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Research and analysis of the operation of vehicles with various propulsion systems, including costs and CO_2 emissions

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The article analyzes and evaluates costs, transport time and CO_2 emissions by selected vans. The research was carried out on the example of three models of Iveco Daily vehicles powered by: diesel oil, electricity and compressed natural gas (CNG). The result of the research presented in the article is the determination of the operating costs of vehicles powered by various energy sources and the level of CO_2 emissions. The comparative analysis was carried out on real data for the established transport task. Vehicles with engines powered by compressed natural gas are characterized by the highest savings in terms of transport costs. As the authors pointed out, this may be due to the fact that this type of engines, despite the low interest of buyers at the moment, may gain much more popularity in the future. On the other hand, in relation to vehicles with electric motors, the cost of transport is the highest, which means that this type of technology is ineffective in relation to long-distance transport.

Key words: *combustion engine, electric motor, exhaust emissions, comparative analysis, operation*

1. Introduction

The operation of combustion, electric and compressed natural gas vehicles is a topic that attracts a lot of interest among both scientists and practitioners from the automotive industry. In recent years, with the increase in the ecological awareness of the society, this issue has become even more topical due to the need to reduce the emission of harmful substances into the atmosphere.

In this context, the so-called alternative drives. As indicated by the author of the work [29], alternative drives are all drives whose overriding goal is to reduce the consumption of fossil fuels. In the initial stage of the idea, the introduction of this type of drive units was to make the world independent of the availability of crude oil. Today, however, the goal is a bit broader and much more ambitious: vehicles with alternative drives generally emit less harmful exhaust gases, and thus are more environmentally friendly and contribute less to the progressing climate change [15].

This applies not only to limited carbon dioxide emissions, but also, for example, nitrogen oxides or hydrocarbons, which can contribute to the development of serious diseases, such as cardiovascular diseases or cancer. One of the basic impulses that draw the attention of vehicle manufacturers and users to new technical solutions is also the need for vehicles to meet strictly defined technical requirements [26]. These requirements must be met both at the design stage and at the operational stage. Legislative centers of individual countries or organizations deal with defining new guidelines and setting deadlines for their implementation. Legal acts currently in force in Poland must comply with the guidelines of the European Commission or the European Parliament [3].

The dynamically growing demand for goods generates a constantly growing demand for transport services, which in turn translates into the need to develop technologies in the area of broadly understood transport and logistics. With the progressive development of automotive technologies, more and more attention is paid to alternative sources of vehicle propulsion [42]. One of the biggest challenges in the field of transport is to reduce emissions of harmful substances and limit the impact of the transport sector on climate change. In this context, electric motors and motors powered by alternative energy sources are gaining popularity as a potential alternative to traditional internal combustion engines [37].

Engineers working on modern technological solutions in the field of vehicles powered by alternative energy sources are trying to design transport devices that provide relatively increasing transport efficiency while minimizing costs, which are influenced by factors such as reliability of manufactured devices, fuel/electricity demand or ease of use. The growing problem related to the stringent regulations on exhaust gas emission levels and the increasingly difficult situation with the workforce generates the need for systematic development of this field [3]. From the point of view of employers, an indispensable aspect in the case of designing new technologies in the field of road freight transport is the development of new transport devices, the operation of which requires the involvement of a relatively smaller number of people, and the development of technologies to ensure a greater range of the vehicle on a single charge/refuelling [4].

The main purpose of the study is to analyze and compare the latest technologies available in the field of domestic cargo distribution using delivery vehicles. The performed analysis focuses on the comparison of delivery vehicles powered by different power sources.

The article presents research on the operation of combustion, electric and compressed natural gas-powered vehicles. The authors analyzed the operating costs of selected vehicles in the implementation of transport tasks annually. Attention was focused on taking into account the costs related to CO_2 emissions.

2. Literature analysis

The literature analysis on the operation of internal combustion, electric and CNG vehicles may cover many aspects. The topic of internal combustion vehicles covers primarily issues related to the repair and maintenance of internal combustion engines and diagnostic tests. Among them, one can distinguish the assessment of the technical condition of internal combustion engines and their components, optimization of engine operation in terms of efficiency and economy, or research on exhaust emissions and the impact of internal combustion engines on the natural environment.

Internal combustion vehicle technology is related to the systems and components used in internal combustion engines, which are the main source of propulsion in traditional cars [13, 40]. Combustion engines are based on the principle of combustion of a mixture of fuel and air inside the cylinder, which generates the mechanical energy needed to move the vehicle [42]. The most common internal combustion engines are reciprocating engines, including gasoline and diesel engines. The technology of internal combustion vehicles also includes fuel supply systems, cooling, exhaust and drive systems [1, 6]. Each of these components plays an important role in the proper functioning of the internal combustion engine and ensures optimal performance. The technology is constantly improved in order to improve efficiency, reduce pollutant emissions and increase the economy [13].

In recent years, various innovations have been introduced, such as direct fuel injection systems, turbochargers, stop-start systems or hybrid drive systems to increase efficiency and reduce the negative impact on the environment [22]. However, the disadvantage of internal combustion engines is still the emission of pollutants such as nitrogen oxides and carbon dioxide, which harm the environment and human health. There are many sources of literature that focus on research on internal combustion vehicles. The authors of the work [25] analyzed the assessment of the impact of the temperature management strategy on engine warm-up in modern spark engines. The article presents techniques such as thermal insulation, the use of thermoactive pumps or cooling system control in order to assess the impact of these strategies on engine warm-up time, its efficiency, fuel consumption and exhaust emissions. The authors of the publication [14] examined the influence of the type of fuel on the emission of pollutants from a compression-ignition engine (diesel engine).

