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Article

Comparison of Carbon-Dioxide Emissions of Diesel and LNG Heavy-Duty Trucks in Test Track Environment

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Abstract: Environmental protection and greenhouse gas (GHG) emissions are getting increasingly high priority in the area of mobility. Several regulations, goals and projects have been published in recent years that clearly encourage the reduction of carbon dioxide (CO_2) emission, the adoption of green alternatives and the use of renewable energy sources. The study compares CO_2 emissions between conventional diesel and liquefied natural gas (LNG) heavy-duty vehicles (HDVs), and furthermore investigates the main influencing factors of GHG emissions. This study was carried out in a test–track environment, which supported the perfect reproducibility of the tests with minimum external influencing factors, allowing different types of measurements. At the results level, our primary objective was to collect and evaluate consumption and emission values using statistical methods, in terms of correlations, relationships and impact assessment. In this research, we recorded CO_2 and pollutant emission values indirectly via the fleet management system (FMS) using controller area network (CAN) messages. Correlation, regression and statistical analyses were used to investigate the factors influencing fuel consumption and emissions. Our scientific work is a unique study in the field of HDVs, as the measurements were performed on the test track level, which provide accuracy for emission differences. The results of the project clearly show that gas technology can contribute to reducing GHG emissions of HDVs, and LNG provides a reliable alternative way forward for long-distance transportation, especially in areas of Europe where filling stations are already available.

Keywords: heavy-duty trucks; diesel vs. LNG powertrain; carbon dioxide (CO_2) emission; test track measurements

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1. Introduction

The IEA (International Energy Agency) reports that by 2022, over 60,000 medium- and heavy-duty vehicles (HDVs) were sold globally, representing 1–1.5% of total HDVs. The truck and bus sector are major contributors to greenhouse gas (GHG) emissions, responsible for 2000 Mt of carbon dioxide (CO_2) emissions annually for over a decade [1]. In February 2023, the European Union proposed ambitious CO_2 standards for most HDVs and buses to reduce GHG emissions, furthermore the IEA in the “Clean Energy Programme” has set a global target of Net Zero Emission (NZE) for the sector over the years. The report highlights the need for the launch of zero-emission vehicles, including electric and hydrogen fuel cell HDVs globally [2]. The IEA’s report on “Global HDV and Bus Energy Consumption” outlines that diesel technology still dominates the global market, despite emerging alternative fuel forms in the last decade. Biofuels, comprising less than 5% currently, are projected by the NZE to reach 10% by 2030 [3].

According to the report of European Environment Agency (EEA) in the “Greenhouse Gas Emissions from Transport in Europe”, the EU transportation sector demonstrates a six-year steady increase in GHG emissions from transport, which decreased in 2020 during the COVID-19 pandemic due to lower activity [4]. Current trends show that it will reach the previous higher levels in 2023/24, but the planned regulations will reduce these levels significantly by 2030. The European Commission, in the "European Green Deal" reports, reported that HDVs and buses are responsible for more than 6% of total European GHG emissions; furthermore, these segments are responsible for more than 25% of European road transportation GHG emissions, which is a major sector in the CO_2 viewpoint. Strict emission standards will ensure that this segment of road transportation also contributes to reaching zero-emission mobility and to the European Union's climate and decarbonization goals. The report also describes that, currently, the majority of the European Union's fleet (nearly 98%) is equipped with internal combustion engines (ICE), using primarily imported fossil fuels, which further increase the European Union's energy dependence at global level [5].

Agreeing to a study by Gunawan and Monaghan, in the GHG emissions reduction process, the HDV class is one of the most difficult segments to regulate within transport sector [6]. The HDV class charges for around 4% of GHG emissions globally, and based on the current HDV fleet growth rates, this could double in 20–25 years; for this reason, many countries started to tighten emissions regulations to reduce GHG values. The European Parliament and the Council in 2019 laid down new rules in the 2019/1242 regulation for HDVs in the European Union such as, for example, that manufacturers need to reduce their CO_2 emissions by 15% by the end of next year compared to their 2019 levels. If this is not achieved, an adjustment will be set for the regulation to encourage the replacement of diesel vehicles with lower emission vehicles, and several benefits will be offered to use alternative vehicles in the transportation segment in the European Union [7].

In order to reach the goals and indicators set by the European Parliament and Council, the usage of alternative powertrains and e-fuels with cleaner emission values compared to the diesel technology is needed [8]. Hydrogen can significantly reduce GHG emissions, but its usage in electric or ICE technology has higher production costs, while fuel energy density is low and large investments are needed to achieve sufficient energy efficiency [9]. Furthermore, it is necessary to deal with the hazards of hydrogen gas for safe operation. The research by Engerer and Horn analyse the use of electricity for transportation, pointing out that it is highly dependent on the energy source, the charging time, the relatively high battery costs, and the mass. Their research underlines that the electromobility has been continuously improved over the years, increasing the range and the energy density of today's batteries, but that technology is primarily used in short-range and urban environments for HDVs. The paper highlights the use of liquefied natural gas (LNG), with many environmental benefits, with potential to diversify diesel powertrain, resulting in the reduction of needed import oil, also contributing to energy security in Europe. In terms of liquefied natural gas, it seems to be a relatively cheaper fuel, and even with a huge jump in gas prices, it has been able to stay below the market price of diesel, improving the competitiveness of the powertrain in the HDV sector, as well as many other benefits [10]. Pfoser et al., in 2018, discussed the acceptance of LNG as an alternative propulsion, and found that a few alternative fuel technologies have emerged recently, with the limitation for most of them being the consumption and transportation constraints specific to HDVs [11]. This leads to a similar conclusion to the one that Engerer and Horn found earlier, concluding that all of that alternatives should be used in the appropriate segment, and that the LNG could be a potential solution for reducing CO_2 emission values for HDVs and long-distance transportation sector [10,11].

1.1. Liquefied Natural Gas as Alternative Fuel

Natural gas as an alternative fuel form has been an available technology for mobility for many years, and recently the use of compressed natural gas (CNG) opened the possibility to use it in transportation segment mainly for short distances with spark ignition operation. Isermann described in his book that gas engines have drastically lower particulate emissions and can operate with a suitable stoichiometric air-fuel ratio, compared to a diesel-powered engine, so they do not need complex and sophisticated methods [12]. Using the CNG technology in passenger transport and road freight has the potential to reduce

CO_2 emissions, but it has low energy content, so it is only available for a limited range and requires large fuel tanks [10]. The solution for these disadvantages could be the liquefying of the gas to reach higher energy density, which can be up to 2.4 times more efficient than CNG, as explained by Szilágyi in the 2013 VGF and HLP specialist journal [13]. CNG and LNG are lighter than petrol or diesel but have a lower energy content and therefore require a larger fuel tank for both. LNG density is around 430–480 kg/m^3 at 163 °C and atmospheric pressure, while CNG density is 215 kg/m^3 at 250 bar and room temperature. This demonstrates the benefits of LNG as an alternative propulsion technology to natural gas, as it is suitable for long-distance transport and freight [13].

