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Simulation studies of fleet vehicle selection in terms of pollutant emissions

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This article presents the vehicle selection problem in the vehicle fleet of a retail and service company. In practical solutions, fleet managers focus on minimizing TCO (total cost of ownership) while ignoring the impact of the fleet on the environment. Therefore, a literature review of current solutions in fleet selection and their determinants is presented. Considering the latest trends and regulations, an optimization model for vehicle selection was developed, considering the issues of emissions and external costs. The developed model was implemented in a simulation environment, and a sensitivity analysis of the solutions obtained was carried out. The research made it possible to indicate the impact of the pollutant emission factor on the fleet structure.

Key words: *fleet management, pollutant emission, optimization model, simulation studies, FlexSim*

1. Introduction

Car fleet management is a set of processes to ensure mobility within a given enterprise. They include planning and organizing the transport of people and materials, optimizing the use of rolling stock, managing safety, and ensuring economic efficiency as part of the total cost of vehicle ownership (TCO) [4, 24, 29].

The selection of vehicles for the fleet is an essential aspect of the enterprise functioning, especially for those with high mobility needs and, thus, a large fleet in terms of quantity. Fleet managers in this aspect are mainly guided by TCO, including the costs of financing vehicles, materials, fuel, service, and insurance. Other factors influencing the choice of the vehicle include engine capacity, body style, and equipment. Practical experience shows that environmental impact and safety issues are marginalized or ignored during vehicle selection. These aspects are taken into account only through the economic calculation related to vehicle equipment and fuel consumption [2, 8, 23].

Due to the great emphasis on sustainable transport systems development, which is often overlooked in the actual decisions of fleet managers, this article examines the impact of the selection of vehicles for the fleet in terms of emissions of pollutants (exhaust gases) into the environment. This is an important issue due to the share of fleet vehicles in the total number of vehicles on the road (in Poland 74% are fleet vehicles [27]. Thus, even a slight unit reduction in the negative impact of the fleet functioning on a national scale will bring significant benefits. In addition, this aspect is important due to the impact on the indirect participants of transport processes, their health, and life comfort. It is also significant from the point of view of the company's image, which is increasingly influenced by care for the environment.

Therefore, the purpose of this article is to conduct research showing the impact of the selection of the vehicle fleet according to the main criterion, which is the TCO on pollutant emissions, as well as a comparison of this approach with the approach that takes into account the external costs of exhaust emissions. The article in the following parts has been organized as follows: section 2 is a literature review of vehicle fleet management in terms of TCO and pollutant emissions, section 3 is a description of the research method used in this article, section 4 is a mathematical formalization of the fleet selection problem, and a simulation model, section 5 is a calculation example. The article ends with section 6, i.e., conclusions from the conducted considerations and directions for further work.

2. Literature review

The research undertaken in this article focuses on the area of environmentally friendly transport solutions. The background for the work is research in the aspect of criteria for the selection of vehicles for the fleet, TCO, pollutant emissions, and vehicle fleet management.

Undoubtedly, costs play a vital role in the transport system functioning [11, 13]. The most popular metric is the Total Cost of Ownership [3, 18]. The research conducted in [18] indicates the dominant character of this indicator. They also show that the issues of ecology in terms of exhaust emissions are often overlooked, and the use of alternative fuels is analyzed mainly in terms of TCO. In Polish conditions, based on surveys conducted with fleet managers, a fleet manager who plans to replace the fleet is guided by costs in the first place [3]. In the first place is the monthly cost of the vehicle. A very common approach to cost analysis is to consider only the amount of the rental installment or the cost of leasing or purchasing the vehicle. Thanks to the TCO analysis, and as it results from the research carried out in [3], it is essential in the process of comparing the total costs of different vehicles to take into account operating costs, and mainly fuel. Safety issues are marginalized, and only 10% of fleet managers set the selection criterion focusing on ensuring safety. Only 2% of fleet managers pay attention to ecological issues. TCO is the primary criterion for selecting vehicles to carry out tasks, fleet operational management, and rolling stock renewal planning. Paper [14] presents studies in which TCO is an indicator that allows the selection of vehicles in a short-term rental – in a car rental company. The considerations were mainly based on economic aspects. The TCO criterion also allows fleet managers to consciously plan fleet replacement (FRP –

fleet replacement problem). This aspect was considered in the work [17], where, considering the preferences of fleet users, guidelines for selecting specific vehicles were proposed. The selection of vehicles based on TCO but considering the vehicle loss ratio and its impact on costs was considered in [23]. Another approach to selecting vehicles for the fleet is a detailed analysis of the operational characteristics of the vehicles. Such an approach was presented in [10].

