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Ecological and economic multicriteria optimization of operating alternative propulsion vehicles within the city of Ostrava in the Czech Republic

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Abstract

Research background: Individual car transport significantly burdens the environment, especially in the centres of large cities. There is pollution, traffic jams and an increase in overall noise. In the area of passenger car transport, legislation is being significantly tightened. Therefore, there are also increasing demands on public transport operators in the Czech Republic. Previously, most of the fleet consisted of diesel vehicles. These have been gradually replaced by drives that are significantly more environmentally friendly, such as the Compressed natural gas drive. The require-

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ments defined in relation to the reduction of vehicle emissions are increasingly stricter. A number of cities, not only within the European Union, are addressing significant issues concerning the future of public transport.

Purpose of the article: The main objective of the article is to demonstrate an in-depth analysis of the operation of transport vehicles in the Statutory City of Ostrava, both from the cost and environmental point of view. The comparison of transport means using CNG, electric and diesel propulsion is made. Specific factors such as the route profile or the environmental impact of the mode of transport are also taken into account. The extent of the data processed and the multidimensional nature of the assessment offer a unique analysis of the problem. The article provides an exact view of the advantages and disadvantages of operating specific means of transport. Everything is based on data on transport operations in the city of Ostrava (the Czech Republic, EU).

Methods: The comprehensive evaluation is based on the application of methods from the field of financial accounting, evaluation of measured data from the operation of transport means and, last but not least, on the analysis of empirical data from the given area. The analysed data set is unique due to the time period, as is the multi-criteria evaluation methodology.

Findings & value added: The analysis performed demonstrated the economic viability of operating CNG vehicles. The main added value of the article is the unique multi-criteria evaluation procedure for the vehicles. The paper shows the evaluation of a complex decision problem in the transport field in the form of a case study implemented in the city of Ostrava. The evaluation results then consider both cost and environmental factors, which can be described as a comprehensive and highly innovative approach. The defined assessment can then be applied to other European and world metropolises.

Introduction

Reserves of crude oil are continuously decreasing in parallel with growing population and increasing energy demand. Hence, it becomes necessary to enhance energy efficiency in different aspects especially transport, to make vehicles progressively greener. Thereby, the engine is expected to play a major role towards this goal (Najar, 2013). The amount of fossil fuels present on our planet is limited. The conventional fuels are also a net source of greenhouse gases. Before we run out of fossil fuels, we will have to look for other alternatives for fuels and for sources of energy. A lot of efforts are currently being made worldwide to find alternative fuels which may meet our present and future demands for energy, without causing further global-warming effects (Sangeeta *et al.*, 2014). In the world today, a total of 12,730Mtoe of energy is consumed, of which 7205Mtoe are oil and natural gas. The transport sector with over one billion light-duty motor vehicles in operation is a major consumer of oil worldwide, increasing from 45.5% in 1973 to 59% in 2011, mainly in the form of gasoline and diesel (Khan *et al.*, 2015). Unfortunately, the energy intensity of the present-day consumer-oriented society is constantly increasing. The intensification of transport is influenced by increased efficiency of logistics services. Individual deliveries and higher customer service mean a significant increase in requirements for the frequency of transport services. It is well known that

oil reserves are being depleted at an alarming rate. In addition, the burning of these conventional fuels by transport sector contributes greatly to atmospheric pollution that threatens the very survival of life on this planet (Khan *et al.*, 2015). The emission performance of transport system is a vital area and a wide range of analytical challenges need to be faced. Natural gas as transportation fuel is becoming the subject of interest nowadays, as the combustion of conventional fuel i.e. diesel and gasoline results in the harmful emissions that threaten the very survival of life on this planet (Semín & Bakar, 2008). The growing number of means of transport and the accumulation of negative effects that are reflected in the environment will require other solutions in the long run (Singh *et al.*, 2017). The function of current engines needs to be reviewed today, in the perspective of these two main crises. The energy crisis and serious environmental pollution around the world have triggered the development of low emission and high fuel-efficient vehicle to become major research objective (Aslam *et al.*, 2005; Sansyrbayeva *et al.*, 2020). These two areas are essential for sustainable development (Piwowar, 2020).

From the point of view of current knowledge, it is not possible to expect dramatic changes in the very principle of the design of means of transport in the near future. Various alternative fuels have been introduced into the transport sector e.g., liquefied petroleum gas (LPG), propane, biodiesel, hydrogen, fuel cells. Out of these available alternate fuels, compressed natural gas (CNG), is the one which meets the maximum needs of those countries worldwide which want to switch over to alternate fuels (Kato *et al.*, 1999). The use of natural gas vehicles (NGVs), first introduced in Italy in the mid-1930s as an alternative to gasoline-powered vehicles, began spreading to other countries as early as 1940. Especially after the energy crisis of the 1970s, NGVs have been promoted by governments in both developed and developing countries as a clean alternative to gasoline and diesel vehicles, and also to reduce dependence on foreign oil (Yeh, 2007). Increasing fossil fuel prices and their deterioration to environment have led to the search for alternative fuels since past several decades. Natural gas is one of such fuels available in large quantities in many parts of world at attractive prices. Natural gas is expected to be the promising fuel for many countries in the future because it is a cleaner fuel than oil or coal and not as controversial as nuclear power. Natural gas combustion is clean and emits less CO₂ compared to other fossil fuels, which makes it favorable for utilization in internal combustion engines. Natural gas is used across all sectors including industrial, residential, electricity generation, commercial, and transportation sectors. Natural gas vehicles are widely used in the Asia-Pacific region (especially Iran), Latin America, Europe, and North America

due to increased gasoline prices (Kakaee & Paykani, 2013). The following factors, in particular, speak in favour of the wider use of natural gas:

- small negative effects on the environment,
- mining brings a less environmental burden to the landscape,
- large global deposits,
- possibility of use for current propulsion engines,
- low operating costs,
- low risk with the right technology of use.

The natural gas used in natural gas vehicles is the same natural gas that is used in the domestic sector for cooking and heats. CNG is produced by compressing the conventional natural gas (which is mainly composed of methane — CH₄) to less than 1% of the volume it occupies at standard atmospheric pressure. It is stored and distributed in a rigid container at a pressure of 200–248 bar, usually in cylindrical shapes metallic cylinder planet (Khan *et al.*, 2015). Emissions from properly functioning CNG vehicles (NGVs) are generally considered to be lower than emissions from gasoline operating vehicles (Ristovski *et al.*, 2004). The main source of CNG fuel are mainly underground reserves, it can be made from agricultural waste, human waste and garbage (Wavhal *et al.*, 2016).

The main research gap can be seen in the absence of a comprehensive view at the field of public transport evaluation. This is often analyzed in isolation. Research is mainly focused on the technical issues of using different drives. Costs and the finest environmental factors are not often included in the evaluation.

The article deals with the analysis of the cost of alternative propulsion systems for vehicles used in the Transport Company of Ostrava. A comparison of the cost of vehicle operation was performed for the period 2017–2020 for compressed natural gas and electric vehicles. The solution also includes the concept of overall quality of monitored propulsion systems, created based on a synthesis of key criteria evaluating the consequences of vehicle operation.

The article structure consists of the basic literature search, the analysis of the monitored means of transport, and the overall evaluation. The monitored transport vehicles were then assessed not only in terms of cost, but also on the basis of the principles of multicriteria decision-making based on a wider range of criteria. The fundamental innovative contribution of the article can be seen in the multidimensional evaluation system. Cost aspects, as well as environmental impacts, are compared. Everything is done for more types of drives. The evaluation is, therefore, based on a single combination of different parameters.

Literature review

The use of natural gas vehicles is becoming increasingly important. The reasons are economic, but also ecological. The use of alternative fuels is also determined by their availability in individual countries. Worldwide quantities of natural gas vehicles are increasing so speedily that the statistics lag behind, and no consistent sources of information are available. However, as per the recent authentic sources, the world leader in NGVs (natural gas vehicles) is Iran, with 4.07 million NGVs (Khan *et al.*, 2015). This is significantly influenced by cost aspects, but also by the nature of the means of transport used. In countries with a high standard of living, more expensive means of transport are used to a much greater extent. Following closely behind Iran is China, with 3.99 million NGVs. Worldwide, the NGVs population has escalated speedily at an annual rate of 24% with the biggest contribution coming from the Asia-Pacific and Latin America regions. This trend is expected to continue with the average annual growth rate of 3.7% up to 2030, with a major fraction of growth contributing by non-OECD countries. In recent years, there has also been a large increase in sales of these passenger cars in countries where customers have long preferred engines with high performance, but also consumption (USA, Canada) (Khan *et al.*, 2015).

