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Prediction of Fuel and Exhaust Emission Costs of Heavy-Duty Vehicles Intended for Gas Transportation

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Abstract: This research focuses on heavy-duty vehicles intended to transport compressed natural gases, i.e., class-2 dangerous goods. The analysis includes heavy-duty vehicles powered by diesel and compressed natural gas and trailers with two body types. The body types used in the research are battery bodies and multiple-element gas containers, with pressure vessels made of composite materials (Type-4) and steel (Type-1). The paper presents the methodological procedure for predicting fuel and exhaust gas emission costs as a function of fuel consumption and transported gas quantities. The effects of different types of bodies and different types of fuel on the transported quantities of gas, vehicle mass utilization, fuel consumption, and exhaust gas emissions are shown. The obtained results show that bodies with Type-4 pressure vessels transport 44% more gas than bodies with Type-1 pressure vessels for one turn. The most cost-effective solution for emission costs is diesel-powered, newer-technology vehicles and Type-4 vessels, requiring EUR 2.82 per ton of gas. Similarly, the most economical choice for fuel costs is compressed natural-gas-powered vehicles with Type-4 bodies and a cost of EUR 19.77 per ton of gas. The research results' practical application pertains to the selection procedures of vehicles and bodies intended for the transport of gases; they should be considered in the decision-making process, with the aim of attaining a sustainable transport sector with lower costs and less impact on the environment.

Keywords: heavy-duty vehicle; dangerous goods; compressed natural gas; fuel consumption; exhaust emission; cost

Citation: Vašalić, D.; Ivković, I.; Mladenović, D.; Sekulić, D.; Miličević, D.; Suljovrujić, E. Prediction of Fuel and Exhaust Emission Costs of Heavy-Duty Vehicles Intended for Gas Transportation. *Sustainability* **2024**, *16*, 5407. https://doi.org/10.3390/su16135407

Academic Editor: Maxim A. Dulebenets

Received: 15 May 2024
Revised: 16 June 2024
Accepted: 17 June 2024
Published: 25 June 2024

1. Introduction

The development of economic activities in Europe and the world imposes a demand for significant amounts of natural gas (NG), which challenges the sustainability of gas transportation from distribution centers to end consumers [1,2]. The most common forms of NG transportation are gas pipelines, ships, and, to a lesser extent, road transport. Road transport of NG is applied in places with gas infrastructure limitations caused by insufficient pipeline development or limitations caused by the terrain's geography. It belongs to the system of road transport of dangerous goods (RTDG), and transport is carried out with special vehicles intended to transport gases via battery bodies or multiple-element gas containers (MEGC) [3–5]. The development of the economy and the demand for greater amounts of gas require the application of new construction solutions for developing body types (pressure vessels) intended for storing and transporting gases. New body construction solutions depend on many parameters, some of the most influential being the pressure vessel type approval, the body's production materials, the vehicle's type approval, the vehicle's dimensions, and the vehicle's technical limitations regarding the maximum permissible axle loads. Answering the demands of the economy for more quantities of gas with sustainable economic activity, safety, and environmental protection introduces new composite materials for the production of bodies and pressure vessels [6–

8]. The use of lightweight composite materials in RTDG is primarily defined via procedural approvals and verifications of the production process of the body types (battery or MEGC), with the purpose of type approval specified in the relevant Agreement [9].

The European Union (EU) gas pipeline network is a well-developed network with significant distribution and storage capacities [1]. However, some countries on the European continent and their economies are in the transition process and have an insufficiently developed gas pipeline network [10]. This work focuses on economies with insufficiently developed gas pipeline infrastructure and where road transport plays a significant role in gas transport, with attention paid to preserving economic and environmental sustainability. To this end, the model of NG road transport in the Republic of Serbia was discussed in this paper, and the effects of the transition from conventional methods of gas transport to new contemporary methods were presented. The strategy for developing the Republic of Serbia's energy sector defines the directions of technological modernization and market restructuring, focusing on economic and ecological sustainability until 2025 [10]. One direction of technological modernization is constructing and connecting gas pipeline infrastructure with regional gas pipeline systems and improving existing distribution capacities. Existing NG distribution capacities are based partly on internal gas pipeline infrastructure and partly on road transportation. The main research question is whether applying an adequate strategy for the selection of vehicles and body types in the road transport of gases can contribute to the economic sustainability of transport while preserving the environment.

Following the above, this research comprehensively analyzed heavy-duty vehicles (HDV), i.e., tractors and trucks, powered by compressed natural gas (CNG) and diesel fuels, and semi-trailers and trailers with battery and MEGC bodies. This study determined the effects of bodies made of steel and composite materials on vehicle mass utilization, fuel consumption, transport gas amounts, fuel costs, and exhaust emissions.

1.1. Context Background

In recent decades, HDV manufacturers have made substantial investments in both financial and engineering resources to enhance vehicle efficiency, reduce exhaust emissions, and minimize fuel consumption. These improvements are primarily attributed to the application of alternative fuels, innovative exhaust after-treatment technology, and the use of lightweight materials in vehicle and body construction [11–27].

The European Commission (EC) has influenced the implementation of alternative fuels in the transport sector with a series of Regulations and Directives [13–16]. One of the main aims of the EC action plan is to reduce exhaust emissions and decarbonize the transport sector. The Directive [13] popularized alternative fuels by applying for economic benefits, reducing or exempting them from taxes. Directive [14] defined the conditions for setting up infrastructure to supply alternative fuels in the European Union (EU). The conditions define fuel supply points and types of alternative fuels, including natural gas, biofuels, hydrogen, and electric vehicle charging systems. The Directive [15] defined the obligations of the EU member states regarding the use of renewable energy sources to achieve a share of at least 14% of energy consumption in the transport sector being obtained through renewable sources by 2030. Directive [16] under consideration promoted clean, energy-efficient road transport vehicles and defined the conditions for procuring new vehicles for member states; these conditions include the operating costs incurred during a vehicle's life cycle, including greenhouse gas (GHG) and other pollutant emissions, based on a relevant methodology employed to determine their monetary value.

The results of the implementation of Directives [13–16] can be considered by the number of registered NG HDVs. The number of registered NG HDVs in the EU, looking at the period from 2015 to 2022, increased from 9349 [28] to 34,042 [29]. The member states with the highest percentage share are Spain, Italy, France, and the Netherlands. Predictions of the impact of alternative fuels, biomethane, and NG on decarbonization and the reduction of exhaust emissions in the transport sector of Latvia are presented in reference [30].

Improvements in the field of exhaust gas after-treatment technology for diesel-powered HDVs are presented in references [17–21]. Reference [17] shows the nitrogen oxide (NO_x) emissions results for heavy-duty engines (HDE) powered by diesel and biodiesel equipped with selective catalytic reduction (SCR). The results show that NO_x emissions are lower for biodiesel fuel. References [18,19] show the effects of the application of a diesel oxidation catalyst (DOC), a diesel particulate filter (DPF), and SCR technology on NO_x and carbon dioxide (CO_2) emission values in accordance with on driving conditions. The results show that NO_x and CO_2 emissions are higher for urban driving conditions. The authors show the effects of SCR system failure on the emission values of NO_x and CO_2. At lower speeds, emissions are higher for HDVs with a deactivated SCR than those with a working SCR system [20]. Research shows the effects of applied after-treatment technologies (i.e., a DOC), a catalyzed diesel particulate filter (CDPF), and SCR on the exhaust emissions of diesel HDE. The applied technologies reduce carbon monoxide (CO), NO_x, and solid particles (PM) emissions and have a negligible impact on engine power reduction [21].

The research based on improving exhaust after-treatment technology for NG HDVs is presented [22,23]. The authors [22] compare CO_2 and methane (CH_4) emissions for NG HDVs with three-way catalytic converter (TWC) technology and diesel HDVs with DOC, DPF, and SCR technology. The results show that NG HDVs emit more CO_2 and CH_4 on routes with higher engine loads. The authors [23] show the exhaust emission values for HDVs equipped with oxidation catalyst converter (OC) technology and powered by NG, depending on the driving style. Aggressive driving behaviors increase emissions in urban areas and at low speeds.

Improvements in the field of vehicle efficiency and environmental protection have also been recognized through the use of lightweight composite materials for the construction of vehicles and their bodies [24–27]. The authors of reference [24] evaluate the application of lightweight composite materials to utilize the mass capacities of semi-trailers more efficiently; using lightweight materials can reduce the weight of the empty vehicle by up to 30%. Reference [25] mentions improvements in vehicle efficiency and reduced CO_2 emissions in the transport sector via the use of lightweight materials to produce HDVs. The potential of using lightweight materials is reflected in the expected reduction in the mass of articulated vehicles (vehicle combinations) by 16% by 2030. The estimates of the cost savings that can be achieved by using lightweight materials during the production amount to 1.3 EUR/kg for 2020 or 6.3 EUR/kg until 2030. The authors of reference [26] show that applying the advanced lightweight package for producing HDV makes it possible to reduce fuel consumption by 2.4% for regional driving conditions. The influence of modern aerodynamic solutions and lightweight materials for producing semi-trailers affects the reduction of fuel consumption by approximately 20.2% in the case of vehicle combinations [27].