The liquefaction process reduces the volume of natural gas by about 600 times, which makes it more economical to transport. It is a colourless, odourless, non-toxic and non-corrosive chemical that can contain up to more than 98% methane (CH_4), in addition to propane, butane, ethane and nitrogen, according to research of Smalja et al. from 2019 [14]. Methane oxidizes are very efficient, burning almost perfectly without ash, with low emissions of carbon monoxide (CO), mono-nitrogen oxide (NOx), and sulphur dioxide (SOx). In connection with this, Kumar et al., in their research in 2011, found that LNG-fuelled gas engines contain less concentrations that can cause respiratory illness due to their higher purity, around 80% less CO, 70% less NOx and 45% less non-methane volatile organic compounds (NMVOCs) [15]. Osorio-Tejada et al., in 2017, highlighted in their research that SOx and particulate-matter (PM) concentrate reductions of more than 97% are achieved with the LNG powertrain, so the gas technology can easily perform the EURO VI emission standard without aftertreatment, using a compact three-way catalyst, which does not require regeneration or chemical reagents [9]. Schwarzkopf's thesis from 2019 discusses the disadvantages of LNG application, which are mainly due to the density of the fuel. The diesel density is about 840–850 kg/m^3, which is almost twice of LNG. This means that for the same range, the LNG tanks require almost twice as much space as diesel vehicles. Further differences can be observed between the two components as, in the case of calorific value, the diesel has 43 MJ/kg and the LNG has 50 MJ/kg [16].

In terms of emissions, Le Fevre reports in his research that LNG producers make a well-to-wheel (all life-cycle phases, all emissions related to fuel production, processing, distribution, and use) CO_2 emissions value difference of between 15–20% compared to diesel (Table 1). Although it is difficult to measure the environmental impact of different fuels directly, a number of studies have recently been carried out worldwide in this field [17]. In addition to diesel, LNG, and CNG, the use of biocomponents (such as biomethane or hydrogen additives) with compressed or liquefied natural gas, as well as biofuels and e-fuels can lead to further emission reductions. E-fuels and biofuels, in particular, can significantly reduce GHG emission levels [18].

Table 1. Emission values of well-to wheel analysis by fuel type [17].

Fuel Type	Diesel	CNG	LNG	80% CNG + 20% Biocomponent	80% LNG + 20% Biocomponent
CO_2 (g/km)	1074	908	912	738	749

Investing in new technology has always been a risky decision, which requires an economic analysis. The reluctance to invest in new technologies may stem from the concept of the hurdle rate, which represents the minimum rate of return required for an investment to be deemed feasible. The freight transport market exhibits high levels of competition and relatively narrow profit margins for heavy goods vehicle (HGV) operators. Coupled with fluctuating fuel prices, this scenario might indicate an elevated expected rate of return for investors, potentially resulting in a higher discount rate [19]. From an economic point of view, we need to compare the cost of purchasing and the cost of fuel. In this article, the LNG HDV is 1.36 times more expensive than the diesel HDV. At the end of 2023, the diesel fuel price approximately 1.46 EUR/L, and the LNG fuel price approximately

1.26 EUR/kg. The compared HDVs in tests showed that the LNG truck had an average consumption of 21.2 kg/100 km, while the diesel trucks had an average consumption of 24.6 L/100 km. The average long-range HDVs cover approximately 15,000–20,000 km in one month, which means the LNG HDV consumes around 3200–4200 kg of LNG, and the diesel HDV consumes around 3700–4800 litres of fuel. In this research, this represents around a 30–35% fuel cost difference in economic terms, which is excellent value from the point of view of the purchase cost.

The European HDV market relies on internal combustion engines for more than 95% of its fleet, with fuel being partly produced domestically and partly imported from various parts of the world. Ensuring a reliable fuel supply requires advanced technology, infrastructure, and logistics. Currently, Europe is not capable of providing enough liquefied natural gas (LNG) to replace the entire fleet, because of the missing infrastructure and technology—although, promising efforts have emerged in recent years [20]. As for fueling stations, Europe has reached around 700, with Germany having the most, followed by Italy, Spain, and France. In contrast, there are over 140,000 conventional fuel stations. This indicates that good logistical capabilities are necessary for the reliable use of LNG-powered trucks in long-haul transportation throughout Europe [21]. The demand for LNG has increased recently, but not primarily from the transportation sector. LNG and diesel fuel are produced from different sources—LNG from natural gas and diesel from crude oil. Significant LNG production takes place in about 20 countries, with the largest producers being Qatar, Australia, USA, and Russia, from where most of the fuel is imported to Europe. These countries can produce 400–500 million tons of LNG, while diesel production is nearly 20 times that amount [22].

1.2. Comparison of Preliminary Emission Values and Influencing Factors

There have been several recent publications and scientific papers published in the HDVs emission topic. Giechaskiel et al. point out in their research that the fuel consumption of different tractors cannot be directly compared but can be evaluated from an economic point of view. The price of fuel, sustainability or from a technical point of view, the energy content of the fuel used is comparable, furthermore the CO_2 emissions can be evaluated [23]. The use of a portable emissions measurement system (PEMS) can be an excellent solution to this issue, but in addition to this, there is scientific work using software-based emission measurements. The former is a costly measurement tool for the measurements of total hydrocarbon emissions (THC), CO_2, NOx, NO_2 and CO, as explained by Vermeulen et al. in their research, where they highlight driving style as a major factor influencing the variance of differences [24]. In their scientific work, the emissions of several different diesel-powered and two LNG-powered tractors were measured, with a focus on CO_2 emissions. The authors determined a difference of about 10% in the measurements, where LNG had a lower emission value on the motorway and in rural highway conditions. In urban area, the average difference was found to be only 5%, but there is discrepancy within each type, which may be due to non-standardised conditions, and the constantly changing environment may affect the outcome of the measurements; to overcome this, it is necessary to define a solution that solves these problems and ensures repeatability and reproducibility [24].

