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RESEARCH ON THE EFFECTIVENESS OF ALTERNATIVE PROPULSION SOURCES IN HIGH-TONNAGE CARGO TRANSPORT

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Abstract:

The progressive degradation of the environment makes implementing pro-ecological solutions in various areas of our lives more meaningful. These measures also apply to transport, responsible for around 30% of total carbon dioxide emissions in the EU. Implementing ecological solutions in road transport encounters various barriers resulting mainly from the specificity of transport tasks. One of the most promising solutions in the high-tonnage road transport sector seems to be LNG-fueled engines, which allow for similar operating conditions to traditional combustion vehicles.
The article aims to identify the environmental benefits of the use of high-tonnage LNG-fueled vehicles in freight transport and to conduct a comprehensive assessment of the economic efficiency of this solution. The article assesses the effectiveness of using an LNG-fueled vehicle and a diesel-fueled vehicle that meets the highest exhaust emission standard in high-tonnage transport, both in terms of economy and an impact of these solutions on the environment. The research was carried out on a given route, taking into account variants of vehicle manning and simulations of transport cycle time. In conclusion, a discussion of the obtained results was carried out, emphasizing the factors determining the profitability of using high-tonnage vehicles with LNG drive or its lack.
Regardless of the indicated lack of clarity in the economic assessment of the effectiveness of LNG drives in high-tonnage vehicles, the identified environmental benefits from implementing these solutions seem to be quite unequivocal. Thus, it should be expected that in the event of loss of economic competitiveness of these solutions, appropriate fiscal instruments should be used - especially since LNG drives in the policies of individual countries are considered pro-ecological solutions.

Keywords: *LNG, high-tonnage transport, transport costs.*

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1. Introduction

The dynamic development of road freight transport, combined with the awareness of the negative impact on the environment, makes it necessary to implement pro-ecological solutions in this area. Research in this area is undertaken all over the world (see e.g. Dasgupta et al., 2021, Jacyna et al., 2014, Jacyna et al., 2017, Jacyna et al., 2021, Kholod et al., 2016, Ramacher et al., 2020, Tischer et al., 2019, Wasiak et al., 2020). At the same time, in case of high-tonnage vehicles, many barriers to implementing low- and zero-emission solutions effective in case of light vehicles are identified (see e.g. Ellingsen et al., 2016, Wolfram & Wiedmann, 2017). As a result, the search for pro-ecological solutions in the field of high-tonnage transport must be carried out here while considering the possibility of their application. In this context, many authors see the use of LNG as a pro-ecological solution for high-tonnage vehicles, for which both ecological (Song et al., 2017, Zhao et al., 2021 and others) and economic benefits (Report, 2017, Zhao et al., 2021 et al.).

Considering the arguments mentioned above, it can be noticed that the use of methods of multi-criteria evaluation of solutions also in relation to the problem under consideration. Such methods allow at the same time to take into account conflicting evaluation criteria, including criteria expressed in various terms, such as cost and pollutant emissions[1].

The article aims to identify the environmental benefits of the use of high-tonnage LNG-fueled vehicles in freight transport and to conduct a comprehensive assessment of the economic efficiency of this solution, taking into account both the benefits of lower fuel consumption and its price, as well as road usage fees in Germany accentuated in the literature, as well as less favorable cost items as a consequence of the higher price of these vehicles.

In the following parts of the article, an analysis of the state of knowledge in the field of identifying the environmental and economic benefits resulting from the replacement of diesel-fueled vehicles with LNG-fueled vehicles, as well as the assessment of the effectiveness of solutions in transport was performed. Both environmental and economic performance have been specified in this respect. Then, a case study is described concerning the transport on the given route carried out by a vehicle fueled by diesel oil or LNG and driven by one or two drivers. The planned transport cycles were described, as well as the parameters identified for this analysis, the obtained cost results, and the obtained CO_2 emissions. In conclusion, a discussion of the obtained results was carried out, emphasizing the factors determining the profitability of using high-tonnage vehicles with LNG drive or its lack.

2. Assessment of economic and environmental benefits from the implementation of high-tonnage LNG-fueled vehicles – state of the art

Many authors note the positive impact on the environment of the LNG drive, which is increasingly used in heavy-duty vehicles. For example, Song et al. (2017) assessed China's greenhouse gas reduction by replacing diesel engines with LNG-fueled vehicles.

The studies described in the literature also show a simultaneous positive and negative impact of using this technology for powering heavy-duty vehicles. The studies described by Tu et al. (2017) indicated that a vehicle fueled by LNG, compared to a vehicle with a diesel engine, reduces NOx, Sox, and PM emissions by 32,83%, 83,68%, and 100%, respectively, but causes a 21,39% increase in CO emissions and as much as a 7,83-fold increase in HC emissions. In addition, it found that the CO_2 emissions of LNG commercial vehicles during the use phase are 6,82% lower than that of a diesel vehicle, but 8,88% higher over the entire life cycle. At the same time, some researchers point out that in urban traffic, LNG-fueled vehicles are less ecological than diesel-fueled vehicles (see e.g. Cornelis, 2019 or Kollamthodi et al., 2016), while others emphasize both the economic and environmental benefits of applications of LNG drives in large cities (see e.g. Zhao et al., 2021). As indicated by Zhao et al. (2021), the use of high-tonnage transport to drive LNG allows the Chinese city of Shenzhen to reduce the cost of fuel consumption by 10-17% and reduce PM2,5 and NOX emissions by 36,0% and 16,3%, respectively.