1.2. Literature Review

The research we are discussing pertains to the procedures for assessing fuel consumption, exhaust emission, and exhaust emission costs for HDVs and their environmental impact. These aspects are covered in Regulation [31] and references [32–38]. Regulation [31] defines the conditions for determining the CO_2 emissions and fuel consumption of new HDVs, aiming to establish measures by which to obtain accurate information on the EU markets. The authors of reference [32] presented a model for estimating fuel consumption and exhaust emissions for diesel-powered HDVs, which is based on input operating variables and model parameters that define the constructive characteristics of the vehicle, engine power, engine speed, fuel rate, engine-out emissions, and after-treatment emissions. The authors of reference [33] developed a methodology for estimating GHG emission costs for the road and air transport sectors. This methodology is based on average fuel consumption and pollutant emission factors. These factors are derived from the European Monitoring and Evaluation Programme (EMEP) and European Environment Agency (EEA) data, widely recognized and accepted as reliable environmental data sources. The estimation of average fuel consumption for vehicles depends on the vehicle's category, the vehicle's speed, and the regression parameters determined for the distinct types of terrain.

The authors of reference [34] presented a methodology for estimating exhaust emissions based on vehicle speed. The methodology is based on the road and transport conditions of vehicle exploitation (changing of traffic volumes, design and operating speeds, the quality of the pavement structure, type of terrain, and category of road sections). The authors of reference [35] developed a model for estimating the emission of diesel HDV's exhaust gases. The model is based on the bilinear interpolation of data from the EMEP/EEA and fuel consumption for different operating conditions. The model determines the observed vehicles' fuel consumption and exhaust emission depending on the average vehicle speed, road gradient, and load factor. Reference [36] presented a model for estimating the external costs of CO_2 emissions in buses with CNG and diesel engines. The model is based on fuel consumption and operating conditions corresponding to intercity sections. Reference [37] proposes a method for estimating HDV exhaust emissions using the modified Multi-Scale Motor Vehicle and Equipment Emission System (MOVIES) model. The model calculates emission factors based on air pollutants, road sections' average speed, and road type. The authors of reference [38] propose a methodology for the emission of NO_x, $PM_{2.5}$, and CO pollutants for HDVs to reduce air pollution and enhance environmental sustainability. The methodology is based on vehicle kilometers traveled and the capacity of goods traveled by the HCVs.

Previous research [32–38] has shown comprehensive analyses of many HDV parameters under different operating conditions and their effects on predicting fuel consumption, exhaust emissions, and exhaust emissions costs. However, these studies have not considered the vehicles intended to transport gases and the restrictions that apply to them. Therefore, this research presents a different approach to evaluating these vehicles' efficiency and their bodies' effects on predicting fuel consumption and fuel and exhaust emissions costs. It provides a basis for companies in the RTDG system to transition from bodies with conventional steel pressure vessels to bodies with composite pressure vessels. The practical implications of this study refer to improving the efficiency of vehicle fleets in RTDG by applying modern composite bodies and alternative fuels while preserving transport safety, economic sustainability of transport, and the environment.

1.3. Research Objectives

The research objective is to predict fuel and exhaust emission costs for HDVs that transport compressed gases. This study evaluates the impact of various variable, such as vehicle types, fuel and body types, vehicle mass utilization, and the amount of gas transported, on fuel consumption, fuel costs, and exhaust emissions. The aim is to provide valuable insights for decision-making in the field of sustainable and cost-effective gas transport. The main contribution of this research is to the selection procedures for vehicles and optimal body types, offering a novel perspective on achieving sustainable transport and environmental protection.

In this sense, the proposed research is divided into the following chapters: Introduction, where the context background, literature review, and research objectives are listed (Section 1); Methodology, where our method for predicting fuel and exhaust emission costs is presented (Section 2); Results (Section 3); Discussion, with a comparative review of existing research, limitations, and future research (Section 4); and Conclusions (Section 5).

2. Methodology

The methodology for predicting the fuel and exhaust emission costs of different construction characteristics of vehicles and body types intended for gas transportation is based on specific fuel consumption and average values of emission factors. Depending on the immediate objective of the test, the availability of data on vehicles, and their technologies, test installation, and measuring equipment, the methodological step approach shown in Figure 1 was defined.

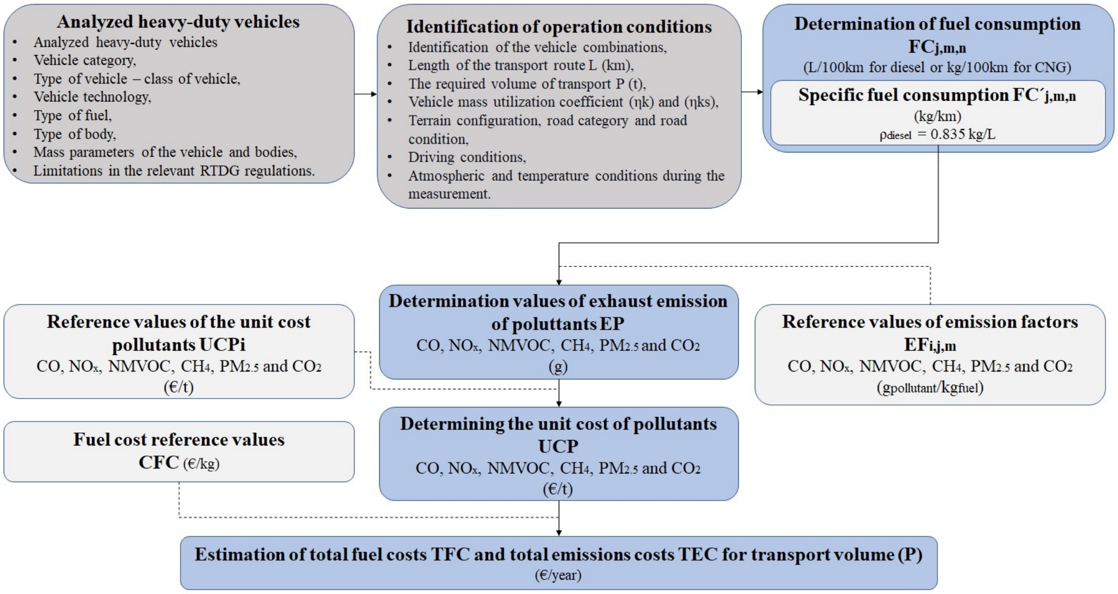

Figure 1. Schematic representation of the methodological step approach.

In the first step of the methodology, the construction characteristics of vehicles and body types intended to transport CNG were analyzed. The comparative analysis was performed according to vehicle category and type, vehicle technology, fuel type, body type, mass parameters, and limitations in the relevant RTDG regulations. In the second step of the research, the combinations of vehicles and their operating conditions were identified. Operating conditions included transport, road, and climatic conditions. Transport conditions include the classification of goods, the identification of vehicle combinations (trucks and trailers; body types equipped with pressure vessels made of steel and composite materials), the required annual transport volume on the defined route, and the length of the defined route. Road conditions refer to terrain configuration, road categories, type of road construction, and driving conditions on the transport route. The technical–operational indicators of vehicle mass utilization were introduced to analyze and evaluate the efficiency of the compared vehicle combinations. Vehicle mass utilization coefficients represent the technical–operational indicators η_k and η_{ks}. Coefficients η_k and η_{ks} show the relationship between the calculated utilization and the "*real*" exploitation utilization of vehicle masses intended for gas transportation. Climatic conditions of exploitation are defined via atmospheric and temperature conditions during the research. The Republic Hydrometeorological Institute of Serbia [39] presents data sources on climate and weather conditions in the Republic of Serbia's territory.

In the third step, fuel consumption ($FC_{j,m,n}$) was determined for the compared vehicle combinations on the transport route with a repeating itinerary. The transport process is based on the movement of vehicles with loads from the place of loading to the place of unloading and the return of the empty vehicle to the starting point, i.e., the place of loading. The determination of $FC_{j,m,n}$ for the compared vehicle's combination depends on the pollutant (j) values, the vehicle category (m), the body type (n), and the transported gas amounts. The measurement $FC_{j,m,n}$ includes trucks and tractors powered by diesel and CNG fuel and trailers and semi-trailers equipped with batteries and MEGC bodies, with two types of pressure vessels: Type-1 and Type-4. For the purposes of estimating fuel costs and exhaust emissions, the amount of gas transported during the measurement $FC_{j,m,n}$ was chosen as the reference amount of gas (*Mt*). The reference *Mt* represents the mass of transported CNG during one turn and corresponds to the following conditions: working pressure, 20 MPa; temperature, 15 °C: and gas density, 0.70 kg/m^3.