Greenhouse gas emissions were investigated by Quiros et al. in 2017, who found that, comparing diesel-to-diesel hybrid and natural gas HDVs, the latter one's alternative powertrains emitted approximately 10% less CO_2 than conventional diesel [25]. This fact was also pointed out by Giuliano et al. in 2021, who investigated the United States (US) HDV market and tested several types of HDVs with different powertrain technologies, such as diesel and natural gas hybrids [24,26]. Related to the US market, Cunanan et al.'s publication in 2021 described that medium and heavy-duty vehicles account for more than 20% of GHG emissions in the US, where more than 90% use conventional diesel technology, which is critical in terms of CO_2 emission [27]. Connected to the latest US GHG emission findings, Toumasatos et al.'s research in 2024 shows a significant CO_2

equivalent difference between a natural gas HDV and a conventional diesel HDV. In this article, the authors analysed four different route types, including highway, urban area, and simple transportation routes with elevation. The results showed an average CO_2 equivalent difference of more than 15% in favour of the natural gas HDVs [28]. This article partly builds on the results of a natural gas HDV study published by Zhu et al. in 2020, which was also conducted in California [29]. In the European market, a total of seven different tractor types were tested by Quiros et al. in 2017. The results show that natural gas HDVs had up to 3–15% lower CO_2 equivalent emissions on average over the measurements compared to conventional and hybrid diesel vehicles. In the motorway section, this figure produced a difference of more than 10%, which supports the results of Vermeulen et al. from 2017 [24,25]. Di Maio et al.'s research report shows encouraging differences in CO_2 emissions of 6–8% for urban areas and up to more than 10% for highway emissions [30]. These values show a consistent difference across research papers; however, Quiros et al. in 2017 also point out in their publication that these differences are highly route and driving style-dependent; therefore, in a climbing mode, this difference can be turned due to the sudden high energy demand for the LNG powertrain, because in this area the conventional technology can produce better values, but it is only a transient condition [25,30].

Within Europe, there are a number of other studies that specifically examine the difference in GHG emissions between LNG and diesel vehicles in the field of freight and long-distance transport, primarily in terms of CO_2 emissions. Arteconi et al., in 2010, analysed the life-cycle CO_2 emissions of these fuels in Europe; they used well-to-wheel analysis for the fuel type of EU-15. The results of the publication show that a 10% reduction in GHG emissions is possible by using LNG compared to diesel [31]. A further European comparison was reported by Gnap and Dočkalik in 2021, whose research results detail the measurement of CO_2 emissions in a similar way to Arteconi et al. in 2010, considering emissions from fuel production, processing, and transport. In their study, they measured a Slovakia–Germany route and a Slovakia–Hungary section, with continuous data recording. The results showed that diesel and LNG HDVs were involved on routes with different topography and environmental conditions, with an overall difference of 8%, also in favour of the LNG powertrain [31,32].

Looking outside Europe, the research of Ou and Zhang from 2013 provides further confirmation at the level of the carbon emission gap between technologies in HDVs. Their publication analysed the primary energy consumption and CO_2 emissions of natural gas-based alternative fuels in China. The results show that the use of CNG and LNG technology can reduce GHG emissions by 5–10% compared to conventional diesel technology, but stress that this figure is highly dependent on the efficiency of the liquefaction of natural gas and the process used [33].

Overall, several parts of the world, primarily Europe, show that alternative HDVs have positive emission performances, especially LNG technology, which is reported to reduce CO_2 emissions from HDVs by at least 5% and up to 10% in a few cases. However, one important point to note, which is also emphasised by Wang et al. in their study, is that speed and driving style play a fundamental role in the evaluation of vehicle emissions. Aggressive behaviour will produce higher values, which may even degrade the emission benefits to a certain level [34].

1.3. The Aim of the Research

The aim of the research is to determine the emission difference and investigate the effect of vehicle speed on the CO_2 emissions of the vehicle for diesel- and LNG-powered tractors, where the necessary data were measured directly from the vehicle network, and then calculate the emission from the logged data. It is assumed that the two types of propulsion have significantly different emission characteristics.

Our research hypotheses are as follows:

- Based on preliminary research and market feedback, we expect that the LNG tractors will have more favourable CO_2 emissions and thus that they are less sensitive to changes in speed;
- Under sudden high load conditions (such as hills and rising grounds), the diesel and LNG vehicle engine will behave inherently differently in terms of emissions compared to normal load conditions.

2. Materials and Methods

To prove the hypothesis of the research, a diesel tractor and a trailer, as well as an LNG tractor and a trailer combination, were used and tested for five days and 600 km. Both the vehicles were made by the same OEM (Original Equipment Manufacturer), and were equipped with engines of 13,000 cm^3, 12-speed automatic gearboxes and similar-sized tyres (Table 2). The trailers in the vehicle combination were box body semitrailers and the weight differences were compensated by adjusting the personnel distribution during the tests.

Table 2. Technical data of the diesel and LNG tractors.

Type	Diesel-Fuelled	LNG-Fuelled
Model	AS440S49T/P—AF4T	AS440S46T-P 2LNG—AG4T
Weight	8465 kg	8279 kg
Gearbox	ZF Traxon 12TX 2210 TD (Friedrichshafen, Germany)	ZF Traxon 12TX 2010 TO (Friedrichshafen, Germany)
Tyre	Pirelli FH01/TH01 Proway 315/70R22,5 (Settimo Torinese, Italy)	Michelin X Multi Energy Z/D 315/70R22,5 (Clermont-Ferrand, France)
Fuel capacity	1190 L	2 × 540 L
AdBlue tank	135 L	-
Rear axle ratio	2.47	3.36
Performance	357 kW/1900 rpm	338 kW/1900 rpm
Torque	2400 Nm/950 rpm	2000 Nm/1100 rpm
Cylinder capacity	12,882 cm^3	12,900 cm^3
Number and layout of cylinders	Six vertical in line	Six vertical in line
Bore	135 mm	135 mm
Stroke	150 mm	150 mm
Firing Order	1-4-2-6-3-5	1-4-2-6-3-5
Volumetric compression ratio	20.5 ± 0.5:1	12 ± 0.5:1
Injection type	Direct	Indirect

As of the test method, the same driving cycle was run for both vehicles in the ZalaZONE Proving Ground (www.zalazone.hu, accessed on 5 July 2024) on five different tracks (Figure 1), where the complete cycle consisted of 66 sub-sections.

The complete test cycle was diversified from an environmental point of view, with a primary focus on simulating motorway mode and rural road transportation, supplemented by hill, slopes and urban environment. The data required for the measurements is derived from data available via the controller area network (CAN) system of the vehicles, with real-time readout and post-processing. The fleet management system (FMS) gateway provided a connection point to extract CAN data with a bus speed of 250 kbit/sec, which is a standard access point and bus speed. The decoding of the data is derived from the FMS standardised uniform system, with filtering the consumption specifically and influencing values. The data previously were read and processed by a CAN-based telemetry system (Figure 2) for test purposes, which included the following elements: a Kvaser Memorator R SemiPro CAN USB (Universal Serial Bus) interface (Mölndal, Sweden), a Terminating Resistor 120 Ω (Palmdale, CA, USA), a CL-CAN contactless CAN-data sensor (Budapest, Hungary) and a 12 V power supply.