Today, there are over 18 million natural gas vehicles distributed within more than 86 countries of the world with major concentrations in Iran, China, Pakistan, Argentina, India, Brazil, Italy, and Colombia (Khan *et al.*, 2015). The majority (93%) of CNG vehicles are light-duty and commercial vehicles. In addition to these, there are more than 26,677 CNG refuelling stations throughout the world (Khan *et al.*, 2015). These are mainly lower and middle-class vehicles for a less demanding group of customers, which, however, are sold in large volumes. From a historical point of view, the possibility of using this medium was analysed in the first cars.

Heavy-duty CNG engines and vehicles, such as buses, were commonly mass produced in the mid-2000s. Until EURO-V emission regulation, lean-burn natural gas engines were widely used because those are favorable for fuel economy and thermal durability. Until now, the lean-burn natural gas engine has been able to cope with EURO-V emission regulations without requiring expensive after-treatment systems (Scholl *et al.*, 2012).

The search for cheaper energy sources for means of transport is also closely linked to the high competition that exists in the current market environment. Increasing fossil fuel prices and their deterioration to environment have led to the search for alternative fuels since past several decades. Meeting the needs of present-day customers is becoming more and more chal-

lenging, as is looking for potential competitive advantages. Another significant aspect that supports the use of CNG is the current ecological and environmental requirements. Customers increasingly prefer products with minimal impact on the environment. In many industries, this aspect is becoming increasingly dominant.

Demands for the ecological operation of means of transport also stem from higher requirements in the area of laws and legislation. The issue of emissions in the case of diesel engines has recently attracted considerable attention. With this example, it was also possible to identify current customer requirements for environmentally friendly vehicle operation. This trend is not limited to developed countries, but can be observed worldwide. All these factors can fundamentally contribute to the further development of CNG, but also other alternative fuels.

The environmental risks have become an important ground to measure the ability to govern a territory and in which economic factors intersect with the scientific knowledge, with the available technical solutions and, most importantly, with the beliefs, the expectations and the fears of the citizens. With regard to the environmental risks, the already existing gap between technicians and the population is emphasized, as the population generally disagrees with the "objective" estimates of the impact and the risk that the technicians propose (Bertaccini & Biagi, 2018).

The present-day society has mainly used fossil fuels based on oil derivatives to build its prosperity. However, raising living standards, as well as the growing population of our planet, limits the use of these resources. In the long run, the trend is to reduce emissions and promote fuels that are less harmful to the environment than diesel and petrol. These include, for example, natural gas, biogas or biomethane.

A natural gas vehicle is an alternative fuel vehicle that utilizes CNG or liquefied natural gas (LNG) as an environmentally friendly alternative fuel instead of fossil fuels. Exhaust emissions from NGVs are much lower compared to equivalent gasoline-powered vehicles. In addition, less carbon dioxide is produced by combustion of natural gas than by combustion of both diesel fuel and gasoline, which makes natural gas engines favorable in terms of the greenhouse effect. NGVs also emit very low levels of carbon monoxide (approximately 70% lower than a comparable gasoline-powered vehicle) and volatile organic compounds. They have considerable effect on breaking down methane and some other greenhouse gases in the atmosphere, and thus increase the global rate of methane decomposition. Regarding environmental performance, LNG is a poor fuel compared to CNG, because it requires energy to be liquefied and to be transported. However, LNG is still superior to alternatives such as fuel oil or coal in most cases

(Demirbas, 2010). Natural gas represents one of the few available options to displace diesel from HGVs, with liquefied natural gas in particular being favoured for long-haul distribution due to its greater energy density relative to compressed natural gas (Kumar *et al.*, 2011).

Transport is responsible for a quarter of greenhouse gas (GHG) emissions in Europe and remains the only major sector in which they continue to rise (Langshaw *et al.*, 2020). A great advantage is also its wide industrial use. There are, in particular, applications in the production of electrical and thermal energy or in the production of fertilizers. A dynamically developing area is the use of natural gas as a fuel for vehicles. In addition to the widespread form of CNG, natural gas can also be used in the form of LNG.

The price of natural gas per 1 MWh (Megawatt hour) according to the PXE index (Power exchange Central Europe) was one of the lowest in history in 2019 and continues to have a downward trend (Figure 1).

Dependence on imports from the Eastern countries has also decreased, due to the diversification of transport routes, partial energy savings in connection with the global oversupply of natural gas, especially due to the shale gas boom in the US. The price of natural gas is also significantly less correlated with the price of oil, which fundamentally affects the market situation (Zilvar, 2016). Natural gas as a fuel used in diesel engines, reconstructed into dual-fuel is one of the cheapest ways considering energy-saving and environmental protection. This method is very popular in countries which have less developed energy networks and technologically older transport fleets. As a result, many studies are carried out which are related to natural gas or bio gas use in the existing compression ignition engines, reconstructing them to work in the dual-fuel mode (Daukšys, 2019). Another interesting alternative is the use of waste products from human activity in the form of biogas.

Biogas and biogas systems are energy sources with a highly positive contribution to environmental protection and sustainable development of society. The basic essence of biogas is the decomposition of organic matter in several stages (Nijaguna, 2006). Energy usable biogas is produced in biogas plants, wastewater treatment plants (sludge gas), and is also produced in municipal landfills (Dohányos *et al.*, 2014).

The basis of biogas technologies clearly emerged from sewage treatment processes. Only the technical success of biogas in this field motivated efforts to extend the application to organic substrates other than sewage sludge. Biogas is naturally formed in most landfills, under the above conditions. However, the consumerist lifestyle, which is characterized by an extreme increase in the amount of waste, has brought fundamental importance of the industrial use of biogas. There has been a dramatic increase

in the number of landfills, but also an increase in the volume of existing waste sites. Biogas production has been steadily increasing, and the possibility of its further industrial use has also increased.

Natural gas consumption in transport is rising sharply, which is contributing to reducing emissions, especially in large cities. This phenomenon is also evident in urban public transport, where urban transport companies are trying to gradually replace non-ecological diesel-powered vehicles with vehicles that are powered by alternative fuels. The Transport Company of Ostrava has fundamentally changed the structure of its means of transport when most diesel engines have been replaced by CNG propulsion systems (Jiríček, 2019).

The increasing consumption of natural gas and the fact that first-generation biofuels (bioethanol — made from grain, sugar beet, sugar cane, maize, starch or vegetable waste) are already reaching their limits lead to the need for change and the transition to new alternative fuels — second-generation biofuels such as BioCNG. In order for the produced biogas to be used as propulsion for vehicles, most often buses, it must first be converted into biomethane and then imported into the network. Therefore, the biogas plant must be equipped with both cogeneration and biogas purification elements. The biggest current obstacle to the use of BioCNG is the large investment costs in the purification itself (Ministry of Industrial and Trades, 2019).

The pilot testing of the use of bioCNG arising from the treatment of wastewater for the propulsion of public transport buses within the Transport Company of the City of Brno was a success. During the test period, the bus covered 4,750 km using only energy from sewage sludge. In terms of driving characteristics and performance, no changes in vehicle behaviour have been reported (Vaškevič, 2019). However, the cost aspects of implementation were not mentioned in the publication of the results of this project.

Another case study of transport in the town Kragujovac considered the main advantages of using CNG vehicles. In the city, it was possible to decrease the CO₂ emissions from transport and also to decrease the local emissions of dust, sulphur and NO_x. During the prototype bus exploitation, a better fuel economy with CNG compared to diesel drive was confirmed (Milojević & Pešić, 2011).

The pointed studies stressed the key positive environmental impacts of alternative fuels. However, the evaluation was not based on a multicriteria comparison of several factors. The utilisation of electric drives in public transport can be considered as an example of this problem. As a result, many case studies evaluating emission-free buses provide conflicting im-

pacts on the environment. The problem is given by the structure of energy resources in the given country. The economic benefits resulting from implementing zero-emission buses in an urban transport fleet are often limited by the current energy mix structure of the given country. An unfavourable energy mix may lead to increased emissions of SO₂ and CO₂ resulting from operation of this kind of vehicle (Pietrzak & Pietrzak, 2021).