In the fourth step, values of the exhaust emission of pollutants (*EP*) were determined for the compared combinations of vehicles on the defined route for *Mt*. The determined values of *EP* are based on $FC_{j,m,n}$, and the reference values of emission factors ($EF_{i,j,m}$) are interpolated from the report in [40].

$EF_{i,j,m}$ values represent the average emission values of pollutants (*j*) for a vehicle category (*m*) and the emission of pollutants (*i*). In the fifth step, the unit cost of pollutants (*UCP*) was determined using *EP* data, the average values of the unit costs of pollutants (*UCPi*) [41,42], and Regulation [43]. The first part of the average *UCPi* values for the pollutants—non-methane volatile organic compounds (NMVOC), NO_x, $PM_{2.5}$, and CO_2—represents an interpolation from the report in [41] on the estimated values of polluter costs for each European country. The second part of the *UCPi* for CO and CH_4 is determined based on their respective value in terms of Global Warming Potential (GWP) according to the reports in [42], Regulation [43], and the reference values of CO_2. The total fuel costs (*TFC*) for the annual volume of transport (*P*) were determined based on the estimated total fuel consumption and the average fuel value for the observed period, and the average fuel value represents reference values for fuel cost (*CFC*) [44,45]. In the last step, the total *TFC* and the total emission costs (*TEC*) for the *P* on the defined transport route were estimated based on previously determined data. The following subsections comprehensively present the input parameters, variables, and equations to provide a thorough understanding of the methodology's steps. Appendix A provides detailed and comprehensive explanations of the input parameters and variables.

2.1. Analyzed Heavy-Duty Vehicles

Figure 2 shows the vehicle combinations considered in the research. The vehicle combinations belong to vehicle categories N_3 and O_4. Vehicles of category N_3 are divided according to the shape and purpose of the body into tractors (BC) and trucks (BA). Respectively, the vehicles of category O_4 are divided according to classes into trailers (T) and semi-trailers (ST). Trucks and trailers, in their load area, are equipped with MEGC bodies with two types of pressure vessels: Type-1 and Type-4. The semi-trailers in their load area are equipped with two types of bodies: battery bodies with pressure vessels (Type-1) and MEGC bodies with pressure vessels (Type-4). Depending on the construction solution for connecting the bodies and the vehicle, we identify MEGC separable and battery non–separable bodies.

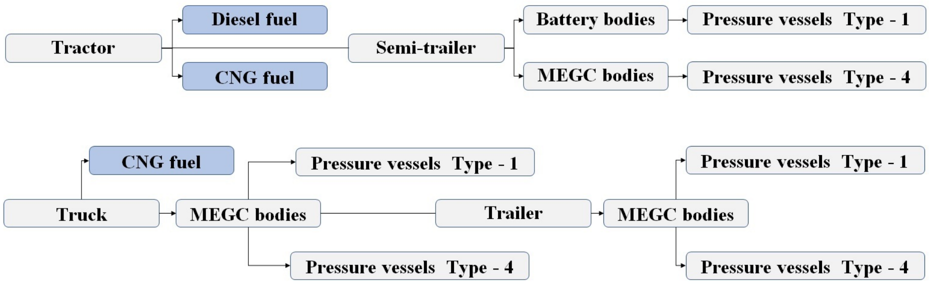

Figure 2. Considered vehicle combinations.

The Agreement in [9] and Regulation [46] define the provisions and conditions that apply to vehicles and bodies intended for RTDG, which aim to increase the safety of international road transport. Provisions and conditions related to the vehicle's construction characteristics are mentioned in paragraph 9.1.1.2 from part 9 of the Agreement in Ref. [9] and in the Regulation [46], which defines the conditions related to the approval of the type of vehicle intended for RTDG. Transport CNG is carried out by vehicles marked FL, intended to transport flammable gases, according to paragraph 9.1.1.2, with MEGC or battery bodies [9]. The HDVs, body types, and pressure vessels mentioned in the research (see Tables 1 and 2) follow the requirements specified in references [9,46]. These tables also provide the necessary information about the vehicles and bodies considered for the methodology. The vehicles listed in Table 1 are classified into three sections depending on the year of manufacture, fuel type, conditions applicable to alternative fuels, engine power, transmission type, and exhaust gas aftertreatment technology. The first section includes CNG vehicles (years of production: MY2018–MY2019) with 338 and 294 kW engine powers, 12-speed automatic transmissions, and TWC technology. The use of CNG as a fuel in the RTDG system is recognized and, through provisions, adapted to the transportation of dangerous goods following the Agreement in [9] and the Regulation [47], which refer to unique elements of the construction of vehicles powered by alternative fuels. The second section includes a diesel-powered vehicle (MY2006) with 12-speed automatic transmissions, a 410 kW engine power, and DOC- and DPF-based technology. The third section includes a diesel vehicle (MY2015) equipped with a 12-speed automatic transmission, 310 kW engine power, and technology based on DOC, DPF, SCR, and subsequent urea dosing.

Table 1. Information on the considered tractors and trucks.

Vehicle:	Tractor	Tractor	Tractor	Truck
Mark according to paragraph 9.1.1.2:	FL	FL	FL	FL
Fuel:	CNG	Diesel	Diesel	CNG
Engine power [kW]:	338	310	410	294
Engine displacement [cm^3]:	12,900	12,809	12,902	8710
Exhaust after-treatment technology:	TWC	DOC + DPF + SCR	DOC + DPF	TWC
Model year (*MY*):	2018	2015	2006	2019
Axle configuration:	4 × 2	4 × 2	4 × 2	6 × 2
Tires:	315/70 R 22.5	315/70 R 22.5	315/70 R 22.5	315/70 R 22.5
Technically permissible maximum laden masses [kg]:	20,000	18,000	20,500	26,000
Mass of a vehicle in running order (*Ms*) [kg]:	8119	8119	7440	13,676 [1]/20,066 [2]
Reduced vehicle payload capacity (*Mkr*) [kg]:	-	-	-	9324 [1]/1934 [2]

[1] *Ms* and reduced *Mkr* vehicles with MEGC bodies and pressure vessels (Type-4); [2] *Ms* and reduced *Mkr* vehicles with MEGC bodies and pressure vessels (Type-1).

Table 2. Information on the considered trailers with battery bodies and MEGC bodies.

Vehicle:	Semi-Trailer	Semi-Trailer	Trailer	Trailer
Mark according to paragraph 9.1.1.2	FL	FL	FL	FL
Mkr [kg]:	5541 [1]	11721 [2]	3834 [1]	6524 [2]
Ms [kg]:	28,340	22,160	14,166	10,476

Technically permissible maximum laden masses [kg]:	39,000	39,000	18,000	18,000
The number of axles and wheels:	3/6	3/6	2/4	2/4
Tires:	385/65 R22.5	385/65 R22.5	385/65 R22.5	385/65 R22.5
Body types:	Battery	MEGC	MEGC	MEGC
Types of pressure vessels:	Type-1	Type-4	Type-1	Type-4
length of the vessel [mm]:	1850	2300	1850	2300
diameter of the vessel [mm]:	356	510	356	510
Number of vessels:	149	114	78	54
Mass of empty vessels [kg]:	147	94	147	94
Test and working pressure [MPa]:	30/20	37.5/25	30/20	37.5/25
Volume of one vessel [L]:	150	350	150	350
Total body volume [L]:	22,350	39,900	11,700	18,900
Vessel material:	Steel	Composite	Steel	Composite

[1] Reduced *Mkr* for vehicles with pressure vessels (Type-1); [2] reduced *Mkr* for vehicles with pressure vessels (Type-4).

The National Regulation on the division of motor and trailer vehicles and technical conditions for vehicles in road traffic defines restrictions regarding the maximum permissible weight of vehicles [48]. The maximum permissible mass of a combination of vehicle, truck, and trailer is 40 t, i.e., 42 t for a tractor and a semi-trailer. The values of the reduced *Mkr* for trucks shown in Table 1 and trailers in Table 2 correspond to the limits set out in the Regulation [48].

2.2. Analyzed Battery and MEGC Bodies with Type-1 and Type-4 Pressure Vessels

Type-1 and Type-4 pressure vessels, which realize a compact unit (with a system of connecting pipes, safety devices, measuring instruments, and charging and discharging devices), are called battery bodies or MEGC bodies Figure 3.

Figure 3. Considered semi-trailers with MEGC bodies (left and right) and battery bodies (middle).

Technical solutions of pressure vessels, Type-1 and Type-4, can vary in terms of volume, the thickness of the material, and the working pressures according to the standards of making vessels [49,50]. The number of pressure vessels per vehicle is determined by technical limitations related to vehicle dimensions, the maximum permissible mass of the vehicle combination, and the maximum permitted axle loads.