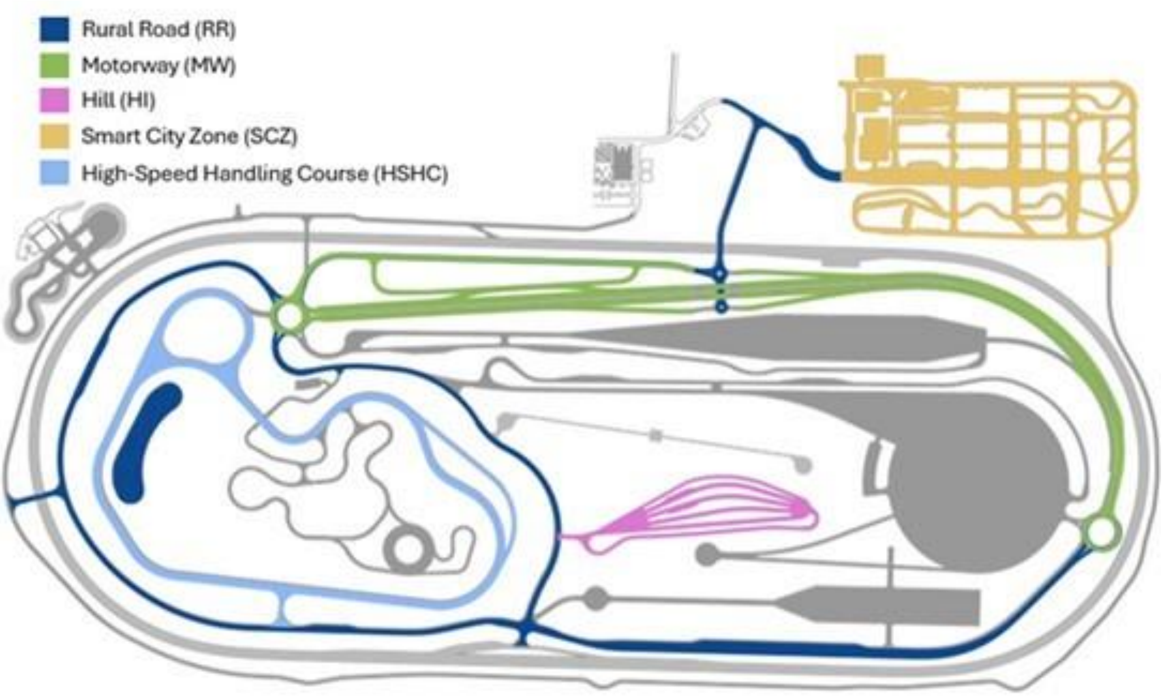


Figure 1. Track elements used to implement driving cycles in the ZalaZONE Proving Ground.

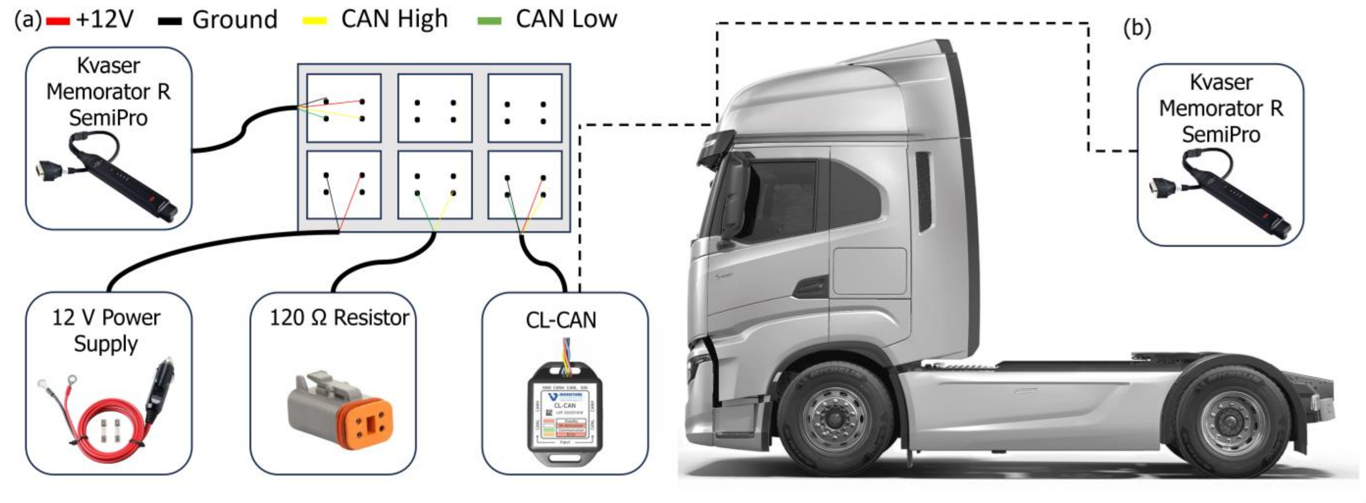


Figure 2. Application of telemetry system to read CAN messages: (**a**) test process; (**b**) measurement process.

In the live measurements, the number of the devices was reduced. The only used device we needed was the Kvaser Memorator R-SemiPro CAN bus interface, which had CAN-Low, CAN-High, a +12 V power supply and protective grounding integrated into D-SUB 9-pin connector. Therefore, only one USB connection was needed for the measurements.

During the driving cycles, the speed of each vehicle was measured at a resolution of 100 Hz, from which an average speed value was calculated for each test sub-section. At each sub-section, the amount of consumed fuel was also measured, from which the CO_2 emissions were calculated using the following derivation for LNG (Equation (1)) and for diesel (Equation (2)), was described in Dezsényi, Emőd and Finichiu's specialized literature [35].

In the case of LNG fuel:

$$CH_4 + 2O_2 = CO_2 + 2H_2O \tag{1}$$

In Equation (1), methane (CH_4) is the main component (CH_4 = 16.04 g/mol, CO_2 = 44.01 g/mol, where 16 g CH_4 becomes 44 g CO_2 emission); it follows that the combustion of 1 kg CH_4 becomes 2.75 kg of CO_2 emission.

In the case of diesel fuel:

$$C_{16}H_{34} + 49/2O_2 = 16CO_2 + 17H_2O \tag{2}$$

In Equation (2), diesel ($C_{16}H_{34}$) is the main component ($C_{16}H_{34}$ = 226,445 g/mol, $16CO_2$ = 704.16 g/mol, where 226,445 g $C_{16}H_{34}$ becomes 704.16 g CO_2 emission); it follows that from the combustion of 1 kg, $C_{16}H_{34}$ becomes 3.11 kg of CO_2 emission. Based on the Equation (2), 1 L of diesel produces 2.61 kg of CO_2, at density of 840 kg/m^3 of diesel.

The correlation between the measured data (average speed) and emissions (CO_2 value calculated from the average amount of fuel consumed) was investigated and evaluated using correlation analysis, and conclusions on hypotheses were drawn on this basis. The statistical processing of the data was carried out using the R Studio (version 3.6.0+) statistical software.

3. Results

The results are shown in Figure 3, in the form of a scatter plot, including all the data plots. As shown in (Figure 3), two subgroups of data can be clearly separated in the range of results for both vehicles. One of the separated data groups illustrates the tests performed under high load (on the upslopes track module), while the other points illustrate the data recorded in normal operation at urban, highway and motorway track modules. Therefore, in order to evaluate the results, the whole data set is separated, segmented into two types of data and analysed separately. Therefore, these Figure 3 charts are separated into the usual run measurements (see Cluster (a1) and Cluster (a2) data points) and special high load measurements (see Cluster (b1) and Cluster (b2) data points).