Regarding heavy goods vehicles, the authors of the report [7] considered the total cost of ownership. They performed a spatial and temporal analysis of different vehicles for six powertrain technologies, including diesel, hybrid electric, plug-in hybrid electric, compressed natural gas, battery, and electric fuel cell. More and more often, in terms of TCO, a comparison of the use of vehicles with different drive technologies is considered. As the authors of the paper [24] indicate, eLCV vehicles (electric light commercial vehicles), even though they have a higher TCO/km than conventional vehicles, are a significant competition to conventional vehicles, taking into account financial and regulatory incentives and the possibility of charging them at the company base. The authors [29] analyzed the use of eLCV from the economic and environmental point of view. The research presented included an analysis of trends in the EU and the impact of vehicle electrification on CO_2 emissions reduction, showing that it is possible to reduce emissions by 30% by 2030 with LCV. They also addressed the issue of total cost of ownership (TCO) compared to conventional vehicles. A similar case was discussed in works [2, 4, 25]. From the point of view of environmental impact, interesting studies are presented in article [8], discussing the issue of noise emission from eLCV.

The works presented above consider the aspect of using environmentally friendly vehicles. However, their selection is mainly based on assessing TCO or CO_2 emissions. More detailed studies on exhaust emissions are not directly related to the selection of vehicles for the tasks in the company's fleet. These studies include analyzes of exhaust gas emissions in transport systems on a macro scale, e.g., in works [5, 12, 22].

An important basis for these studies are the pollution emission models. In this respect, measurements are carried out in real conditions to determine the actual level of exhaust gas emissions depending on various road conditions and traffic areas [1, 20]. However, these studies are expensive, and a detailed analysis of a wide range of vehicles, various drives, and environmental conditions would be ineffective in decision-making models and practical use by fleet managers. Hence, it is possible to use predictive models for pollutant emissions based on averaged indicators. Detailed characteristics and possibilities of their use are presented in a review article [15].

A rather difficult issue is assessing the impact and the possibility of using zero-emission vehicles. Such research regarding selecting zero-emission vehicles to carry out tasks was presented in works [9, 21].

Many factors, as well as an extensive structure of processes within the vehicle fleet management framework, require appropriate methods and tools. For this purpose, optimization and simulation tools are used to support decision-making processes. They are based on mathematical models of the task assignment problem in terms of single and multi-criteria, as well as algorithms that allow to determine solutions. The work [6] presents the integration of forecasting, simulation, and optimization techniques in the performance and revenue management system in a short-term rental company – Europcar. Such approaches, often called hybrid ones, allow to consider the problem of fleet selection in a multi-faceted and comprehensive way and to study the impact of the fleet structure on its effectiveness. Similar works considering the hybrid approach in the application of decision support in fleet management were presented for example in [19, 30].

Summing up the literature analysis, it should be stated that in both scientific and industry publications, the problem of selecting vehicles, considering alternative technologies that reduce pollutant emissions is increasingly discussed. In these studies, however, the main emphasis is placed on economic efficiency or possibly CO_2 emissions. Therefore, this article proposes a method that assesses the impact of the selected fleet structure and the driver to carry out tasks on exhaust emissions in terms of other harmful substances.

3. Research methodology

This article's research subject is the problem of vehicle fleet selection regarding the harmful substances emission. The works will be carried out according to the diagram presented in Fig. 1. It should be emphasized that the research is of an iterative nature, i.e., in the course of the work, both the mathematical model and its implementation were modified to represent the real problem best. The results presented in the article are the result of numerous calculations and synthetically present a solution to the problem of fleet selection, taking into account the issue of harmful substance emissions.

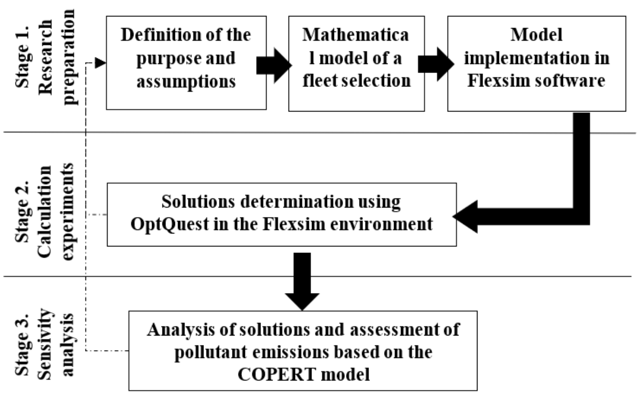

Fig. 1. Methodology of the research on the impact of the vehicle fleet selection on pollutant emissions

Stage 1. Research preparation. This stage consists of three elements. The first element is to define the research's purpose and make assumptions for the calculations. Another element is the development of a mathematical model containing the characteristics of the input data, decision variables, constraints imposed on the solution, and the criterion function. The last element is the implementation of the developed mathematical model in the Flexsim environment and the mapping of the process of carrying out tasks by the vehicle fleet. These elements in the application for the fleet selection problem are presented in Chapter 4.

Stage 2. Computational experiments. At this stage, based on the developed model, its implementation, and adopted assumptions, solutions to the fleet selection problem are determined, i.e., the values of decision variables that meet the task constraints are defined. This is achieved using the OptQuest module in the Flexsim environment. Searching the solution space in the OptQuest module is achieved using a metaheuristic algorithm. Thus, a set of solutions is returned. Computational experiments were carried out considering single and multi-criteria optimization. The results of the calculations are presented in Chapter 5.2.