Technical restrictions regarding vehicle dimensions, the maximum permissible mass of vehicle combinations, and the maximum permitted axle loads in the Republic of Serbia are defined in the Regulation [48]. The Type-1 pressure vessels used in the Table 2 represents seamless pressure vessels made of steel, following the manufacturing standard [49] and regulations specified in the Agreement in reference [9] and Directive [51]. The Directive [51] defines the rules on transportable pressure equipment to improve safety and safe exploitation in the EU. The number of Type-1 vessels per vehicle depends on the vehicle type and the vehicle's permitted axle loads. The Type-4 pressure vessels used in the research, shown in Table 2, are vessels with a polymer base coated with composite materials following the manufacturing standard [50], the regulations specified in the Agreement [9], and the Directive [51].

The research findings reveal that the influence of the mass of empty Type-4 vessels on the technical limitations regarding the maximum permissible axle loads of vehicles is significantly lower compared to the mass of empty Type-1 vessels. This underscores the potential benefits of Type-4 vessels. The limiting factor for the number of Type-4 vessels per vehicle is not the vehicle's permitted axle loads but the dimensions of its load area, as illustrated in Figure 3. The efficiency rating of pressure vessels is represented by the vessel's mass ratio to the compressed amount of gas. The compressed amount of gas in the vessels is influenced by several factors: the chemical characteristics of the gas, gas density, working pressure of the vessels, volume of the vessels, and temperature conditions at the filling time. The compressed amount of gas for working conditions (working pressure, 20 MPa; temperature, 15 °C, and gas density, 0.70 kg/m^3) in a Type-1 vessel of 150 L is about 26 kg; for the same working conditions in a Type-4 vessel of 350 L, it is about 62 kg. The ratio of the mass of vessels to the compressed amount of gas for Type-1 is 5.65, and for Type 4, it is 1.55. The smaller mass of Type-4 vessels enables better utilization of the vehicle's mass, representing a significant advantage. The unfavorable mass ratio of bodies with Type-1 vessels affects the increase in the *Ms* of the vehicle. The increase in the *Ms* of the vehicle adversely affects the vehicle's operational characteristics, which will be discussed in detail in the next part of the research.

2.3. Identification of Operation Condition

Determination of fuel consumption ($FC_{j,m,n}$) was realized on the Pančevo–Prahovo itinerary at a length of 538 km (Figure 4). The transport route belongs to part of the road network of the Republic of Serbia. According to the categorization of state roads, they are divided into roads of category IB and category II [52]. Pavement conditions and the quality of the road infrastructure are acceptable and correspond to the mentioned categories. Depending on the configuration of the terrain, the following conditions are represented on the transport route: flat, hilly, and, to a lesser extent, hilly–mountainous operation conditions. The route includes urban and highway sections with variable driving conditions corresponding to average vehicle operating conditions. The *P*-value for the Pančevo–Prahovo itinerary is 2461 t goods of CNG. The *P*-values included in the research are based on the annual transport plan and represent the actual annual needs of the industrial sector in Prahovo.

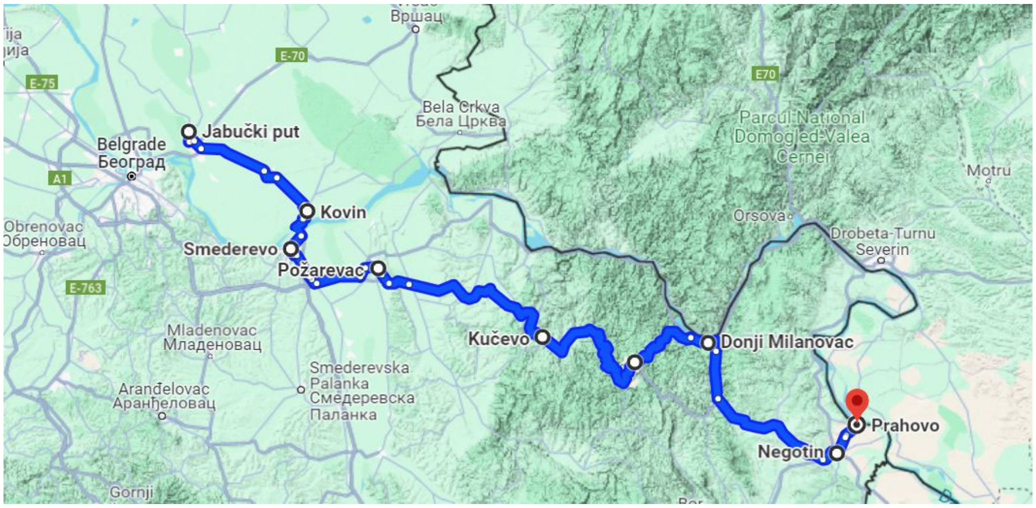

Figure 4. Considered itinerary: Pančevo–Prahovo. Map source: [53].

Climatic conditions during fuel consumption measurement were acceptable without the influence of wind and precipitation [39]. The vehicles included in the research are technically correct, have passed mandatory technical inspections, and meet all technical correctness requirements. The vehicles had no difficulties performing work activities. During the measurement, the vehicles were at operating temperature and with full tanks, and they were driven by a professional driver with regular driving habits. The measurement was performed for all vehicle combinations in the same time intervals without traffic jams that could significantly affect fuel consumption and exhaust emissions. The measurements took place in the period from March 2022 to April 2022 for the following vehicle combinations:

- BC + (ST), Type-4: BC (MY 2006) powered with diesel fuel and ST with MEGC body and Type-4 vessels;
- BC + (ST), Type-1: BC (MY 2006) powered with diesel fuel and ST with battery body and Type-1 vessels;
- BC + (ST), Type-4: BC (MY 2015) powered with diesel fuel and ST with MEGC body and Type-4 vessels;
- BC + (ST), Type-1: BC (MY 2015) powered with diesel fuel and ST with battery body and Type-1 vessels;
- BC + (ST), Type-4: BC (MY 2018) powered with CNG fuel and ST with MEGC body and Type-4 vessels;
- BC + (ST), Type-1: BC (MY 2018) powered with CNG fuel and ST with battery body and Type-1 vessels;
- BA Type-4 + (T), Type-4: BA (MY 2019) powered with CNG fuel and MEGC body with Type-4 vessels and T with MEGC body and Type-4 vessels;
- BA Type-1 + (T), Type1: BA (MY 2019) powered with CNG fuel and MEGC body with Type-1 vessels and T with MEGC body and Type-1 vessels.

2.4. Determination of Fuel Consumption

The fuel consumption $FC_{j,m,n}$ for the compared vehicle combinations was determined in actual operating conditions. Measurement of $FC_{j,m,n}$ was carried out continuously using the diagnostic device on the vehicle OBD on the entire length of the route [54,55]. Fuel consumption data was determined using standard OBD protocols and external OBD scan-ning tools that support all standard protocols for HDVs. The determined values of $FC_{j,m,n}$ for combinations 1, 2, 3, and 4 are expressed per liter of fuel consumed per 100 km traveled distance (L/100 km); likewise, the determined values of $FC_{j,m,n}$ for combinations 5, 6, 7, and 8 are expressed in kilograms of fuel burned per 100 km traveled distance (kg/100 km). The

$FC'j_{m,n}$ values in Table 3 are shown as the mean specific average fuel consumption for the considered vehicle combinations and represent the fuel consumption on the section with a repeating itinerary. The specific $FC'j_{m,n}$ values are expressed in kilograms of fuel consumed per kilometer of traveled distance. The specific density (ϱ diesel) of diesel fuel is 0.835 [kg/L] [56]. The $FC'j_{m,n}$ values for combinations 1, 2, 3, and 4 were determined using Formula (1).

$$FC'^{diesel}_{j,m,n} = FC_{j,m,n} \times 0.01 \times \rho_{diesel} \tag{1}$$

The total fuel consumption ($\Sigma FC_{j,m,n}$) for the required P was determined by applying Formula (2) and depends on the j, m, and n. The number of turns (N_n) also depends on P and n.

$$\Sigma FC_{j,m,n} = FC'_{j,m,n} \times L \times N_n \tag{2}$$

The evaluation of the efficiency of the combinations of the vehicles (1, 2, 3, 4, 5, 6, 7, and 8) included in the measurements is a crucial aspect of this research; it is shown by the vehicle mass utilization coefficients η_k and η_{ks} in Formulae (3) and (4). The coefficient of vehicle mass utilization coefficients η_k, shown in Formula (3) [57], represents the ratio of the Mkr and the ΣMs (ΣMs represents the sum of the Ms of truck or tractor and trailer vehicles). The derived coefficient (η_{ks}) equals the ratio of the transported Mt and the ΣMs combinations of the vehicles.

$$\eta k = \frac{Mkr}{\Sigma Ms} \tag{3}$$

$$\eta ks = \frac{Mt}{\Sigma Ms} \tag{4}$$

The evaluation of the efficiency of the compared combinations of vehicles and the results of measurements are shown in Table 3.

Table 3. Results of fuel consumption measurements for the compared vehicle combinations.