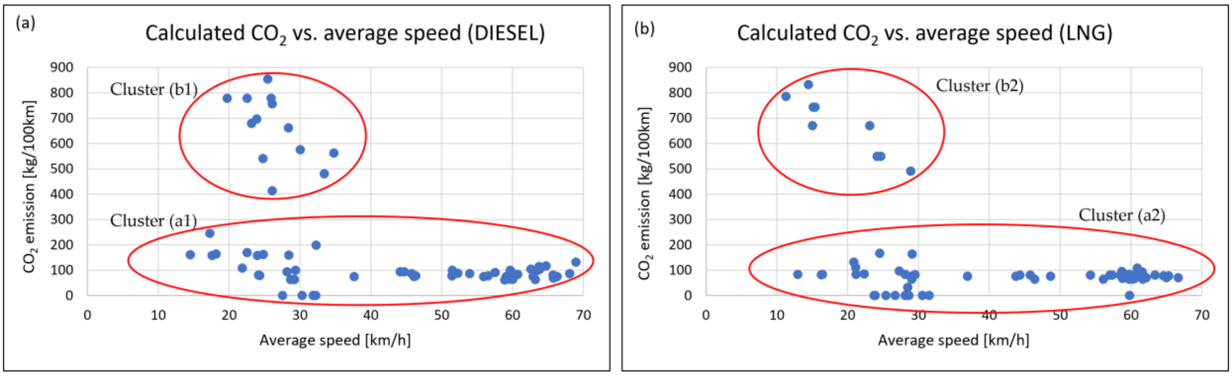


Figure 3. Measurement results for CO_2 emissions (**a**) in case of diesel tractor; (**b**) in case of LNG tractor.

3.1. Data Analysis: Normal Traffic Mode

The segmented data set used for the analysis was created by filtering the most common operating conditions (motorway and highway environment) and after removing the non-complete data records. Firstly, we examined the shape of the distribution of the dependent variables, rather the emission data (Figure 4). As it is shown in Figure 4, it does not completely follow the character of the normal distribution, but it is slightly shifted to the left at both vehicle types.

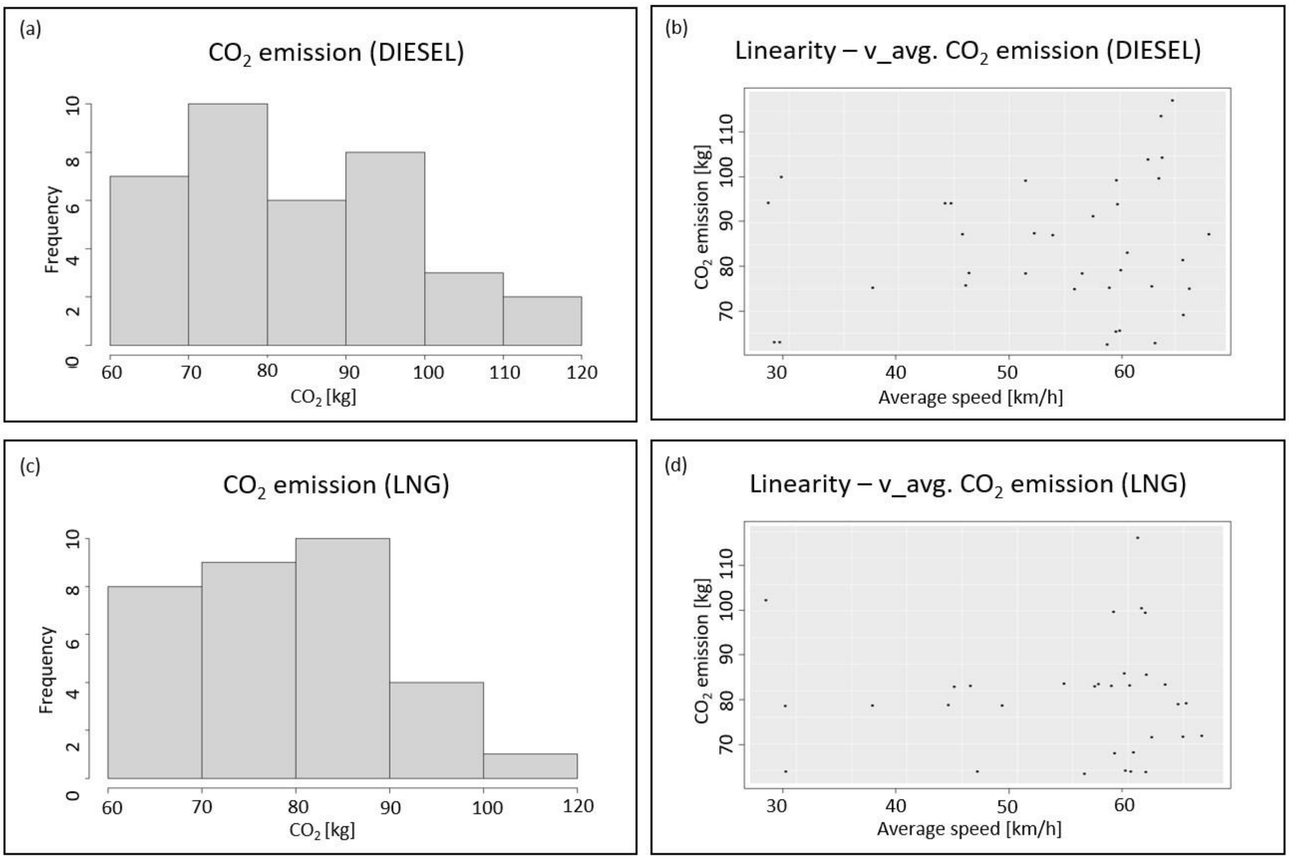


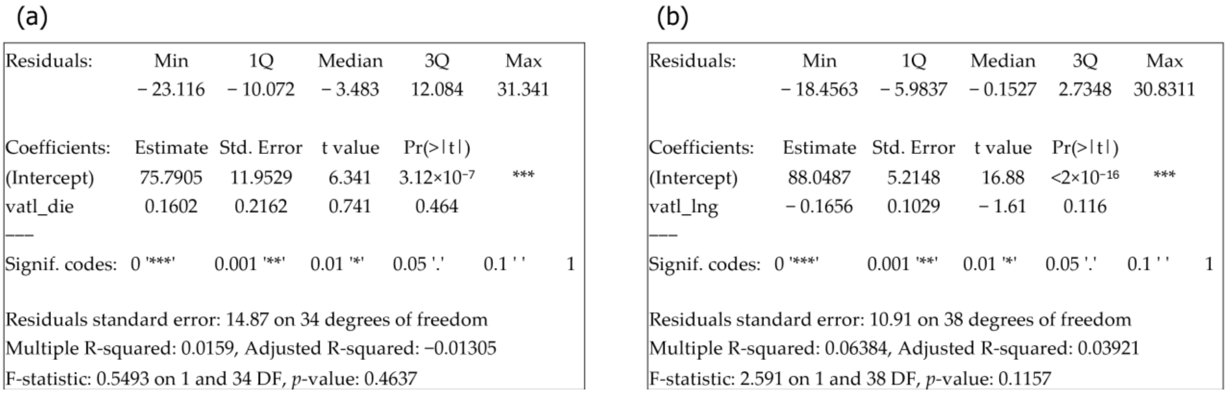
Figure 4. Distribution of data—normal traffic mode. (**a**) CO_2 emission frequency of diesel tractor; (**b**) CO_2 emission and average velocity figure for diesel tractor; (**c**) CO_2 emission frequency of LNG tractor; (**d**) CO_2 emission and average velocity figure for LNG tractor.