Step 3. Sensitivity analysis. The last stage of the research is the analysis of the sensitivity of the solutions to changes in the input data, as well as the assessment of the emission of harmful substances. The input data and vehicle traffic conditions, including the average speed and average distance, as well as the number of serviced areas, were changed for the best solutions identified during optimization. Additional assessment indicators were determined in the field of ownership costs and exhaust gas emissions using the COPERT model [16]. The analysis of solutions is presented in Chapter 5.3.

4. Mathematical and simulation model

4.1. Assumptions

As already indicated, vehicle fleet management is a complicated decision-making process. At the same time, it is possible to use mathematical and simulation modeling tools to map existing problems and support managers in making decisions. The aim is to conduct research showing the impact of the selection of the vehicle fleet according to the main criterion, which is the TCO, on pollutant emissions, as well as comparing this approach with the approach that considers the external costs of exhaust emissions. For research, the following assumptions were made:

- the mathematical model of fleet management is developed using the set theory
- the simulation model is developed in the Flexsim environment
- the mapped decision problem concerns a commercial enterprise and is built for the needs of managing a fleet of passenger vehicles in terms of the selection of resources for the implementation of the tasks
- the solution of the formulated task includes the determination of decision variables for the interpretation of the vehicle number and the driver number assigned to the service of a given area
- the analysis period is the number of days in which the solution to the fleet selection problem is considered
- the analysis period should correspond to the time horizon of vehicle financing or depreciation
- the selection of the driver-vehicle set for serving the area does not change during the analysis period, and this is based on the assumption that the vehicle is regarded as an individual working tool and an additional benefit for the employee
- the number of services in the area is the expected value of the sum of random variables defining the occurrence of the service. The occurrence of service, and the intensity, is described by a certain probability distribution
- the distance during the service of a given area is also a random variable, and its value is described by a certain probability distribution
- the vehicle fleet may be heterogeneous in terms of make, model, or vehicle characteristics
- the model includes driver training in the field of eco-driving
- own financing of the vehicle was adopted
- the optimization criteria were the average income from completed tasks and external costs resulting from CO_2 emissions per task
- only exhaust emissions resulting from vehicle use are considered in the model. Other emissions are omitted. In addition, noise emissions or, for example, particulate matter from the braking system are not taken into account
- solving the optimization task in terms of various criteria results in a set of solutions subject to further analysis, including the use of emission factors from the COPERT model.

The developed model considers the randomness of two model parameters, i.e., the occurrence of service and the distance covered during its implementation. This approach is aimed at mapping the variability in the tasks performed and the different characteristics of service areas. For example, in urban areas, there may be a lot of tasks, and the distance covered during their implementation may be small.

4.2. Mathematical formulation of the vehicle fleet selection problem in terms of pollutant emissions

The developed model considers elements such as drivers, vehicles, service areas, and their characteristics. In addition, it was necessary to define decision variables, criterion functions, and constraints to formulate optimization tasks. This is presented in the next part of the article. For the formalization of the model, a time horizon (analysis period) was adopted, defined as a set T which elements are the numbers of individual days $\mathbf{T} = \{t: t = 1,2,\ldots,T\}$ where value T depends on the length of the analysis period, e.g., for a period of one year, it will be 365. The set of vehicles in the model was formulated as $\mathbf{NV} = \{nv: nv = 1,2,\ldots,NV\}$, a set of drivers as $\mathbf{ND} = \{nd: nd = 1,2,\ldots,ND\}$ and a set of service areas $\mathbf{NA} = \{na: na = 1,2,\ldots,NA\}$. The elements of the above sets have the interpretation of the numbers of vehicles, drivers, and service areas, respectively, and take values from the set of natural numbers. The decision variables in the vehicle fleet selection problem have binary values: y1(nv,na) and have the interpretation of the vehicle assignment to the service area and interpretation of the driver assignment to the service area. Decision variables have value 1 when the vehicle nv and driver nd are assigned to service area na. Two criteria functions were formulated. Function F1 (equation 1) has an interpretation of the company's income from the tasks performed. Function F2 (equation 2) has an interpretation of CO_2 emission as a result of the tasks implementation.

$$F1 = \frac{\sum_{na \in \mathbf{NA}} [INC(na) - CC(na) - CE(na) - CD(na)]}{\sum_{na \in \mathbf{NA}} \sum_{t \in \mathbf{T}} s(na,t)} \rightarrow \max \quad (1)$$

$$F2 = \frac{CCO_2 \cdot \sum_{na \in \mathbf{NA}} \left[\sum_{nv \in \mathbf{NV}} \left[\begin{matrix} y1(nv,na) \cdot \\ \cdot \sum_{t \in \mathbf{T}} \left[\begin{matrix} s(na,t) \cdot dist(na,t) \cdot \\ fu(nv) \cdot \\ \cdot \sum_{nd \in \mathbf{ND}} \left[\begin{matrix} dr(nd) \cdot \\ y2(nd,na) \end{matrix} \right] \\ \cdot ECO_2(nv) \end{matrix} \right] \end{matrix} \right] \right]}{\sum_{na \in \mathbf{NA}} \sum_{t \in \mathbf{T}} s(na,t)} \rightarrow \min \quad (2)$$

