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Exploitation and Maintenance of Biomethane-Powered Truck and Bus Fleets to Assure Safety and Mitigation of Greenhouse Gas Emissions

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Abstract: Motor vehicles in transport, as one of the important sectors of the economy, emit a significant amount of carbon dioxide and other products in the form of exhaust gases, which are harmful to human health. The emission of exhaust gases from motor vehicles is limited by appropriate regulations in accordance with environmental goals, such as the Paris Climate Agreement. Reduced emissions and fuel (energy) consumption is mainly achieved by applying modern technologies for the production of internal combustion engines; transitioning to cleaner fuels, such as renewable natural gas or biomethane; and using alternative propulsion systems. Biomethane stored in a liquid state in on-board reservoirs has advantages in truck transport, ships, and air traffic. The reason for this is due to the higher concentration of energy per unit volume of the reservoirs and the lower storage pressure and thus higher safety compared to the high-pressure storage option (compressed biomethane). The presented research is related to a proposition regarding the design of drive systems of city buses using biomethane as fuel in cases when fuel is stored on-board the vehicle as gas in a compressed aggregate state. In this study, the results of a calculation method regarding the roof-supporting structure of an experimental bus with gas reservoirs under higher pressure are discussed as well. This study also presents the possibility of reducing harmful emissions if biomethane is used instead of conventional fuels as a transitional solution to electric-powered vehicles. For the sake of comparison, it is suggested that the engaged energy and the amount of produced carbon dioxide emissions within the drive systems of different fuels are calculated according to the recommendations of the standard EN16258:2012.

Keywords: biomethane; energy consumption; greenhouse gas emission; maintenance; sustainable energy emissions; vehicles

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1. Introduction

Extreme global climate change is a current issue. Some regions of Asia have seen strong impacts from climate change: schools were closed in Bangladesh due to extreme heat, contrary rice fields froze in Vietnam, and residents of India struggled with extremely high temperatures when going to vote during the election. In parallel, record ocean temperatures are having an increasing impact on marine systems. The average temperatures recorded during certain months are higher compared to the same period before the age of industrialization. Record heat is a consequence of the long-term trend of global warming due to human activities, which is accompanied with the burning of fossil fuels in the transport sector, households, etc. On the other hand, the burning of fossil fuels in motor vehicles produces exhaust gases that are harmful to human health. This refers mainly to the emission of particles, which are the combustion products of the exhaust gases of vehicles with diesel engines, such as heavy trucks, buses, ships, etc. [1,2].

One of the ways to reduce emissions from vehicles is the application of new technologies in internal combustion (IC) engines, as well as technologies for the subsequent catalytic processing of combustion products [3]. Hybrid drives are considered a transitional solution to electric or other alternative drive modes for mobile systems [4–6].

The use of electric vehicles is gaining increasing importance. However, one should not forget that positive effects can only be achieved if the electricity used to charge the batteries is obtained from renewable energy sources [5,7]. Additionally, optimizing vehicle routing, such as by using metaheuristic approaches in multi-trip capacitated vehicle routing problems, can help reduce fuel consumption and associated emissions by minimizing the distance travelled and time vehicles spend on the road [8].

Renewable natural gas, or biomethane, has a significant application as fuel for various mobile systems as well. For example, following practices in other cities in the world, in Kragujevac city in the Republic of Serbia, low-floor buses powered by biomethane were first implemented for public passenger transport [9].

The aim of this project was to demonstrate the possibility of reducing exhaust emissions and dependence on petroleum fuels if diesel buses in urban transport are replaced with gas buses. Additionally, the engine of this bus can run on natural gas stored in a gaseous or liquid state or with up to 100% biomethane, i.e., renewable natural gas, obtained from biogas or landfill gas to improve fuel quality [1,10].

Reduced emissions and fuel consumption can also be achieved by applying alternative drives and artificial intelligence to utility vehicles by using biomethane trucks to collect waste from which biogas or biomethane is produced. Biomethane can further be used to heat households or as a replacement or supplement to natural gas to power city buses and other vehicles [11,12].

Biomethane is a pure form of biogas, and in this pure form, it can be used as a natural gas substitute. Biomethane is a natural gas formed in an anaerobic process, which involves the decomposition of organic matter without oxygen access. Biogas cannot be identified with biomethane. Biogas is a mixture of methane and other substances that cannot be injected into the gas grid due to different physico-chemical properties compared to natural gas. Biomethane is only produced in the process of purifying biogas [13,14].

Bearing in mind the large number of biomethane and natural gas vehicles (NGVs), the conditions for the safe use of these vehicles in the transport systems of cities are investigated and systematized in this paper. Considering the differences between buses or other NGVs and their diesel versions, the main goal of this study was to present experiences and, from that aspect, recommendations regarding their production, exploitation, and maintenance.

According to experiences, gas-powered buses and other NGVs need to be equipped with fire protection systems, and all the devices and equipment must be of an approved type and homologated [15,16]. On the other hand, the importance of properly using and maintaining NGVs and their equipment is pointed out [17,18]. Requirements for the installation and homologation of vehicles, as well as devices and equipment for natural gas, are prescribed by the following regulations: UN ECE 110R and UN ECE 115R [19,20].

As a short reminder, this paper examines the implementation and impact of gas propulsion systems in motor vehicles, specifically the exploitation and maintenance of biomethane-powered trucks and buses. Starting with an introduction outlining the issue discussed, it proceeds with a literature review and characterization of relevant propulsion systems. The methodology, including the data and methods used for establishing a standardized correlation between greenhouse gas emissions and fuel (energy) consumption, is then described. The Results Section focuses on motor vehicle equipment and installation conditions for cylinders on NGVs and the requirements for periodical technical and safety inspections. The discussion interprets these findings, considering broader implications and potential applications. Finally, the conclusions summarize the key findings and offer insights into the feasibility and benefits of NGVs.

2. Literature Review

The use of hydrogen and biomethane to achieve sustainable transport in the circular economy concept was considered by Saravanakumar et al. [21]. They highlighted the high potential of hydrogen as a sustainable fuel for long-distance heavy vehicles, showing better climate performance even when electricity from fossil fuels is used in production. In addition, they analyzed hydrogen and biomethane in terms of infrastructure development, raw material availability, and economic viability.

In their study, Chiaramonti and Testa analyzed innovative and sustainable agro-energy chains in which biomethane is the energy carrier used to produce sustainable aviation fuels (SAFs) and methanol for marine transport [22]. In their study, decentralized biomass fermentation and centralized biomethane conversion in the refinery were combined considering key Gas-to-Liquid (GTL) pathways: Fischer–Tropsch synthesis and methanol and gas/alcohol fermentation to stream.

Xie and others analyzed the key biological and technological features and mechanisms related to the production of biohydrogen and biomethane in the photo-fermentation process [23]. They conducted their analysis from the point of view of using wastewater or biowaste as raw materials for the photobiological production of hydrogen, analyzing factors affecting biohydrogen yield and various improvement methods. In addition, they examined processes, methods, and mechanisms for improving photo-fermentation biomethane production. By combining biohydrogen and biomethane, they emphasized the complementary roles of these bioenergy sources in a unified photo-fermentation framework.

Bužinskienė analyzed five perennial mixtures of grasses and legumes in terms of biomethane production considering the subsidy policy in Lithuania [24]. The analysis showed that the best mixtures for biomethane production with subsidies were the following scenarios: 35% red conifer, 45% meadow thyme, 20% multi-colored vine, 55% red conifer, and 45% multi-colored vines.

An analysis of existing and planned technical infrastructure for biomethane as an alternative fuel for the EU road sector was carried out by Prussi and others [25]. Their study highlighted the need for a policy perspective focused on the synchronized introduction of CNG- and LNG-powered vehicles, including refueling infrastructure and bio-CNG/LNG production.

Masilela and Pradhan conducted a Life Cycle Sustainability Assessment (LCSA) to compare biomethane with biohydrogen produced from organic waste streams in different African environments, such as agro-industry, cities, and rural areas [26]. Biomethane and biohydrogen were also used in cogeneration systems to generate electricity and as transport fuel for motor vehicles. In the agro-industrial setting, applying biohydrogen in the electricity generation system results in a higher sustainability performance compared to the vehicles' operation.

Li et al. conducted a strategic analysis of the trucking fleet against net zero emission targets [27]. For liquefied natural gas, biomethane, electricity, and hydrogen, strategic analysis frameworks, such as PEST-SWOT models, were developed to enable a comprehensive comparison and determine their long-term implementation potential.

Trazzi et al. analyzed emissions from garbage dumps in Italy powered by biomethane from waste biomass [28]. Environmental benefits are enhanced by capturing and using or sequestering off-gas CO_2 from biogas upgrading and by developing interconnected systems of waste collection, biomethane production, pressurization, and vehicle refueling. The results indicate that GHG emission reductions ranging from 55% to 75% for compressed biomethane were achieved compared to compressed natural gas.

For clarity and insights, the following two paragraphs present the current unfavorable situation (i.e., the beginning of 2025) in the context of the use of alternative fuels in relevant categories of road vehicles in the Slovak Republic (Table 1).

Table 1. The number of registered road vehicles of relevant categories in the Slovak Republic at the beginning of 2025 [29].