In the article [38], experimental studies related to the efficiency and emission characteristics of a turbocharged diesel engine, which is fueled with fuel mixtures consisting of aviation kerosene and diesel oil, were carried out. The aim was to evaluate the application potential and to understand the effect of the kerosene-oil mixture on engine performance and pollutant emissions. In publication [39], optimization of the compression ratio of a spark engine fueled with mixtures of methanol and gasoline was carried out. The study was based on the use of a multi-criteria method that takes into account various quality indicators, such as combustion efficiency, power, torque and pollutant emissions.

Despite many years of development of internal combustion vehicle technology, interest in alternative power sources, such as electric drive, has recently increased. Literature on electric vehicles focuses mainly on issues related to their power supply or maintenance in proper technical conditions. The discussed topics concern the design and operation of power supply systems, energy management in vehicles and their charging, safety issues during operation or the comparison of the costs of using internal combustion and electric vehicles [31, 32].

Electric vehicles use accumulators or batteries to store electricity that drives the engine [18]. The cars are characterized by low emissions of exhaust gases and carbon dioxide, which makes them environmentally friendly. Electric motors are characterized by quiet engine operation, which allows for a more comfortable ride. The constantly growing interest in electric vehicles contributes to the development of the charging infrastructure [2, 24]. More and more public and private places offer charging stations.

However, despite the continuous development of electric vehicles, the issue of the limited driving range on a single charge remains a big challenge. This is still a big problem for some users. This creates some challenges, extending the charging time compared to refueling and limiting the availability of charging stations in some areas [20]. Despite this, electric vehicles contribute to reducing greenhouse gases and improving air quality [26]. There are many scientific publications that analyze various aspects of electric vehicles. In the article [24], the authors examine issues related to electromobility, such as charging infrastructure, batteries, or power grids.

Many publications, e.g. [12, 42] refer to research related to the emission of harmful substances from the drive system. The papers show that emissions are dependent on the source of electricity, but even with a fossil fuel-based energy mix, emissions from electric vehicles tend to be lower than those of internal combustion vehicles. Publication [17] focuses on the study of CO_2 emissions generated by internal combustion and electric vehicles in car-sharing systems. Position [5] focuses on the analysis of the impact of the network effect on profits and social welfare related to the introduction of electric vehicles. In [8], an effective approach to estimating energy consumption by electric vehicles is presented, which is important when planning and optimizing the fleet of vehicles, as well as managing energy costs in service companies.

The literature on cars powered by compressed natural gas (CNG) provides information on the efficiency, emissions, infrastructure availability and economic aspects related to this type of propulsion. Natural gas is compressed to reduce its volume and increase its density. It is then used as fuel to power the vehicle's engine. In order to use CNG, cars must be equipped with appropriate gas supply systems [35]. Articles [33] or [19] present the current situation of air pollution caused by vehicles powered by compressed natural gas and possible technologies for reducing these emissions. Similarly, [37] provides conclusions and data related to the ecological and economic benefits resulting from the use of CNG power systems in small wood shredders. This is important because small internal combustion engines often generate a significant amount of harmful emissions. The publication [16] analyzes the emission of the particle number (PN – Particle Number) generated by various types of vehicles, including light vehicles powered by CNG while driving in real road conditions. The aim was to compare the PN emissions for different types of cars, which is important for assessing their impact on air quality. CNG is one of the alternative fuels used to reduce pollutant emissions and reduce the negative impact of transport on the environment. Vehicles powered by compressed natural gas are considered more environmentally friendly than vehicles powered by traditional fuels.

3. Costs of the transport task

3.1. General remarks

The factor that plays an important role in the development of transport technology is the cost of carrying out transport tasks. Transport activity incurs costs that can be divided into fixed and variable costs. Fixed costs do not depend directly on the level of production or sales. These are costs that occur regardless of whether the enterprise is fully operational or has no activity at all [11]. Variable costs are directly related to the level of production or sales. Increasing the company's activity, such as selling more goods, leads to an increase in variable costs. If, on the other hand, the company's activity decreases, variable costs also decrease [11, 23].

Fixed and variable costs will be analyzed in the article for individual vehicles (variants).

Fixed costs:

- depreciation costs of means of transport
- costs of taxes on means of transport (vehicles up to 3.5 tons are not taxed)
- costs of insurance of means of transport
- driver salary costs.

Variable costs:

- road toll costs (vehicles with a GVM up to 3.5 tons are not subject to tolls and there are no motorway tolls in the analyzed section)
- fuel consumption costs
- parking costs of electric cars at charging stations
- costs of environmental fees (for delivery vehicles meeting the EURO VI emission standard, the rate of fees for the introduction of gases and dust is not provided)
- drivers' allowance costs
- costs of servicing means of transport
- costs of replacing tires in means of transport.