$$\forall na \in NA \quad INC(na) = zp(na) \cdot \sum_{t \in \mathbf{T}} s(na,t) \quad (3)$$

$$\forall na \in NA \quad CC(na) = \sum_{nv \in \mathbf{NV}} \left[\begin{matrix} y1(nv,na) \cdot T \cdot \\ \cdot (cp(nv) + ci(nv)) \end{matrix} \right] \quad (4)$$

$$\forall na \in NA \quad CE(na) = \sum_{nv \in \mathbf{NV}} \left[\begin{matrix} y1(nv,na) \cdot \\ \left[\begin{matrix} \sum_{t \in \mathbf{T}} [s(na,t) \cdot dist(na,t)] \cdot \\ \left(\begin{matrix} cr(nv) + \\ cf(nv) \cdot fu(nv) \cdot \\ \sum_{nd \in \mathbf{ND}} [dr(nd) \cdot y2(nd,na)] \end{matrix} \right) \end{matrix} \right] \end{matrix} \right] \quad (5)$$

$$\forall na \in NA \quad CD(na) = \sum_{nd \in \mathbf{ND}} \left[\begin{matrix} y2(nd,na) \cdot \\ [T \cdot cd(nd) + cs(nd)] \end{matrix} \right] \quad (6)$$

$$\begin{matrix} \forall na \in NA \quad \sum_{nd \in \mathbf{ND}} y1(nv,na) = 1 \\ \wedge \quad \sum_{nd \in \mathbf{ND}} y2(nd,na) = 1 \end{matrix} \quad (7)$$

The F1 function is determined on the basis of the difference in the company's income INC(na) – equation 3, fixed costs of vehicles CC(na) – equation 4, running costs CE(na) – equation 5, as well as the driver costs CD(na) – equation 6. Company income INC(na) is the product of the average income from a single service in the area – zp(na) and the number of services in the area s(na,t). Value s(na,t) = 1 means service of area na in moment t, 0 when there is no such a service. Area service in moment t is performed with the probability described by the selected distribution. Vehicle fixed costs CC(na) results from the involvement of vehicle nv, analysis period T and unit costs of vehicle depreciation cp(nv) and the insurance costs ci(nv). Vehicle running costs CE(na) depends on the total travel distance of a vehicle nv, which results from the number of services s(na,t) and a distance dist(na,t) in a given area. Distance covered during the service in an area na in moment t is a random variable described by a certain probability distribution. These costs are the product of the distance and the service costs per unit of distance – cr(nv), as well as the unit costs of fuel cf(nv) and the amount of fuel consumed per unit of distance fu(nv). Fuel consumption can be reduced with driver training dr(nd). The correction factor dr(nd) may have values of less than 1 when the driver applies eco-driving principles. Still, it may also be greater than 1 when the driver incorrectly uses the vehicle. The last component of function F1 is the driver cost CD(na), which consists of the product of the length of the analysis period and the unit cost of employing the driver cd(nd), as well as the training costs cs(nd). The F2 criterion function has an interpretation of the CO_2 emission costs and thus is calculated based on the total distance and fuel consumption as well as the unit ECO_2(nv) emission and the external cost of the unit CO_2 emission. In the defined problem, there is one constraint described by the formula (7) and has the interpretation of assigning exactly one vehicle and exactly one driver to service a given area.

4.3. Simulation model in the Flexsim environment

The *next* step was to implement the developed model in the Flexsim environment. This environment was chosen because of its high functionality and the ability to use the simulation-optimization approach to conduct research. It is possible to map the structure of the transport system of a given company using the basic elements of the mass service theory in the simulation model. Thus, it is possible to study the impact of various assumptions and changes in given assumptions on the obtained results. To map the transport system, the following were used:

– the source, responsible for generating tasks in the area with the intensity determined by the selected probability distribution
– the processor corresponding to the process of servicing the area by a given set (driver–vehicle) and counting the distance traveled
– the queue corresponding to the counter of completed tasks and the collection of results against specific optimization criteria, as well as other evaluation indicators
– the source-queue system, responsible for counting the analysis time and returning the results of the criterion function.

A diagram for two areas is shown in Fig. 2. To test more service areas, it is necessary to duplicate such a system. To solve the problem of fleet selection, the built-in OptQuest module was used, which is parameterized in accordance with the developed mathematical model and the adopted assumptions.