	Categories of Motor Vehicles			
	M2	**M3**	**N2**	**N3**
Total number of vehicles	862	7959	24,511	55,415
LNG—liquefied natural gas	-	-	-	127
CNG—compressed natural gas	1	257	12	74

Categories of motor vehicles: M2—buses with more than 9 seats and maximum mass not exceeding 5000 kg; M3—buses with more than 9 seats and maximum mass exceeding 5000 kg. Vehicles used for carriage of goods with maximum masses exceeding 3500 kg but not exceeding 12,000 kg (N2) and those exceeding 12,000 kg (N3).

Based on the analysis of numbers of registered road vehicles in total in the Slovak Republic, it is clear that the use of vehicles with alternative fuels (CNG and LNG) is still minimal compared to the total number of vehicles in the M2, M3, N2, and N3 categories. In category M2, which includes passenger vehicles with smaller capacities, there is currently only one vehicle registered with a CNG propulsion system, representing approx. 0.1% of the total of 862 vehicles. In category M3, which includes buses, the situation is slightly better, whereby 257 vehicles use CNG, representing approx. 3.2% of the total of 7959 vehicles. In freight transport, the share of alternative fuels is even lower. In category N2, which includes medium–heavy trucks, there are 12 registered CNG vehicles, representing only approx. 0.05% of the total of 24,511 vehicles. In category N3, which includes heavy trucks, there are only 127 LNG and 74 CNG vehicles in total, representing only approx. 0.2% and 0.1%, respectively, of the total of 55,415 registered vehicles (Table 1).

In comparison with other countries, especially Western European Union countries, the share of vehicles with alternative fuels in Slovakia is significantly lower. In countries such as Germany, the Netherlands, or Sweden, the share of CNG and LNG vehicles in freight and public transport is much higher. This difference is mainly due to insufficient infrastructure for alternative fuels in Slovakia as well as lower state support. In many Western EU countries, various incentives are implemented in terms of support for the purchase and operation of vehicles with alternative fuels, such as tax breaks, subsidies, or preferential road tolls [29].

Due to the higher octane number, natural gas is a quality fuel for all IC engines in which the combustion process is realized according to the Otto cycle. The combustion of natural gas is more complete, and the final result involves reductions in fuel consumption, exhaust gas emissions, and noise [30,31].

However, due to the low concentration of energy per unit volume of the natural gas reservoir, problems may arise in the exploitation of motor vehicles due to a smaller radius with one filling with fuel [31,32]. Differences in energy density per unit of reservoir volume for different fuels are systematized in (Figure 1) [33].

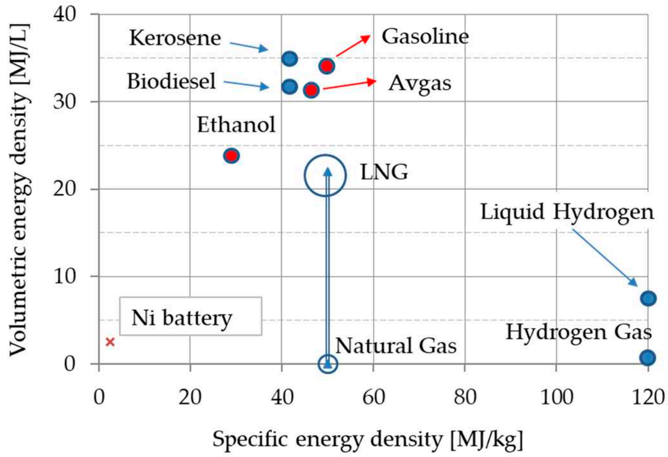


Figure 1. Fuel energy density comparison chart.

Natural gas is stored on-board vehicles in a liquid state in cryogenic reservoirs as liquefied natural gas (LNG) or in a gaseous state under high pressure as compressed natural gas (CNG) [34,35].

As an example, the first author (S.M.) achieved the serial production of city buses (MAZ-BIK) powered by CNG and presented the logistics of their implementation for the needs of public passenger transportation in Kragujevac city in the Republic of Serbia [9].

Through the liquefaction process of natural gas at −162 °C, its volume can be reduced by about 600 times, which is advantageous from the aspect of on-board storage in motor vehicles. In the second case, as shown on the concrete example of the city bus below, natural gas is stored in reservoirs on the roof under a pressure of 20 MPa. Generally, biomethane has a number of commercial, environmental, and energy advantages over traditional fuels when used both as a motor fuel and as a fuel for power plants [36,37]:

- It is non-toxic, non-carcinogenic, not hazardous to water, slightly soluble in water, colorless, and odorless, with no increased hazard potential compared to diesel.
- The density of natural gas, or methane, is 0.68 kg/m^3 @ 15 °C, so it is lighter than propane (1.87 kg/m^3) and butane (2.44 kg/m^3). From the aspect of safety and fire protection, it is necessary to know that in case of damage to equipment or cylinders, biomethane flows upwards because it is lighter than air.
- The auto-ignition temperature range of natural gas (480–650 °C) is much higher compared to that of other fuels: methane (595 °C), propane (495 °C), butane (480 °C), gasoline (range of 260–430 °C), and diesel (less than 260 °C).
- It is flammable as gas in concentrations (5–15%) in combination with air, for propane (2.4–9.3%), butane (1.8–8.8%), gasoline (1.4–7.6%), and diesel (0.6–7.5%).

There is a persistent misconception about the dangers of biomethane due to its physical properties. Methane is lighter than air, so it quickly escapes into the surroundings in the case of leaks. It has a very high auto-ignition temperature, and an explosive concentration is reached only with a sufficiently large proportion of gas in the air.

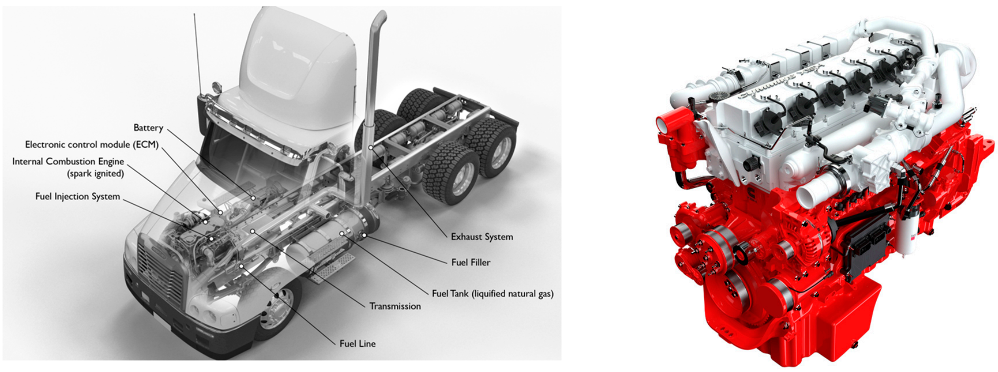
From an ecological point of view, the use of biomethane reduces the quantity of harmful substances in combustion products. It has an increased detonation resistance (the octane rating is about 105). If the concrete autonomy of motor vehicles is analyzed, it is necessary to know the following: 1 L (L) of diesel fuel corresponds to 5 L of CNG or 1.8 L of LNG. From that aspect, if the smaller number of pumping stations is considered, CNG is a good fuel for shorter distances, while LNG is more suitable for longer distances, for highway trucks, tankers, ships, etc. [10,35].

If the transition period is considered until the complete transition to gas propulsion, there are several options for the conversion of the existing vehicle fleet and application of biomethane:

- Only biomethane drive (dedicated);
- A propulsion system on two independent fuels (bi-fuel);
- A propulsion system mainly for truck engines, where diesel fuel is used for the initial ignition of biomethane (dual-fuel).

The problem of biomethane storage as a CNG was solved over time by using cylinders made of aluminum (type III) or composite and plastic materials (type IV) coated with carbon or fiberglass fibers and resin instead of all-steel cylinders and a steel liner with fiberglass hoop wrap (types I and II). In this way, the weight of the CNG cylinder was reduced over time, which made it possible to store a larger amount of biomethane in the motor vehicle. Modern cylinders (type III and type IV) are up to 70% lighter than original steel ones as follows: type I (1.2–1.5 kg/L), type II (0.7–1.4 kg/L), type III (0.3–0.4 kg/L) and type IV (0.35–0.5 kg/L) [19,20,23,24].

Figure 2 shows the parts of the LNG supply system for the converted diesel engine on the dual-fuel truck and bus [9]. The engine control unit (ECU) regulates the diesel fuel and biomethane mixture ratios depending on the operating regime. A cold start of the engine is realized with diesel fuel before switching to operation with LNG.