[1] Numerous examples of multi-criteria approaches can be found in literature. They are related to both selection of pro-ecological solutions in transport (see e.g. Jacyna & Wasiak, 2014) and to supporting decisions in area of transport, taking into account other aspects (see e.g. Jacyna & Wasiak, 2015, Izdebski & Jacyna, 2018, Leleń & Wasiak, 2019).

The benefits of using LNG technology to reduce CO_2 emissions and fuel consumption costs are described in the Report (2017). For the two vehicles analyzed there with similar mileage and average load, one of which was fueled by LNG gas and the other by diesel, an 11% reduction in CO_2 emissions from 0,73 kg/km to 0,65 kg/km and a 23% reduction in the unit cost of consumption was identified. fuel from € 21,7/100 km to € 16,6/100 km (for 2017 prices), with specific diesel fuel consumption of 27,7 l/100 km and LNG consumption of 23,6 kg/100 km.

Apart from reducing fuel consumption costs, significant savings are also introduced in some countries by the preferences for LNG-fueled vehicles in the field of road tolls. In Germany, vehicles fueled by compressed and liquefied natural gas (CNG and LNG) are exempt from road tolls until December 31, 2023. However, from January 1, 2024, vehicles fueled mainly by natural gas will be partially covered by road tolls: a partial rate for infrastructure costs and a partial rate for noise (BFStrMG, 2011).

Accordingly, regardless of the scope and detail of the research to date, the implementation of LNG drives in high-tonnage vehicles brings several environmental benefits and undoubtedly is associated with certain economic benefits. On the other hand, LNG-fueled vehicles are much more expensive than traditional ones, have a shorter range on one refueling. Moreover, refueling operation is more cumbersome (including time-consuming and specialized), and the network of available refueling points is very limited. As a result of the above, when planning transport processes, it is also necessary to consider the type of propulsion, and the effectiveness of the implementation of vehicles with LNG propulsion may be quite strongly dependent on the transport relations being handled.

In the further part of the article, the efficiency of vehicles fueled by diesel oil and LNG gas for the selected transport cycle was compared. The analysis was carried out taking into account the conditions of May 2021.

3. The efficiency and its importance in cargo transportation

3.1. General remarks

In line with previous remarks, cargo transport by road has a significant negative impact on the environment, making it necessary to implement pro-ecological solutions in this area. On the one hand, enterprises' implementation of these solutions results from the so-called corporate social responsibility, and on the other, taking into account economic incentives. Much attention has been paid to integrating environmental, social, and economic aspects called TBL (triple-bottom-line) in the literature (Carter & Rogers, 2008, Drake & Spinler, 2013, Elkington, 2004). The relationships between the various aspects of cargo transportation are shown in Fig. 1.

Social aspects are related to equal access to resources among the society and the freedom to choose the method and scope of the services provided. From the point of view of sustainable development, it is one of the most challenging issues to implement on the one hand and to evaluate on the other. Economic efficiency refers to planning services in such a way that any investment and costs incurred in transporting cargo result in increased efficiency and better use of resources while at the same time meeting the demand. Environmental issues related to the impact that transport activities have on the environment. It mainly concerns environmental pollution and issues related to congestion and safety, which are ignored later in the article.

As Jacyna-Gołda et al. (2018) points out, the assessment of the efficiency of cargo transport must be based on indicators defined, taking into account the following features:

- *adequacy* – proper description of the relationship and resistance to changes in external factors,
- *capacity* – taking into account the essential features of the distribution system in the formalism,
- *adaptability* – the degree of substantive content,
- *economic dimension* – relation between the effect of using the measure and the costs of its determination (measurements).

The indicators should enable the assessment of cargo transport at a different level of detail, i.e. from global features (e.g. the cost of the system operation) to specific features, e.g. the number of drivers and other resources involved. The level of detail at which a given system or solution is assessed depends on many factors, including the ability to measure parameters and the needs of decision-makers. Moreover, it should be noted that beyond the scope of action or the type of indicators taken into account, the differentiation occurs, e.g. depending on the implemented processes.

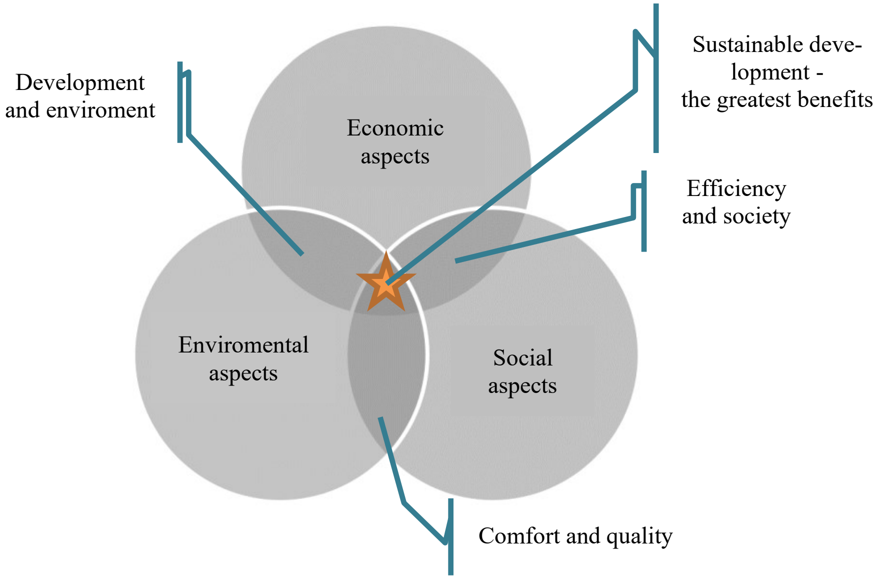

Fig. 1. Aspects of a transport activity assessment
Source: own study based on (Carter & Rogers, 2008).

