison of selected financing options for an average annual mileage of 30 000 km – optimal vehicles and operating periods

Evaluation criteria and maximum budget	Form of financing		Difference	
	Leasing with low buyout	Cash purchase	Absolut	Percentage
TCO (PLN)	507 212	525 055	17 842	3,5%
NTCO (PLN)	526 667	556 704	30 037	5,7%
EC (g)	44 477 434	44 477 434	0	0,0%
ZE (kJ)	463 981 384	463 981 384	0	0,0%
Budget required for the first month (PLN)	391 489	75 730	-315 759	-80,7%

Support for the development of electromobility may also take the form of legislative incentives for users of alternatively powered vehicles, including subsidies for their purchase. However, at present the only support program available in Poland is the NaszeEauto program, which is limited to private individuals, sole proprietors and national parks. As a result, such support is no longer accessible to larger companies. Currently, car dealers offer substantially higher discounts on new BEVs, which partially compensates for the absence of state subsidies for corporate fleet purchases.

Regardless of this, when a company places greater emphasis on environmental considerations in its fleet composition decisions, BEVs consistently emerge as the better option (see table 5).

In addition to economic considerations, the implementation of alternatively powered vehicles in a company's fleet should include an analysis of employee demand for such vehicles or, in the case of rental fleets, customer demand. It should also involve an assessment of technology availability and the development of appropriate charging infrastructure within the company. The availability of public charging stations in the areas where the company's vehicles will operate is likewise an important factor.

The fleet composition model proposed in this article is relatively complex due to the large number of parameters considered. However, it enables a detailed assessment of how fleet composition decisions affect both standard and discounted TCO, as well as selected environmental criteria. Moreover, the model can be applied to a wide range of practical fleet management scenarios.

The model developed in this article made it possible to optimize a three-year fleet composition consisting of five vehicles. As demonstrated, depending on the scale of transport tasks, the category of transport needs (vehicle segment), and, of course, the evaluation criteria, the optimal choice may be combustion engine vehicles, PHEVs, or BEVs. It is also important to highlight the significant influence of numerous parameters on the solution of the problem, including negotiated discounts and vehicle financing conditions. Optimal decisions regarding the choice of financing method may also vary depending on the company's fleet budget.

Both fleet size and the planning horizon pose challenges to the large-scale practical application of the model. Therefore, further research is needed to develop a more efficient decision-support tool. In addition, the earlier-mentioned difficulties in identifying parameter values in a rapidly changing environment justify the need for a simulation model that would allow sensitivity analyses of the optimal solutions. Such a tool could also incorporate random variables, which would, on the one hand, bring the model closer to real-world conditions, but on the other hand, may lead to solutions that are difficult to interpret. For instance, stochastic variation in the size of transport tasks may influence the optimal vehicle operating life, making a single simulation run insufficient.

Integrating the fleet composition model with existing databases is also essential—for example, to import residual values of selected vehicles as a function of their age and mileage. However, solving the fleet composition problem still requires a time-consuming process of gathering unique data, including information on vehicle prices, financing conditions, and insurance offers.

An important direction for further research may also be to incorporate artificial intelligence techniques to support decision-making in the area of car fleet composition (Semenov et al., 2025).

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