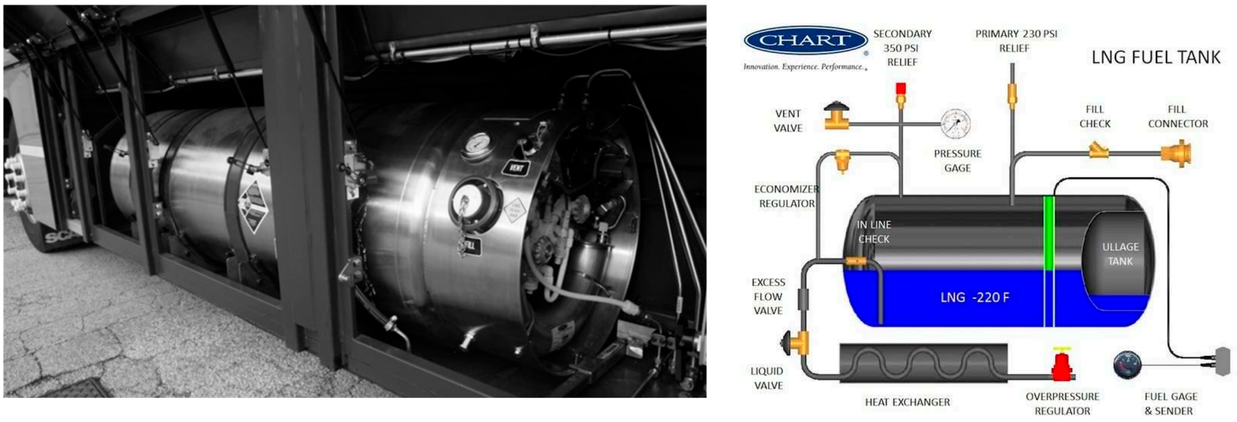


(**a**) (**b**)

Figure 2. Parts of the LNG fuel supply system applied to the converted diesel engine, (**a**) with an LNG cylinder and (**b**) the main engine equipment for sequential natural gas injection into the intake manifold.

The basic mounting positions of the LNG cylinder in the intercity bus, as well as the main equipment of the LNG cylinder (fuel reservoir), are shown in Figure 3 [9].

In the case of vehicles powered by biomethane, similar to gasoline engines, an external system for the ignition of the fuel–air mixture is necessary. This is realized by means of an ignition system with a spark plug in case of engines that run exclusively on biomethane (dedicated), or as already explained, a small quantity of diesel fuel in biomethane initiates the ignition (dual-fuel engine), (Figure 2) [38]. In general, as shown in Figures 2 and 3, in addition to the additional fuel supply system and the electronic control of the injection system, if natural gas is stored in the form of LNG in a vehicle, it is necessary to install a heat exchanger. Inside the exchanger, the natural gas is converted from a liquid to a gaseous state and, as such, is injected into the engine at a low pressure. Similarly, if natural gas is stored under pressure as CNG, the gas supply system (rather than installing a heat exchanger in LNG) is equipped with a gas reducer that reduces the gas pressure before it is injected into the engine.



(**a**) (**b**)

Figure 3. (**a**) A photograph of the cylinder for LNG fuel, mounted under the intercity bus floor. (**b**) The cross-section of the LNG cryogenic cylinder with basic safety equipment.

In both cases, the fuel supply system applied to the engine is electronically controlled. This also applies to the case of a multi-fuel drive, where the amount of a certain fuel in the mixture is regulated by means of dedicated electronic control units. Diesel fuel and natural gas are stored separately in reservoirs inside a vehicle (Figure 2).

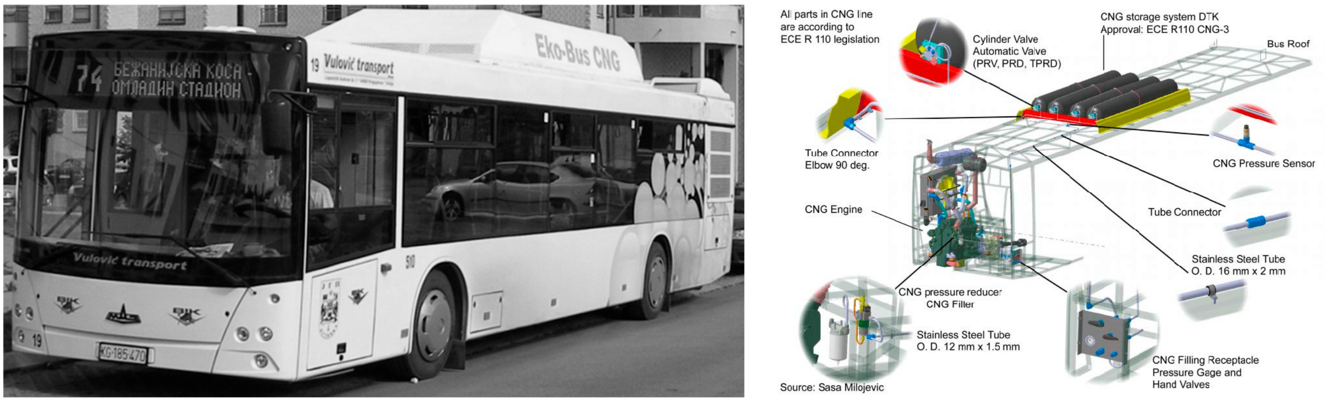
Another conceptual difference between diesel and IC engines for biomethane is the combustion products' composition. The combustion of dedicated biomethane in a mixture with diesel fuel reduces and eliminates particulate matter (PM), nitrogen oxides (NOx), and smoke in the exhaust gases of diesel engines [1,38].

Additionally, inside dedicated biomethane engines and vehicles, the catalytic treatment of the raw combustion products is similar to that in gasoline engines. Exhaust gases in that case, regarding the raw emissions, consist of the emissions of hydrocarbons (HCs), carbon monoxide (CO), and methane (CH_4). Ceramic catalysts coated with precious metals are usually used for catalytic processing. In that case, the problem is the emission of carcinogenic formaldehydes, which are produced by burning CH_4, because they can clog the catalyst house.

In biomethane engines that operate with a stoichiometric mixture, the emission of harmful gases in the exhaust system (HC, CO, Nox, and CH_4) is regulated by the use of three-way catalysts. The second option is characteristic of larger engines and involves working with a lean mixture. These engines are more economical and therefore have lower emissions. Due to the lower temperature of the combustion process, the raw NOx emission is also lower in that case [1,39].

However, from a conceptual point of view, apart from the systems used for the fuel mixture formation and catalytic treatment, the conceptions of NGV differ fundamentally according to the manner in which fuel is stored in the vehicles. The option of a liquid storage state at ambient pressure is shown in Figure 3 for the example of an intercity bus.

In the second case, biomethane is stored in a gaseous state under high pressure to increase the energy concentration of the fuel per unit volume. In this second case, an example can be the project of the low-floor city bus powered by biomethane stored as CNG (Figure 4) [9].

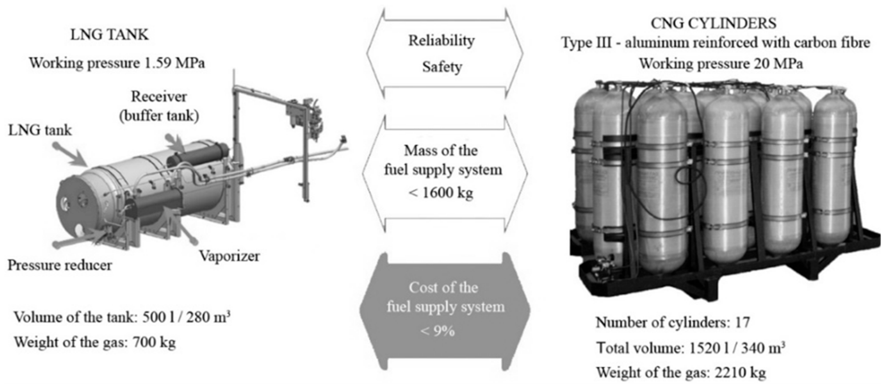


(**a**) (**b**)

Figure 4. Example of biomethane storage in gaseous aggregate state under high pressure. (**a**) Photograph of low-floor city bus (MAZ-BIK 203CNG-S prototype) in use. (**b**) Part of installation for CNG supply from cylinders on bus roof to pressure reducer and engine.

The problem regarding the increased weight because of the external weight inside this bus concept was solved by the use of CNG type III cylinders located on the bus roof. This method makes it possible to maintain the maximal number of passengers transported by bus, i.e., the load capacity in the case of trucks, compared to vehicles that use a diesel propulsion system [9].

Figure 5 shows the most commonly used characteristics of the cylinders for LNG and CNG inside a dump truck with a maximum weight of 13,000 kg regarding differences compared to the base diesel power system equipment. The possibilities regarding the mounting of special gas equipment, equal to those of diesel vehicles, are shown in the same figure as well. The fuel pressure in the cylinders is an important difference from the safety perspective, as explained above.



(**a**) (**b**)

Figure 5. Differences in (**a**) LNG fuel storage cylinder for dump truck compared to (**b**) CNG storage system.

Researchers are currently thinking about using biomethane in river, sea, and rail transport in the future. Aircraft builders have also come to grips with this problem. As a comparison, from the safety perspective, LNG as an option is applicable as a jet fuel, too. However, in this case, some essential airframe and engine modifications are needed.

As an example, in the mid-eighties, Tupolev specialists had the opportunity to create an aircraft powered by LNG. Based on the serial TU-154 passenger-liner aircraft, they built the TU-155 flying laboratory. Experimental flights of the TU-155 provided invaluable experience for further improvement in aviation cryogenic fuel systems. Now, a new cryogenic-fueled aircraft, the TU-156, is being designed not for testing but for commercial operation (Figure 6) [33,40].