3.2. Economic efficiency

The basis for determining the economic efficiency of transport is to estimate the costs of their implementation. Considering the transport and warehouse system as a whole, its operating costs K_{pm} are the sum of the transport costs K_{tr} and the maintenance costs and involvement of K_{ob} warehouse facilities incurred in t-th period:

$$K_{pm}(t) = K_{tr}(t) + K_{ob}(t) \text{ (PLN)} \quad (1)$$

This view on transport costs is justified due to their strong relationship with storage costs. Achieving low transport costs is often associated with higher storage costs and vice versa (see Figure 2). This is the justification for a broader look at transport processes. Of course, the presented cost estimation formula is very general and may consider various components and a different organizational and functional structure of the transport and warehouse system (Szczepański et al., 2017; Szczepański et al., 2019). In cargo transport, more attention is paid to determining the costs of carrying out transportation processes. Here, the cost components of vehicle involvement, driver involvement costs, infrastructure access costs, information systems costs, and other overheads, respectively, are among the cost components. These costs, depending on their specificity, are divided into fixed costs and variable costs depending on the volume of shipped loads, transport distance, working time, and many other elements in the period t:

$$K_{tr}(t) = Ks_{tr}(t) + Kz_{tr}(t) \text{ (PLN)} \quad (2)$$

Fixed costs of transport include general costs of running a transport activity (including licenses and permits as well as costs of management information systems and telematics) and costs of consumption or renting of vehicles, motor vehicle insurance, taxes on means of transport, periodic inspections, fixed components of drivers' remuneration. On the other hand, variable costs include the costs of fuel consumption, costs of spare parts and other consumables and components of remuneration depending on working time, tolls for road sections, bridges, tunnels and crossings, additional cargo insurance, and, among others, fees for permits for the transport of specific loads. Detailed components of transport costs are presented in Wasiak & Jacyna-Gołda (2016).

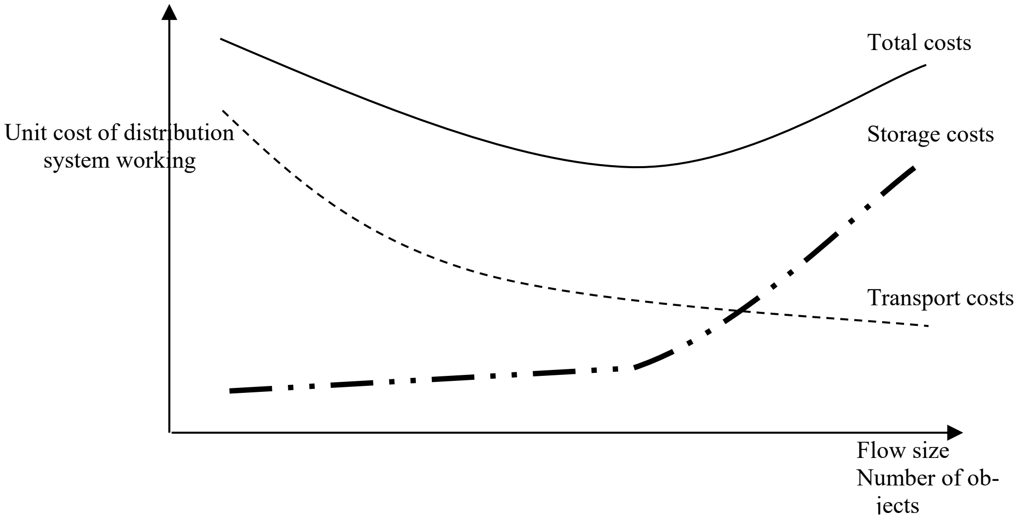

Fig. 2. The relationship between the cost of transportation and the cost of storage
Source: McKinnon (2003).

Comparing two solutions ensuring the implementation of the same transport tasks in terms of costs, it is evident that the cheaper solution is more economically effective. Often the efficiency assessment is made concerning the transport processes related to various tasks. Then, the evaluation of their economic efficiency requires determining the cost per unit of cargo, mileage, or, for example, transport work. Starting from the general definition of efficiency, as the quotient of the obtained effects to the expenditure incurred, it should be assumed that the economic efficiency indicators of transport should be the reciprocal of the relevant cost indicators. For example, the economic efficiency index in terms of the vehicle load mileage L in period t is determined as follows:

$$EE_{trL}(t) = L(t) \,/\, K_{tr}(t) \text{ (km loaded/PLN)} \quad (3)$$

Apart from the costs of performing transport tasks, the obtained revenues can also be considered as part of economic efficiency. In this approach, the economic efficiency ratio can be interpreted as gross income (or loss) obtained as a result of the implementation of tasks in relation to the costs incurred in the period t:

$$EE_{trD}(t) = (P_{tr}(t) - K_{tr}(t)) \,/\, K_{tr}(t) \; (–) \quad (4)$$

An important issue that can be considered in economic efficiency assessment is the competitiveness of services. It can be expressed as the ratio of the unit cost of delivering a cargo unit to the average market price. In this case, it has a financial interpretation, but competitiveness can also be expressed in terms of delivery time, reliability or quality.
The presented formulas include ingredients that can be obtained when designing transport processes. The most acquisition is based on historical data, similar to other processes or expert estimates. Usually, in the analysis of the effectiveness of transport processes, the costs of marketing, administration, legal and financial services, etc. are not taken into account. Of course, taking into account such components is possible but difficult to estimate at the stage of planning solutions. However, due to the assessment of the efficiency of cargo transportation, it is not necessary.

