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Emission analysis of liquefied natural gas and diesel heavy-duty trucks using on-board monitoring method

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ABSTRACT

Environmental protection and the reduction of greenhouse gas (GHG) emissions are becoming top priorities in the mobility sector especially in heavy-duty truck (HDT) sector. In recent years, numerous regulations, targets, and initiatives have been introduced, all of which strongly promote the reduction of carbon-dioxide (CO_2) emissions, the adoption of eco-friendly alternatives, and the use of renewable energy sources. The study compares CO_2 emissions and fuel consumption between conventional diesel and liquefied natural gas (LNG) heavy-duty vehicles (HDVs) from the same original equipment manufacturer (OEM). The research was conducted on multiple levels, with a primary focus on control based on test track measurements. This was preceded by a simulation phase and followed by public road measurement-based validation process. In this study, we used the onboard monitoring (OBM) emission analysis method, a cost-effective and accurate process where data was recorded from the fleet management system (FMS) using controller area network (CAN) messages. The results are presented in several stages from simulation to data validation. Our research represents a unique study in the field of HDVs, as the measurements were conducted on a test track, supported by simulations and public road tests. The results of the project clearly demonstrate that gas technology can contribute to reducing GHG emissions in HDVs, and LNG provides a reliable alternative for long-distance transportation.

Keywords: heavy-duty trucks, diesel vs. LNG powertrain, carbon-dioxide (CO_2) emission, transportation.

INTRODUCTION

Environmental protection, sustainability, and emissions reduction are key trends today, closely linked to transportation. HDVs play a prominent role in this area, with the International Energy Agency [2023] reporting that approximately 60.000 medium- and heavy-duty trucks were sold globally in 2022, representing 1–2% of the world's sales figures. However, the truck and bus sectors contribute significantly to GHG emissions, emitting over 2000 Mt of carbon-dioxide (CO_2) annually. According to Krause et al.'s [2023] publication, the transport sector is one of the largest emitters of greenhouse gases in the EU, with trucks and buses responsible for 6% of total GHG emissions and 25% of CO_2 emissions. This is further confirmed by the European Commission [2023] in the "European Green Deal" report from 2023, which emphasizes that stricter European regulations require the medium-and heavy-duty vehicle segments to contribute to reducing GHG emissions and lowering CO_2 emissions, while also encouraging the market to transition to low or zero-emission alternatives. On a global scale, China (with over 9.500 million tons) and the USA (with over 5.000 tons) are by far the largest emitters, while in Europe, Germany (with over 900 million tons) is a significant GHG emitter, followed by the United Kingdom (470 million tons) and France (460 million tons). These emissions are primarily attributed to the energy sector, industry, and transportation as discussed by Anderhofstadt and Spinler [2020].

Currently, more than 95% of the European Unio's medium-and heavy-duty vehicle fleet is powered by internal combustion engines, relying on imported fossil fuels. This dependence affects the EU's energy security and impacts the environment, as only 5% of the current fuel types come from biofuels [European Commission, 2023; International Energy Agency, 2023]. Reducing and controlling air pollution from transportation has become a global challenge. In Europe, the EURO emission standards introduced in the early 1990s aimed to reduce air pollutants from the transport sector. Today, the EURO VI standard limits emissions of carbon-monoxide (CO), nitrogen-oxides (NO_x), hydrocarbons (HC), particulate matter (PM), and ammonia (NH_3) per kilometer. The regulations specify different emission limits for passenger cars and heavy-duty vehicles as reported by Williams and Minjares [2016]. These regulations have driven developments aimed at reducing emissions from internal combustion engines, allowing compliance with tightening EURO emission standards while meeting the demands of the transport sector as discussed by Selleri et al. [2022]. Although diesel engines are highly efficient, multiple factors must be considered regarding emission control. Initially, a simple catalytic converter was sufficient to meet emission standards but changing regulations have required more complex and often costly solutions. Compression-ignition, direct-injection engines began incorporating diesel particulate filters (DPF) to reduce particulate matter emissions, while selective catalytic reduction (SCR) systems and exhaust gas recirculation (EGR) are used to reduce NO_x emissions by lowering peak combustion temperatures [Kulikov et al., 2020; Selleri et al., 2022]. These systems require complex design and control, and two major components in diesel emissions – PM and NOx – do not reach their minimum values under optimal conditions simultaneously, posing a calibration challenge for developers. Moreover, while these technologies reduce targeted pollutants, they may increase the emission of other pollutants that are either unregulated or only minimally regulated by the EURO standards, such as NH_3, nitrous-oxide (N_2O), solid particle number (SPN_{10}), or formaldehyde (HCHO) as reported by Isermann [2014] and Selleri et al. [2022].