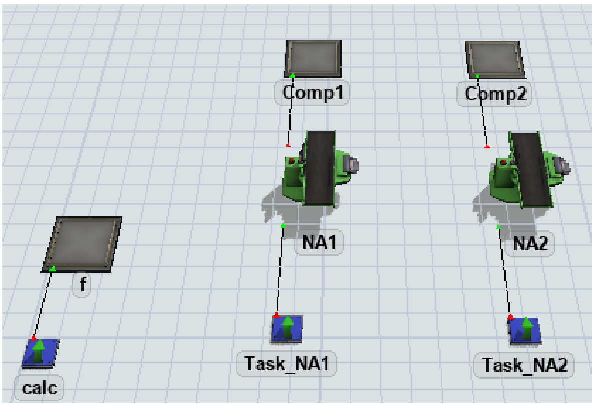

Fig. 2. A block of simulation elements representing the implementation of tasks in the company's transport system

5. Calculation example

5.1. Input data

The calculation example was prepared for a certain fragment of a real transport system of a trading company. The following input assumptions were adopted for the analyses:

- the research was performed on a representative part of the company's fleet to present a method to select resources for tasks
- analysis period T = 1095 days
- number of service areas NA = 5
- number of vehicles NV = 5
- number of drivers NA = 5
- the cost of CO_2 emissions was estimated based on research [6], and as a result, it was adopted as CCO_2 = EUR 0.33/kg
- intensity and distance were described by the Poisson distribution (X~Poiss(λ)) and the values λs(na,t) for the call intensity and λdist(na,t) for the distance were adopted, respectively, when s(na,t) = 1
- the OptQuest module using metaheuristic methods was used, and the number of iterations of the algorithm was 250 for each scenario.

The data characterizing the vehicles comes from analyzing car dealers' market offers and ADAC reports. The fuel consumption data came from vehicle manufacturers but was further verified against actual fuel consumption based on the company's operating history. The cars were selected from the segment of popular C-class cars (compact, middle class – lower). Due to the nature of the research, the brand and model were considered irrelevant. The lease period was assumed to be 5 years, and the monthly instalment was converted to 1 day. Data for vehicles are presented in Table 1. Characterizing the vehicles descriptively, it should be noted that the vehicle nv = 1 is a diesel vehicle with the Euro 5 combustion standard, characterized by low financing costs, but high service costs (due to age), it is the current vehicle used in the enterprise. Other vehicles are new vehicles. Vehicle nv = 2 is a spark-ignition vehicle with Euro 6 combustion standard, nv = 3 is a compression-ignition vehicle with Euro 6 combustion standard, nv = 4 is a gasoline-free hybrid vehicle with Euro 6 combustion standard, nv = 5 is an electric vehicle. 4 categories of drivers were identified, where nd = 1 drivers are characterized by average driving experience and a neutral impact on fuel consumption, nd = 2 drivers are less experienced drivers with a lower unit bone but higher fuel consumption, nd = 3 drivers are medium experienced drivers with eco-driving training, drivers nd = 4 are drivers with little experience, but with eco-driving training. The cost of the training is around EUR 250. Fuel savings are set at 25% from baseline. Data for drivers is presented in Table 2.

Table 1. Vehicles characteristics

Vehicles (nv)						
nv	unit	nv = 1	nv = 2	nv = 3	nv = 4	nv = 5
cp(nv)	EUR/day	6.7	12.6	14.0	14.5	30.1
ci(nv)	EUR/day	0.201	0.380	0.420	0.440	0.903
cr(nv)	EUR/km	0.078	0.020	0.28	0.17	0.11
cf(nv)	EUR/l	1.08	1.23	1.08	1.23	0.44
fu(nv)	l/km	0.048	0.060	0.045	0.047	0.155
ECO_2(nv)	g/l	2.68	2.35	2.68	2.35	0

Table 2. Drivers characteristics

Drivers (nd)					
data	unit	nd = 1	nd = 2	nd = 3	nd = 4
cd(nd)	EUR/day	55	37	55	37
cs(nd)	EUR	0	0	250	250
dr(nd)	–	1	1.4	0.75	1.05

The areas have the characteristics of mixed areas (urban and rural routes) with different intensities, distances, and revenues. Data for areas are presented in Table 3.

Table 3. Service areas characteristics

Service area (na)						
data	unit	na = 1	na = 2	na = 3	na = 4	na = 5
cp(na)	EUR/task	150	200	250	300	350
λs(na,t)	– (days)	1.2	1.2	1.5	2	2.5
λdist(na,t)	– (km)	60	100	100	120	150

5.2. Experiment results

As a result of the calculations carried out using the experimenter module (OptQuest) in the Flexsim environment, solutions to the problem of selecting vehicles and drivers for tasks in service areas were determined. The obtained solutions are presented in Table 4 according to:

- Single-criteria optimization with respect to F1 (3 best solutions S1.1, S1.2, S1.3) – Fig. 3
- Single-criteria optimization with respect to F2 (3 best solutions S2.1, S2.2, S2.3) – Fig. 4
- Multi-criteria optimization (3 solutions selected from the Pareto front S3.1, S3.2, S3.3) – Fig. 5.