3.3. Environmental efficiency

The environmental efficiency of cargo transportation concerns mainly the following environmental impacts of transportation:
- emissions of exhausts and other harmful substances,
- noise emission,
- congestion,

– safety of road users,
– land occupancy and degradation,
– destruction of infrastructure.

Due to the scope of the article, only the first environmental impacts of transport are considered in the following.

In terms of exhaust emissions, the impact of transport processes is relatively easily measurable. The increase in their efficiency may be manifested by reducing the emission of pollutants per kilometer of the road, or e.g. per delivered unit of load. The emission of pollutants is also related to the specific consumption and fuel type. Currently, there is a noticeable trend in the use of environmentally-friendly vehicles. Thus, the share of such vehicles in the transport performance can also be considered an efficiency assessment indicator. Environmentally friendly vehicles and their implementation aim to reduce the negative impact of transport on the environment. It manifests itself in the context of both harmful pollutant emissions and noise. Various types of environmentally friendly vehicles can be distinguished, but generally, the best way to classify them is the type of fuel and propulsion system (Jacyna & Merkisz, 2014; Jacyna et al., 2018; Visvikis et al., 2010). The main types of environmentally friendly road vehicles include:

– electric vehicles,
– hybrid vehicles,
– hydrogen-fueled vehicles,
– LPG-fueled vehicles,
– LNG-fueled vehicles,
– CNG-fueled vehicles,
– vehicles powered by biofuels.

The previously described economic efficiency is also strongly associated with implementing pro-ecological solutions. Currently, the greatest attention is paid to passenger vehicles. This trend is understandable due to the more significant number of passenger vehicles than commercial vehicles. This is also related to appropriate transport policy measures supporting the replacement of vehicles with environmentally friendly ones through privileges such as surcharges, free parking, free entry to urban zones, or the possibility of using separate bus lanes. Nevertheless, the return on investment for a private vehicle is spread over time. Assuming an average mileage of 15,000 km per year, the return on investment can be around 10 years. Therefore, at the moment, it is more a question of consumer awareness than economic (Mirhedayatian & Yan, 2018, Visvikis et al., 2010).

In case of commercial applications, distribution vehicles and passenger vehicles used, for example, by sales representatives or rental vehicles, are already much more advantageous in terms of finance. Entrepreneurs obtain measurable savings in the form of tax deductions, investment subsidies, as well as fuel and lower service costs. The obvious profits also include the increase in the marketing value of the company that uses ecological vehicles.

Vehicles with a GVM of over 3,5 t are mostly diesel-fueled vehicles (compression-ignition). However, the interest in alternative fuels is also growing in this area. Until now, the leading alternative solution has been to power an LPG or CNG vehicle, but currently, manufacturers are developing prototypes of electric and electric tractor units with hydrogen fuel cells. On the other hand, due to the relatively large range of high-tonnage vehicles, the LNG-fueled vehicles analyzed in this article have been increasingly used in this segment in recent years.

Considering the pollutant emissions in the criteria for assessing the effectiveness requires using a model for its estimation. The most accurate models are based on vehicle emissions testing under regular road use. However, most tests are based on laboratory tests, which may significantly differ from the actual emission values. Detailed models allow for accurate estimation of emissions from a single vehicle and require very accurate data on its journey (duration of driving phases, speed values, accelerations, ambient temperature, engine, etc.), not to mention the exact parameters of the vehicle. However, such models are complicated to use on a large scale. Therefore, some simplifications are applied to estimate emissions, e.g. for a whole group of vehicles and many journeys, by averaging specific driving parameters. The degree of simplification may vary depending on the desired accuracy and the nature of the research. Three models emerge from the above discussion (Demir et al., 2014). Model on a micro-scale (very high accuracy per unit of time, requires a lot of input data), a model on a macro scale (accuracy to a group of vehicles or a given region over a longer period), and the so-called indicator models based on the most straightforward data (e.g. GVM and fuel type) and distance traveled.

Based on a review (Demir et al., 2014), the main representatives of each type of pollutant emission estimation model can be distinguished. Microscale models allow for accurate estimation of fuel consumption and/or pollutant emissions and require a lot of detailed data on operating conditions and variables regarding the driving mileage. However, they allow you to know your consumption and emissions at any given time. Micromodels include, for example, CMEM (Scora & Barth, 2006), VT-CPFM (Rakha et al., 2011), and PERE (Nam & Giannelli, 2005).

The first model was developed to estimate fuel consumption and a wide range of harmful compounds, including (CO, HC, NOx), considering cold start for various vehicles and technologies. It allows for the estimation of pollutant emissions and fuel consumption. In the second case, there are essentially two models for estimating fuel consumption. However, it also allows for estimating CO_2 emissions (resulting directly from fuel consumption). The third model allows modeling the fuel consumption of conventionally powered vehicles as well as hybrids and fuel cell vehicles.

The second group of models is macroscopic models. They allow for the estimation of fuel consumption or pollutant emissions for the entire modeled facility, e.g. intersections, public transport system in the city, etc. Therefore, it is possible to conduct research on a larger scale and observe the impact of the transport system on the environment. However, this comes at the cost of accuracy. The main models of this type include, for example, COPERT (Ntziachristos & Samaras, 2017), HBEFA (Keller et al., 2017), EMITRANSYS (Ambroziak et al., 2014, Jacyna & Merkisz, 2014).