No.	Vehicle Combinations	MY	Fuel	Mt [kg]	L [km]	η_k	η_{ks}	$FC'_{j,m,n}$ [kg/km]
1	BC + (ST) (Type-4)	2006	Diesel	7020	538	0.39	0.23	0.299
2	BC + (ST) (Type-1)	2006	Diesel	3932	538	0.15	0.11	0.314
3	BC + (ST) (Type-4)	2015	Diesel	7020	538	0.39	0.23	0.232
4	BC + (ST) (Type-1)	2015	Diesel	3932	538	0.15	0.11	0.243
5	BC + (ST) (Type-4)	2018	CNG	7020	538	0.39	0.23	0.303
6	BC + (ST) (Type-1)	2018	CNG	3932	538	0.15	0.11	0.339
7	BA Type-4 + (T) (Type 4)	2019	CNG	6650 [1]	538	0.66	0.28	0.312
8	BA Type-1 + (T) (Type 1)	2019	CNG	4117 [1]	538	0.17	0.12	0.346

[1] It represents the sum of the amounts of gas Mt, which are transported with a vehicle combination of trucks and trailers.

Table 3 shows that the combinations of the vehicles (1, 3, 5, and 7) with a Type-4 body transport significant amounts of gas Mt per turn. Comparing the results of transported Mt for the reference conditions, for the vehicle combination 7 and 8, combination 7 transported about 38% more gas for one turn. Vehicle combinations 3 and 5 transported 44% more gas than 2 and 4 for one turn. If we compare the ratio of engaged mass capacities of vehicles for transporting one ton of gas, vehicles with bodies with Type-4 vessels have slightly better mass ratios. The lower values of the coefficients η_k and η_{ks} for the combination of vehicles with Type-1 bodies with pressure vessels are conditioned primarily by the material of the containers and the limitations of the axle loads of the vehicle. Comparing the results of η_{ks} for the transport of one ton of gas with vehicle combination 2, it is necessary to accrue an average of 9.2 t of vehicle mass capacity, and in the case of vehicle combination 1, it is necessary to accrue an average of 4 t. Combinations 7 and 8 of the trucks and trailers have a slightly better utilization of mass capacity, whereas for transporting one ton of gas, attaining 8.4 tons of vehicle mass capacity is necessary in the case of vehicle combination 8. For the vehicle combination 7, about 3.7 t of the mass capacity of the vehicle was required. Comparing $FC'j_{m,n}$ results for vehicle combinations 5, 6, 7, and 8, powered with CNG, fuel consumption is higher for sets 6 and 8 with Type-1 vessels, ranging from 9.9% to 10.6%. Comparing fuel consumption results for vehicle combinations 2 and 4 with Type-1 pressure vessels powered by diesel, the results show that fuel consumption is higher by 22.7% for vehicle combination 2 with older technology.

2.5. Determination of Exhaust of Pollutants and Unit Cost of Pollutants

By applying the Formula (5), the values of *EP* were calculated for the compared combinations of vehicles on the Pančevo–Prahovo route for the required *P*. *EP* values are determined for vehicles with newer (MY 2015, MY 2018, and MY 2019) and older (MY 2006) exhaust after-treatment technology, as shown in Table 4.

$$EP = FC'_{j,m,n} \times EF_{i,j,m} \times L \times N_n \tag{5}$$

The adopted reference values $EF_{i,j,m}$, shown in Table 4, represent the average European pollutant values and depend on the vehicle category, fuel type, and year of application of exhaust after-treatment technology [40]. These $EF_{i,j,m}$ values are expressed in grams of pollutants per kilogram of burned fuel.

Table 4. Reference values of $EF_{i,j,m}$ [$g_{pollutans}/kg_{fuel}$].

Vehicle Category	Fuel	Technology Start/End Date	CO	NMVOC	NO_x	CO_2	$PM_{2.5}$	CH_4
HDV	Diesel	2005–2008	0.41	0.04	15.52	3169	0.090	0.59
HDV	Diesel	2013–2019	0.40	0.04	1.70	3169	0.004	0.58
HDV	CNG	2013–2019	2.19	0.09	5.49	2743	0.002	2.15

The values of *UCPi* [41] are the average pollutant costs for each European country and depend on the country's economic characteristics and geographical location. The *UCPi* values of NMVOC, NO_x, $PM_{2.5}$, and CO_2 pollutants for the Republic of Serbia were determined based on an estimated GDP growth of 2% until 2030 and an income elasticity coefficient of 0.85. Reference values for CO and CH_4 pollutants were determined based on their estimated GWP (GWP CO = 3 [42]; GWP CH_4 = 28) [43]) and CO_2 values obtained from reference [41]. (*UCPi* CH_4 = GWP CH_4 × *UCPi* CO_2 = 1148 EUR /t; *UCPi* CO = GWP CO × *UCPi* CO_2 = 123 EUR/t.) Table 5 shows the adopted *UCPi* reference values for the Republic of Serbia for 2022.

Table 5. Reference values of unit costs of polluters [EUR /t].

Pollutant	CO	NMVOC	NO_x	CO_2	$PM_{2.5}$	CH_4
Costs	123	608	10,892	41	27,984	1148

The *UCP* is determined by applying Formula (6) based on certain *EP* values and adopted reference values of *UCPi*.

$$UCP = EP \times UCPi \times 10^{-6} \tag{6}$$

Total *TFC* fuel costs are determined based on reference *CFC* values and estimated total fuel consumption $\Sigma FC_{j,m,n}$ for *P*. The total costs of exhaust emission *TEC* were determined based on the specific values of *UCP* for *P*. The analysis of the results is presented in the next chapter.

3. Results

The results of fuel consumption measurements were performed for the eight vehicle combinations, as explained in Section 2.4. The measurement aimed to determine the fuel consumption, depending on the vehicle's utilization (types of bodies) and the fuel type. The effects of body type on fuel consumption were determined for characteristic driving conditions on the selected route. One of the main parameters affecting driving conditions on the route is the vehicle's utilization. During the measurement, the vehicles departed full and returned empty. Total fuel consumption is calculated as the mean consumption values for the mentioned driving conditions, shown in Table 3. Applying the calculated mean values of fuel consumption for each vehicle combination for the annual volume of transport of 2461 t of gas, pollutant emissions, total fuel, and exhaust emission costs were predicted. The annual volume of transport for the economic area varies and depends on demand and economic development. The obtained results are used as decision-making criteria in the selection phase of new HDVs and bodies intended for gas transport, as well as during the conversion of existing vehicle fleets equipped with diesel vehicles with older technologies and bodies with steel pressure vessels (Type-1). This part of the research shows the results of estimating the exhaust emission of pollutants, the total fuel cost, and the exhaust emission costs for the compared combinations of vehicles. Figure 5 shows the estimated $\Sigma FC_{j,m,n}$ depending on the N_n and required ($P = 2461$ t).

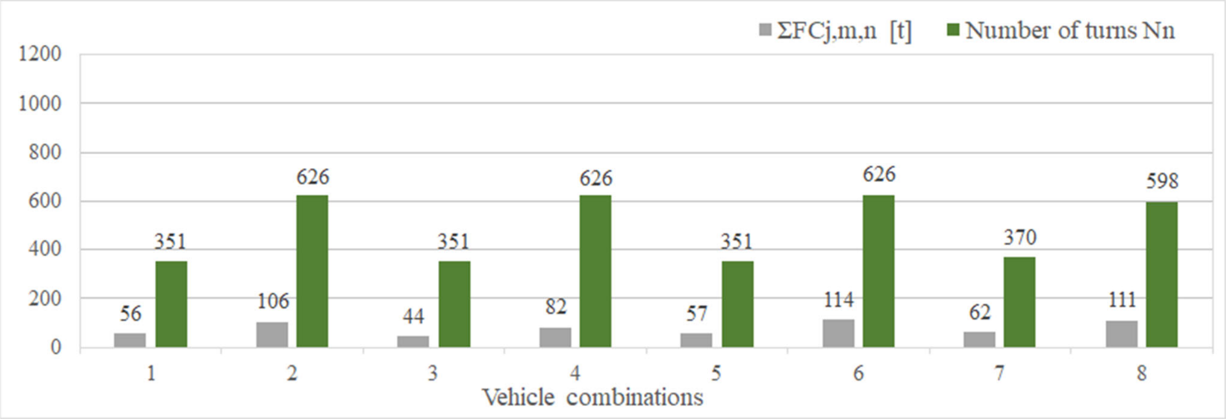

Figure 5. Estimated fuel consumption for considered vehicle combinations.