Case studies usually show an analysis of selected parameters. The main impact of this article is the broader evaluation system. This article synthesizes cost as well as environmental criteria. At the same time, the complexity of this assessment should ensure universal use across a wide range of cities.

The case study presentation and research method

The aim of the analysis within the research is to compare the cost of selected drives (electric and CNG) for bus transport. Vehicles using electric propulsion and CNG were included in the evaluation. The cost of additional funds was evaluated in the analysis for a longer period (2017–2019). Data for 2020 are not available yet. On the other hand, they will not be very relevant, because 2020 was significantly affected by the pandemic situation. In particular, data on the number of passengers carried and kilometers traveled. Due to these factors, the analysis focused only on the stated years.

The research also included an analysis of the influence of the line's driving profile on the consumption of vehicles. The complex quality of the operated means of transport was also assessed experimentally. Not only the cost, but also environmental parameters were included in the evaluation. To determine the complex quality of means of transport, mathematical tools of multicriteria decision making were used. The cost-effectiveness of operating vehicles was based on data relating to costs and revenues for a given period.

Naturally, the cost aspect of operating vehicles is also an important criterion when choosing an environmentally friendly fuel. The Transport Company of Ostrava has been solving the optimization of means of transport for a long time in connection with the reduction of the ecological load of transport on the surroundings. The company is one of the largest carriers and operators of vehicles in the Czech Republic. Within the city of Ostrava, it provides passenger transport by tram, trolleybus and bus transport. Tables 1–3 show the basic characteristics of individual modes of transport.

In terms of the number of transported persons in the Ostrava city, tram transport is the most important. This is primarily due to the capacity of this vehicle. In terms of all other indicators, the key transport is bus transport. This has by far the highest number of operated lines, the length of the routes, but also the total annual distance that the means of transport cover. Bus transport also has the significantly highest number of stops in the city. Thus, these vehicles can potentially contaminate the largest area with their harmful emissions. The total number of bus transport vehicles used in 2019 was 291, which is comparable to tram transport (259). However, bus transport has a significant negative impact on the environment, especially if it is provided by means of transport that use traditional liquid fuels (diesel, petrol). However, in the last ten years, the Transport Company of Ostrava has fundamentally changed the fleet it operates. Currently, the number of buses using CNG propulsion is 262, the number of electric buses is 19, and there are only 10 diesel vehicles. Graphically, the current status is shown in Figure 2.

Buses powered by diesel engines, which no longer met the limits for environmental protection, were gradually replaced by CNG-powered vehicles and, in recent years, also by electric buses. However, many of them have to be replaced by new ones due to wear. In recent years, the Transport Company of Ostrava has also been continuously striving to increase the number of electric buses, which have a minimal impact on the environment in terms of the operation itself. In terms of the long-term strategy of fleet development, it was decided to conduct research dealing with transport optimization. As part of this research, the cost of the operation of CNG and electric buses was also assessed. Three means of transport for each category were included in the evaluation. The aim was to obtain detailed information on the operating costs of both types of equipment, which can be one of the bases for creating a long-term strategy in this area. For these means of transport, the cost of their operation over a period of three years was monitored.

In the case of electric buses, the following means of transport were selected:

- Electron 12,
- Iveco Daily Elektro minibus,
- SOR EBN 10,5.

The following means of transport were evaluated for the area of CNG-powered buses:

- Solaris Urbino 10,

- Solaris Urbino 15,
- Iveco – 70C14G.

All means of transport were used within the same lines, so that comparisons could be made on the same profile of the transport track. For all means of transport, direct operating costs, indirect costs, revenues but also their performance were evaluated. In the area of costs, items related to the operation of the vehicle were considered, such as fuel, tyres, operating fluids, repairs, maintenance, wages and other direct and indirect costs. Based on this information, the cost per vehicle kilometre of their operation was determined. The calculation of the cost per vehicle kilometre was performed using equation (1):

$$NZV = \frac{\text{Direct costs} + \text{Indirect costs} - \text{Revenues}}{\text{Performance}} \quad (1)$$

All information for the three monitored electric buses is listed in Tables 4-6 for the years 2017, 2018, 2019. The performance of a means of transport is understood as the number of kilometres travelled within the transport lines of Ostrava.

In the case of the Electron 12 electric bus, the cost per vehicle kilometre was in the range of CZK 16.32-39.51 within the monitored years. The big difference is mainly due to the different number of kilometres travelled in individual years. In 2019, this means of transport was used significantly more due to the increase in service to the line. Compared to the previous period, the number of kilometres travelled was almost six times higher. The Iveco Daily electric bus had costs per vehicle kilometre in the range of CZK 8.09-11.74 in the monitored period. It was used in individual years at a comparable level. Low operating costs are also affected by the fact that no major repairs or modifications to the equipment have been carried out. The highest operating costs in the range of CZK 42.37-49.16 were reported by the SOR EBN 10.5 electric bus. This means of transport was also the busiest on the particular line. As a rule, it covered the largest peaks of traffic and times in which the intensity on the given route is the highest. The number of kilometres travelled also affected the amount of direct and indirect costs.

The total costs for the individual years were determined for all monitored electric buses. The calculation principle was based on the formula (1) and included all data on monitored items in the given year. Therefore, the identified costs are again related to the number of kilometres travelled for each means of transport. The final values of costs are given in Table 7. The

costs per kilometre were by far the highest in the first year of the evaluation. In 2019, on the other hand, the operating costs were reduced by more than half. The amount of costs is related to performance, the efficiency of use, but also the cost of repairs and maintenance of the equipment. In the monitored period, none of the means of transport had a significant accident, which would have dramatically affected the costs. Graphically, the development of costs per vehicle kilometre for the three monitored electric buses is shown in Figure 3.

In a similar way, the operating costs of CNG-powered vehicles (Solaris Urbino 10, Solaris Urbino 15, Iveco-70C14G) were determined. CNG-powered buses travelled a total of 598,642 km within the monitored period. Table 8 shows the number of kilometres travelled for both categories of means of transport in the stated years.

The buses were operated in the same mode for both categories and served the same track profile. For each type of monitored motorization, the means of transport were divided according to the intensity of use (high, medium, low) and the intervals of planned distances were set. The exact division for these means of transport is shown in Table 9.

CNG buses and electric buses always have one representative in each category. Everything was designed with regard to the objectivity of the evaluation. The buses were operated all day, but usually the intensity of use varied. The aim was to maintain the same conditions for both motorizations and for individual categories of use. The means of transport were also included in transport according to the prepared schedule.

The determination of costs for CNG buses was carried out in the same way as for electric buses, i.e. on the basis of direct and indirect costs, revenues and mileage. Table 10 shows the total cost per vehicle kilometre. The lowest costs were found in 2017, when they amounted to CZK 35.69/km. In the last year, the costs of operating CNG drives were the highest (40.32). Everything is affected by the number of kilometres travelled, but also by the number of unplanned repairs.

For comparison, Table 10 also shows the identified operating costs of electric buses. The big difference is especially in the first year 2017, when the operation of electric buses was significantly more expensive.

In addition to the analysis of the total costs per vehicle kilometre, the consumption of the above-mentioned means of transport was also partially analysed within the research. Fuel consumption was monitored for means of transport at intervals of 60 days, taking into account the intensity of transport and the profile of the transport track. Within the Transport Company of the City of Ostrava, three transport lines (40, 48, 64) of a different character were selected for the evaluation. The aim was to verify the devel-

opment of fuel consumption under different loads. Table 11 shows the basic character of the operated transport lines. For each type of line transport, key parameters, such as travel time, route length, number of stops and track profile are listed.