The analysis of the spread of alternative fuels is driven by the growing demand for international land transport, freight, and logistics, as well as the associated high GHG emissions and numerous environmental concerns. Freight companies face various challenges, including economic, technical, bureaucratic, legal, physical, and political issues, which can influence the heavy-duty fleet used. The spread of alternative technologies also encounters multiple challenges in terms of financial, environmental, political, functional, and social matters as reported by Jahaniagdam et al. [2023]. However, the EU and governments aim to incentivize the adoption of alternative technologies by offering various benefits, such as tax breaks, free access to road networks, route permits, and extended access beyond regular hours as reported by the European Parliament and Council [2019].

Today, several alternative propulsion technologies are available for heavy-duty vehicles, which either reduce exhaust emissions or do not emit greenhouse gases during operation. The latter category includes hydrogen propulsion, which offers substantial development potential, and battery technology capable of electric energy storage as discussed by Aryanpur and Rogan [2024] . Both powertrains share the ability to power the vehicle with an electric motor, produce zero greenhouse gas emissions, and offer regenerative braking functions [Cunanan et al., 2021]. Each technology has its own advantages and disadvantages that must be considered. For example, hydrogen technology can significantly reduce emissions, but its high current costs, reliance on non-green hydrogen production, and low fuel energy density do not provide an optimal solution for fully replacing the diesel-powered heavy-duty vehicle market. Large investments, further developments, and safe handling are required to enable favorable operation as discussed by Osiro-Tejada et al. [2017] and Van Kranenburg et al. [2020]. The efficiency of battery technology depends heavily on the energy source, charging times, storage costs, weight, energy density, and lifespan. The powertrain is simpler compared to conventional diesel engines, leading to lower maintenance costs, but current battery lifespans are not yet optimal for making these vehicles competitive in all HDV transport segments [Giuliano et al., 2021]. This issue is compounded by inadequate infrastructure and charging systems, which are crucial for low-storage-capacity vehicles in both electric and hydrogen propulsion. Sugihara et al. [2023] publication focuses on this topic, discussing compromises between extended range, weight, and initial costs. They also explore potential political regulations, such as weight exemptions and charging infrastructure development. However, the realistic application of electric technology remains limited, being currently suitable only for short-distance freight transport as discussed by Ribberink et al. [2021].

Another important alternative to highlight is natural gas-based technology, which, compared to diesel propulsion, contains significantly fewer harmful chemical elements for the environment and human health, particularly in terms of CO_2, NO_x, SO_x (sulphur-dioxide), and PM concentrations as reported by Askin et al. [2015] and Šarkan et al. [2022]. Systems powered by natural gas can easily meet EURO VI emission standards, operating with the appropriate stoichiometric air-fuel ratio, eliminating the need for complex after-treatment and regeneration systems, requiring only a compact three-way catalyst [Kumar et al., 2011]. Natural gas propulsion has been available in mobility for years, initially used in compressed natural gas (CNG) form as discussed by Caban and Ignaciuk [2018]. However, due to its low energy content, its liquefied form, LNG, began to be utilized, which has up to 2.5 times the energy content of the compressed form [Thiruvengadam et al., 2018]. The liquefaction process reduces the volume of natural gas by about 1/600th, making its transport economically viable, with a density of 430–480 kg/m³ at -162 °C and atmospheric pressure. LNG is colorless, odorless, non-toxic, non-corrosive, and can contain up to 98% pure methane (CH_4), which oxidizes with high efficiency, burns almost perfectly without producing ash, and can result in up to 10% lower greenhouse gas emissions, making it a suitable alternative for long-distance transportation as discussed by Teixeira et al. [2020] and Pfoser et al. [2018]. However, LNG's disadvantages include its lower density compared to diesel (diesel density is 840–860 kg/m³), which means that nearly twice the tank volume is needed to achieve the same range. One liter of diesel is approximately equivalent to 1.7 liters of liquefied natural gas in terms of energy value, according to Smajla et al. [2019] publication. In terms of heating value, diesel fuel has around 45 MJ/kg, while natural gas has a heating value of about 54 MJ/kg [Schwarzkopf, 2019].