A descriptive statistical characterization of the data is shown in Table 3. Since we have only one independent variable and one dependent variable, we did not make tests for hidden relationships between variables. As can be seen at comparable mean values of velocity, the mean CO_2 values are remarkably lower for the LNG vehicle. The same is shown by the median values. Additionally, the range of CO_2 emission values is also narrower for the LNG.

Table 3. Descriptive statistical characterization of measurement results—normal traffic mode.

Statistical Indicator	Avg. Velocity DIESEL [km/h]	CO_2 DIESEL [kg]	Avg. Velocity LNG [km/h]	CO_2 LNG [kg]
Min.	28.17	62.52	27.29	64.40
1st Quarter	46.28	75.21	48.04	70.55
Median	58.98	82.36	59.24	77.57
Mean	54.10	84.46	54.56	78.40
3rd Quarter	63.00	94.37	61.37	81.27
Max.	68.06	117.50	66.65	108.80

The detailed statistical test results show (Figure 5) that the correlation between average speed and emissions is relatively loose, but still stronger at the LNG tractor.


(a)

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Residuals:        Min        1Q      Median      3Q       Max
               − 23.116   − 10.072   − 3.483   12.084   31.341

Coefficients:  Estimate  Std. Error  t value  Pr(>|t|)
(Intercept)     75.7905    11.9529    6.341   3.12×10^-7   ***
vatl_die         0.1602     0.2162    0.741    0.464
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Signif. codes:  0 '***'   0.001 '**'   0.01 '*'   0.05 '.'   0.1 ' '   1

Residuals standard error: 14.87 on 34 degrees of freedom
Multiple R-squared: 0.0159, Adjusted R-squared: −0.01305
F-statistic: 0.5493 on 1 and 34 DF, p-value: 0.4637
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(b)

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Residuals:        Min         1Q       Median      3Q       Max
               − 18.4563   − 5.9837   − 0.1527   2.7348   30.8311

Coefficients:  Estimate   Std. Error  t value  Pr(>|t|)
(Intercept)     88.0487     5.2148    16.88   <2×10^-16   ***
vatl_lng       − 0.1656     0.1029   − 1.61    0.116
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Signif. codes:  0 '***'   0.001 '**'   0.01 '*'   0.05 '.'   0.1 ' '   1

Residuals standard error: 10.91 on 38 degrees of freedom
Multiple R-squared: 0.06384, Adjusted R-squared: 0.03921
F-statistic: 2.591 on 1 and 38 DF, p-value: 0.1157
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Figure 5. Results of the detailed statistical analysis in R Studio software (**a**) in case of diesel tractor; (**b**) in case of LNG tractor.

A detailed regression analysis was conducted on the database and the results are shown in Figure 6 for diesel and in Figure 7 for LNG. The results of the regression analysis show different preferences for the statistical analysis, such as non-linearity, the distribution of the random variable and heled identify influential cases, if there is any in the data analysis. Q-Q plots are in line with well-interpretable distributions as shown in Figure 4, allowing the use of regression analysis.

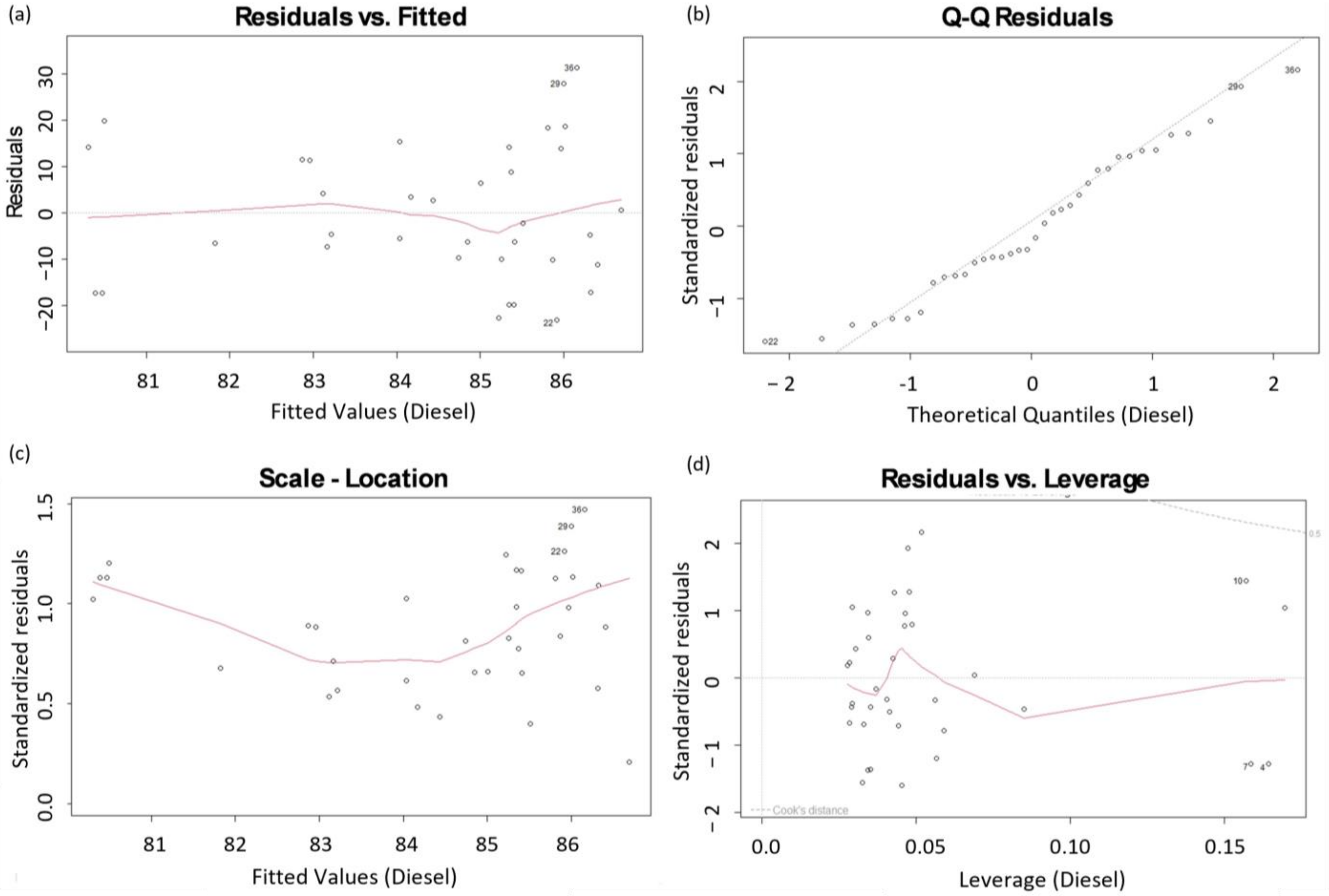


Figure 6. Results of regression analysis for diesel tractor (**a**) non-linearity unequal error variances detection; (**b**) helps to find the type of distribution for random variable; (**c**) shows if residuals are spread equally along the ranges of predictions; (**d**) helps to find influential cases if there are any.