Table 4. Summary of solutions to the problem of selecting vehicles and drivers (decision variables and values of the criterion function)

ScenarioID	S1.1	S1.2	S1.3	S2.1	S2.2	S2.3	S3.1	S3.2	S3.3
y1(1)	1	1	1	5	5	5	4	1	5
y2(1)	4	2	4	4	4	3	4	4	4
y1(2)	1	1	1	5	5	5	5	1	1
y2(2)	4	4	2	4	1	4	4	1	4
y1(3)	1	1	1	5	5	5	5	5	1
y2(3)	4	4	4	4	4	3	4	4	4
y1(4)	1	1	1	5	5	5	5	5	5
y2(4)	4	4	4	4	4	3	4	2	4
y1(5)	1	1	1	5	5	5	4	1	1
y2(5)	4	4	4	4	3	4	4	4	4
F1 (EUR/task)	161.6	161.4	161.3	111.9	111.6	111.1	125.6	137.8	144.4
F2 (EUR/task) [$F2 \cdot 10^{-3}$]	4.7	4.9	5.0	0.0	0.0	0.0	1.6	2.7	3.1

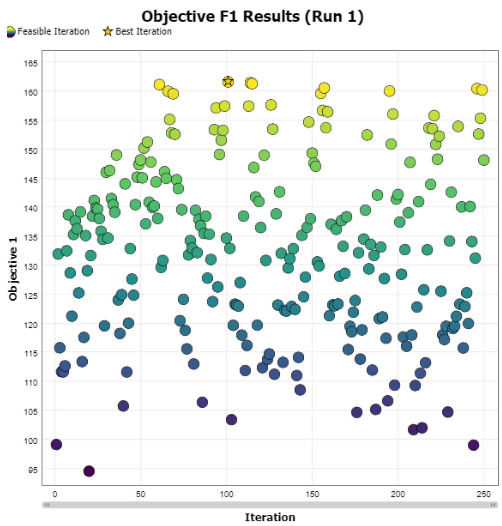

Fig. 3. The space of solutions with respect to the function F1

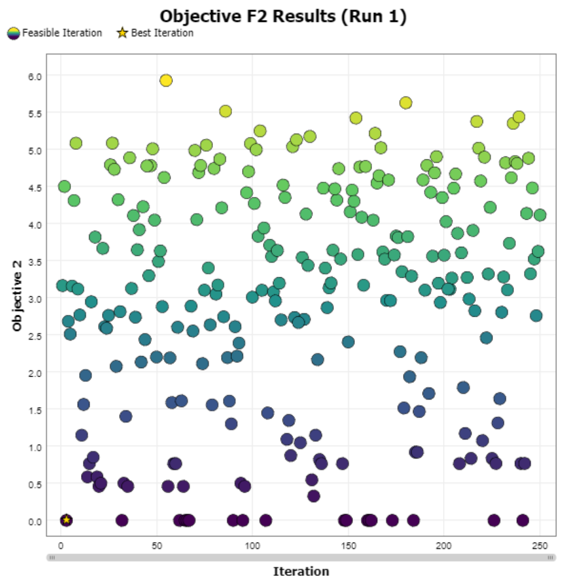

Fig. 4. The space of solutions with respect to the function F2

The graph in Fig. 3 shows the solution space of the formulated decision problem against the F1 criterion. The Y axis is the value of the criterion in EUR/task, while the X axis is the number of iterations of the algorithm. The best solutions are marked in yellow (maximized criterion), and the best solution is marked with an asterisk. Similarly, the space for the F2 function is shown in Fig. 4. In this case, however, the best solutions are marked in black (minimized criterion). On the other hand, Fig. 5 shows the solution space in multi-criteria optimization. The Y-axis shows the F2 (minimized) criterion, and the X-axis shows the F1 (maximized) criterion. Non-dominated solutions, i.e., Pareto optimal, are marked with asterisks. The indicated graphs of the F2 function are in the conversion of 10^{-3}. Analyzing the results presented, the great diversity of the solution space and the relationship between the criterion functions should be pointed out. The increase in corporate income for the assumptions made is associated with higher external costs of CO_2 emissions.

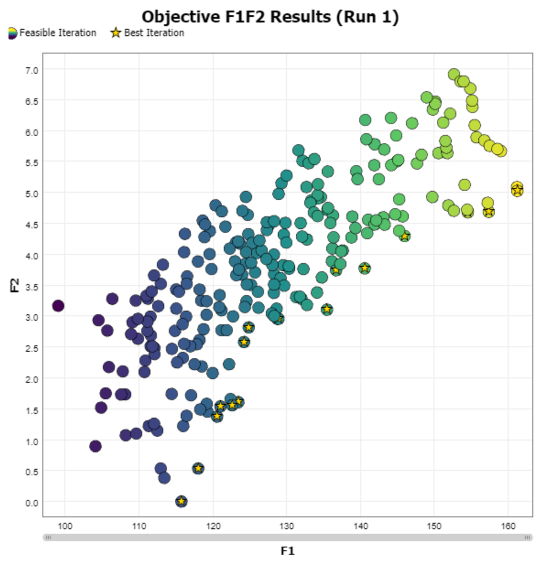

Fig. 5. Pareto solution in multicriteria optimization

5.3. Sensitivity analysis

For further analysis of the obtained solutions, additional measures were introduced, i.e., functions F1.1 and F2.1 presenting income and costs in units [EUR/km], and therefore it is a modification of formulas (1) and (2):

$$F1.1 = \frac{\sum_{na\in NA}[INC(na) - CC(na) - CE(na) - CD(na)]}{\sum_{na\in NA}[s(na,t)\cdot dist(na,t)]} \quad (8)$$

$$F2 = \frac{CCO_2 \cdot \sum_{na\in NA}\left[\sum_{nv\in NV}\left[\begin{array}{l} y1(nv,na)\cdot \\ \cdot \sum_{t\in T}\left[\begin{array}{l} s(na,t)\cdot dist(na,t)\cdot \\ fu(nv)\cdot \\ \cdot \sum_{nd\in ND}[dr(nd)\cdot y2(nd,na)] \\ \cdot ECO_2(nv) \end{array}\right]\end{array}\right]\right]}{\sum_{na\in NA}[s(na,t)\cdot dist(na,t)]} \quad (9)$$