It is noticeable from Figure 5 that the combinations of vehicles 2, 4, 6, and 8 with Type-1 vessels have higher fuel consumption and that they have to make more turns for the same volume of transport *P*. The unfavorable mass ratio of bodies with Type-1 vessels affects the increase in the ΣMs of the vehicle combinations, reflected in the increase in fuel consumption. Technical limitations and the smaller total volume of bodies with Type-1 vessels, explained in Section 2.2., affect the increase in the number of turns. Comparing vehicle combinations 1, 3, and 5 with Type-4 vessels and vehicle combinations 2, 4, and 6 with Type-1 vessels, combinations 2, 4, and 6 for the same volume of transport, on average, make 44% more turns. With respect to combinations 7 and 8 (trucks and trailers), combination 8 with Type-1 vessels for the same volume of transport makes, on average, 38% more turns. Analyzing the evaluation results of pollutants CO, NMVOC, NO_x, $PM_{2.5}$,

CO_2, and CH_4, it is noticeable that the combination of vehicles (2, 4, 6, and 8) with Type-1 vessels have higher *EP* values.

3.1. Emission of Pollutants NMVOC and $PM_{2.5}$

We compare the results of the NMVOC and the $PM_{2.5}$ emission of pollutants assessment shown in Figure 6. Combinations of vehicles (1 and 2) with older exhaust after-treatment technologies have higher $PM_{2.5}$ values than combinations of vehicles with newer technologies (3, 4, 5, 6, 7, and 8). It is also noticeable that combinations (2, 4, 6, and 8) with a body with Type-1 vessels have higher $PM_{2.5}$ values. The situation is different for the pollutant NMVOC results. The results show that the combinations of CNG-powered vehicles (5, 6, 7, and 8) have higher values than those of diesel-powered vehicles (1, 2, 3, and 4).

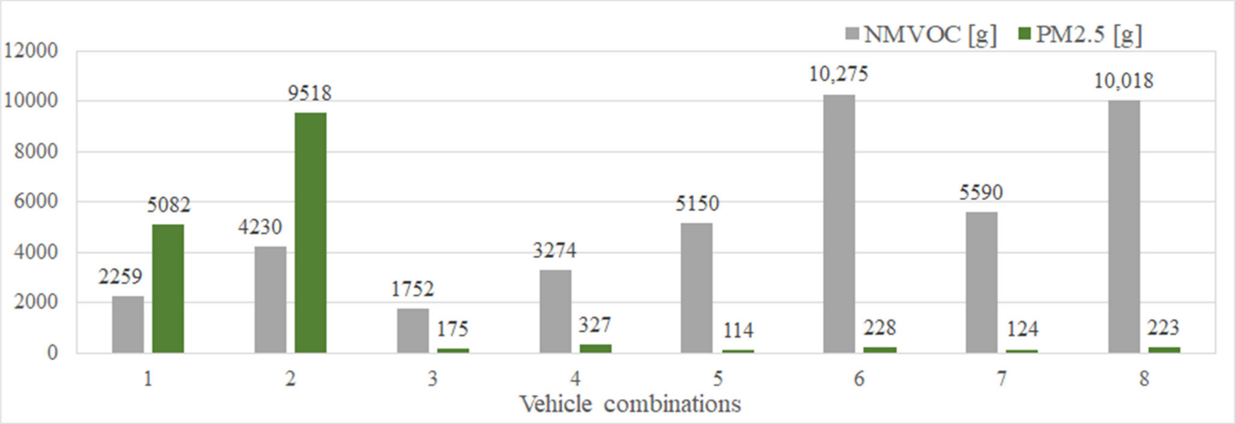

Figure 6. Estimated of pollutants NMVOC and $PM_{2.5}$ for the volume of transport ($P = 2461$ t).

There are certain coincidences if we compare the obtained calculation results with the experimental results of earlier research [58,59]. Study [58] presents research results on the value of pollutants PM and NO_x for diesel and CNG HDVs, depending on the year of application of the exhaust after-treatment technology. The values of pollutant PM and NO_x for HDV diesel equipped with DOC and DPF technology are higher than those of HDV diesel with DOC, DPF, and SCR technology, and HDV CNG with TWC technology. According to reference [59], values of pollutants PM and NO_x are higher for HDV powered by diesel than for HDV powered by CNG.

3.2. Emission of Pollutants CO and NO_x

Figure 7 shows the results of the emission of CO and NO_x pollutants for the compared vehicle combinations. The combinations with older technologies (i.e., 1 and 2) have significantly higher NO_x pollutant values than combinations 3, 4, 5, 6, 7, and 8. Our research presents the results of the emission of CO and NO_x pollutants for various vehicle combinations, as shown in Figure 7. Notably, vehicle combinations powered by diesel (1, 2, 3, and 4) exhibit lower CO pollutant values than those powered by CNG (5, 6, 7, and 8). Combination 3, powered by diesel with newer technologies and a body with Type-4 vessels, demonstrates the lowest CO values. Comparing our results with previous research, we observe certain coincidences.

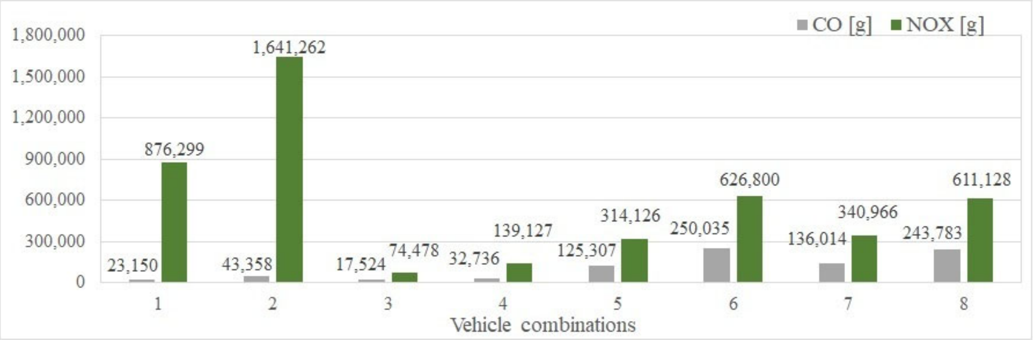

Figure 7. Estimated of pollutants CO and NO_x for the volume of transport (*P* = 2461 t).

The authors of reference [60] compared the CO and NO_x pollutants values for diesel and CNG HDVs with newer technologies, depending on the vehicle velocity. The research results show that the values of CO and NO_x are higher for CNG HDVs. Study [58] compared the pollutant CO results for CNG HDVs with TWC technology and diesel HDVs with DOC, DPF, and SCR technology. The results show that CO values are higher for CNG-powered HDVs. Studies [59,61] show the results of the measurement of CO and NO_x for buses powered by CNG and diesel, and the values of CO pollutants are higher for CNG-powered buses. In the case of NO_x pollutants, there are noticeable differences in the pollutant values of buses with and without subsequent treatment with urea. The CNG buses without urea after-treatment have higher NO_x values than diesel buses with newer exhaust after-treatment technologies [61].

3.3. Emission of Pollutants CO_2 and CH_4

Figure 8 shows the results of the emission of CO_2 and CH_4 pollutants that influence the greenhouse effect for the compared vehicle combinations.

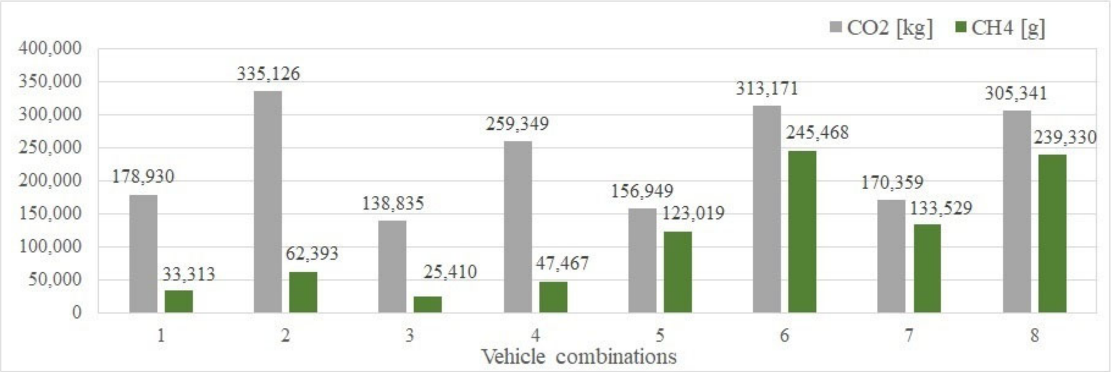

Figure 8. Estimated of pollutants CO_2 and CH_4 for the volume of transport (*P* = 2461 t).