3.2. Depreciation costs of means of transport

The Accounting Act [33] and the Corporate Income Tax Act [32] provide information that means of transport are subject to depreciation as fixed assets with a useful life longer than one year when calculating their initial value. The depreciation rate for vans is 20% in accordance with the Classification of Fixed Assets.

$$\mathrm{K_{AP}} = \mathrm{K_{A1P}} \cdot \mathrm{L_{poj}}\ [\mathrm{PLN/year}] \tag{1}$$

where: $\mathrm{K_{AP}}$ – annual depreciation costs for the total number of vehicles, $\mathrm{K_{A1P}}$ – annual depreciation costs for one vehicle, $\mathrm{L_{poj}}$ – number of vehicles (on an annual basis).

The annual depreciation cost of the vehicle was calculated using the formula:

$$\mathrm{K_{A1P}} = \mathrm{W_{PD}} \cdot \alpha_\mathrm{D} [\mathrm{PLN/year}] \tag{2}$$

where: $\mathrm{W_{PD}}$ – initial value of the delivery vehicle, α_D – annual depreciation rate for the car.

3.3. Costs of insurance of means of transport

Commercial vehicle insurance includes various types of policies that provide financial protection in the event of damage [43]. The insurance of the analyzed vehicles includes OC, AC and accident insurance. Liability insurance is obligatory and covers damage caused to third parties as a result of an accident caused by a van. Another insurance that applies to the analyzed vehicles is AC (auto-casco), which protects against situations such as accident, theft, fire and unforeseen events.

The AC policy covers the costs of repair or replacement of a delivery vehicle as a result of undesirable damage. The last type of insurance is NNW (Accidental Consequences), which provides financial protection in the event of personal injury that may be suffered by the driver or passenger. Such policies cover all analyzed vehicles – internal combustion, electric, and CNG-powered.

The total annual cost of insurance is calculated from the following relationship:

$$\mathrm{K_{UP}} = \mathrm{K_{U1P}} \cdot \mathrm{L_{poj}}\ [\mathrm{PLN/year}] \tag{3}$$

where: $\mathrm{K_{U1P}}$ – annual costs of insurance of the delivery vehicle.

3.4. Driver salary costs

In the enterprise, drivers are employed on the basis of an employment contract. The costs of drivers' remuneration include net remuneration and overheads for remuneration and benefits – social security contributions (pension, accident and disability pension), as well as write-offs to the Labor Fund (FP) and the Guaranteed Employee Benefits Fund (FGŚP). The number of drivers needed to perform a transport task results from the number of vehicles that are necessary for this purpose. In addition, one reserve driver is employed.

The number of drivers can be calculated using the formula:

$$\mathrm{L_k} = \mathrm{L_{KP}} + \mathrm{L_{KR}}\ [\mathrm{drivers}] \tag{4}$$

where: $\mathrm{L_{KP}}$ – number of employed drivers, $\mathrm{L_{KP}} = \mathrm{L_{poj}}$, $\mathrm{L_{KR}}$ – number of reserve drivers, $\mathrm{L_{KR}} = 1$.

The monthly total remuneration costs of drivers can be determined using the following relationship:

$$\mathrm{K_{WK}} = (\mathrm{K_{WP}} + \mathrm{K_{NW}}) \cdot \mathrm{L_K}\ [\mathrm{PLN/month}] \tag{5}$$

where: $\mathrm{K_{WP}}$ – monthly salary costs of the employed driver [PLN/month], $\mathrm{K_{NW}}$ – monthly costs of mark-ups on the driver's remuneration [PLN/month].

3.5. Fuel/energy costs

The cost of fuel consumption depends on the average fuel consumption of the vehicle and the price of this fuel.

Annual fuel consumption costs are calculated for the total number of means of transport:

$$\mathrm{K_{RRP}} = \mathrm{K_{ZP}} \cdot \mathrm{L_{poj}}\ [\mathrm{PLN/year}] \tag{6}$$

where: K_{ZP} – annual costs of fuel consumption for one vehicle [PLN/year].

$$K_{ZP} = \frac{Z_p \cdot C_p}{100} \cdot L_{RP} \text{ [PLN/year]} \quad (7)$$

where: Z_p – average fuel/energy consumption of a delivery vehicle [dm^3/100 km]/[kWh/100 km]/[m^3], C_p – average net price of fuel/energy [PLN/l]/[PLN/kWh]/[PLN/m^3], L_{RP} – annual vehicle mileage [km], $L_{RP} = L_{MP} \cdot 12$, L_{MP} – monthly vehicle mileage in km.

3.6. Costs of parking electric cars at charging stations

The cost of parking an electric car at charging stations may vary depending on many factors, such as location, charging station operator, type of charger, parking time and service charges. In the case of multiple stations, fees may be charged based on the time of stoppage or the amount of energy delivered. The amount of charging rates and parking fees for electric cars is presented in Table 1.

Table 1. Charge rates and parking fees for electric cars [27]

Charger type	Charging rate [PLN/kWh]
AC	1.89
DC (≤ 50 kW)	2.69
DC (50 kW < x ≤ 125 kW)	2.89
DC (> 125 kW)	3.19
The rate for parking is 0.40 [PLN/min] – charged after 45 minutes from the start of charging for DC connectors.	

In the analyzed case, due to the greatest availability of DC chargers with a power of ≤ 50 kW, selected locations for charging electric vehicles have such devices. Therefore, the power supply is carried out using DC chargers with the specified power.