Intentionally, different types of transport lines were chosen for the evaluation. The brief characteristics can be summarized in the following points:

- City centre (city traffic)
High variability in transport performance. The bus provides transport in an environment of high-intensity traffic density. Traffic jams often occur in a number of places on the route. The vehicle does not move at a steady speed. Acceleration and braking occur repeatedly. It is not usually possible to use the maximum speed that is possible in a given section.
- Outskirts (normal city traffic)
Medium variability in transport performance. These are lines that provide passenger transport from the outskirts of the city to the centre. They are characterized by a higher number of stops. The vehicle can move at a constant speed in selected parts. In exposed parts of the city, it gets into traffic jams and unsteady traffic flow sections.
- Suburban areas (service around the city)
Less variability in transport performance. The bus transports passengers from areas that are close to the city. The transport is realized on a longer route. The bus often moves at a constant speed. Acceleration and braking are at their lowest level.

An important parameter that also fundamentally affects fuel consumption is the profile of the transport track. The three lines listed in Table 1 are classified in categories A, B, C in terms of their track profile. The basic data on these categories are shown in Table 12. For each type of track profile, information on altitude is given — the lowest point, highest point, average value. At the same time, the coefficient of variation (Equation 2) of altitude was determined, which characterizes the fluctuation of the track profile. Its increasing value means fluctuations in altitude along the transport route. The Coefficient of variation (V_x) was determined using the following equation (2):

$$V_x = \frac{S_x}{\bar{x}} \cdot 100 \quad (2)$$

where \bar{x} is the simple arithmetic mean, S_x is the standard deviation. The traffic line, which has the character A (City Center), is flat in terms of track

profile. The difference in altitude is negligible (8 m), and the overall variability of the profile is small (2%) according to the value of the coefficient of variation. These are flat sections in the centre of Ostrava. Line B of the city line has the track profile B. The difference in the individual sections of the track is greater, as well as the overall variability. The line passes through parts of Ostrava which are more varied. The line of the suburban part (C) is of the most diversified nature. This provides passenger transport to the adjacent area of Ostrava. The difference in altitude is 151 meters in the individual sections of the route. The entire track profile has by far the highest variability (21%). During the journey, the means of transport on this line moves mainly uphill. Graphically, the individual profiles of the lines are shown in Figure 4–6. In terms of the frequency of change of direction, the transport lines in the city centre and the outskirts are significantly more demanding compared to that. The suburban line, which has a predominantly ascending character, contains a larger proportion of sections without bends and changes in driving directions.

CNG buses and electric buses were operated on these lines during the period. Figure 4–6 show the driving profile for each line. The data were obtained directly from the computing unit of the vehicle. The driving profile in the city centre (Figure 7) is characterized by constant changes in driving speed, acceleration and braking. Everything is determined by the intensity of traffic in the city centre, but also by the variedness of buildings and the shape of the road. The vehicle also moves at a significantly lower speed than it is possible in the specific sections. The driving profile on the outskirts of the city (Figure 8) already shows a higher degree of smoothness of driving. In many places, the vehicle runs constantly. At the same time, there are no major changes in speed while driving. However, the route of this line also leads partly to the city centre, which will affect the driving profile of the vehicle. The greatest stability of the driving profile is in the case of the suburban area (Figure 9). The means of transport travel outside Ostrava, where the traffic intensity is significantly lower. The number of stops is also smaller in the case of this line. The bus can repeatedly move at constant speeds over longer sections. In the case of this line, however, the track profile itself is mostly ascending.

The data were processed on the basis of records from the GPS device of means of transport. The consumption of all means of transport was monitored within all operated lines. The consumption was monitored during the day with the intervals of 6–18 hours. Night times were not evaluated, due to large differences in traffic on individual lines. The load of the vehicle from the point of view of the number of passengers was also not monitored. However, individual buses were operated on the same routes and at identi-

cal times. Tables 13–14 show the average consumptions for both categories of propulsion, for all three transport lines. The average consumption is based on data for a period of 60 days of operation. For each vehicle, its standby weight is also stated.

In the case of CNG vehicles, consumption is clearly the highest in the city centre. This also corresponds to the driving profile. If we compare the consumption of CNG propulsion in the city centre and in the outskirts, the difference for individual vehicles is as follows: Iveco — 70C14G (22.5%), Solaris Urbino 10 (14.5%), Solaris Urbino 15 (16.2%). Higher consumption in the city centre can also be affected by the number of passengers. The second highest consumption in the case of CNG propulsion is in suburban areas. The difference compared to the city centre is smaller and for the monitored means of transport, ranges in the interval (7.1–10.1%). The suburban part has an advantageous driving profile (Figure 9), but the amount of consumption is affected by the track profile (Figure 6), which has an ascending character. Overall, CNG vehicles had the lowest consumption on the line serving the outskirts of the city. The more favourable driving profile, but also the flat character of the route, contribute to this.

The operated electric buses also showed the highest consumption in the city centre on the monitored lines. However, the difference compared to the edge parts was smaller than in the case of the previous propulsion: Iveco Daily (11.9%), SOR EBN 10.5 (12.5%), Electron 12 (14.7%). However, the main difference was in energy consumption in the suburban area. This is comparable to running a bus in the city centre. In the case of the Electron 12 vehicle, consumption in the suburbs was even higher than in the city centre itself. Higher consumption is naturally influenced by the track profile when the vehicle does not travel on the flat terrain most of the time. Another aspect that can affect the power consumption of this line is the current state of the battery and its charging. Within the suburbs, there are currently limited possibilities for recharging electric buses, which takes place in the city centre. Figure 10 shows the development of battery power consumption in the case of vehicle Electron 12.

However, data on electricity consumption for electric buses show significantly smaller differences in the case of the city centre and suburbs compared to CNG vehicles. This can encourage greater use of this type of propulsion in city centres, which is also environmentally beneficial.

However, energy consumption is one of a number of criteria by which we can evaluate means of transport. As part of the research, a procedure was created for evaluating the complex quality of vehicles on the basis of categorically different criteria. Based on the performed analysis, the results of the consumption of individual means of transport were used. For reasons

of easier comparison, in the case of CNG vehicles, consumption values were converted from m³ to kWh (1 m³ — 10.55 kWh) (Bahadori, 2014). The recalculated values and a comparison with the consumption of electric buses are shown in Table 15.

In order to determine the comprehensive quality of vehicles, the average value from all three city districts was used for each type of drive. The evaluation of the complex quality was based on the quantification of several criteria, through multi-criteria decision-making. The criteria were selected on the basis of two aspects: using key attributes for the evaluation of means of transport, and basing the evaluation on a smaller number of criteria. This will also allow potential use in transport companies. Table 16 shows a list of all defined evaluation criteria. The determination of the complex quality of vehicles was also performed for diesel engine propulsion. This type of propulsion was not part of the realized research, but the data on the operation of these vehicles within the transport company of Ostrava was evaluated for a period of one year. The first criterion is the found consumption, converted to an identical unit. The second evaluation criterion is the noise level of the operated vehicle. This parameter is important, especially in the city centre, where the road is close to pedestrian zones. Therefore, higher noise levels represent a negative aspect. The third criterion evaluated is the efficiency of converting the primary energy into motion. In the case of electrical energy, which is supplied to the electric motor from the mains via accumulators, this is an efficiency of 90% (Jones *et al.*, 2017). In the case of CNG, this value is 40% (Gallivan, 2013). The fourth selected criterion is the ecological consequences of the motorization operated. These can be assessed from the perspective of a wider range of indicators. Therefore, this criterion was based on the quantification of three separate areas (Table 17): the amount of emissions, the ecological footprint of the energy used and the risks of operation and waste. For all three sub-criteria, the values were set on a scale of 0-100. In the case of emissions, the relevant parameters are the contents of CO₂, CH₄, NO_x, solids or NH₃ (Mulligan, 2010). It is possible to evaluate in detail the operation of the engine within a cold start, a cold engine, a warm engine and other specific conditions. The values on the scale 0-100 were determined for individual types of propulsion on the basis of operating standards (Euro 6). The second sub-criterion was the ecological footprint of the type of energy used. It should be taken into account that in the Czech Republic, approximately half of the total amount of electricity is produced in power plants that use the combustion of fossil fuels. Although the actual operation of means of transport for electricity is essentially emission-free, the production of electricity represents a significant environmental burden. The last sub-criterion assesses the risks of the

specific propulsion, including the waste produced. The risks of operation (0–50 points) and the significance of waste for the environment (0–50 points) were assessed separately. In the case of electric vehicles, an important aspect is a problem of disposing of rechargeable batteries. In Table B, the sum of all sub-criteria is given for criterion K4 Ecological Impacts.