The first one enables the estimation of emissions and fuel consumption for various types of propulsion (including hybrid vehicles or energy consumption for electric vehicles) at three levels of detail. From general estimation based on distance and vehicle structure to take into account hot/cold emission and traffic conditions. The second is a set of emission factors for car transport in Europe that enable estimating fuel consumption and pollutant emissions. The third, EMITRANSYS, is a model developed by the Faculty of Transport of the Warsaw University of Technology and the Faculty of Working Machines and Transport of the Poznań University of Technology. It is a methodology of shaping the transport system based on testing the difference between the emissions determined for vehicles in laboratory conditions for the purposes of E_N certification and measurements in real conditions E_{rz}. On this basis, the authors determined the multiplicity factors for each t of harmful substances:

$$k(s) = E_{rz}(s) / E_N(s) \; (–) \quad (5)$$

The $k(s)$ coefficient allows the determination of appropriate emission factors for LGV (vans) vehicles whose emissions are expressed in grams per kilometer [g / km] and HGV (heavy-duty vehicles) for which emissions are expressed in grams per kilowatt-hour [g / (kWh)]. At the same time, it takes different values for different conditions (Jacyna & Merkisz, 2014).

The most convenient of the models to be used in the assessment of the environmental performance of transport processes is the COPERT model. On its basis, it is possible to estimate the emissions of various harmful substances.

4. Case study

4.1. Variants and organization of transport

The advantage of LNG-fueled trucks is usually a relatively long-range (compared to other alternative propulsion sources) and the benefits of exemption from road tolls in some countries. Therefore, a comparison was made between using an LNG-fueled tractor unit and a modern diesel-fueled tractor for a medium-length transport cycle. In this cycle, two transport routes are handled: Andrychów (PL) - Gersheim (DE) and Metzingen (DE) - Suchy Las (PL), both of which carry neutral cargo. It was assumed that the base of the enterprise is located in Tychy. On the other hand, the negotiable freight for individual orders is approximately EUR 1,300 (export) and EUR 1,100 (import).

The route of a diesel-fueled vehicle is shown in Table 1, and for an LNG-fueled vehicle in Table 2. The characteristics of the vehicles in question are summarized in Table 3, assuming that they will be operated for 5 years.

For the transport cycle, in case of a diesel-fueled vehicle, one refueling is sufficient (39,1 km of the route are planned), and the LNG-fueled vehicle must be refueled twice, with additional distances necessary. The first refueling with LNG is planned in Germany for 271 km of section 4 (additional 8 km and 11 minutes of driving), and the second in Poland for 203,5 km of section 8 (additional 6 km and 11 minutes of driving). The mileage utilization factor for the first vehicle is 0,7418 and for the second vehicle is 0,7409. It should be emphasized that the slight difference in both routes results from the careful selection of transport orders, and in most cases, it can be much more significant. Nevertheless, an improvement in this respect should be expected in the future.

Table 1. Route of a diesel-fueled vehicle

No.	Beginning of the stage	End of the stage	Roads	Country	Length (km)	Driving time
1	Tychy Graniczna 5	Andrychów Krakowska 83	Local road, 44, 1, S1, 52, local road	PL	74	01:17
2	Andrychów Krakowska 83	Cieszyn-Chotebuz	local road, 52, S1, S52	PL	67	01:04
3	Cieszyn-Chotebuz	Grenzübergang Waidhaus/Rozvadov	A48, 11, D1, D35, 276, D46, D1, D0, D5	CZ	565	06:57
4	Grenzübergang Waidhaus/Rozvadov	Hauptstraße 4-8, 66453 Gersheim, Niemcy	A6, A61, 9, 272, 10, A8, L465, L101, L201, local road	DE	450	05:52
5	Hauptstraße 4-8, 66453 Gersheim, Niemcy	Stuttgarter Str. 54, 72555 Metzingen, Niemcy	local road, L105, B423, A8, B10, A65, B10, A5, A8, B27, B312, local road	DE	224	03:08
6	Stuttgarter Str. 54, 72555 Metzingen, Niemcy	Świecko-Frankfurt/Oder	local road, B312, B27, A8, A81, B19, A7, A70, A71, A4, A9, A10, A12	DE	733	08:47
7	Świecko-Frankfurt/Oder	Suchy Las Sucholeska 1	A2, 307, S11, local road	PL	179	02:26
8	Suchy Las Sucholeska 1	Tychy Graniczna 5	local road, 433, 196, 3,9, S5, A8, A4, 44, local road	PL	396	06:12
				SUM	**2688**	**35:43**

Table 2. Route of LNG fueled vehicle

No.	Beginning of the stage	End of the stage	Roads	Country	Length (km)	Driving time
1	Tychy Graniczna 5	Andrychów Krakowska 83	local road, 44, 1, S1, 52, local road	PL	74	01:17
2	Andrychów Krakowska 83	Cieszyn-Chotebuz	local road, 52, S1, S52	PL	67	01:04
3	Cieszyn-Chotebuz	Grenzübergang Waidhaus/Rozvadov	A48, 11, D1, D35, 276, D46, D1, D0, D5	CZ	565	06:57
4	Grenzübergang Waidhaus/Rozvadov	Hauptstraße 4-8, 66453 Gersheim, Niemcy	A6, A61, 9, 272, 10, A8, L465, L101, L201, local road	DE	458	06:03
5	Hauptstraße 4-8, 66453 Gersheim, Niemcy	Stuttgarter Str. 54, 72555 Metzingen, Niemcy	local road, L105, B423, A8, B10, A65, B10, A5, A8, B27, B312, local road	DE	224	03:08
6	Stuttgarter Str. 54, 72555 Metzingen, Niemcy	Świecko-Frankfurt/Oder	local road, B312, B27, A8, A81, B19, A7, A70, A71, A4, A9, A10, A12	DE	733	08:47
7	Świecko-Frankfurt/Oder	Suchy Las Sucholeska 1	A2, 307, S11, local road	PL	179	02:26
8	Suchy Las Sucholeska 1	Tychy Graniczna 5	local road, 433, 196, 3,9, S5, A8, A4, 44, local road	PL	402	06:23
				SUM	**2702**	**36:05**