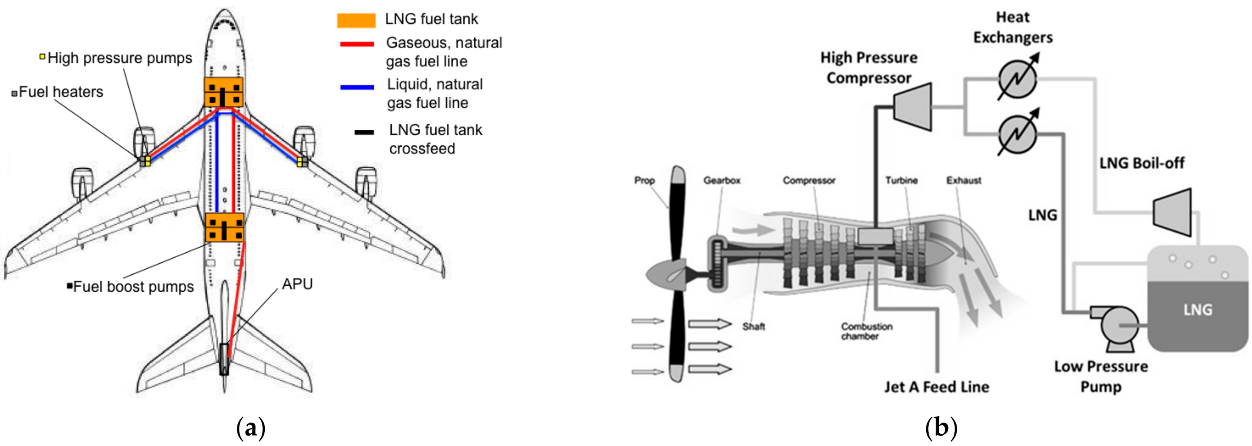


Figure 6. (**a**) The LNG fuel line system for aircraft. (**b**) The jet engine fuel system (LNG–kerosene).

Unlike its predecessor (TU-154M production aircraft), the TU-156 is equipped with three Kuznetsov NK-89 engines with separate fuel systems (one standard tank for kerosene, and one cryogenic tank for LNG). Like the NK-88, the new engine is equipped with a turbopump unit powered by air that comes from the compressor of the turbojet engine. Behind the turbine, the LNG is heated and then passes into a gaseous state and enters the combustion chamber of the engine, where the gas and kerosene nozzles are installed. The above examples indicate the possibility of using biomethane stored as LNG to power aircraft propulsion systems with appropriate modifications and safety measures. The refueling of the aircraft takes only 30 min (for an example, see Figure 6) [40,41].

The designers of the TU-156 considered many options for placing the fuel cylinder (under the wing, on the fuselage, etc.) and chose one that does not violate aerodynamics while maintaining the stability and controllability of the aircraft. A main cryogenic cylinder with a capacity of 13,000 kg, a diameter of more than 3 m, and a length of almost 5.5 m was placed in the rear passenger compartment, and a centering cylinder (3800 kg) was placed in the front luggage compartment under the cockpit floor. The main part of the passenger compartment was turned into a cargo compartment (Figure 6) [40,41].

The cryogenic cylinders for LNG storage inside TU-156, as an example, are equipped with a drainage system that releases methane vapor in the case of emergency situations. The position of the LNG cylinder, as well as the gas lines (from the LNG cylinders to the heat exchanger and the injectors on the engine manifold), is marked in Figure 6.

Issues of special importance regarding aircraft and passenger safety are the integration of an anti-fire protection system, as well as protection against explosion. Aircraft powered by LNG has its own specifics. To avoid the possible ignition of methane, all spark-producing electrical equipment is removed and isolated, and gas analytical sensors that signal an emergency are installed. In addition, forced ventilation is provided inside all compartments.

With this layout solution, the carrying capacity of the TU-156 decreased to a maximum of 14,000 kg. However, designers did not exclude other, more cost-effective solutions. The range of cargo transportation, according to calculations, would be at least 2600 km when working on aircraft using LNG, and on aircraft using LNG and kerosene, it would be 3200 km. Thanks to two separate fuel systems (for kerosene and LNG), the TU-156 will be able to refuel with gas, fly to an airport where there is no equipment for its production and storage, and fly away on kerosene. In an emergency situation, it can switch from one type of fuel to another in just 5 s. Those benefits improve flight safety and make LNG airliners more mobile [33,41].

For LNG flights to become regular, it is necessary to create ground infrastructure at airports (liquefaction plants and filling equipment). Additionally, since most airports are located distant from main gas pipelines, where the gas is under high pressure, gas pumping and distribution stations are also needed. Currently, work is underway to convert LNG into a liquid state without using additional energy.

3. Data and Methods for Emission Quantification

The subject of this research generally includes the process of replacing the existing fleet with diesel vehicles with suitable alternative fuels (fuel cell, biomethane, etc.). To define the benefits and compare CO_2 emissions and fuel consumption, in the case of a multi-fuel motor vehicle, the methodology prescribed by the EN16258 European Standard can be used [42,43].

The standard calculation of greenhouse gas emissions includes both primary and secondary energy carriers and processes. Primary ones include production and delivery to consumers, and secondary ones include the combustion process and the conversion of the fuel chemical energy into the mechanical work of combustion products in IC engines. According to the standard, the total energy and emission consumption for a vehicle can be calculated using Equations (1) and (2), respectively [44–46]:

$$E_{ec}^{wtw} = S_{fc} \cdot e_{wtw};\ E_{ec}^{ttw} = S_{fc} \cdot e_{ttw} \tag{1}$$

where

- E_{ec}^{wtw}—wheel-to-wheel (WtW) energy consumption [MJ·(100 km)$^{-1}$];
- E_{ec}^{ttw}—tank-to-wheel (TtW) energy consumption [MJ·(100 km)$^{-1}$];
- S_{fc}—fuel consumption [L·(100 km)$^{-1}$];
- e_{wtw}—the WtW energy factor regarding consumed fuel [MJ·(L)$^{-1}$];
- e_{ttw}—TtW energy factor regarding consumed fuel [MJ·(L)$^{-1}$].

$$G_{ec}^{wtw} = S_{fc} \cdot g_{wtw};\ G_{ec}^{ttw} = S_{fc} \cdot g_{ttw} \tag{2}$$

where

- G_{ec}^{wtw}—WtW emissions of CO_2 [gCO_{2e}];
- G_{ec}^{ttw}—TtW emissions of CO_2 [gCO_{2e}];
- g_{wtw}—the WtW emission factor regarding consumed fuel [gCO_{2e}·MWh^{-1}];
- g_{ttw}—the TtW emission factor regarding consumed fuel [gCO_{2e}·MWh^{-1}].

CO_{2e} is a measure for comparing emissions of different greenhouse gas sources based on their global warming potential (GWP). In essence, it converts an amount of other gases into an amount of CO_2 that has the same GWP. Tank-to-Vehicle (TtW) represents a system that starts from sources and extraction to the chemical energy transformation of different fuels inside IC engines (diesel, biomethane, hydrogen, etc.) or the transformation of electric energy into mechanical work and the kinetic energy inside motor vehicles. The wheel-to-wheel (WtW) system includes the use of energy within the vehicle or the processes of transforming chemical or electrical energy into kinetic energy that is used to drive motor vehicles [46,47].

This calculation is considered necessary because the use of alternative drives instead of conventional oil-based fuel drives only makes sense if the fuel or electricity is obtained from renewable sources. From this aspect, a detailed application of both the model and standard recommendations are presented in [48].

Also, a more detailed analysis regarding the differences, i.e., the efficiency of transformation of different forms of energy for electricity production, as well as the impact on emissions and environmental pollution depending on the primary energy for fuel production, was carried out in [49].

In general, this European Standard prescribes a unique methodology for the calculation and declaration of energy consumption and CO_2 emissions in the transport sector (including the transport of passengers or freight or both).

The type approvals of specific equipment for natural gas (CNG and LNG) on motor vehicles, as well as installation conditions for specific retrofit system components, are defined in the UN ECE 110R and 115R regulations. These standards outline the conditions for the periodical control and maintenance of natural gas vehicles [19,20].

In addition, there are regulations at the state level. Those mainly include appropriate laws related to traffic safety and regulations that prescribe the conditions of testing, that is, the periodical control of biomethane vehicles, with the aim of ensuring their safe use in traffic.

The emission limits of heavy-duty engines for motor vehicles, with a gross vehicle weight over 3500 kg, are defined by the European emission standard Euro VI (2013.01). This standard applies to all motor vehicles with diesel and spark-ignition engines using biomethane or ethanol (E85), petrol, etc., as fuel, as well as dual-fuel engines. For biomethane engines, the standard, in addition to other exhaust components, additionally prescribes a permitted limit for methane emissions of 0.5 g/kWh. Biomethane engine emissions need to be measured according to the World Harmonized Transient Cycle [1,50].

4. The Results of Calculating the Bus Structure

As a special contribution, specific empirical data and recommendations regarding the production, exploitation, and maintenance of CNG-powered city buses are presented in this section. The primary aim was to contribute to increasing and understanding the safety measures of such vehicles in traffic.

Biomethane cylinders for CNG or LNG in motor vehicles must be marked with stickers or plates that contain prescribed information, which may be mandatory or non-mandatory [19].

Mandatory information includes the name of the manufacturer and the serial number of the cylinder, the type of gas used to fill it (CNG or LNG only), the working temperature and pressure, the type of approved automatic valve, and the certificate number. Non-mandatory information that can be written on the cylinder plate includes the date of the pressure test, the nominal water capacity, the gas temperature range, etc.