The cost of parking an electric car at a charging station in a transport relation is expressed by the following formula:

$$K_{PSE} = \gamma_P \cdot t_ł \cdot n_ł \text{ [PLN]} \quad (8)$$

where: γ_P – the rate for parking at the charging station [PLN/min], $t_ł$ – electric vehicle charging time (reduced by 45 minutes) [min], $n_ł$ – number of loads in a transport task.

The total cost for parking cars at charging stations is:

$$K_{ŁP} = K_{PSE} \cdot d_r \cdot L_{poj} \text{ [PLN/year]} \quad (9)$$

where: d_r – number of working days, $d_r = 250$.

3.7. Driver allowance costs

The Regulation of the Minister of Labor and Social Policy of 2022 [30] states that drivers are entitled to a business travel allowance. Domestic travel is considered in the analyzed case. The diet is granted for food costs and currently amounts to PLN 45 per day of travel. According to the regulation, when the trip is shorter than a day and amounts to:

- up to 8 hours – the diet is not due
- from 8 to 12 hours – 50% of the diet is due
- over 12 hours – 100% of the diet is due.

Considering the above, the transport route for a combustion vehicle and a CNG-powered vehicle is from 8 to 12 hours, therefore the value of the business trip allowance is 50%. In the case of electric cars, the entire route (including charging) will be over 12 hours, which means that the driver is entitled to 100% of the allowance. The amount of the annual cost of business travel allowances can be determined by the following formula:

$$K_{DK} = K_{DK}^{PL} \cdot 12 \text{ [PLN/year]} \quad (10)$$

where: K_{DK}^{PL} – monthly costs of allowances for 1 driver [PLN/year].

The rate of annual business trip allowance costs for the total number of drivers carrying out the transport can be calculated from the following relationship:

$$K_{CDK} = K_{DK} \cdot L_{KP} \text{[PLN/year]} \quad (11)$$

3.8. Vehicle service and tire replacement costs

The costs of services include the costs of replacement of operating fluids, as well as the costs of servicing vehicles resulting from wear and tear, as well as breakdowns and repairs. Annual service costs for the total number of vehicles are expressed as follows:

$$K_{SP} = K_{S1P} \cdot L_{poj} \text{ [PLN/year]} \quad (12)$$

K_{S1P} – annual cost of servicing one vehicle [PLN/year].

The annual costs of replacing tires depend on the rate of their wear. For the purposes of the analysis, it was assumed that tires are replaced every 100,000 km. The cost of tires for the total number of vehicles is:

$$K_{ZO} = K_{Z1O} \cdot L_{poj} \text{ [PLN]} \quad (13)$$

where: K_{Z1O} – cost of a set of tires for one delivery vehicle [PLN].

The total number of tire changes per year is 3.

4. Analysis of transport costs and CO_2 emissions based on real data

4.1. Determining the parameters of the cargo to be transported

For the purposes of the analysis, it was assumed that the transported load would be the engine oil filter. It is characterized by high transport susceptibility and relatively low weight. The analyzed pallet load unit consists of collective packaging in the form of 24 cartons, the contents of which include 12 filters. The retail unit is, in turn housed in a unit package. Figure 1 shows the scheme of creating a pallet load unit being the subject of transport.

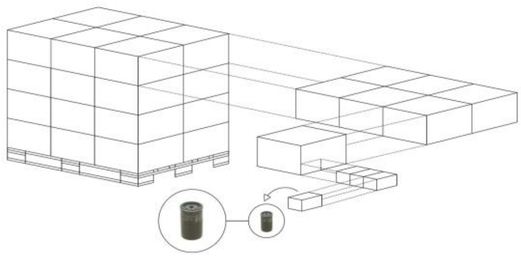

Fig. 1. Scheme of creating a pallet load unit being the subject of transport [own elaboration based on AutoCAD]

One transport includes four pallet load units, which means that the total weight of the load on the vehicle is 800 kg. Transport is carried out once a day, which directly translates into the need for one vehicle to carry out a transport task.

4.2. Technical and operational parameters of vehicles

The selection of the right vehicle for the transport task is a key element of effective logistics and can have a significant impact on the costs, efficiency or equivalence of transport operations. Before making a choice, several important factors should be taken into account [9]:

- Load requirements – The first and most important step is to correctly understand the characteristics and individual requirements of the load itself. Estimate the weight, external dimensions, weather sensitivity, value and any special transport requirements.
- Transport route – a very important aspect is the distance to be covered as part of the transport task and the nature of the route. If the transport will be performed over short distances within the city, electric vehicles may be more appropriate. On the other hand, for long distances, where the range and availability of charging places are important factors, combustion vehicles may be a better alternative.
- Fuel efficiency – When it comes to minimizing vehicle operating costs, the fuel efficiency of different types of vehicles should be considered. In the case of traditional internal combustion engines, attention should be paid to fuel consumption, and thus also to the level of emission of harmful substances into the atmosphere. In the case of electric vehicles, fuel savings may be greater, and the transit time may be adversely affected due to the long charging time of the battery.
- Infrastructure and availability – The availability of refueling/charging infrastructure is also an important factor. While the availability of petrol stations is very high, the situation with vehicle charging stations and available charging stations is a bit more complicated.
- Operating costs – An analysis of operating costs is an indispensable element when choosing a vehicle. When planning, the costs of purchase, maintenance, repairs, insurance and fuel or electricity should be taken into account.