Table 3. Vehicle comparison

Parameter	Diesel-fueled vehicle	LNG-fueled vehicle
Tractor unit		
EURO emission standard	6	6
New vehicle – net price	78 499 EUR	141 000 EUR,
Vehicle residual value	124 000 PLN	220 000 PLN
Fuel tanks capacity	1200 l diesel oil	380 kg LNG
Number of axles	2	2
Number of wheels	6	4
Fuel consumption - unloaded	26,4 l/100 km	23,0 kg/100 km
Fuel consumption - loaded	29,4 l/100 km	24,5 l/100 km
Semitrailer		
New semitrailer – net price	55 000 EUR	
Semitrailer residual value	130 000 PLN	
Number of axles	3	
Number of wheels	6	

Only driving time is included in the route tables. Additionally, in case of both variants, the analyzes included: time to prepare the vehicle and collect documents (10 minutes), time of daily vehicle maintenance (5 minutes), time to hand over the vehicle and documents (10 minutes), and the time of vehicle service at the place of loading (90 minutes each). minutes per load operation) as well as refueling times (16 minutes for the first vehicle and 23 and 24 minutes respectively for the second vehicle). Due to the length of the transport route, it was also necessary to take into account the times of breaks and daily rests resulting from legal regulations (Regulation 561/2006, the Labor Code Act (RP, 1974), the Act on the working time of drivers (RP, 2004)) (in this respect, drivers employed under an employment contract in an equivalent time system were taken into account). The analyzes took into account both the one-person and two-person vehicle manning options. Consequently, four variants were obtained.
The developed schedules for the implementation of the transport cycle take into account the night time used to determine the working time between 2:00 and 6:00 and the night time used to determine the wage supplement between 23:00 and 7:00. Data on the involvement of vehicles and drivers in implementing the transport cycle, resulting from the schedules of its implementation for single and double manning of both vehicles, are included in table 4.

4.2. Cost analysis of variants

The economic assessment of vehicle selection variants and their stocking was carried out, taking into account the methodology described, inter alia, in (Lewczuk & Wasiak, 2011; Jacyna & Wasiak, 2015; Wasiak & Jacyna-Gołda, 2016).
For the purposes of these analyzes, as of May 21, 2021, the exchange rates, the applicable national and foreign diet rates for Germany and the reimbursement limits for accommodation costs, or the rates of the minimum wage and lump sum for food and the minimum gross wage applicable in Poland were taken into account. As well as the relevant costs of excerpts from the Road Transport Permit and the costs of excerpts from the Community license for international road transport of goods. Also taken into account are 252 working days a year, 168 working hours a month, and the 6% cost of freezing capital.
Concerning drivers, it was assumed that their holiday absenteeism coefficient was 0.0984 and their sickness absenteeism coefficient was 0,0568. The monthly basic gross salary of PLN 5 000 PLN and the remuneration coefficient (0,2001) was also taken into account. The obligation to carry out medical and psychological examinations every five years, replace the driving license and driver card for the digital tachograph, and renew the Certificate of Professional Qualification was also considered.
For the vehicles, their cost parameters presented in Table 3 were taken into account. Their working time per year was 5 650 hours. And the cost of their insurance is equal to 14 948 PLN/year for the first set of vehicles and 21 546 PLN/year for the second set of vehicles, the cost of periodic technical inspections of 493 PLN/year for the first set of vehicles and 693 PLN/ year for the second set of vehicles, as well as tax on means of transport equal to 2 772 PLN/year

Table 4. Use of vehicles and drivers in the implementation of the transport cycle

Parameter	Variant 1 (diesel, one driver)	Variant 2 (diesel, two drivers)	Variant 1 (diesel, one driver)	Variant 2 (diesel, two drivers)
Vehicle involvement time	80:04:00	60:29:00	80:57:00	61:22:00
Working time – driver 1	43:34:00	22:02:00	44:27:00	23:32:00
Driving time – driver 1	35:43:00	17:46:00	36:05:00	18:45:00
Other working time – driver 1	7:51:00	4:16:00	8:22:00	4:47:00
On-call time - driver 1	0:00:00	0:00:00	0:00:00	0:00:00
Other on-call time - driver 1	3:30:00	20:27:00	3:30:00	19:50:00
Oversized working time - driver 1	0:30:00	0:00:00	0:30:00	0:00:00
Nominal working time – driver 1	43:04:00	22:02:00	43:57:00	23:32:00
Night working time – driver 1	0:31:00	7:20:00	0:31:00	6:28:00
Working time – driver 2	0:00:00	22:13:00	0:00:00	22:07:00
Driving time – driver 2	0:00:00	17:57:00	0:00:00	17:20:00
Other working time – driver 2	0:00:00	4:16:00	0:00:00	4:47:00
On-call time - driver 2	0:00:00	0:00:00	0:00:00	0:00:00
Other on-call time - driver 2	0:00:00	20:16:00	0:00:00	21:15:00
Oversized working time - driver 2	0:00:00	0:00:00	0:00:00	0:00:00
Nominal working time – driver 2	0:00:00	22:13:00	0:00:00	22:07:00
Night working time – driver 2	0:00:00	3:15:00	0:00:00	4:31:00
Domestic travel time	14:54:00	23:20:00	15:13:00	23:39:00
Foreign travel time	64:50:00	36:49:00	65:24:00	37:23:00
Domestic accommodation - driver 1	1	24:00:00	1	24:00:00
Overseas accommodation in Czech Republic – driver 1	1	0	1	0
Overseas accommodation in Germany – driver 1	1	1	1	1
Domestic accommodation - driver 2	0	1	0	1
Overseas accommodation in Czech Republic – driver 2	0	0	0	0
Overseas accommodation in Germany – driver 2	0	1	0	1