The plate or sticker must be permanently attached and protected on the cylinder surface. In addition, NGVs must be properly marked; this is important information in hazardous situations, such as if a vehicle catches on fire, etc. On the other hand, for safety reasons, NGVs must be equipped with an alarm and an automatic fire extinguishing system. That is recommended due to the fact that the cause of fire in biomethane-powered vehicles can be other systems, such as insufficient tire pressure, hydraulic oil leakage, human-related factors, the fuel system, etc.

During mandatory testing, i.e., the pressure test, cylinders must be equipped with approved equipment. The test pressure of the LNG cylinder, for example, must be at a minimum pressure that is 1.3 times higher than the working pressure [51].

When analyzing the cylinder installation conditions, it is first necessary to prevent metal-to-metal contact and to use adequate insulation and protection. As they can be built into the vehicle chassis, similar to diesel reservoirs, LNG cylinders must not be closer than 200 mm to the road surface (Figure 3a).

Additionally, the other equipment in the natural gas supply system, from the cylinder to the engine, must be of an approved type and protected. In particular, parts of the electrical installation must be protected and isolated to prevent contact with fuel or parts of the exhaust system. An example of approval identification on the natural gas equipment on motor vehicles is shown in Figure 7.

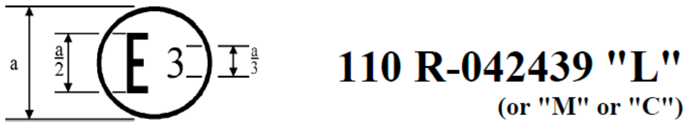


Figure 7. Biomethane equipment approval.

Explanations of the homologation approval number for biomethane gas equipment as presented in Figure 7 are as follows:

E3—biomethane equipment is approved in Italy;
R-042439—the approval number according to the homologation UN ECE 110R;
L—the product is compatible with LNG;
M—the product is intended for use in working conditions at moderate temperatures;
C—the product is intended for use in working conditions at cold temperatures.

Requirements for the safe installation of biomethane cylinders in vehicles are also defined by standards. The connection of the cylinder to the vehicle must be appropriate and subject to periodical inspection. The cylinder or a battery of several cylinders on the rack (supporting structure) must be attached to the vehicle such that they can absorb the appropriate accelerations and decelerations without damage (Table 2) [19].

Table 2. Accelerations that biomethane cylinders must absorb without damage.

Categories of Motor Vehicles	M1 and N1	M2 and N2	M3 and N3
The acceleration of a vehicle:			
—in the driving direction	20·g	20·g	6.6·g
—perpendicular to the driving direction	8·g	5·g	5·g

Categories of motor vehicles: M1—passenger cars with no more than 9 seats; N1—vehicles used for the carriage of goods with maximum masses not exceeding 3500 kg. Gravitational acceleration (g).

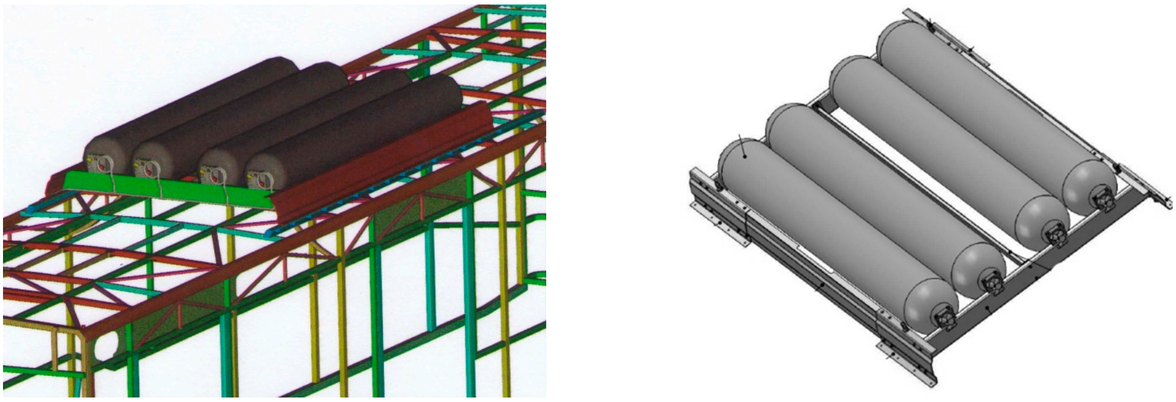
According to the conditions shown in Table 2, as an example, for this research scope, a diesel-powered bus was reconstructed to run on biomethane. During the reconstruction process, a battery of four CNG cylinders was installed on the bus roof. In order for the system to be better, safer, and easier to maintain during periodical technical inspections, the cylinder carrier was removable with screws instead of being realized by welding (Figures 4 and 8).

Type III cylinders made of aluminum alloy with appropriate tribological characteristics were selected for installation. The cylinders have an extended filling cycle life and are lighter than the steel one's counterpart, which reduces the load on the bus roof structure [50,52].

The UN ECE 110R standard stipulates that the load conditions of the supporting structure of an NGV can be determined through calculations with appropriate programs. For this purpose, a model of the supporting structure of the bus was created (see Figure 8), and the conditions required according to Table 2 were simulated by the model [19,53].

The model is formed in the form of beam elements with a total of 287 nodes and 487 elements. For this purpose, we used the FEM PAK software (software version S for Structural Analysis) developed at the Faculty of Engineering, University of Kragujevac, Serbia. Inside the FEM PAK software, the bus chassis beam elements are classified into

22 groups. The bus chassis is made of four groups of box-profile elements (40 mm wide, each with different heights of 100, 120, and 135 mm) [54,55].



(**a**) (**b**)

Figure 8. (**a**) Supporting roof structure for carrier of CNG cylinders on reconstructed city bus, MAZ-BIK 203CNG-S. (**b**) Homologated carrier of CNG cylinders.

During calculation, the mass of the cylinders was used as the input (m = 733 kg or G = 720 daN). The calculated height of the center of gravity of the cylinder rack in relation to the bus roof is h = 200 mm.

To standardize the calculation, the values from Table 2 were also used to calculate the input values of inertial forces in the longitudinal and transverse directions of the M3 class prototype bus (in this case, low-floor city bus):

$$F_a = 6.6 \cdot m \cdot g = 4750\ daN \text{ and } F_b = 5 \cdot m \cdot g = 3600\ daN. \tag{3}$$

The load model of the supporting roof structure of the bus for the first simulated case of acceleration in the longitudinal direction (received according to Equation (4)) is presented in Figure 9.

$$Z = (-F_a) = (-4750\ daN) \text{ and } Y = (-G) = (-720\ daN). \tag{4}$$

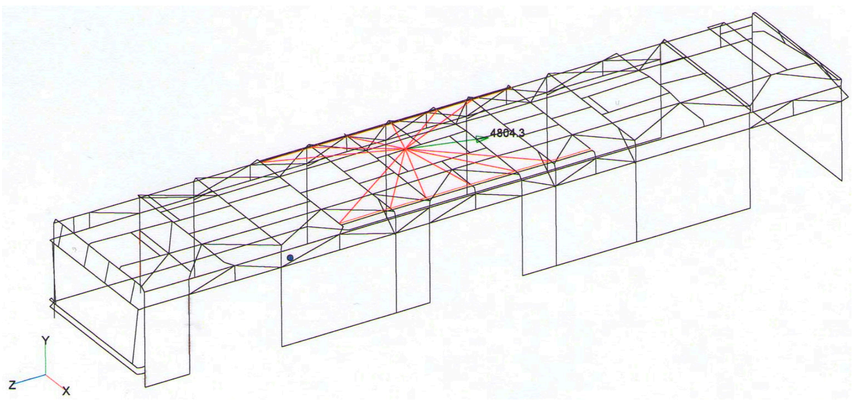


Figure 9. The load model for simulated acceleration in the first case.

The maximal dilatation of the construction obtained by calculation for this load case is Δu_{max} = 5.95 mm. The distribution of equivalent tensions for the first load case is shown in Figure 10. The maximal tension value (σ_{max} = 19.95 daN/mm^2) exists in the box-like profiles.

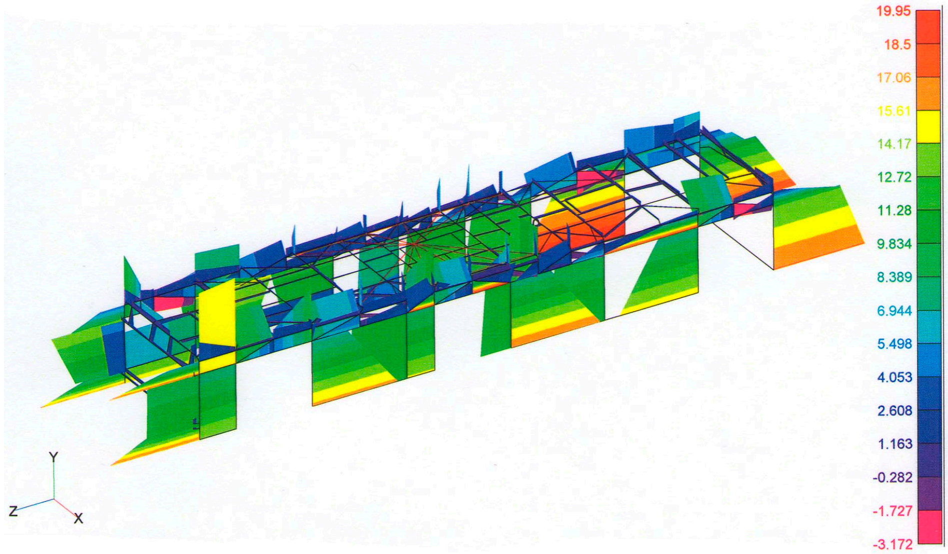


Figure 10. The distribution of equivalent tension within the model for the first acceleration case.