The fifth criterion concerns the complexity of the infrastructure for each motorization evaluated. From this point of view, CNG transport is the most demanding, due to the requirements for gas storage and gas containers. The last sixth criterion is the distance travelled. From this point of view, diesel vehicles are the most advantageous. In the case of electric buses, the range can be fundamentally affected by the type and capacity of the battery used. Higher capacity, however, also means significantly higher weight. The values given for the individual propulsion types, as determined on a scale of 0–100, are for the same vehicle categories.

The determination of the complex quality of the monitored drives was realized through multi-criteria decision-making. In the first step, it is necessary to determine the meaning (weight) of each criterion. This is possible by a system of direct determination of weights, or by the principles of pairwise comparison of individual criteria. Both procedures are fundamentally unsuitable for the defined set of criteria. The direct allocation of weights will be burdened by subjectivity in decision-making. In the case of pairwise comparison, it will be difficult to compare categorically different criteria. The weights of these criteria were determined in three steps. First, the criteria were divided according to their nature into the groups, as shows box 1.

In the second step, the weight of each group was determined. The groups are first sorted in descending order of significance (1st — 3rd). The group in the first place is evaluated 3 points, in the second place 2 points, and in the third-place one point. The weight is then determined as the ratio of the number of points for a given group and the total number of points, using the following equation (3):

$$v_i = \frac{b_i}{\sum_{i=1}^k b_i} \quad (3)$$

where b_i is the point evaluation of the given group, v_i is the weight of the criteria. The weights of the criteria within the individual groups are then determined in the same way. The final weights of a specific criterion are obtained by the product of the value of the weight of the given group and the value of the weight of the given criterion (example Equation 4, 5, 6).

The calculation of the weight (meaning) for group A can then be performed as follows:

$$v_A = \frac{3}{6} = 0.500 \quad (4)$$

The calculation of the partial weight in group A for criterion K4 can then be performed as follows:

$$v_A = \frac{2}{3} = 0.667 \quad (5)$$

The total weight for criterion K4 is then calculated as follows:

$$v_{K4} = 0.500 \cdot 0.667 = 0.333 \quad (6)$$

Table 18 shows the whole principle of determining the meaning of individual criteria and the final value of the weights. Based on the implemented procedure, it was found that the K4 Ecological impacts criterion is of the highest importance. On the contrary, the K3 Efficiency criterion is the least important. The principles of multi-criteria decision-making were used to determine the complex quality of individual propulsion systems. The values of the criteria were analysed by determining the distance from the fictitious variant. This tool is based on the principles of measuring Euclidean distance in space. The determination of the distance from the fictitious variant was performed using Equation 7, which can be written as follows:

$$D = \sum_{i=1}^n v_i \left(\frac{x_i^* - x_{ij}}{x_i^* - x_i^0} \right)^2 \quad (7)$$

where D is Euclidean distance from the ideal variant, x_i^* is the length of action, x_{ij} is the mean width of the elongated bar, x_i^0 is the mean width of the elongated bar, v_i is the weight of the criteria. The calculation is based on the quantification of the differences of individual criteria from the best variant. The detected differences are then normalised using the determined weights. The most suitable variant is the one that has the smallest distance from the ideal variant overall. Table 19 shows the main parts of the solution. The weights for the individual criteria were determined using the above procedure.

Table 19 shows the weights for each criterion (v_i), the best value for each criterion (x_i^*), the worst value for each criterion (x_i^0). For each type of propulsion, the standardised differences are then given, which represent the

partial distance from the ideal variant, determined by Equation 4. The final distance from the ideal variant (D) then represents the sum of all partial values. According to this parameter, we can evaluate the overall quality of individual drives. A lower value then represents a better variant, because it is less distant from the ideal variant. From the point of view of complex quality, electric drive buses are the best option (D=0.256). CNG is in second place (D=0.440), and the last is diesel (0.711). The distance from the ideal variant was also converted to a percentage. If we take the analysed criteria and their values into account, the most suitable vehicle in terms of complex quality is an electric vehicle.

Results

As part of the research carried out on the optimization of transport solutions and the results of the project of methodological and application tools for effective management of the territorially divided statutory city of Ostrava, the cost of operating buses with CNG drive and an electric energy source was assessed. For both categories, three means of transport were evaluated at intervals of three years. The means of transport served the same line and travelled on the same track profile. Vehicles with both types of propulsion covered a comparable distance during the observed period (Table 8). At the same time, they were divided into categories, according to the intensity of use (Table 9). The primary consideration in the study was the cost of using both modes of transport. The management of the Transport Company of Ostrava is considering a potentially higher share of the use of electric buses with regard to lower impacts on the environment. Based on the obtained data, the average value of costs per vehicle kilometre was determined. Tables 20–21 show the calculated values for both propulsion types. These tables summarize the data on the number of kilometres travelled for each year and the costs per kilometre of operation. Based on these values, the average cost per vehicle kilometre was determined for each type of drive, using a weighted arithmetic average.

This value was CZK 40.24/km for the group of electric buses and CZK 38.31/km for CNG. In 2019, all buses providing transport within the Transport Company of Ostrava covered a total distance of 16,269,000 km. Tables 20 and 21 set out the cost data for the stated number of kilometres at the calculated average costs for CNG and electric buses. The potential costs for electric buses would be CZK 654,664,560 and for CNG vehicles CZK 623,265,390, at set average costs. Therefore, if transport was potentially provided only by CNG buses, the costs of their operation for the given

number of kilometres would be lower by CZK 31,399,170, which represents costs lower by 4.79%.

The performed evaluation based on the processed data shows that the use of CNG vehicles is more cost-effective than the use of electric vehicles. A number of studies also indicate that the service life of CNG vehicles is slightly longer than that of electric buses. However, this has not been analysed in the research. The limiting factor in the use of electric drives, not only in the field of public transport, are the parameters of currently used batteries. Especially from the point of view of the distance travelled, but also the possible influences of the external environment, especially the air temperature, which can fundamentally affect the range (battery capacity). However, current developments in the field of batteries may minimize these disadvantages in the near future. Another aspect that can affect costs is the track profile. For comparison, the means of transport for both drives were operated on one transport line. Thus, the character of the entire track profile is rather flat, which, however, applies to most of Ostrava. It can be assumed that in the case of operating vehicles in rough, mountainous terrain, it would be possible to find more significant differences in the average costs per kilometre travelled. The Transport Company of Ostrava currently predominantly uses CNG propulsion. The big advantage is, in addition to low emissions, also the price and availability of fuel.

In the case of vehicles powered by diesel engines which are still used, it is possible to recommend, on the basis of the research carried out, their replacement both with CNG buses, but also partly with electric buses, for example in the ratio of 70:30. Further support for CNG motorization is also in the context of the built infrastructure. At present, the Transport Company of Ostrava operates two CNG filling stations and is completing the construction of the third. Within the city of Ostrava, there are also a number of other options for replenishing this fuel from external entities. The operation of CNG vehicles is more cost-effective, as research has shown. However, the electric drive has a minimal burden on the environment, and with the expected development of technologies in this area, partial diversification of the vehicle fleet can be recommended.

In the case of consumption of means of transport, the character of the given transport route plays a fundamental part. The movement of buses in the city centre with high traffic intensity will affect fuel consumption. The track profile itself also plays an important role. The means of transport operated showed a similar level of consumption within comparable transport lines. In the case of electric buses, a smaller difference in consumption was found in the city centre and its peripheral parts within the monitored period. However, consumption was significantly higher on the

route which had a predominantly ascending character. However, it would be good to assess the influence of the condition of the battery on its operation when operating in varied terrain. A big advantage when operating electric buses in the city centre is their minimal environmental impact.

If we evaluate the operation of these vehicles only according to the cost per vehicle kilometre, the research has shown the advantage of CNG propulsion. However, when evaluating the means of transport, we can use a number of important criteria related to the consequences of operating buses. For this reason, the comprehensive quality of the monitored means of transport was evaluated separately. Diesel-powered buses were also included in the evaluation. The determined consumption of the means of transport was one of the criteria used. Based on the evaluation performed through multi-criteria decision-making, electric propulsion was identified as potentially the most suitable type. The evaluation was based on the quantification of criteria from different areas of vehicle operation. Electric vehicles are the most advantageous in quantifying all the criteria mentioned above. The worst result is for the diesel vehicles. The detected value is an order of magnitude worse than for CNG and electric vehicles.