for a group of vehicles. The standard depreciation rate for the vehicles included is 14%, and the cost of registering them is 302 PLN. The net price of the tire with its replacement was also assumed to be 1 860.00 PLN/ item and its lifetime of 200 000 km.
One of the most important assumptions of the cost analysis is the gross unit price of fuel. Considering the data from the fuel stations included in the schedules, this price on the day of the study was set at 5,17 PLN/l of diesel oil and 4,07 PLN/kg of LNG gas. The road charges identified for individual transport variants are summarized in Table 5. General costs to the transport cycle were assigned, taking into account their level of 600 000 PLN year and 14 vehicles used in the enterprise.
In addition, the lengths of the route sections resulting from Tables 1 and 2 as well as the drivers 'activity times resulting from the transport schedules and the corresponding working hours under full-time, overtime, or night time, as well as the drivers' on-call times and the times of their business trips and the resulting of them, the number of domestic and foreign diets and the number of diets, as well as overnight stays in individual countries. The obtained economic assessment results of the considered variants of the transport cycle are summarized in Tab. 6.

Table 5. Road charges for individual variants

Country	Variant 1 (diesel, one driver)	Variant 2 (diesel, two drivers)	Variant 1 (diesel, one driver)	Variant 2 (diesel, two drivers)
Poland	173,65 PLN	173,65 PLN	173,65 PLN	173,65 PLN
Germany	256,84 EUR	256,84 EUR	–	–
Czech Republic	2 682,72 CZK	2 682,72 CZK	2 682,72 CZK	2 682,72 CZK

Table 6. Costs of the transport cycle implementation depending on the propellant and vehicle stocking (PLN)

Cost	Variant 1 (diesel, one driver)	Variant 2 (diesel, two drivers)	Variant 1 (diesel, one driver)	Variant 2 (diesel, two drivers)
Salaries with derivatives	**2 939,58**	**3 996,42**	**2 976,68**	**4 063,37**
Cost of drivers' work resulting from the base salary	1 808,87	1 858,57	1 845,97	1 917,38
Cost of drivers' overtime work	26,79	0,00	26,79	0,00
Cost of drivers' work during night hours	2,07	42,34	2,07	43,94
Cost of drivers' work during on-call time	62,51	727,14	62,51	733,69
Cost of work resulting from domestic and foreign drivers' allowances	690,88	941,18	690,88	941,18
Cost of domestic and overseas accommodation	348,47	427,19	348,47	427,19
Special allowances for work abroad	0,00	0,00	0,00	0,00
Consumables	**4 157,58**	**4 157,58**	**2 873,89**	**2 873,89**
Cos of fuel comsumption	3 234,20	3 234,20	2 155,74	2 155,74
Cos of tires	299,98	299,98	251,29	251,29
Cost of other consumables, technical services, and repairs	623,40	623,40	466,86	466,86
Tolls	**1 801,60**	**1 801,60**	**646,88**	**646,88**
Cost of using vehicles and other fixed costs	**2 031,46**	**1 536,21**	**2 866,49**	**2 174,74**
Cost of using vehicles (balance sheet depreciation)	822,95	621,67	1 388,79	1 052,81
Cost of freezing capital due to purchase of vehicles	334,68	252,82	496,79	376,61
Remaining fixed costs	260,52	196,80	360,78	273,50
Cost of training and examinations of drivers and the renewal of the validity of their documents	5,97	6,14	6,09	6,33
General operating cost of the company	607,33	458,79	614,03	465,49
Cost of using the environment	**1,06**	**1,06**	**0,00**	**0,00**
Total costs	**10 931,28**	**11 492,87**	**9 363,94**	**9 758,88**

The results summarized in Table 5 confirm the economic benefits of using LNG-fueled engines in high-tonnage truck transport to service the considered transport tasks. Depending on the staffing of vehicles, the economic benefits of implementing LNG propulsion, in this case, are equal to 19,1% for a single crew or 19,6% for a two-person crew. More significant benefits in the latter case result primarily from the shorter time of vehicle involvement in variants 2 and 4. Overall, the profitability of carrying out transport on medium-length routes by one driver compared to two-person crews has been confirmed. Nevertheless, in case of using LNG-fueled vehicles, the difference in the range decreases by less than 1 pp from 5,14% to 4,22%

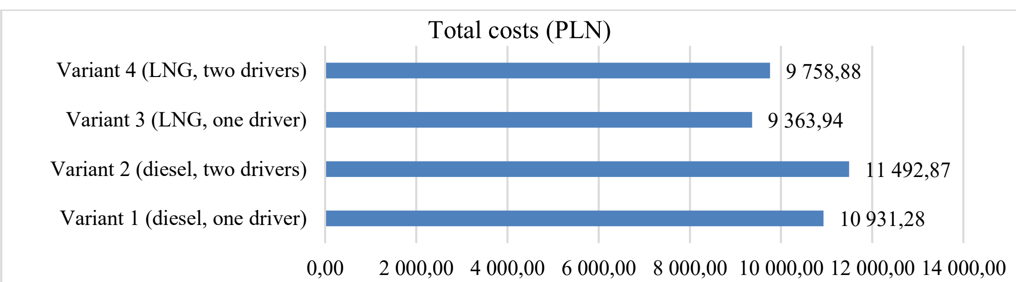

Fig. 3. Total costs of transport cycle depending on propulsion and number of drivers