Transport will be carried out using delivery vehicles with a maximum weight of up to 3.5 tons powered by three energy sources. The paper presents the technical parameters of vehicles powered by diesel oil (variant 1), electricity (variant 2) and compressed natural gas (CNG) (variant 3). The vehicle under analysis is the IVECO Daily in the following versions: standard, electric and natural power. The maximum permissible weight of each vehicle is 3.5 tonnes. The engine power of the vehicle powered by diesel oil and compressed natural gas is respectively 136 horsepower, while the electric vehicle generates 110 horsepower. Each of the vehicles is equipped with "Back Sleeper" type sleeping cabins, enabling rest during the transport. Due to the clearly defined technical parameters of the shipment and for the needs of the cargo, whose transportability is relatively high, a vehicle with a box body was selected. The company carries out domestic transport in various relations. The analyzed route has one dedicated vehicle and one driver. One transport cycle is carried out in one day. In the case of variant one and variant 3, the duration of the journey does not include the driver's daily rest, while in variant 2 the daily rest is carried out in the vehicle cabin while the vehicle's battery is being charged. The table below summarizes the basic data of the transport task.

Individual parameters were determined on the basis of the vehicle configurator available on the manufacturer's website. The work assumes the speed of travel on highways up to 90 km/h. Favorable weather conditions and no capacity disturbances on the analyzed section of the route were assumed. In Table 3 presents the technical data of the analyzed vehicles.

Table 3. Vehicle technical data [7]

Vehicle type / Parameter	Variant 1	Variant 2	Variant 3
Max. range [km]	900	200	350
Refueling/charging time [min]	2	150	5
CO_2 emissions per 100 km [kg]	26.8	0	22.8
Cost of traveling 100 km [PLN]	67	81	51
Noise emission [dB]	85	50	70
Exhaust emission standard	EURO VI	–	EURO VI

4.3. Determination of routes and locations of vehicle power supply points

The article outlines the route from Warsaw to Wroclaw. The return route was also taken into account when designing the journey. Transportation will be performed using combustion, electric and compressed natural gas vehicles. During the planning of the route, power points for the above-mentioned types of vehicles were determined. On the basis of the outlines containing the technical data of the analyzed vehicles, the range of a given vehicle on one refueling/charging was analysed. Due to the above, it was possible to determine at what kilometer intervals the supply points should be considered. Attention was paid to refueling/charging cars before reaching the reserve. Appropriate level of energy/fuel and their regular monitoring ensures smooth driving and a guarantee of delivering the load in accordance with the guidelines. Determining the location of vehicle charging points required an analysis of available charging/refueling points on the road, types of chargers, availability, opening hours and prices.

Figure 2 shows the course of the transport route for a combustion vehicle, taking into account petrol stations, loading and unloading places.

Fig. 2. The course of the route for a combustion vehicle [own elaboration based on PTV Map&Guide]

The next diagram (Fig. 3) shows the course of the road for an electric vehicle, including charging points and places of delivery/collection of the charge.

Fig. 3. Transport route for an electric vehicle [own elaboration based on PTV Map&Guide]

Figure 4 illustrates the transport relation for a vehicle powered by compressed natural gas, taking into account the place of refueling and delivery and collection of the cargo.

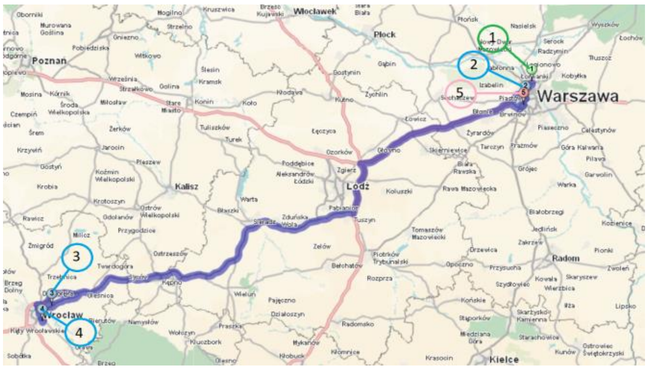

Fig. 4. Transport route for a CNG-powered vehicle [own elaboration based on PTV Map&Guide]

The numbers used in the figures are discussed in Tables 4 and 5.

Table 4. Locations of loading, refueling/loading and unloading points for vehicles on the Warsaw–Wroclaw route

Warszawa – Wroclaw route			
	Designation	Location	Operation
Combustion vehicle	1	Panttoni Europe Warsaw Odlewnicza 6	Loading
	2	Gas station ORLEN al. 3maja 1a	Refueling
	3	DHL Wrocław, Bierutowska 75	Unloading
Electric vehicle	1	Panttoni Europe Warsaw Odlewnicza 6	Loading
	2	Gas station ORLEN al. 3maja 1a	Charging
	3	Gas station ORLEN Sięganów 79d	Charging
	4	DHL Wrocław, Bierutowska 75	Unloading
CNG-powered vehicle	1	Panttoni Europe Warsaw Odlewnicza 6	Loading
	2	Station PGNiG CNG I. Prądzyńskiego 16	Refueling
	3	DHL Wrocław, Bierutska 75	Unloading