It is noticeable that combinations powered by CNG (5, 6, 7, and 8) have higher CH_4 values than combinations powered by diesel (1, 2, 3, and 4). By comparing the obtained values for all vehicle combinations, differences are observed for combinations with Type-1 vessels (2, 4, 6, and 8). The highest CO_2 value is for combination 2, powered by diesel with older gas after-treatment technologies, followed by combinations 6 and 8, powered by CNG. The results for combinations 2, 4, 6, and 8 show that body type has a noticeable effect on the increase in ΣMs and fuel consumption, reflected in the increase in CO_2 emissions. We note certain coincidences when comparing the results obtained with previous research [22,58]. Researchers [58] have compared the CO_2 emission values for HDVs with different technologies and driving conditions. Diesel HDVs with DOC and DPF have significantly higher CO_2 values than CNG HDVs with TWC and diesel HDVs with DOC, DPF, and SCR. The authors of [22] presented the results of CO_2 and CH_4 pollutants for diesel and CNG HDVs, depending on the terrain and driving conditions. The results show that the values of pollutants CH_4 and CO_2 are higher for CNG HDVs with TWC technology than fir diesel HDVs with DOC, DPF, and SCR technology.

3.4. Estimated TFC and TEC

Figure 9 shows the estimated *TFC* and *TEC* for the vehicle combinations that were compared for the required annual transport (*P* = 2461 t). Comparing the *TFC* values of all vehicle combinations, the combinations with Type-1 vessels (2, 4, 6, and 8) have higher fuel costs. The unfavorable mass ratio of bodies with Type-1 vessels affects a vehicle's increased mass in running order and negatively affects fuel consumption. The values of cost *TFC* come to the fore for vehicle combinations with older technologies (1 and 2). The values of cost *TFC* depend on the type of bodies, type of fuels, and quantities of gas transported.

When we compare combinations powered by diesel for the transport of one ton of gas (1 and 2), we need to allocate 75.13 EUR in the case of combination 2 or 45.34 EUR in the case of combination 1. The *TFC* has the lowest cost values for the combination of vehicles powered by CNG with Type-4 vessels (5), where one ton of gas needs to be allocated about 19.77 EUR. In the case of the combination powered by CNG with Type-1 vessels (6), we need to allocate 39.44 EUR to transport one ton of gas. When the *TEC* emission cost values for vehicle combinations 1, 2, 3, 4, 5, 6, 7, and 8 are compared, the combination powered by diesel and Type-4 vessels (3) obtains the lowest *TEC* cost values. It is worth noting that modern diesel engines, equipped with advanced exhaust after-treatment technologies, significantly reduce the exhaust emission factor [18–22,60]. The *TEC* is one factor to consider when selecting a vehicle and its impact on environmental impact. The influence of body type on *TEC* costs is noticeable. Transporting one ton of gas with the combination (3) requires an allocation of 2.82 EUR, whereas with combination 4, the cost increases to about 5.28 EUR. For transporting one ton of gas with the combination 1, it needs to allocate about 7.15 EUR, that is, with combination 2, about 13.39 EUR. This result demonstrates the noticeable role of body and fuel types in determining *TEC* costs. Vehicle combinations 7 and 8 (trucks and trailers) have similar *TEC* and *TFC* value costs as combinations (5 and 6). The achieved research results show that:

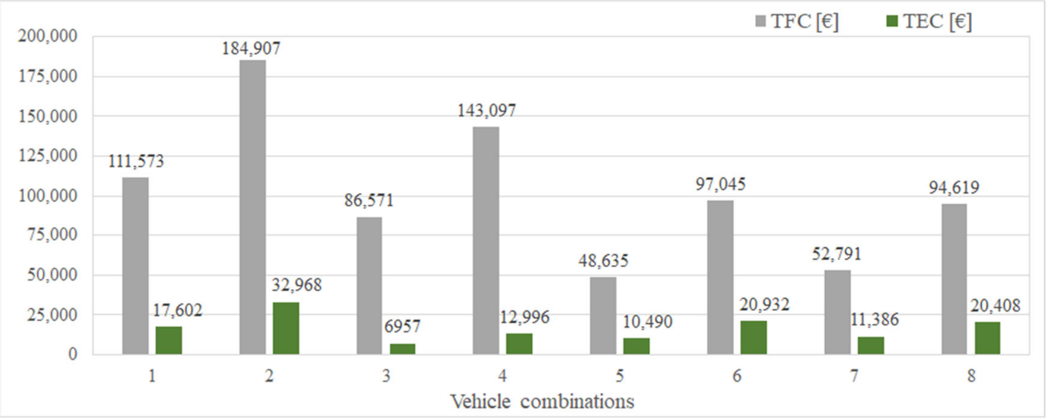

Figure 9. Estimated total fuel costs and the total exhaust emission costs for the volume of transport (*P* = 2461 t).

The vehicles combinations 1, 3, and 5 with Type-4 vessels transport 44% more gas for one turn than combinations 2, 4, and 6 with Type-1 vessels. In the case of combinations 7 and 8, combination 7 transports about 38% more gas for one turn. The differences between combinations 7 and 1, 3, and 5 are due to a smaller cargo space and a slightly smaller number of Type-4 vessels in the MEGC body.

The combinations powered with CNG and bodies with Type-1 vessels (6 and 8) have higher fuel consumption, ranging from 9.9% to 10.6%, than combinations powered with CNG and bodies with Type-4 vessels (5 and 7).

Comparing the fuel consumption results for vehicle combinations with Type-1 bodies and powered by diesel (2 and 4), the results show that fuel consumption is higher by 22.7% for the vehicle combination (2) with older technology.

4. Discussion

The proposed methodology's main contribution is based on the simplification of vehicle selection procedures and optimal types of bodies intended for the transport of gases, which will achieve the economic sustainability of transport while contributing to the preservation of the environment. In addition, the methodology takes into account the vehicle's technical characteristics and operational conditions, introduces specific parameters related to RTDG (body types, vehicle mass utilization, and the amount of transported gas), and connects them with some of the economic and environmental aspects in the context in which the research is implemented. These aspects represent variables, fuel, and exhaust gas emission costs, which depend on the input parameters.

The methodology provides a predictive insight into part of the economic and ecological aspects of using vehicles intended for gas transportation. The results contribute to fleet managers' decisions when selecting new vehicles and bodies or transitioning existing ones to more-modern road gas transportation. It is intended for companies that strive to improve the road transport of gases following new norms to achieve economically sustainable transport while preserving the environment. The innovation of the proposed methodology, incorporating complex parameters related to RTDG with economic and environmental aspects, is achieved by contributing to a new alternative approach to the selection of vehicles in RTDG.

The primary theoretical importance of this research deals with the issue of NG's more efficient and environmentally friendly road transport as a primary attribute, and it was achieved by introducing the body type function and vehicle mass utilization into the mathematical framework of the methodology.

4.1. Comparative Review of Existing Research

The proposed methodology was conceptualized through comparison with existing and adapted versions of the methodological procedures for estimating fuel consumption, exhaust gas emissions, and the costs of exhaust gas emissions found in the relevant literature [32–38]. However, comparisons with other methods brought challenges in classifying and selecting different input parameters, primarily due to data that are often unavailable or inapplicable outside of specific study conditions. The existing models deal with determining the attractiveness (effect) of using freight vehicles in road transport, including aspects related to economics (estimates of emission costs and fuel consumption) and the environment (estimates of emissions). Compared to other methodological procedures, the proposed methodology addresses some of the challenges in gas transportation.

As part of reference [32], several sub-models were developed to estimate fuel consumption and exhaust emissions for diesel HDVs, each corresponding to a specific vehicle category and applied exhaust gas after-treatment technology. The developed models use a parameterized physical approach to estimate consumption and emissions based on the route's input-specific engine parameters vehicle, and the operational conditions. In another study [35], the goal was to develop a model for estimating fuel consumption and exhaust emissions for freight vehicles based on bilinear (repeated linear) interpolation, depending on the input parameters, including the vehicle's technical characteristics and operational conditions. Both models have a unified approach to estimating fuel consumption and emissions, expressed with the technical characteristics of the vehicles and the operational conditions, which follows the objective of the proposed methodology in this research. The model's results indicate the adequacy of the application for vehicle selection procedures. However, the models do not include the physical–mechanical properties of the goods, method way of storage and transportation, or economic aspects.

In the research related to assessing the costs of exhaust gas emissions from HDVs [33,34,36], assessment models were developed based on input parameters, including specific emission factors, vehicle parameters, operational conditions on the road network, specific pollutant costs, and average fuel consumption. The average fuel consumption in the abovementioned studies was determined for each vehicle category using a regression model, representing fuel consumption's functional dependence on speed. Input parameters, such as specific emission factors and polluter costs, follow this research's proposed methodology. The emission costs, depending on the vehicle category and realized traffic volume, represent these models' combined economic and environmental aspects. The mentioned models comprehensively estimate the costs of exhaust emissions to preserve sustainable transport and the environment, and their results contribute to vehicle selection procedures at a strategic level. Input parameters do not include specifics related to cargo vehicles in RTDG, bodies and methods of storage and transportation, or the physical–mechanical properties of goods (cargo). Certainly, there is potential for more precise evaluation and selection of input parameters.