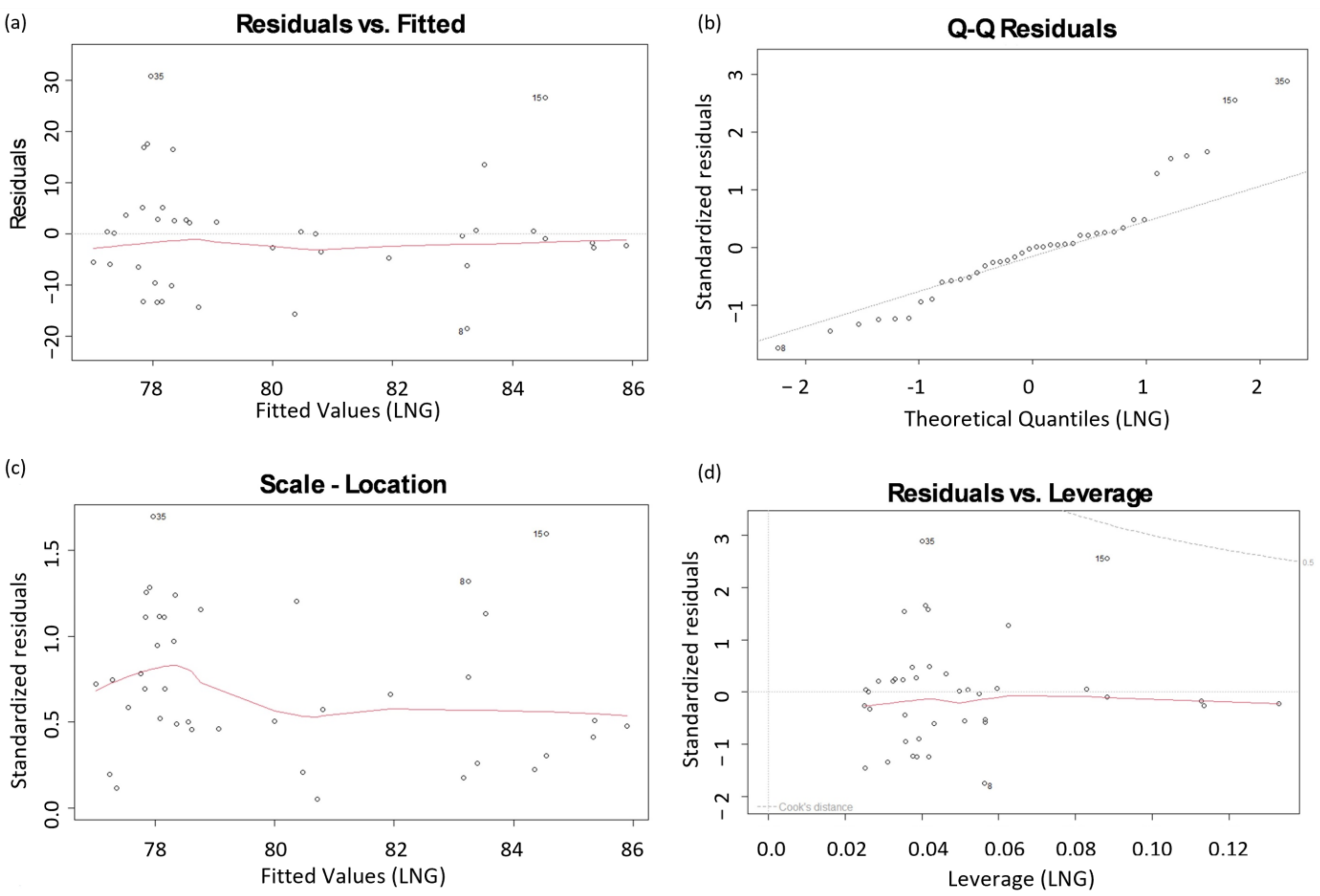


Figure 7. Results of regression analysis for LNG tractor (**a**) non-linearity unequal error variances detection; (**b**) helps to find the type of distribution for random variable; (**c**) shows if residuals are spread equally along the ranges of predictions; (**d**) help to find influential cases if there are any.

The final results of the statistical analysis shown in Figure 8. The figure represents the regression analysis outcomes, showing the reported emissions as a function of the average velocity values. A deviation in the gradients of the regression lines is apparent. The higher gradient for the diesel vehicle indicates the higher sensitivity of emissions to changes in average speed. From this perspective, the LNG-driven vehicle shows a more robust behaviour. This conclusion goes beyond the usual expected outcomes that higher speed results in higher emission. Although the change is not radical, it is still apparent.

3.2. Data Analysis: High Load Traffic Mode

The segmented data set used for the analysis is shown in Figure 9, based on the cleaned database and after the removal of non-complete data records. As it can be seen, in both cases, two data subgroups are visible, separated for lower and higher loadings. At lower loadings, we moved at a constant speed up hills with different gradients, such as 5%, 12%, and 18% (see Cluster (a1) and Cluster (a2) data points). During higher loading tests, we moved up hills at 100% accelerator pedal position (full throttle), using the same gradients (see Cluster (b1) and Cluster (b2) data points. All test cases were recorded on the Slopes (Hill) track element of the ZalaZONE automotive test track.

The amount of data available did not allow for a detailed statistical evaluation and regression analysis. Therefore, potential correlation can be searched for at the upper data set (Cluster (b) data points) of the two graphs (Figure 10) in further research, but further measurement data will be needed by future studies for a more accurate assessment.