Moreover, additional measures were introduced to determine the emission of a given type of harmful substance expressed in [kg], i.e.:

$$CO = \frac{efCO}{1000}\cdot \sum_{na\in NA}\sum_{t\in T}[s(na,t)\cdot dist(na,t)] \quad (10)$$

$$NO_x = \frac{efNO_x}{1000}\cdot \sum_{na\in NA}\sum_{t\in T}[s(na,t)\cdot dist(na,t)] \quad (11)$$

$$NMVOC = \frac{efNMVOC}{1000}\cdot \sum_{na\in NA}\sum_{t\in T}[s(na,t)\cdot dist(na,t)] \quad (12)$$

$$PM = \frac{efPM}{1000}\cdot \sum_{na\in NA}\sum_{t\in T}[s(na,t)\cdot dist(na,t)] \quad (13)$$

The values of efCO, $efNO_x$, efNMOVC, efPM were adopted on the basis of the COPERTV model [16][16] and are presented in Table 5. Since emissions are related to the mileage of a vehicle with a specific technology, calculations were made in accordance with the fuel consumption over that distance.

For the obtained solutions presented in section 5.2, the results of additional assessment measures were obtained. They are presented in Table 6.

Table 5. Specific emissions of harmful substances based on the COPERTV model

COPERT model emission factors						
Harmful substance	unit	nv = 1	nv = 2	nv = 3	nv = 4	nv = 5
efCO	(g/km)	0.62	0.04	0.049	0.043	0
$efNO_x$	(g/km)	0.065	0.008	0.008	0.001	0
efNMVOC	(g/km)	0.061	0.55	0.17	0.013	0
efPM	(g/km)	0.0014	0.0021	0.0015	0.000142	0

Table 6. Evaluation of the obtained solutions using additional measures

Scenario	S1.1	S1.2	S1.3	S2.1	S2.2	S2.3	S3.1	S3.2	S3.3
CO	227.82	239.58	247.83	0.00	0.00	0.00	5.40	135.04	149.52
NO_x	23.88	25.12	25.98	0.00	0.00	0.00	0.13	14.16	15.68
NMVOC	22.41	23.57	24.38	0.00	0.00	0.00	1.63	13.29	14.71
PM	0.51	0.54	0.56	0.00	0.00	0.00	0.02	0.30	0.34
F1.1	7.61	7.59	7.59	5.22	5.07	5.05	5.91	6.51	6.62
F2.1	0.22	0.24	0.24	0.00	0.00	0.00	0.08	0.13	0.13

By adopting the developed criteria, the assumptions were modified, and the designated solutions for the selection of vehicles and drivers for the tasks were re-evaluated. The characteristics of the area where the tasks are carried out have changed. It was assumed that an urban area would affect the change in fuel consumption. The adjusted values are presented in Table 7. It was assumed that hybrid and electric vehicles in urban areas consume less fuel than outside the city, contrary to conventional internal combustion engines. The results of the assessment for the changed assumptions are presented in Table 8.

Table 7. Change in fuel/energy consumption in the sensitivity analysis of the solution

Vehicles (nv)						
data	unit	nv = 1	nv = 2	nv = 3	nv = 4	nv = 5
fu(nv)	l/km or kWh/km	0.062	0.08	0.06	0.042	0.145

To sum up, the considerations carried out should be pointed out that the best solutions from the company's point of view are based on the current fleet and a trained driver. This results from low vehicle financing costs and relatively low fuel consumption, which compensates for higher service costs. Nevertheless, it should also be pointed out that this is definitely the worst solution in terms of pollutant emissions. However, by choosing between scenarios S1.1 and S3.3, giving up 12% of income, it is possible to reduce the external cost of CO_2 emissions by over 41%. The obvious result, guided by ecological considerations, are the S2.1–S2.3 variants, which use electric vehicles, and, thus, in simple terms, do not emit exhaust gases into the atmosphere. However, the cost of financing these vehicles exceeds, for example, in variant S1.1 several times, and thus any savings in operating costs cannot compensate for this in such a period.