The loading model of the supporting structure of the bus for the second case of acceleration in the normal direction, with respect to the bus's driving direction (according to Equation (5)), is presented in Figure 11.

$$X = (-F_b) = (-3600\ daN) \text{ and } Y = (-G) = (-720\ daN). \quad (5)$$

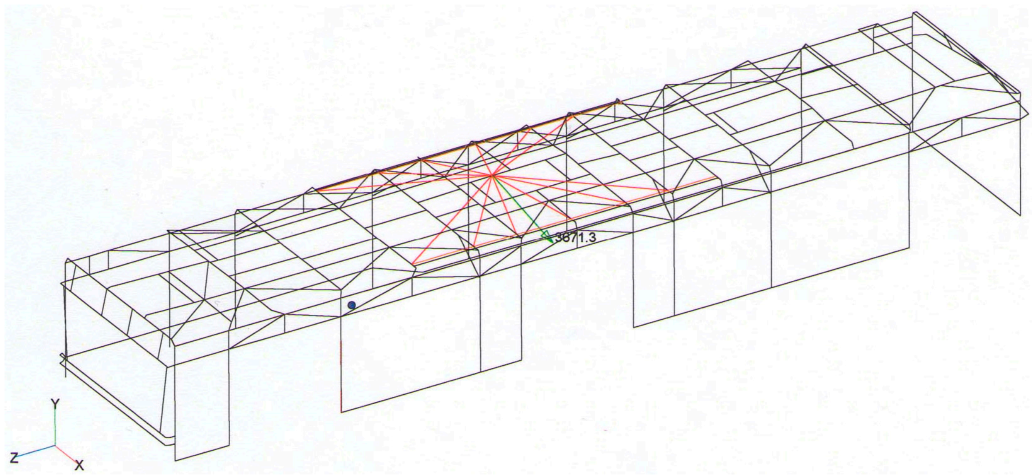


Figure 11. The load model for simulated acceleration in the second case.

In the second case, the maximal dilatation of the construction obtained by calculation is Δu_{max} = 24.19 mm. In this case, a higher value of construction dilatation was obtained.

The distribution of equivalent tensions in the second acceleration and load case is shown in Figure 12. The maximal tension value calculated for box-like chassis profiles with dimensions of 40 × 40 mm is σ_{max} = 26.99 daN/mm^2.

For the chassis construction, the values σ_{mbox} = 41.2 daN/mm^2 and σ_{mp} = 36 daN/mm^2 were adopted as the tensile strengths of the materials ("U" profiles for cylinders support connection with the bus roof construction).

The values for the factor of safety (FoS), expressed as the relationship between tensile strength and calculated tension, were calculated according to the FEM PAK model results, representing the characteristic parts of the bus body chassis (Figure 8):

- FoS = 3.60—for U profiles;

- FoS = 1.68—in the bolts (M12) for the connection of CNG cylinders with U profiles regarding pressure and elongation;
- FoS = 1.53—for the completed supporting roof structure.

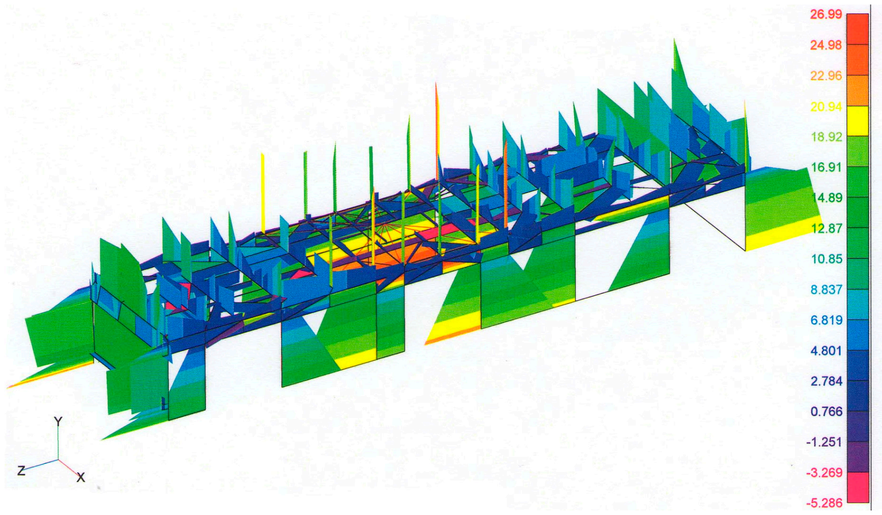


Figure 12. The distribution of equivalent tension within the model for the second acceleration case.

According to data from the literature, the static strength of the bus body structure is accepted to have the minimal value (FoS = 1.5) [56,57].

Based on the obtained FEM PAK calculation results, it can be concluded that the proposed method for the assembly of CNG cylinders with the main bus structure with U profiles meets the conditions prescribed by the relevant standards (UN ECE 110R and UN ECE 115R).

Periodical technical inspection and maintenance of vehicles operating with biomethane:

In terms of safety and proper functionality, periodical technical inspections of NGVs are very important. In the event of regular, daily maintenance, primarily of buses, problems can be noticed over time, and thus, with preventive maintenance, eventual hazardous situations can be prevented.

Motor vehicles powered by biomethane must meet the conditions prescribed by UN regulations (UN ECE 67R, 110R, 115R, or 143R). This specifically applies to the prescribed intervals of periodical technical controls (see Table 3) [19,20].

Table 3. Prescribed intervals for periodical technical control of vehicles using natural gas fuel systems.

Categories of Motor Vehicles Using Natural Gas	Intervals of Regular Inspections (Maximum)
Passenger cars falling into the M1 category (not including taxi vehicles and ambulances) Heavy-duty vehicles: N1 category	Every two years (four years after the date of first registration)
Buses in the M2 and M3 categories Taxi vehicles and ambulances Heavy-duty vehicles: N2 and N3 categories	Every year (one year after the date of first registration)

In addition, each country has its own internal regulations, which are mostly in line with the relevant international regulations [9,58].

During these periodical inspections, appropriate certificates are issued, i.e., certificates on the prescribed forms.

During periodical inspections, it is also very important to determine the conditions of the gas cylinders and completely check the functionality of the natural gas fuel system.

Inspections carried out at certain intervals can be visual, but a hydraulic cylinder test is obligatory [58,59].

Inspection of the cylinders, and issuing a certificate for the vehicle, can only be performed by certified control bodies.

The terms of periodical inspections must be fully respected. In the case of serious damage, the biomethane cylinders must be taken out of the vehicle. The use of biomethane cylinders with traces of corrosion, without mechanical protection, or with traces of impact or metal-on-metal friction is not allowed.

It is also necessary to keep up-to-date records of all the controls, periodical inspections, and maintenance of the biomethane cylinders and fuel system in general.

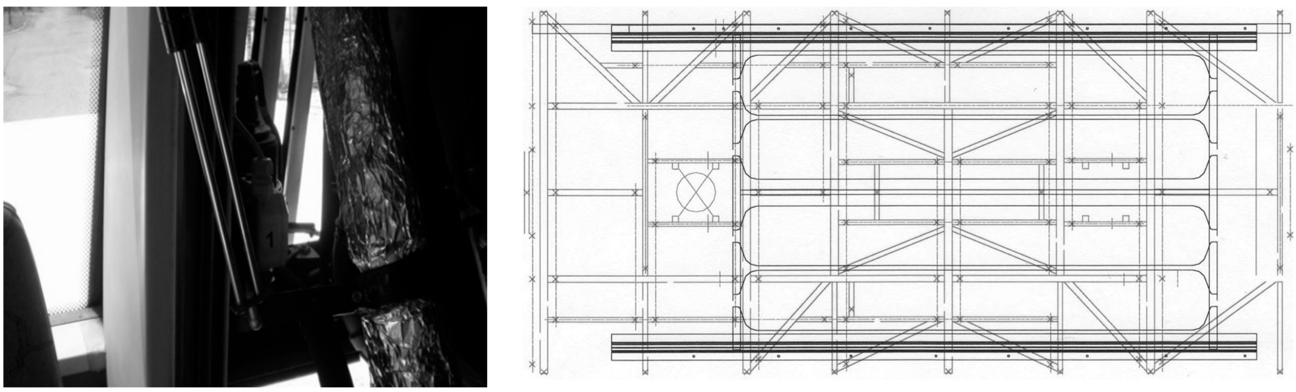
As already emphasized, appropriate maintenance of not only the biomethane fuel system, but also of other systems in motor vehicles, is very important to prevent hazardous situations.