Table 5. Locations of loading, refueling/loading and unloading points for vehicles on the Wroclaw–Warsaw route

Wroclaw–Warszawa route			
	Designation	Location	Operation
Combustion vehicle	3	DHL Wrocław, Bierutowska 75	Loading
	4	Warsaw, Krakowiaków 44	Unloading
Electric vehicle	4	DHL Wrocław, Bierutowska 75	Loading
	5	Gas station ORLEN Maślicka 218	Charging
	6	Service Station, Paprotnia 26a	Charging
	7	Warsaw, Krakowiaków 44	Unloading
CNG-powered vehicle	3	DHL Wrocław, Bierutowska 75	Loading
	4	Gas station Wrocław, Gazowa 3	Refueling
	5	Warsaw, Krakowiaków 44	Unloading

Electric vehicle users can choose to charge their vehicles using two basic types of chargers. These are chargers that generate alternating current (AC chargers) and direct current (DC chargers). A given type of charger is characterized by charging speed and the cost of 1 kWh. AC chargers are a more common type found in versions for personal use (in the so-called Wallboxes) as well as commercial ones. At home, the power of chargers of this type is usually from 3.6 to 22 kW. They use single-phase (230 V) or three-phase (400 V) voltage. The charging time of a vehicle with a battery with a standard capacity of 50 kWh with this type of charger varies from 3 to 5 hours.

DC chargers located in service areas, parking lots or petrol stations are often a better choice for drivers on the road. This is primarily due to the fact that their power is much higher compared to AC, ranging from 50 to 150 kW, but can also have a higher power. In the case of this work, the analysis took into account the charging of vehicles at petrol stations belonging to the Orlen Concern, which has DC chargers with a capacity of 50 kW and 100 kW. The charging time of the battery with a capacity of 75 kWh in the used vehicle is approx. 2.5 hours.

5. Comparative analysis of costs and selected vehicle parameters

5.1. Summary list of fixed and variable costs

The considered case assumes that 2023 the vehicle will be operated for 250 days, because this is the number of working days. The work assumes that the length of the route in one transport cycle is approx. 750 km. The daily fuel consumption for a diesel vehicle is approx. 83 liters, for electricity, it is 225 kWh, while the consumption for a CNG vehicle is 113 m^3 of compressed natural gas. Outlays presented in the work are gross costs.

Based on the adopted assumptions, calculations of individual cost components were made, which are summarized in Table 6.

Table 6. Aggregate data relating to the analyzed costs

Parameter \ Variant	Variant 1	Variant 2	Variant 3
The initial value of the vehicle [thousand PLN]	210	180	190
OC, AC, NNW [PLN/year] (delivery vehicle)	3,500	4,000	4,200
Average fuel consumption	11 [dm^3/100 km]	30 [kWh/100 km]	15 [m^3/100 km]
Fuel/energy price	6.09 [PLN/l]	2.69 [PLN/kWh]	3.40 [PLN/m^3]
Employee allowance cost [PLN]	22.5 (up to 8 hours)	45 (up to 12 hours)	22.5 (up to 8 hours)
Net salary (1 driver) [PLN/month]	5,000	5,000	5,000
Total cost of overheads (1 driver) [PLN/month]	1,014	1,014	1,014
Total gross salary cost (1 driver) [PLN/month]	6,014	6,014	6,014
Cost of servicing one vehicle [PLN/year]	60,000	50,400	60,000
The cost of a set of 4 tires [PLN]	2,400	2,400	2,400

Based on the technical data from section 4.2 and calculations for individual vehicles in section 3, fixed and variable costs were estimated on an annual basis.

Table 7. Fixed and variable costs, detailing the costs related to CO_2 emissions for individual variants

Type cost \ Variant		Variant 1	Variant 2	Variant 3
Fixed costs	Depreciation costs [PLN/year]	42,000	36,000	38,000
	Insurance costs [PLN/year]	3,500	4,000	4,200
	Driver salary costs [PLN/year]	12,028	12,028	12,028
	Total [PLN/year]	**57,528**	**52,028**	**54,228**
Variable costs	Costs of fuel/energy consumption [PLN/year]	126,370	151,313	95,625
	Parking costs at refueling/charging stations [PLN/year]	0	42,000	0
	Costs of drivers' allowances [PLN/year]	5,670	11,250	5,670
	Service costs [PLN/year]	60,000	50,400	60,000
	Tire replacement costs [PLN/year]	7,200	7,200	7,200
	Total [PLN/year]	**193,095**	**256,583**	**162,825**

5.2. Discussion of the results of the conducted empirical research

Freight cost benchmarking is the process of evaluating various cost factors to determine the most cost-effective option. A summary of the fixed costs for individual vehicles, which include the costs of depreciation, insurance and drivers' salaries, is shown in the chart (Fig. 5).