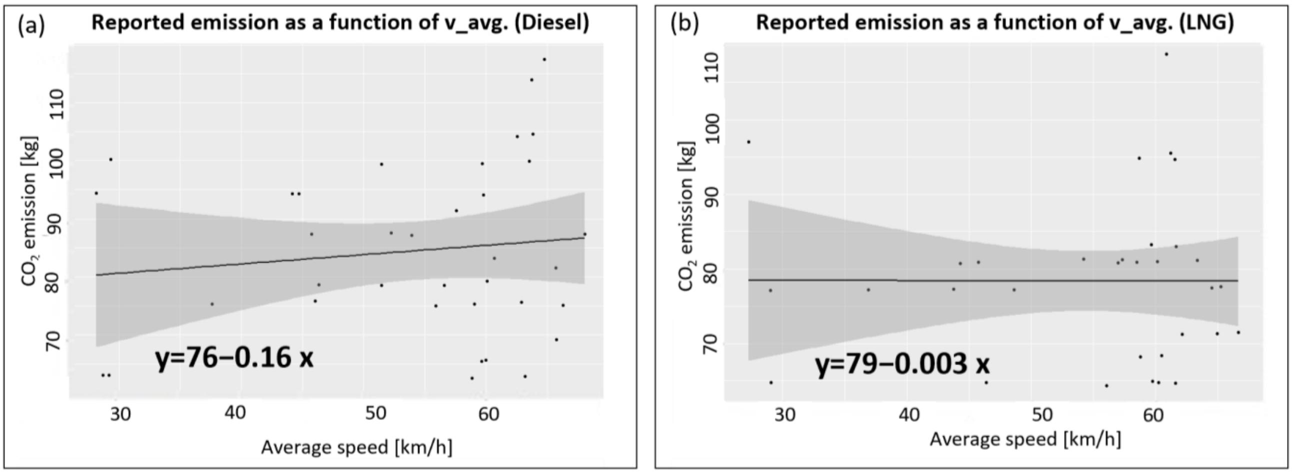


Figure 8. Conclusion of the regression analysis (**a**) in the case of diesel tractor; (**b**) in the case of LNG tractor.

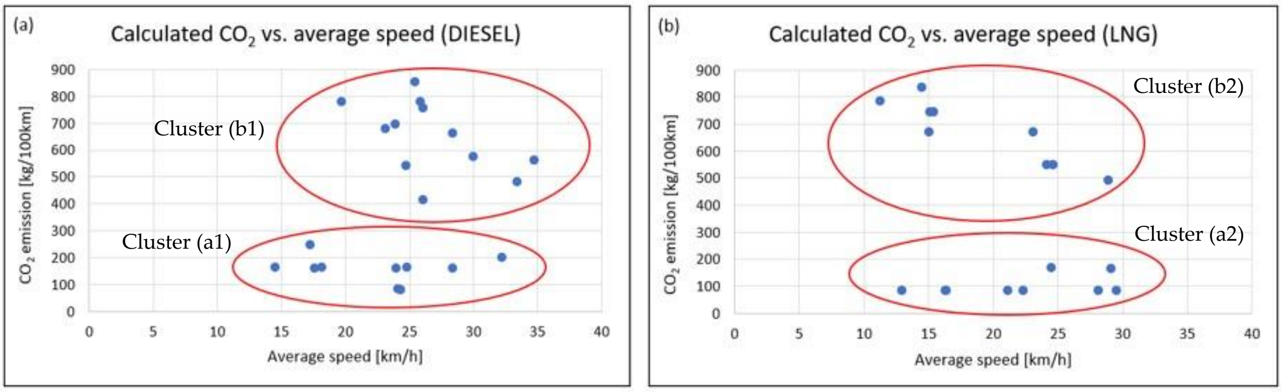
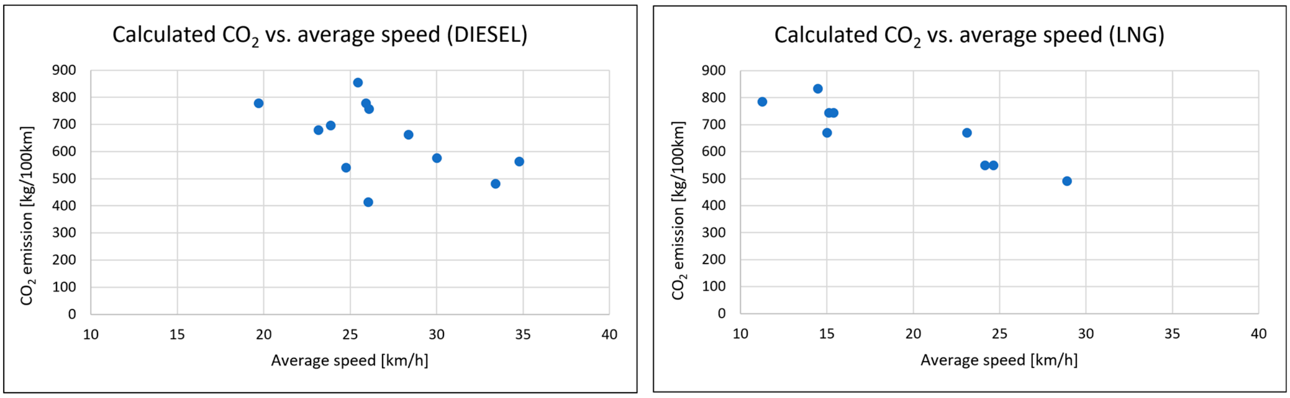


Figure 9. Measurements results: high load mode (**a**) in case of diesel tractor; (**b**) in case of LNG tractor.



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

Figure 10. Potential future research area including relations of speed and emissions at high loads (**a**) in case of diesel tractor; (**b**) in case of LNG tractor.

3.3. Emission Difference Analysis

During our test track investigations, the fuel consumption of the tractors was continuously recorded at high resolution through the vehicle's FMS system. Based on the recorded and processed values, the CO_2 emission values generated by the vehicles were calculated using the equations provided in Section 2, separately for LNG and diesel fuel. The total emissions were also calculated for the tests, showing a 11% reduction in CO_2 emissions in favor of LNG for the 600 km section.

4. Conclusions

Our work compared two HDV technologies that were suitable for long-haul transportation, primarily from an emissions perspective, as well as the factors influencing this comparison, such as vehicle speed.

- Based on the partial test, results show that LNG-fueled HDVs are not as sensitive to sudden acceleration (such as full accelerator pedal position) and deceleration as diesel HDVs in terms of fuel consumption and emission changes;
- The consumption of the LNG-powered vehicle does not increase dramatically with sudden acceleration and aggressive operation, compared to the usual diesel-powered HDV;
- The preliminary research is clearly supported by the fact that driving style is the most influencing factor; the difference in CO_2 between the two propulsion systems normally brings the described level, with a difference of about 10% in favour of the LNG tractor. Our results show that LNG provides a reliable alternative with approximately an 11% reduction in CO_2 emissions instead of diesel;
- The detailed statistical tests performed show that the correlation between average speed and emissions is relatively loose for both LNG and diesel tractors. Nevertheless, the correlation is still apparently stronger with the LNG vehicle;
- Based on the measurements, a preliminary assumption can be made that the emission characteristics of diesel and LNG trucks are relatively similar under particularly high loads, but further research is needed to confirm this perception, such as statistically taking into account all the factors affecting consumption (such as the driver, test track, load, and dynamic or static acceleration).

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