Table 8. Results analysis of the sensitivity of the solution to changes in fuel/energy consumption

Scenario	S1.1	S1.2	S1.3	S2.1	S2.2	S2.3	S3.1	S3.2	S3.3
CO	294.27	309.46	320.11	0.00	0.00	0.00	4.83	174.43	193.13
NO_x	30.85	32.44	33.56	0.00	0.00	0.00	0.11	18.29	20.25
NMVOC	28.95	30.45	31.49	0.00	0.00	0.00	1.46	17.16	19.00
PM	0.66	0.70	0.72	0.00	0.00	0.00	0.02	0.39	0.44
F1	159.90	159.68	159.49	112.34	112.10	111.66	126.22	137.09	143.42
F2	6.11	6.34	6.49	0.00	0.00	0.00	1.44	3.51	4.03
F1.1	7.53	7.51	7.51	5.25	5.10	5.08	5.94	6.48	6.58
F2.1	0.29	0.31	0.31	0.00	0.00	0.00	0.07	0.17	0.17

Performing a sensitivity analysis highlights the differences in pollutant emissions. Undoubtedly, older vehicles generate more pollution and, therefore, even higher external costs. Changing the traffic area, and thus fuel or energy consumption, reduced the cost differences between the variants in favor of new vehicles and electric vehicles. Nevertheless, in the adopted analysis period, this impact is too small to be decisive for changing the approach and selecting other vehicles for the fleet. For conventional vehicles, revenue has declined in urban areas; income increases slightly with electric and hybrid vehicles. However, this indicates a certain regularity that the characteristics of the area of operation of the vehicle-driver combination play an important role in the selection of means of transportation. In urban areas, hybrid vehicles perform best, followed by electric vehicles, while combustion vehicles perform best in rural areas. However, from a purely economic calculus point of view, internal combustion vehicles dominate regardless of the work area. It should be noted that in most variants, the drivers were inexperienced but trained in the principles of eco-driving employees. Lower employment costs outweigh training costs.

Conclusions

The purpose of this article was to conduct research showing the impact of the selection of the car fleet according to the main criterion, which is the TCO for pollutant emissions, as well as a comparison of this approach with the approach that considers the external costs of exhaust emissions. The article proposes a research method based on the developed mathematical model and the use of the Flexsim environment with the OptQuest optimization module. The method was used to conduct experiments on a fragment of the transport system of a selected company. It should be pointed out that the proposed method is easy and quick to apply and can be used by fleet managers in practice. It takes into account the marginalized problem of pollutant emissions in their daily work.

The computational experiments were performed on a small computational example. It should be noted that for a larger scale and more diverse fleet, as well as the tasks carried out, the pollutant emissions will be much higher. Thus, the ecological criterion should be an important indicator in the selection of vehicles. In addition, based on the obtained results, certain regularities are visible, which at the same time are barriers to the development of a sustainable transport system and the increase in the share of environmentally friendly vehicles (EFV). They mainly concern the costs of financing such vehicles in the enterprise. Lower fuel consumption or lower service costs cannot compensate for the vehicle's high price. Thus, in Polish conditions, where the approach to minimizing costs and maximizing profits dominates, the possible choice of EFV vehicles will be dictated by other criteria, such as image benefits. This is also influenced by the country's transport policy. The introduction of additional tax reliefs, preferences for users of such vehicles, or higher subsidies for their purchase could increase the popularity of such vehicles.

The directions for further research can also be indicated based on the sensitivity analysis results. It should be noted that the COPERT (Tier 2) methodology adopted considers constant emission values for different motor vehicle technologies. Therefore, to indicate the impact of changing the characteristics of the service areas, this was related to fuel consumption. However, to more accurately predict the impact of changing the area, it would be necessary to use a detailed COPERT methodology (Tier 3), taking into account the type of traffic area and HOT and COLD emissions. More detailed studies, however, require precise data on the speed profile or atmospheric conditions. Therefore, this is the direction of research that could indicate to what extent the advantage of EFV vehicles in terms of emissions is greater than vehicles with a conventional drive, depending on the area. Another area for further research is the introduction of a limitation in the model regarding the maximum costs or limiting the possibility of using vehicles of a given type. This would better represent the actual decision problem. Additional modifications should also consider many more factors influencing the income effect. It should be pointed out here, for example, the possibility of charging the vehicle at the base (lower energy costs), possible surcharges and discounts, variable operating costs, and finally, reliability and safety. For example, in the case of inexperienced drivers (with lower employment costs), the risk of an accident may increase, and thus the possibility of more damage. As a result, fewer orders will be completed, costs will increase, and the company's revenues will decrease. Another modification to be explored in future studies is the possibility of changing the assignment of a driver to a vehicle within an owned fleet during the analysis period.

Summing up, research in the field of car fleet management in terms of pollutant emissions will be continued because, as indicated based on the literature review and the author's experience, this problem is marginalized in practical applications and, at the same time, is very important from the point of view of the development of a sustainable transport system. At the same time, it should be noted that despite the simplified nature of the decision-making model, based on the research results, it can be indicated that in the current conditions, companies will continue to favor cheaper vehicles to reduce operating costs and maximize income, and thus use vehicles that cause more environmental pollution.

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Nomenclature

CCO$_2$	cost of CO_2 emissions
eLCV	electric light commercial vehicles
EFV	environmentally friendly vehicles
F1	interpretation of the company's income from the tasks performed
F2	interpretation of CO_2 emission
FRP	fleet replacement problem
NA	service areas
ND	set of drivers
NV	vehicles in the model
T	numbers of individual days
TCO	total cost of ownership

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