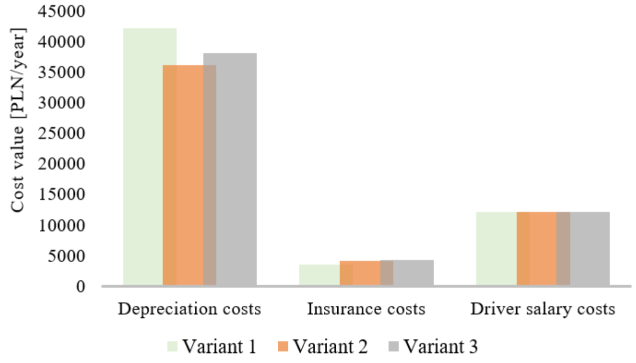

Fig. 5. The structure of fixed costs per year for individual variants

The largest part of fixed costs are vehicle depreciation costs. The electric vehicle with the lowest initial value performed best. For all the analyzed variants, the drivers' remuneration costs are the same. The last cost of insurance differs in small values between given design solutions. The lowest insurance rate is assigned to a combustion engine vehicle, and the highest to a CNG-powered vehicle.

Figure 6 shows a summary of variable costs for the analyzed variants on an annual basis. They include: costs of fuel consumption, parking at charging/refueling stations, drivers' allowances, service and tire replacement.

When analyzing variable costs, it can be seen that the most extensive cost is the cost of fuel/energy consumption of vehicles. For combustion vehicles on an annual basis, it amounted to PLN 126,370 for a given transport task, and PLN 151,313 for an electric vehicle.

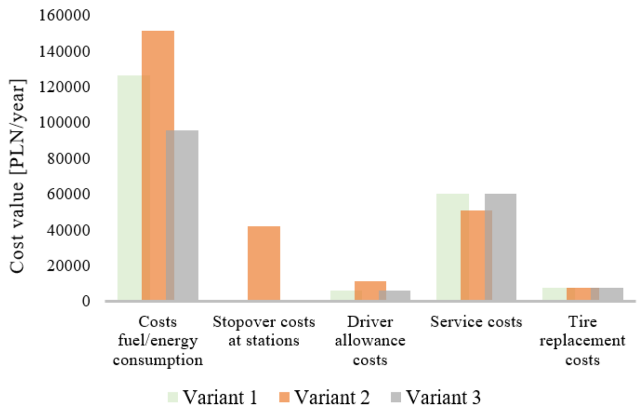

Fig. 6. The structure of variable costs per year for individual variants

In connection with the above, it is determined that this cost for a combustion vehicle is almost 17% lower than for an electric vehicle. Going further, when analyzing the cost of fuel consumption for a CNG-powered vehicle, large fluctuations in value differences with the other two types of vehicles are observed. The cost of fuel consumption of a vehicle powered by compressed natural gas is almost 24% lower than in the case of a combustion vehicle and less than 37% lower compared to an electric vehicle.

Another cost is the cost of parking cars at charging/refueling points. According to the data posted on the websites of selected locations of vehicle charging points, the total cost of parking for electric vehicles was determined, the cost does not apply to combustion and CNG vehicles. Subsequently, the cost of drivers' allowances was also included for all types of vehicles. The total working time of an electric vehicle is over 12 hours, therefore the cost of the daily allowance is PLN 45, which gives a value of PLN 11,250 per year for one driver. In the case of combustion and CNG-powered vehicles, the cost is PLN 5,670 per year.

Vehicle service costs were determined after contacting the local IVECO dealer, and the highest were allocated ex aequo for a combustion engine vehicle and a CNG-powered vehicle. The last factor analyzed is the cost of tire replacement, which was also discussed with the IVECO dealer and it was estimated that the tire replacement per year will be PLN 7,200 for each vehicle, taking into account that they will be changed three times.

In addition to costs, other aspects of the analyzed vehicles will also be compared, which affect the quality of transport services, as well as the natural environment [36]. The analysis takes into account the time of cargo transport on the selected route for given types of vehicles. Determining this parameter involved determining the distance between the starting point and the destination, the average speed of the vehicle, any stops related to loading or refueling the car, or the time of unloading/loading the goods. Data on the time of carrying out the transport task of individual vehicles are presented in Table 8.

Table 8. Time of carrying out the transport task for the analyzed vehicles

Parameter \ Variant	Variant 1	Variant 2	Variant 3
Time of carrying out the transport task [min]	540	990	540

Another parameter is the noise level in selected vehicles. A car with an internal combustion engine that runs on diesel fuel is notorious for making noise. The noise level of combustion vehicles depends on the type of engine, technical condition, driving speed or noise generated as a result of fuel explosion in the combustion chamber [41]. Electric vehicles typically generate less noise than vehicles powered by internal combustion engines. This is the result of the operation of electric motors, which do not use the fuel explosion to generate propulsion, and instead use the rotating motion of the magnet [41]. In addition, electric vehicles have better sound insulation, which contributes to noise reduction [21]. Cars powered by compressed natural gas (CNG) also generate lower noise levels compared to combustion vehicles. This is due to the fact that CNG engines create less vibrations, in addition, the exhaust system is equipped with noise silencers, which work to reduce the noise generated by vehicle exhaust emissions [10]. The aspect of vehicle noise level is very important, considering its impact on the environment and human health. Long-term exposure to high noise levels in humans can lead to hearing damage, sleep disorders or stress. In addition, the noise generated by the vehicle can have a negative impact on fauna and the natural environment, e.g. disrupt the communication of animals and disturb the balance of ecosystems. Table 3 of the article specifies the noise emission parameters of the analyzed vehicles expressed in decibels.