From that aspect, for example, during its reconstruction, the prototype CNG bus MAZ-BIK 203CNG-S was equipped with a system for automatic gas leak detection and fire extinguishing [9,60].

Sensors for detecting biomethane leaks, as well as nozzles of the automatic fire extinguishing system on the bus, are located in three risky places according to the assessment:

- Position 1—within the closed engine compartment (Figure 13a);
- Position 2—near the zone of automatic valves, under the protective cover (Figure 13b);
- Position 3—in the passenger compartment in the roof zone near the middle door.

Figure 13a shows a part of the engine compartment (rear left side) of the bus with the position of the gas leak sensor marked with the number 1, whilst Figure 13b depicts a part of the bus roof with CNG cylinders where, in the automatic valve area near the roof vent, a gas leak detector marked with the number 2 is installed.



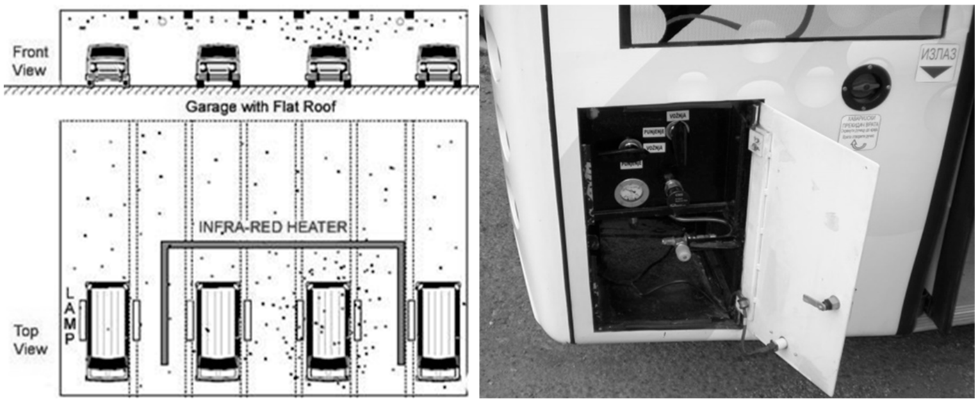
(**a**) (**b**)

Figure 13. (**a**) Position 1 of the biomethane leakage system sensor in the zone of the engine compartment. (**b**) Position 2 of the natural gas leakage system sensor in the zone of the automatic cylinder valves.

Safety and fire protection propositions must be observed at pumping stations when filling the NGV cylinders with biomethane, too [61,62].

The same applies to service stations and closed parking lots; the aim is to equip them with biomethane leak detection sensors, automatic garage doors, and a fire extinguishing system as well. Methane is lighter than air, so in the event of a leak, attention should be paid to the roof areas. In addition, during vehicle maintenance, the use of sparking tools, open flames, etc., is prohibited [63].

In any case, it is necessary to prevent the formation of plugs or pockets with flammable concentrations of biomethane. A model of natural gas concentration in the case of leaks in garages with a flat roof is shown in Figure 14a.



(**a**) (**b**)

Figure 14. (**a**) A model of the release and concentration of biomethane particles in a garage with a flat roof. (**b**) A service panel with connectors for biomethane filling.

Figure 14b shows the control panel for refueling, with connections for dispensers of NGV1 (filling receptacle for passenger cars) and NGV2 (standardized filling receptacle for truck and buses) types. The service connector valve serves to empty the installation and the cylinders. When servicing or maintaining the fuel system equipment, the fuel cylinders and completed system must be drained [64].

The fuel system is also equipped with biomethane purification filters and a pressure absorber with a spring to compensate for the shock loads when filling the NGV.

Manual valves are installed in the fuel system (Figure 14b), which allow for the flow of biomethane to the IC engine to be stopped in the event of an emergency. Additionally, vehicles must be equipped with a main switch near the driver, which stops the flow of fuel when the vehicle is not in use or in an emergency [65].

There are also manual valves on the cylinders integrated with automatic valves (Figure 4), but the automatic valves are also set so that in cases of excessive flow of CNG (when the installation is leaking due to damage, etc.), they automatically stop the flow. This is very important from the perspective of fire protection [66].

Automatic valves need to regulate pressure relief in cases of traffic impact and mechanical damage. In addition, the valves are equipped with temperature-activated devices (by means of a piezo crystal). An increased temperature in emergency situations is additionally detected in the middle and at the opposite end, at the bottom of the cylinder. Therefore, if the bottom and middle of the cylinder overheat (which are far from the automatic valve), timely activation of the valve and the release of gas are possible. In this way, the cylinders are additionally protected from explosion [67].

Defects on biomethane vehicles can be dangerous and require immediate action. In this case, it is necessary to contact a biomethane service center to determine the cause of the problem and eliminate defects for safe driving. Service facilities for NGVs provide proper maintenance and repair. These service centers have professional staff trained to work on NGVs and the equipment and tools to service these vehicles [68].

When it comes to the maintenance of NGVs, various problems can occur, which can be classified according to the type of problem. The following are some examples of the classification of defects in the maintenance of NGVs [69,70]:

- Problems with the biomethane injection system: This can include gas leaks, blocked injectors, or any problems with the gas injection system itself.
- Problems with the gas cylinders: This is where gas leaks, damage to the cylinder, or any other problems related to the gas cylinder itself can occur.
- Problems with the pressure regulator: The pressure regulator is a key part of the biomethane fuel system, and problems with it can cause the entire system to malfunction.
- Problems with electrical installation: Sometimes, problems can be electrical in nature, such as problems with sensors, connections, or electrical installations related to the biomethane fuel system.

These are just some of the possible defects that can occur during the exploitation of NGVs, and each of them requires special attention during maintenance modeling and expertise when solving the problems [71,72].

Dangerous defects of NGVs include the following malfunctions:

- Damage to the protective ventilation cover, which also includes damage to and clogging of the ventilation pipes;
- Damage and clogging of the ventilation pipe of the automatic valve on the cylinder neck;
- Inadequate fastening and protection of pipes, cylinders, and other parts in the fuel supply system;
- Leaking gas.

A gas leak in the engine, passenger, or luggage compartment of an NGV can cause very serious damage. This is a potentially dangerous situation due to the possibility of an explosion or fire. In this case, it is important to get out of the vehicle immediately and call competent services for help to resolve the situation in a safe way [73].

It is important to react immediately to a malfunctioning gas level indicator to avoid a potentially dangerous situation. It is very important to have accurate information about the fuel level in the cylinder.

Additional contributions can be made by modeling and performing numerical simulations of the fire spreading processes in NGVs by using PyroSim 2024.2 or other software [74–76].

Currently, in some countries, there are restrictions for NGVs when transported by ferries, which refer to the maximum allowed amount of gas in the cylinders. For example, in Greece, there are travel restrictions on NGVs, so they can be transported by ferries only if the cylinders for this fuel are filled to a maximum of 50% [77].

Additional optimizations and savings can be further achieved through a more proper vehicle drivetrain management system, for example, by using adequate materials. This primarily concerns the ergonomics of the driver's workplace by using adequate panels to protect against external noise, which can also be applied in the passenger compartment or in the engine compartment, provided that the panels are fire-resistant [76,78].

5. Discussion

The issues of replacement of the fleet of city buses are related to legal regulations, production capabilities, fuel availability, the modernization of current structures, environmental benefits, and conformity of users. For the safety of passengers and traffic in general, it is very important to use newer vehicles, which are also regulated by certain regulations. The ages of the buses and the financial costs incurred should also be considered [77,78].

The regulations contained in the documents, both at the European level (CVD Directive 2019/1161) and at the national level (in the case of Poland, e.g., the law on electromobility and alternative fuels), contain detailed requirements for the market of city buses [78,79].

This directive obliges EU member states to contract for buses in public tenders from 29 to 50% (2025) and from 43 to 75% (2030) (Table 4).

Table 4. Different requirements for the purchase of “clean” buses for selected EU countries [79].

EU Member State	Buses (Category M3)	
	From 2 August 2021 to 31 December 2025 (%)	**From 1 January 2026 to 31 December 2030 (%)**
Luxembourg	45	65
Sweden	45	65
Denmark	45	65
Finland	41	59
Germany	45	65
France	43	61
Spain	45	65
Greece	33	47
Czech Republic	41	60
Lithuania	42	60
Hungary	37	53
Latvia	35	50
Romania	24	33

As far as Poland is concerned, the target is to make 32% of buses “clean” by 2025 (50% zero-emission buses) and 46% by 2030 (50% zero-emissions buses). A similar situation applies to other countries. The term “clean” refers to buses powered by electricity or hydrogen or low-emission vehicles, i.e., vehicles powered by natural gas, including biomethane (see Table 4 and Figure 15).