Conclusions

The results of the evaluation showed the cost advantage of operating CNG-powered vehicles. The difference in the costs was 4.79%, which can generate significant savings with a large volume of kilometres. Therefore, the CNG drive is certainly suitable for vehicles that are operated continuously throughout the year. The advantage of CNG is also the standardized gas quality throughout the Czech Republic and, last but not least, the price of fuel compared to traditionally used ones. In the case of similar large transport companies as the Transport Company of Ostrava, it is also possible to contractually agree on individual conditions of consumption. The disadvantage of operating CNG vehicles is still the relevant amount of emissions. Though, this is significantly lower than with traditional fossil fuels, where carbon dioxide production is 20–30% lower and in the case of nitrogen compounds, it is about half the amount. However, if we compare these values with electric buses, this can be considered a disadvantage.

Greater expansion of vehicles with electric propulsion can be hindered by range, battery capacity (Nikoobakht *et al.*, 2020), charging time, or engine power. In the case of larger vehicles, the electric propulsion is also less suitable for a highly varied profile.

As the research showed, in the case of electric buses the consumption was significantly higher within the transport line which had a considerably rough terrain. However, at the same time, electric buses showed more stable consumption in the city centre, where traffic is highly intensive. In the case of operating electric buses in rougher terrain, it will be necessary to address recharging and battery capacity.

Higher consumption will require the development of a wider infrastructure for replenishing electricity. The ecological footprint of these devices appears to be optically negligible. However, it is necessary to mention that in the Czech Republic, approximately half of the electricity is still produced on the basis of burning fossil fuels (coal). Therefore, the ecological impact on the environment is secondarily partly due to the consequences of coal combustion in the production of electricity. The problem of processing discarded batteries, which contain a large amount of pollutants, has also not been completely solved. Moreover, the question is what the development of the market will be not only in the case of electricity but also of other sources. At present, the Czech energy industry works more with surpluses of electricity, which is partially sold abroad. Increasing electricity consumption in all countries of the European Union could quite significantly affect its price. Predicting future developments is very difficult, as can be seen in the case of oil prices in 2020. The possible disadvantages of electromobility may change in the short term, and the development of technologies will support their further use. Many battery manufacturers are currently working intensively to increase the capacity and stability of the amount of energy stored, regardless of external influences. Major technological changes in this area would probably significantly affect the expansion of this propulsion. Current trends in environmental protection and sustainable development will continue to allow the development of other options for the use of alternative fuels.

If we look at the evaluation of vehicles from the point of view of complex quality, it was found that despite the disadvantages, an electric vehicle is the most suitable option. The environmental aspects that were included in the evaluation significantly contribute to this. The Transport Company of Ostrava currently uses mainly CNG-powered vehicles in bus transport. The research clearly confirmed that this is a cost-effective solution. When the replacement of the vehicle fleet is completed, it would be appropriate to replace diesel vehicles mostly with CNG buses, but also to use, to a lesser extent, modern electric buses, all for example in the stated ratio. The benefits of electric buses can be seen on several levels and the development of their broader use can be expected in the near future. Adequate diversifica-

tion of the drives used in the vehicle fleet can reduce the potential risks arising from the partial unpredictability of today's world.

Major cities and world metropolises are currently addressing similar issues within their transport systems. Global regulation on the amount of emissions from internal combustion engines will put a lot of pressure on changes in the fleet of transport companies. Equally, further restrictions will result from global demands to reduce carbon footprints and other expected environmental demands. Therefore, public transport operators in most major cities will face major challenges in the near future. The analysis conducted and the conclusions of this paper can help to address the complex problems of other large cities of the same nature. A major added value of the analysis carried out is its multidimensional nature, which has made it possible to quantify the environmental aspects of the operation of transport vehicles, in addition to the economic ones. This attribute has made it possible to obtain comprehensive information for complex management decisions and can be considered highly innovative in the given segment.

At the same time, the assessment carried out was based on standard available information. Its applicability to other cities is, therefore, in principle quite universal. Based on the tightening of environmental requirements, not only within European countries, it can be assumed that many large cities are currently dealing with the same problems as the ones which have been analysed in this article. The use of the conclusions of this article and the procedure implemented can be assessed as highly topical from this point of view.

The defined solution offers the quantification of categorically different criteria and also allows to obtain the basis for crucial managerial decisions. A change in the type of means of transport can have significant consequences for a company operating in public transport. As the analysis has shown, the evaluation needs to be based on a broader range of relevant criteria. From this perspective, the next stage of the research can focus on modifying the set of criteria. Other criteria could also be included in the evaluation, whether in relation to environmental, urban planning or user requirements. At the same time, further research can also be measured on the application part of the evaluation. If the evaluation is to be carried out repeatedly within a given city, the creation of an automatic application can be considered to facilitate the evaluation. It would then be very easy to change the defined criteria according to current requirements freely. Another interesting possibility for the development of research in this area is the application of dynamic multi-criteria decision-making methods. In the analysis carried out, a method from the field of static tools was applied. The use of dynamic tools for the problem could bring a number of additional

benefits arising from the nature of these methods. However, the suitability of their use for the given problem would need to be experimentally verified. In conclusion, using a multi-criteria approach for public transport evaluation is highly innovative and can provide key information for critical management decisions.

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Annex

Table 1. Tram transport in the city of Ostrava

Indicators	Year		
	2017	2018	2019
Number of lines (-)	17	17	17
Line length (km)	230	230	230
Number of stops (-)	101	101	101
Number of vehicles (pcs)	261	260	259
Mileage (thousand km)	13,065	13,291	13,306
Transported persons (pcs)	44,386	46,162	49,651

Source: processed according to documents (<https://www.dpo.cz>).

Table 2. Trolleybus transport in the city of Ostrava

Indicators	Year		
	2017	2018	2019
Number of lines (-)	14	14	13
Line length (km)	116	116	116
Number of stops (-)	64	64	64
Number of vehicles (pcs)	67	65	70
Mileage (thousand km)	3,061	2,866	3,128
Transported persons (pcs)	6,960	6,640	7,890

Source: processed according to documents (<https://www.dpo.cz>).

Table 3. Bus transport in the city of Ostrava

Indicators	Year		
	2017	2018	2019
Number of lines (-)	53	53	57
Line length (km)	667	667	710
Number of stops (-)	474	474	485
Number of vehicles (pcs)	288	286	291
Mileage (thousand km)	16,420	16,594	16,269
Transported persons (pcs)	37,172	38,348	40,107

Source: processed according to documents (<https://www.dpo.cz>).

Table 4. Electron 12

Indicators	Year		
	2017	2018	2019
Direct costs (CZK)	758 698	852 141	2 220 563
Indirect costs (CZK)	22 584	19 237	88 063
Revenues (CZK)	2 968	3 913	11 696
Performance (km)	19 698	23 345	140 771
Costs per vehicle kilometre (CZK)	39,51	37,16	16,32

Source: internal materials of the company Dopravní podnik Ostrava a.s.

Table 5. Iveco Daily

Indicators	Year		
	2017	2018	2019
Direct costs (CZK)	258,695	235,918	358,565
Indirect costs (CZK)	14,698	12,081	24,792
Revenues (CZK)	1,095	2,057	44,820
Performance (km)	25,678	30,382	28,833
Costs per vehicle kilometre (CZK)	10.60	8.09	11.74

Source: internal materials of the company Dopravní podnik Ostrava a.s.

Table 6. SOR EBN 10,5

Indicators	Year		
	2017	2018	2019
Direct costs (CZK)	4,408,997	4,456,190	4,400 869
Indirect costs (CZK)	4,400,869	430,035	469,654
Revenues (CZK)	11,580	29,414	22,685
Performance (km)	111,072	100,640	98,623
Costs per vehicle kilometre (CZK)	42.37	48.26	49.16

Source: internal materials of the company Dopravní podnik Ostrava a.s.

Table 7. Total costs of electric buses per vehicle kilometre

Parameter	Year		
	2017	2018	2019
Costs per vehicle kilometre (CZK)	62.95	38.68	27.90

Source: internal materials of the company Dopravní podnik Ostrava a.s.