The last indicator is the analysis of harmful components emitted by selected vehicles. Trucks, vans and passenger cars powered by fossil fuel are associated with high emissions of greenhouse gases, especially CO_2 [22]. Substances contribute to the increase in the greenhouse effect, smog and negatively affect air quality and human health. Electric vehicles do not directly emit exhaust gases or pollutants while driving. However, emissions related to the production of electricity used to charge electric cars can contribute to CO_2 emissions if the energy comes from non-renewable sources, e.g. coal power plants [12]. When using renewable energy, such as solar or wind power, emissions directly related to vehicles are minimal. Cars powered by compressed natural gas (CNG) emit less CO_2 than combustion cars. Combustion of natural gas in the engine causes lower emissions of particulate matter and sulfur compounds compared to traditional fuels [37]. CO_2 emission levels for the purposes of the article were taken from the vehicle manufacturer's outlines. The table below presents data on annual carbon dioxide emissions for selected vehicles based on the data in Table 3.

Table 9. Carbon dioxide (CO_2) emissions on an annual basis

Parameter \ Variant	Variant 1	Variant 2	Variant 3
Annual carbon dioxide emissions [t/year]	67	0	57

6. Summary

The analyzed design variants are defined as the type of delivery vehicles used with engines powered by: diesel oil (in variant 1), electricity (in variant 2) and compressed natural gas (in variant 3). The main point of the article was to determine the route taking into account loading/unloading points and refueling/battery charging points, divided into individual design variants. For the purposes of the research, the elements influencing the operating costs of individual types of vehicles were specified. In addition, the compared parameters were: the duration of the journey and the level of noise emission.

Comparison of vehicles powered by internal combustion engines and those powered by electricity and compressed natural gas can be made on the basis of various criteria, such as: environmental performance, energy efficiency, operating costs, noise emissions and availability of filling stations/charging stations. The article estimates the operating costs of vehicles, broken down into fixed and variable costs of the transport service. The cost of depreciation of means of transport has the greatest impact on the amount of fixed costs.

In the case of variable costs, the largest overheads fall on the costs of fuel consumption. It is worth noting that the highest cost of energy consumption for an electric vehicle is largely due to market fluctuations caused by the economic crisis, which is currently affecting most European Union countries. At the moment, the prices of fuel and gas are slightly falling, so vehicles powered by these resources are taking the lead in the list proposed in this article. Another fact adversely affecting the attractiveness of electric vehicles is the obligation to pay for parking in a parking space that allows free charging of the battery. In terms of financial savings, the most advantageous variant turned out to be a vehicle powered by compressed gas (CNG). The favorable overtones of this type of transport are largely due to the price of gas, which directly translates into the lowest cost per kilometer of the route.

In the case of long-distance cargo transport, an indisputable aspect requiring comparison is also the maximum range of the vehicle on a single refueling/charging. This parameter is extremely important for entrepreneurs operating in the transport industry, because it directly affects the costs related to employees' salaries and allowances. In addition, the large range generates the ability to quickly and efficiently deliver the load to the destination. In this ranking, the electric vehicle is in last place, while the combustion vehicle is the most advantageous solution. The range of a combustion vehicle is more than four times greater than that of an electric vehicle and almost three times greater in relation to a CNG–powered vehicle.

Another analyzed parameter is the total time of carrying out the transport task. This amount is extremely important in the case of carriers performing transport, because it directly translates into wages for employees. In the case of transport performed using an electric vehicle, the transport time is almost twice as long as in the other two variants, which also has a very negative impact on the choice of this means of transport. The main factors influencing such a large discrepancy are: the maximum range on a single charge (for an electric vehicle it is up to 200 km) and the battery charging time, which is about 2.5 using a charger with a power of up to 50 kW, providing direct current during charging.

To sum up: it is definitely too early to minimize the impact of freight transport using internal combustion vehicles on the environment, because the current technologies of powering vehicles with electricity and the capacity of modern batteries are insufficient to effectively and conveniently carry out long-distance transport. With the increase in the capacity of batteries available in electric vehicles and the possibilities of chargers, this type of alternative to internal combustion vehicles may become a very beneficial solution. On the other hand, the method of powering vehicle engines with compressed natural gas is currently a very advantageous solution, ensuring a relatively high range of the vehicle and a favorable price for covering 1 km of the route. Taking into account the main analyzed parameters, such as transport costs, range, travel time or fuel replenishment time, vehicles powered by internal combustion engines continue to lead the way.

The aim achieved by the authors is to indicate the most advantageous variant among the vehicles used for load distribution in terms of transport costs, emissions of harmful substances and the level of emitted noise. The authors, conducting a comparative analysis of three variants of transport, determined that in the case of domestic transport for longer distances, combustion vehicles are still the most advantageous alternative. This is mainly due to the cost of purchasing such vehicles and the time of transport. For electric vehicles, the biggest barrier to long-distance deployment is the relatively low range. Analyzing the criterion of carbon dioxide emission and noise, the most advantageous alternative is an electric vehicle. It is impossible to draw a final conclusion, because the choice of a vehicle is mainly conditioned by the individual economic, technical and technological preferences of the buyer.

Nomenclature

AC	alternating current
AC	auto casco
CNG	compressed natural gas
CO_2	carbon dioxide
DC	direct current
NNW	accidental consequences
OC	liability insurance

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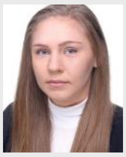

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