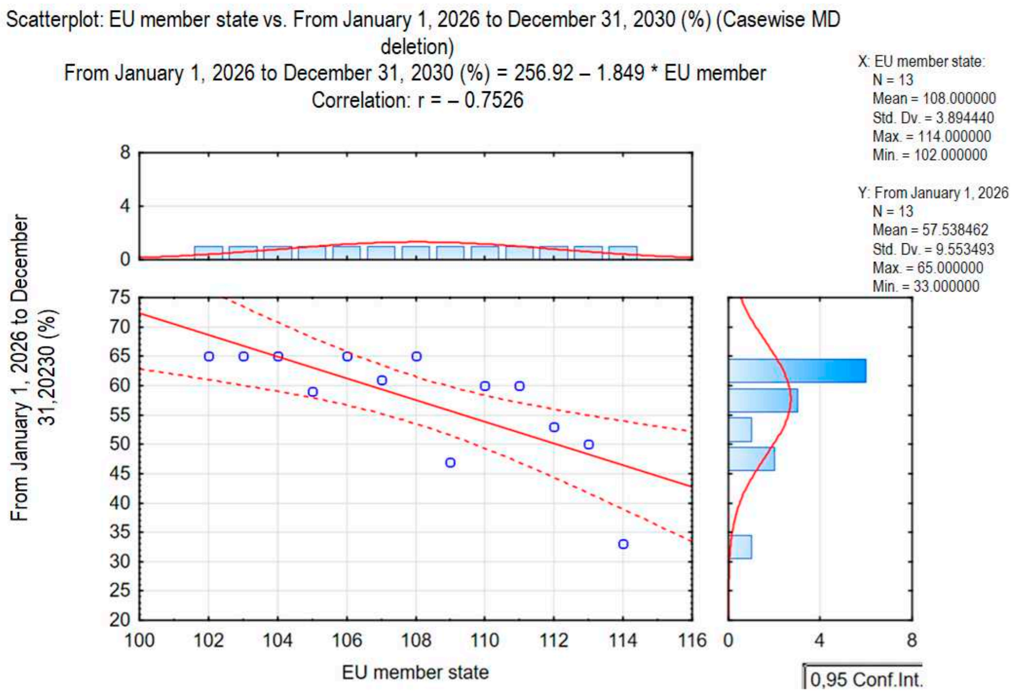


Figure 15. Statistical analysis of requirements for the purchase of “clean” buses for selected EU countries [79].

According to the ACEA, there were 692,207 buses across the European Union in 2019, almost half of which were in three countries: Poland (122,604), Italy (100,149), and France

(94,371) [78]. Buses with diesel engines accounted for 94.5% of the vehicle fleet in the EU. Other alternative vehicles are gas (2.7%), hybrids (0.7%), and battery vehicles (0.6%).

In 2020, 26,811 new buses were registered in Europe. Of these, 2922 vehicles (11%) were gas-powered. A total of 12,068 gas buses were registered over the past 10 years (Figure 16).

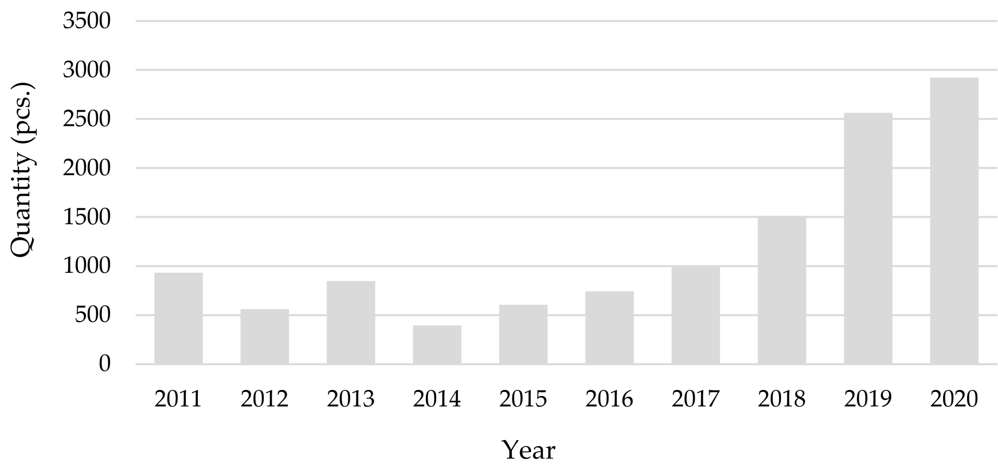


Figure 16. Sales of gas buses in Europe [80].

An advantage of biomethane buses is that they have a slightly higher price compared to diesel buses (about 10%) (Figure 17). Other advantages of gas buses are represented by their range, which is comparable to diesel buses. The average distance traveled by a city bus in Europe is 150–400 km.

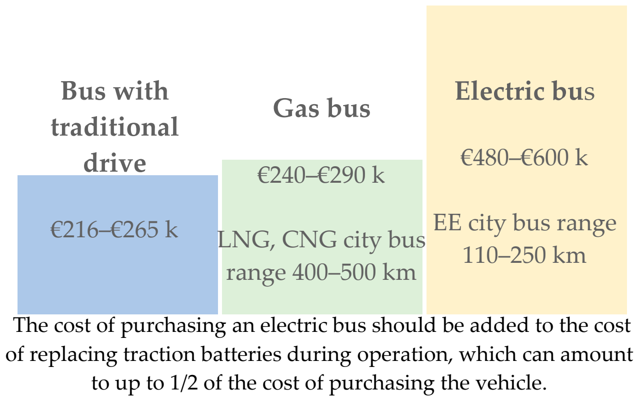


Figure 17. Cost of buying a Maxi class city bus (12M) [81].

The concept of a "fleet mix" has become important in transport. The high cost of purchasing electric and hydrogen buses cannot lead to financial problems for public transport operators. Apart from environmental considerations, the cost calculation and the question of financing the purchase of a bus are decisive. See below for an example from Poland (Table 5).

The total pollution emitted by a CNG bus is almost three times less than the emissions released into the atmosphere by a comparable class of CNG-powered buses. Nitrogen oxides, CO, PM, and sulfur compounds can be reduced by 85%. In addition, the components of biomethane are non-toxic. CNG burns smokeless and does not emit soot particles. In summary, CNG buses emit up to 50% less nitrogen oxides, up to 20% less carbon dioxide, and up to 99% less PM10 dust than diesel-powered buses. Additionally, CNG buses generate noise ranging from 3 to 7 dB [82].

Table 5. Comparison of bus operations in Poland.

Type	Price (EUR)	Level of Participation in Purchase Costs (%)		Fuel Price (EUR/100 km)	Potential Course During Operation (km)
		State	Municipality		
Diesel solo bus	240,530	0	100	245.3	800,000
Gas solo bus	264,580	0	100	251.7	800,000
EV solo bus	505,110	80	20	122.9	600,000
H2 solo bus	721,640	90	10	423.0	800,000

Assumption: Fuel consumption (per 100 km): diesel, 36 dm^3; CNG, 48 m^3; LNG, 36 kg; EV, 150 kWh; H2, 7 kg, Fuel price: diesel, 1.51 EUR/dm^3; CNG, 1.74 EUR/m^3; LNG, 1.04 EUR/kg; EV, 0.14 EUR/kWh; H2, 26 EUR/kg.

All aspects covered in this study show the multiplicity and diversity of issues that will be observed in the urban automotive sector in the coming years. These changes will be dictated not only by legal regulations and environmental protection issues, but also by production, technical, and technological capabilities [83].

6. Conclusions

Some of the basic advantages of using biomethane as a fuel are presented in this paper. Special attention and contributions are being given to the analysis regarding the safe use of these vehicles in traffic. It is emphasized that biomethane (CNG) has potential to be used in city traffic vehicles (buses, garbage trucks, etc.).

Some recommendations for regular preventive inspections of NGVs are systematized, as well as the main conditions for their safe use.

A brief review of the literature is given with the aim of pointing out the basic technologies and conditions for the application of biomethane in motor vehicles.

Whether it is road or river traffic, the number of kilometers traveled is increasing, and vehicles' traveling distances are also longer. In this respect, the application of biomethane stored on-board vehicles as LNG is gaining increasing importance for longer distances.

Biomethane (LNG and CNG) also has a number of commercial, environmental, and energy advantages over traditional fuels when used both as an engine fuel and as a fuel for power plants. The emission of harmful exhaust gases from vehicles powered by biomethane is about 30% lower than that of vehicles with gasoline and diesel engines.

The concepts of an NGV with a drive system in which biomethane is stored on-board as LNG and CNG are compared. Some experiences from the production and exploitation of the first low-floor city bus powered by biomethane (MAZ-BIK 203CNG-S), which was produced in Kragujevac in the Republic of Serbia, are presented as well.

For a practical example of the city bus MAZ-BIK 203CNG-S, we proposed a method to equip it with cylinders for CNG type III; we also proposed safe systems for the automatic detection of gas leaks and distinguishing fires.

The European standard EN16258 is proposed for the calculation of CO_2 emissions and energy consumption; it is important to check crucial environmental benefits if using alternative fuels.

The method of installing CNG cylinders, with support on a city bus roof, was investigated in accordance with demands inside UN regulations ECE 110R and ECE 115R. Within these standards, it is defined that the decision regarding the installation of CNG cylinders can be made through calculations instead of experimental investigations.

A solution for installing CNG cylinders with support on the bus roof, by means of steel U profiles, is proposed to enable easy disassembly for inspection and maintenance.

Based on the obtained FEM PAK calculation results, the factor of safety for the bus supporting structure is 1.53, which is greater than the minimum threshold value of 1.5. In this way, the verification of the CNG cylinder's installation with factory supports, by means of the U profile, was confirmed as appropriate.

Periodical technical inspections of motor vehicles powered by natural gas must meet the conditions prescribed by UN regulations (UN ECE 67R, 110R, 115R, or 143R).

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