Table 8. Number of kilometres travelled for both monitored bus categories

Propulsion	Year			In total
	2017	2018	2019	
CNG (km)	149,368	161,078	288,196	598,642
Electric buses (km)	156,448	154,367	268,227	579,042

Source: internal materials of the company Dopravní podnik Ostrava a.s.

Table 9. The nature of the use of individual buses

Bus type	Propulsion	Intensity	Number of kilometres travelled	Use
Iveco - 70C14G	CNG	Low	0-120,000	night connections, covering failures
Iveco Daily	Elektro			
Solaris Urbino 10	CNG	Medium	120,000-240,000	less busy times of the day
Electron 12	Elektro			
Solaris Urbino 15	CNG	High	240,000-360,000	peaks, exposed times
SOR EBN 10,5	Elektro			

Source: internal materials of the company Dopravní podnik Ostrava a.s.

Table 10. Total costs of CNG buses per vehicle kilometre

Parameters	Propulsion	Year		
		2017	2018	2019
Costs per vehicle kilometre (CZK)	CNG	35.69	37.17	40.32
Costs per vehicle kilometre (CZK)	Electro	62.95	38.68	27.90

Source: internal materials of the company Dopravní podnik Ostrava a.s.

Table 11. Basic parameters of the transport lines used

Line type	Travel time (minutes)	Route length (km)	Number of stops (-)	Track profile (-)
City centre	34	11.5	14	A
Outskirts	41	13.5	19	B
Suburban areas	42	24.8	8	C

Source: processed according to documents (<https://www.dpo.cz>).

Table 12. Characteristics of line profile categories

Altitude	Track profile		
	A	B	C
Lowest point (m)	204	208	211
Highest point (m)	219	241	362
Diameter (m)	211	224	260
Coefficient of variation (%)	2	10	21

Source: processed according to documents (<https://www.google.cz/maps>, <https://mapy.cz>).

Table 13. Consumption of CNG-powered buses

Bus type	Weight (kg)	Consumption (m ³ /100 km)		
		City centre	Outskirts	Suburban areas
Iveco – 70C14G	7,200	29.8	23.1	27.5
Solaris Urbino 10	9,300	42.7	36.5	38.4
Solaris Urbino 15	12,700	52.4	43.9	48.7

Source: data from the vehicle.

Table 14. Consumption of electric buses

Bus type	Weight (kg)	Consumption (kWh/100 Km)		
		City centre	Outskirts	Suburban areas
Iveco Daily	8,500	183.6	174.7	182.1
SOR EBN 10.5	10,120	202.1	189.3	201.7
Electron 12	12,040	218.7	203.4	219.1

Source: data from the vehicle.

Table 15. Comparison of the consumption

Propulsion type	Consumption		
	City centre	Peripheral areas	Suburban areas
CNG (m ³ /100 km)	41.63	34.5	38.2
CNG (kWh/100 Km)	439.2	363.9	403.0
Electro (kWh/100 Km)	201.5	189.1	200.9

Source: internal materials of the company Dopravní podnik Ostrava a.s.

Table 16. Criteria for the evaluation of the complex quality

No.	Character	Propulsion type		
		CNG	Electro	Diesel
K1	Consumption (kWh/100 km)	402.1	197.2	468.4
K2	Noise (dB)	45	15	84
K3	Efficiency (%)	40	90	45
K4	Ecological impacts (-)	135	70	190
K5	Infrastructure intensity (-)	60	55	10
K6	Range (km)	380	180	620

Source: internal materials of the company Dopravní podnik Ostrava a.s.

Table 17. Environmental impacts — sub-criteria

Character	Propulsion type		
	CNG	Electro	Diesel
Emissions (-)	50	0	85
Energy (-)	35	30	70
Risks and waste (-)	50	40	35

Table 18. Determination of criteria weights

Criteria group	No.	Order	Value	Criteria group weights	Order	Value	Criteria weights within groups	Resulting weights
A	K4	1.	3	0.500	1.	2	0.667	0.333
	K2				2.	1	0.333	0.166
	Σ					3	1.000	
B	K1	2.	2	0.333	1.	3	0.500	0.166
	K5				2.	2	0.333	0.111
	K3				3.	1	0.167	0.057
Σ					6	1.000		
C	K6	3.	1	0.167	1.	1	1.000	0.167
		Σ	6	1.000	Σ	1=	1.000	1.000

Table 19. Determination of complex quality for the propulsion systems mentioned above

No.	v_i	x_i^*	x_i^0	Propulsion type		
				CNG	Electro	Diesel
K1	0.166	197.2	468.4	0.094	0	0.166
K2	0.166	15	84	0.031	0	0.166
K3	0.057	90	40	0.057	0	0.046
K4	0.333	70	190	0.098	0	0.333

Table 19. Continued

No.	v_i	x_i^*	x_i^0	Propulsion type		
				CNG	Electro	Diesel
K5	0.111	10	60	0.111	0.089	0
K6	0.167	620	180	0.049	0.167	0
D (-)				0.440	0.256	0.711
Share of total distances D (%)				31.27	18.19	50.53
Rank				2.	1.	3.

Source: internal materials of the company Dopravní podnik Ostrava a.s.

Table 20. Average operating costs of electric buses

Parameters	Year		
	2017	2018	2019
Mileage (km)	156,448	154,367	268,227
Costs (CZK/km)	60.95	38.68	27.90
			Total
Average costs (CZK/km)			40.24
Total distance for buses in Ostrava per year (km)			16,269,000
Total costs (CZK)			654,664,560

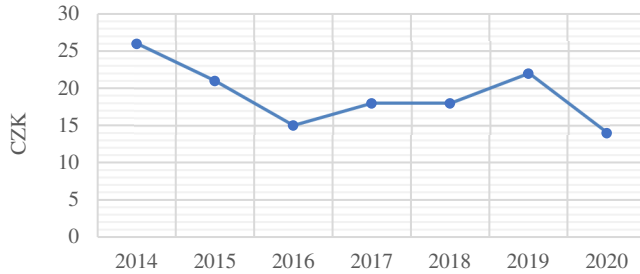
Source: internal materials of the company Dopravní podnik Ostrava a.s.

Table 21. Average operating costs of CNG

Parameters	Year		
	2017	2018	2019
Mileage (km)	149,368	161,068	288,196
Costs (CZK/km)	35.69	37.17	40.32
			Total
Average costs (CZK/km)			38.31
Total distance for buses in Ostrava per year (km)			16,269,000
Total costs (CZK)			623,265,390

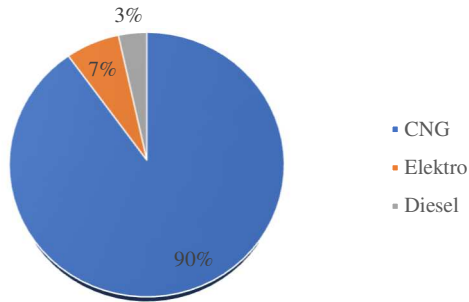
Source: internal materials of the company Dopravní podnik Ostrava a.s.

Figure 1. Price of natural gas per 1MWh/CZK (Price of natural gas (2020))



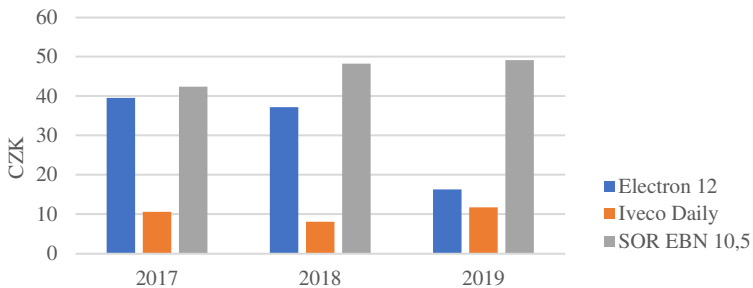
Source: <https://www.kurzy.cz/komodity/zemni-plyn-graf-vyvoje-ceny/>