Other research has been undertaken to assess the exhaust gas emissions from cargo vehicles and their environmental impact [37,38]. Reference [37] proposed a modified, widely accepted model for evaluating the emissions of freight vehicles and quantifying the emissions in the area of the transport route. Estimated emissions on road segments are calculated by integrating specific emission factors, the length of each road segment, and data on the traffic volume. Reference [38] presented a model for pollutant emission estimation based on integrating specific emission factors, the number of vehicles, and the average annual kilometrage depending on the vehicle's category and technology. The proposed models relate to environmental aspects and predict freight transport's impact on the targeted areas of transport or countries. The mentioned models take a comprehensive approach to emission assessment, and their results contribute to, and can be used in, vehicle selection procedures to preserve transport and the environment, both on a tactical and a strategic level. The models do not include the specifics that apply to vehicles in RTDG, the effects of bodywork and the physical–mechanical properties of goods on vehicle use, the economic aspects of pollutant impacts, or the impacts of CO_2 pollutants.

4.2. Limitations and Future Research

This study has several limitations, present potential project for future research. Due to the study's complexity and the availability of the vehicles, we collected and calculated data with time lags. The study does not include all fleet operational and external costs, such as the acquisition costs of vehicles and bodies and the maintenance and transportation risks. Subsequent studies will focus on the application and possible improvements of polymer and composite materials for producing bodies intended for the road transport of dangerous goods, their exploitation costs and transport risk assessment, and the incorporation of the achieved results and data into new advanced optimization algorithms.

Incorporating the achieved results and data into the new methodological procedure based on advanced optimization algorithms can contribute to optimizing road gas transport depending on the operational conditions. Selecting the optimal transport route depends on specific parameters related to RTDG, transport risk, and the economic and ecological aspects discussed in the previous part of the manuscript.

Conceptualizing a new methodological approach to the optimization of road gas transport would include applying and comparing it with the existing optimization algorithms presented in the relevant literature [62–66]. Reference [62] presents new constructive hyper-heuristic generations based on an ant colony using the novel ant-based generation constructive hyper-heuristic algorithm. This approach's potential application is reflected in optimizing the transport route and choosing the optimal route from the place of loading to the place of unloading. Reference [63] presents a new self-adaptive fast fireworks algorithm (SF-FWA) to efficiently implement large and complex optimizations. The possibilities of applying the model to the concept of a new methodological procedure are reflected in solving the problem of classification and compatibility (dangerous goods, bodies, vehicles) with operational conditions and choosing the optimal transport route.

Other research is based on the adaptive polyploid memetic algorithm (APMA) [64] and the diffused memetic optimizer (DMO) [65]. These studies focus, above all, on solving and planning the work schedule of freight vehicles in logistics centers during operations such as the loading and unloading goods; that is, they aim to solve and optimize the reception and distribution of goods in sea container terminals using a model based on the DMO algorithm [65]. The contributions of the model were presented by optimizing the work of logistics centers, reducing the time of detention and costs. The potential application of these approaches is reflected in the optimization of the operation of gas transport vehicles through the full utilization of driving capacities and the selection of the optimal route from the place of loading to the place of unloading goods. Reference [66] presents a new optimization model for more efficient vehicle utilization based on the multi-objective red deer algorithm (MORDA). The model combines economic, environmental, and social aspects to reduce travel time, delay, CO_2 emissions, and transport costs. The model can be applied to solve the problem of transport optimization by choosing the optimal route, vehicle, and body to preserve sustainable transport and the environment.

5. Conclusions

The methodological approach to the prediction of fuel costs and emission costs for heavy-duty vehicles intended for gas transportation presented in this paper takes into account a large number of input parameters related to the vehicle's constructive characteristics and operating conditions (vehicle types, fuel types, body types, vehicle mass utilization, amount of gas transported, type of road section terrain, road section category, etc.). The approach shows the mutual interaction of input parameters to reveal the dependence of fuel consumption on vehicle mass utilization, that is, the dependence of exhaust gas emissions on fuel consumption. Based on the above, the following contributions, conclusions, and directions for future research can be drawn.

In this paper, the authors comprehensively analyzed vehicles intended for transporting gases, which are class-2 dangerous goods, from a different perspective. The paper focuses on the economic and environmental aspects of gas transportation activities, representing them with fuel and emission costs while not neglecting safety aspects. Additionally, the contribution of this research is reflected in its application and processing of data conducted during the actual conditions of measuring and testing the vehicles and bodies.

Second, the paper presents research results that provide predictive insight and offer practical solutions to companies seeking to improve road gas transportation. The advantages and disadvantages of using steel and composite pressure vessels in terms of the transported quantities of gas and vehicle mass utilization are presented, as well as their effects on the differences between the use of conventional and alternative fuels in terms of fuel consumption and gas emissions. These findings directly impact the decision-making process for companies, making the research highly relevant and impactful.

The general conclusion is that, in the future the use of lightweight composite materials to produce bodies (pressure vessels) intended to transport gases has a role to play in the road transport system of dangerous goods.

Consequently, the directions of future research can be divided into segments. The first segment will focus on applying polymer and composite materials to produce bodies intended for transporting dangerous goods, both for class 2 and other classes of dangerous goods, aiming to determine the impact of different materials and goods on transport risk and exploitation costs.

The second segment will present the application and validation of the developed model for other dangerous classes, incorporating the achieved results and data into advanced optimization algorithms to find a balance between the complexity of the model (safety, economic, and environmental aspects) and optimal route selection.

Author Contributions: All authors contributed equally to this paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research was financially supported by the Ministry of Science, Technological Development, and Innovations of the Republic of Serbia (Contract No. 451-03-66/2024-03/200017, and No. TR36027).

Data Availability Statement: All relevant data, literature and results are presented in the manuscript.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this research.

Appendix A

Appendix A explains the input parameters and variables described in detail in the methodology.

Set	Description–[Unit]	Acquisition
i	The emission of pollutants for *m*-th vehicle category [g];	The set of values related to the vehicle(s) and the study area.
j	The index of pollutants (CO, NMVOC, NO_x, $PM_{2.5}$, CO_2, and CH_4) [-];	The set of values related to the vehicle(s) and the study area.
m	The index vehicle category [-];	The set of values related to the vehicle(s).
n	The index body type (Type-1 and Type-4) [-];	The set of values related to the vehicle(s).
ϱ	The density of fuel [kg/L];	The set of values related to the study area.
L	The length of the road section [km];	The set of values related to the study area; pre-defined single value.
P	The annual transport volume [t];	The set of values related to the study area; pre-defined single value.
Ms	Mass of a vehicle in running order the *m*-th with *n*-th [kg];	The set of values related to the vehicle(s).
Mt	The reference amount of gas transported of the *m*-th with *n*-th [kg];	The set of values related to the vehicle(s).
Mkr	Reduced vehicle payload capacity of the *m*-th with *n*-th [kg];	The set of values related to the vehicle(s).
Σ*Ms*	Represents the sum of *Ms* for the vehicle combinations [kg];	Determined values are based on the vehicle(s).
$EF_{i,j,m}$	The reference average emission values of *j*-th for *m*-th and *i*-th [$g_{pollutans}/kg_{fuel}$];	The set of values related to the vehicle(s) and the study area.
UCPi	The reference values of the unit costs of pollutants *j*-th [EUR /t];	The set of values related to the vehicle(s) and the study area.
CFC	The reference values of fuel cost [EUR /kg].	The set of values related to the vehicle(s) and the study area.
Variable	**Description–[Unit]**	**Acquisition**

η_{ks}	The mass utilization coefficients of the *m*-th with *n*-th depends on *Mt* [-];	Determined values are based on the vehicle(s).
η_{k}	The mass utilization coefficients of the *m*-th with *n*-th depends on *Mkr* [-];	Determined values are based on the vehicle(s).
N_n	The number of turns of the *m*-th with *n*-th for annual transport volume *P*-th [-];	Determined values are based on the vehicle(s) and the study area.
$FC_{j,m,n}$	The fuel consumption on the road section for the *m*-th with *n*-th and *j*-th—for the fuel type CNG [kg/100 km] or diesel [L/100 km];	Determined values are based on the vehicle(s) by measuring on the road section.
$FC'j_{,m,n}$	The specific fuel consumption on the road section for the *m*-th with *n*-th and *j*-th [kg/km];	Determined values are based on the vehicle(s) and the study area.
EP	The values of exhaust emission of pollutants on the road section for the *m*-th with *n*-th for N_n [g];	Determined values are based on values related to the vehicle(s) and the study area.
UCP	The unit cost of pollutants *j*-th on the road section for the *m*-th with *n*-th for *Nn* [EUR];	Determined values are based on values related to the vehicle(s) and the study area.
TFC	The total fuel costs on the road section of *m*-th with *n*-th for annual transport volume *P*-th [EUR/year];	Determined values are based on values related to the vehicle(s) and the study area.
TEC	The total emission costs on the road section of *m*-th with *n*-th for annual transport volume *P*-th [EUR/year].	Determined values are based on values related to the vehicle(s) and the study area.

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