Nevertheless, when planning an investment in the field of replacing vehicles with LNG-fueled vehicles, one must take into account various risks, including those resulting from changes in road tolls in Germany expected at the beginning of 2024, or, for example, from changing road traffic conditions that may result in an extension of the transport time and, consequently, reduce the competitiveness of LNG due to a greater share of fixed costs resulting from the use of a much more expensive vehicle in transport. In addition, the fuel prices included in the analysis will certainly not be constant in the long run. Consequently, the obtained results may significantly differ in the future. For example, changes in the fuel market in the last six months (an increase in the price of diesel oil to PLN 6,10 / l and the price of LNG gas up to PLN 9,39 per kg) resulted in the total costs for the analyzed variants being as follows:

– variant 1 (diesel, one driver): 11 571,23 PLN,
– variant 2 (diesel, two drivers): 12 132,82 PLN,
– variant 3 (LNG, one driver): 12 463,49 PLN,
– variant 4 (LNG, two drivers): 12 858,44 PLN.

This means that after the increase in fuel prices, the cost obtained for an LNG vehicle is higher than the cost for a diesel-fueled vehicle by 7,7% for a single crew or 6,0% for a two-person crew, respectively. Thus, without radical support for the use of high-tonnage LNG vehicles in transport - also in the field of state fiscal policy - the development of this technology may face financial barriers.

4.3. Assessment of the impact of solutions on the environment

The test results described in the Report (2017) were taken into account to assess the impact of individual solutions on the environment. Adjusting the CO_2 unit emissivity indices given therein to the example analyzed in the article, the following values were obtained:

– unit CO_2 emissivity of the diesel-fueled vehicle: 0,754 kg/km,
– unit CO_2 emissivity of the LNG fueled vehicle: 0,664 kg/km.

The total CO_2 emissions for the transport cycle and individual variants obtained considering the determined indicators are shown in Fig. 4.

The results obtained for the analyzed case mean an 11,5% reduction in carbon dioxide emissions thanks to the use of LNG propulsion for each transport cycle from 2 028 to 1 794 kg.

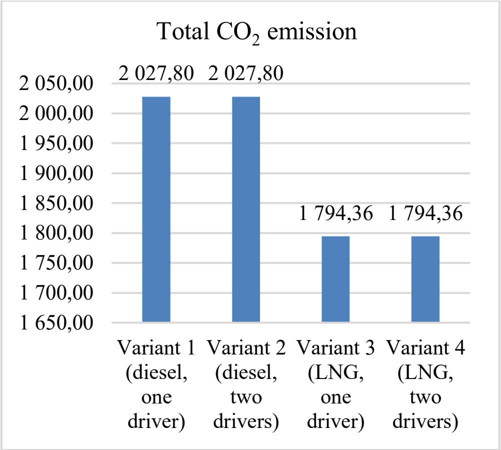

Fig. 4. Total CO_2 emission of transport cycle depending on propulsion and number of drivers

4.4. Selected indicators for assessing the effectiveness of solutions

When evaluating the effectiveness of the solutions analyzed in the paper, the total cost of transport and economic and environmental efficiency in terms of CO_2 emissions were taken into account. The results of the conducted analyzes are summarized in table 7.

Table 7 clearly shows the highest efficiency of the analyzed transports with an LNG-fueled vehicle driven by one driver.

Table 7. Selected indicators for assessing the effectiveness of solutions

Indicator	Variant 1 (diesel, one driver)	Variant 2 (diesel, two drivers)	Variant 3 (LNG, one driver)	Variant 4 (LNG, two drivers)
Total cost	10 931,28	11 492,87	9 363,94	9 758,88
Economic efficiency [km loaded /PLN]	0,1824	0,1735	0,2138	0,2051
Environmental efficiency [km loaded / kg of CO_2 emission)	0,9833	0,9833	1,1157	1,1157

5. Conclusions

The economic benefits resulting from the use of LNG in tweeter vehicles shown in the literature on the subject primarily emphasize the lower costs of fuel and road tolls in Germany. At the same time, the cost items that are less favorable in case of LNG vehicles, such as the cost of vehicle wear or the cost of its insurance, are not mentioned. In case analyzed in the article, the costs in these areas increase by approximately 68,8–69,4% and 48,4–49,0%, respectively.

At the same time, as indicated earlier, it is justified to conduct analyzes in the field of the implementation of LNG drives, taking into account various risks, including those resulting from possible changes in the area of: toll collection, fuel tax burdens, and changes in its price, or the threat of changing the time of carrying out transport tasks in relation to planning, as well as the lack of a sufficient number of refueling places near the planned transport route. An interesting approach to risk assessment in various areas of transport can be found e.g. in (Jacyna & Semenov, 2020).

Regardless of the indicated lack of clarity in the economic assessment of the effectiveness of LNG drives in high-tonnage vehicles, the identified environmental benefits from implementing these solutions seem to be quite unequivocal. Thus, it should be expected that in the event of loss of economic competitiveness of these solutions, appropriate fiscal instruments should be used - especially since LNG drives in the policies of individual countries are considered pro-ecological solutions.

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