Figure 2. Current distribution of propulsion used in bus transport



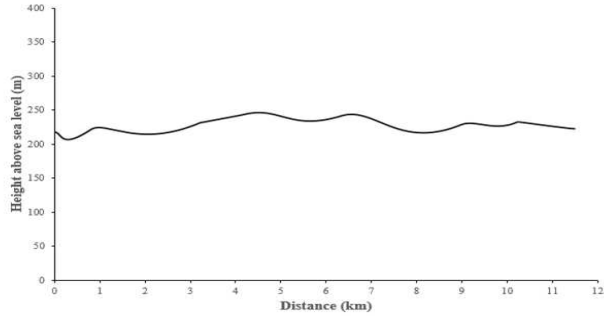
Source: processed according to documents (<https://www.dpo.cz>)

Figure 3. Development of costs for the monitored electric buses



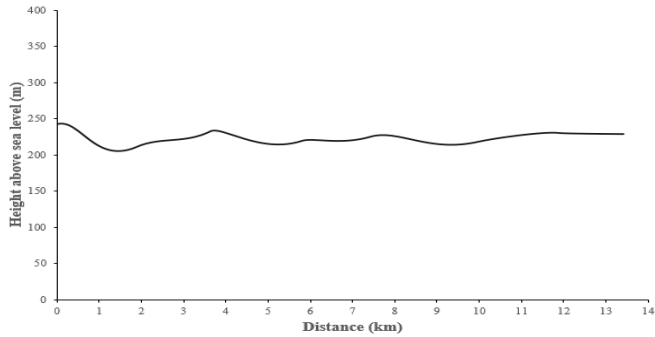
Source: internal materials of the company Dopravní podnik Ostrava a.s.

Figure 4. Track profile A — City centre



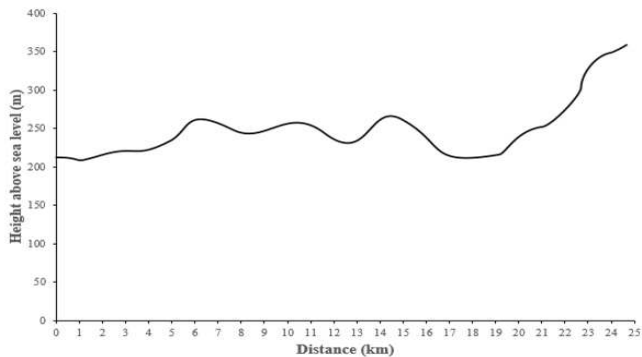
Source: processed according to documents (<https://www.google.cz/maps>, <https://mapy.cz>).

Figure 5. Track profile B — Outskirts



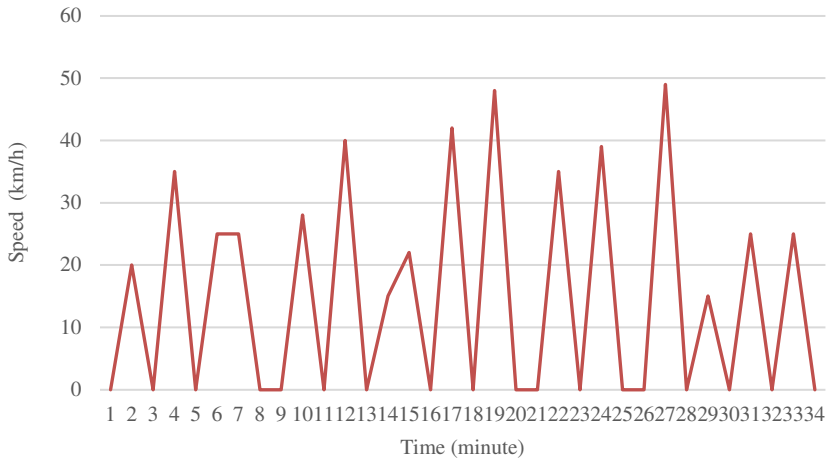
Source: processed according to documents (<https://www.google.cz/maps>, <https://mapy.cz>).

Figure 6. Track profile C — Suburban areas



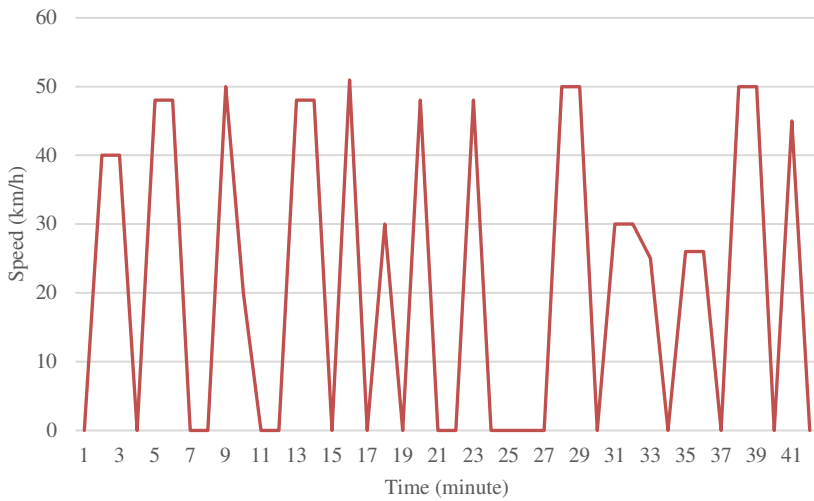
Source: processed according to documents (<https://www.google.cz/maps>, <https://mapy.cz>).

Figure 7. Driving profile — City centre



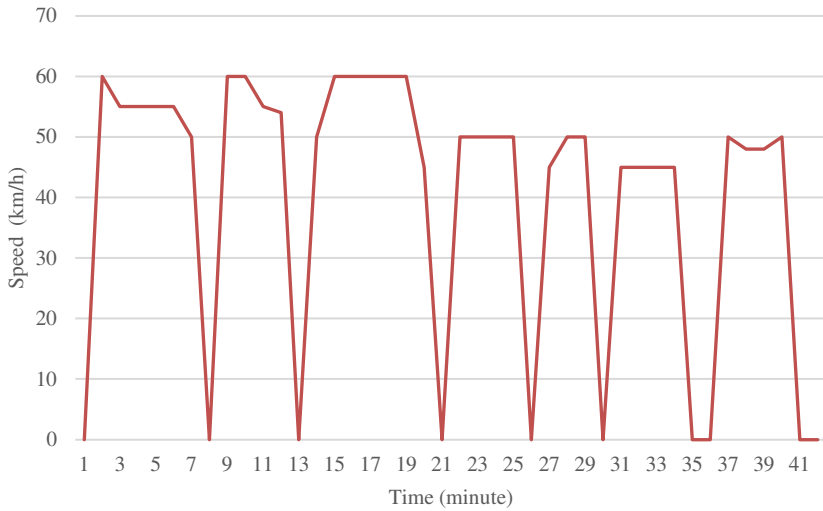
Source: measured data.

Figure 8. Driving profile — Outskirts



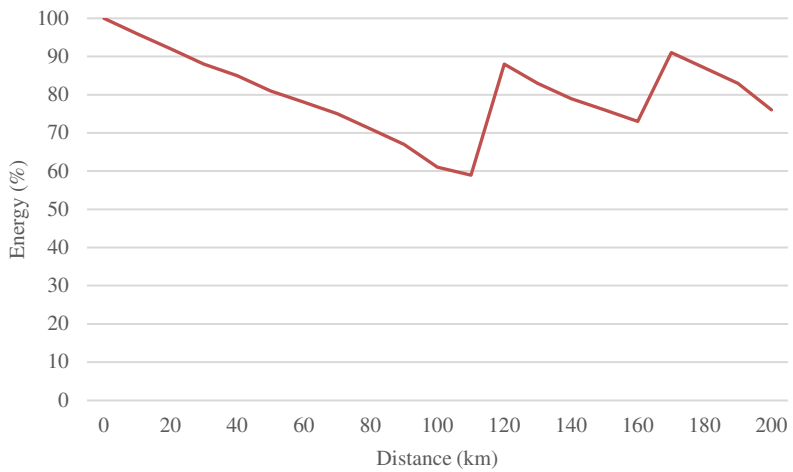
Source: measured data.

Figure 9. Driving profile — Suburban areas



Source: measured data.

Figure 10. The course of electricity consumption of the battery — Electron 12



Source: data from the vehicle.

Box 1. Criteria groups

A. Environmental
K4 – Ecological impacts
K2 – Noise level

B. Cost
K1 – Consumption
K5 – Infrastructure intensity
K3 – Efficiency

C. Operating
K6 – Range