Comparison of preliminary diesel and LNG emission values

The natural gas-based technology has become a primary alternative for heavy-duty vehicles in several countries. It is widely used in urban transportation due to its significant role in improving air quality, especially in the United States (U.S.), Canada, Europe, and China. In China, for instance, conventional diesel HDVs are responsible for 16.8% of CO emissions, 6.9% of THC (total hydrocarbon), 57.8% of NOx, and 66.3% of PM emissions from the total vehicle fleet, even though HDVs make up only 3.1% of the total fleet as reported by Wang et al. [2021]. Therefore, China is working intensively on introducing alternative heavy-duty vehicles, leading to the implementation of the largest LNG heavy-duty vehicle program, integrating nearly 15.000 trucks, which significantly reduces NO_x, PM, and CO emissions as reported by Zhao et al. [2021].

Emission measurements for heavy-duty vehicles are typically conducted using chassis dynamometers, tunnel testing, remote sensing, or with portable emission measurement systems (PEMS). Chassis dynamometer test cycles cannot fully replicate real-world conditions, leading to different physical characteristics in emission analysis [Jin et al., 2017]. In tunnel tests, measurement devices are placed at the testing site to capture the average emissions of passing vehicles, but these conditions may not represent all field conditions, and distinguishing individual vehicles from the data can be challenging [Littera et al., 2017]. Remote sensing measures a vehicle's instantaneous emissions at a specific location, but it does not accurately represent the entire operational cycle [Bishop and Stedman, 2012]. PEMS devices offer an excellent solution for measuring harmful emissions in real-world conditions and in real time across all operating conditions of the vehicle, including CO_2, NO_x, NO_2, THC, and CO concentrations, thanks to their portable design. Overall, among the available emission measurement methods, PEMS provides the most accurate results across the broadest range of conditions, though it is a costly instrument and procedure [Vermeulen et al., 2017]. Hao et al. [2023] analyzed NO_x and CO_2 emissions from diesel-powered heavy-duty vehicles using OBD (on board diagnostic) data to substitute for PEMS analysis. Since the vehicles lacked CO_2 sensors, they calculated CO_2 equivalent emissions based on fuel consumption and combustion mechanisms. The study demonstrated that OBD data aligned with emission analyzers, with an error margin of less than 3% during test cycles. This low error makes OBD-based data collection viable for CO_2 emissions analysis in heavy-duty vehicles as part of an OBM (on board monitoring) system.

Recent studies have examined emissions differences between diesel and LNG-powered vehicles. Quiros et al.'s [2017] publication compared greenhouse gas emissions from diesel, diesel-hybrid, and natural gas-powered heavy-duty vehicles. They tested seven different trucks, and the results indicated that natural gas trucks produced 5–15% lower CO_2 equivalents on average compared to diesel-powered vehicles, with this figure exceeding 10% on highways. Vermeulen et al.'s [2017] found similar differences, with LNG trucks emitting 10% less CO_2 on highways and rural roads, and 5% less in urban environments, where non-standard conditions can influence results. To address these variables, our study focuses on using a test track as a controlled environment to ensure repeatability and reproducibility. Di Maio et al. [2019] also highlighted a 6–8% reduction in CO_2 equivalents for LNG vehicles in urban settings and a 10% reduction on highways. Other studies from Europe also focus on diesel and LNG HDV emissions in long-haul transport. Arteconi et al. [2010] conducted a well-to-wheel analysis (covering the entire lifecycle from resource extraction to consumption) and found that using LNG can reduce greenhouse gas emissions by 10% compared to diesel. Gnap and Dočkalik [2021] also analyzed CO_2 emissions from diesel and LNG-powered trucks, similar to Arteconi et al.'s [2010] publication, considering emissions from fuel production and transportation. Their measurements along routes in Slovakia-Germany and Slovakia-Hungary showed an 8% average CO_2 equivalent difference in favor of LNG, though the exact breakdown of road types (hills, slopes, flat sections) was not specified. In our study, we predefined the road distribution to provide representative results.

Outside of Europe, Ou and Zhang [2013] provided further confirmation of the CO_2 emission differences. They analyzed the primary energy consumption and CO_2 emissions of natural gas-based alternative fuels in China, concluding that CNG and LNG technologies could reduce greenhouse gas emissions by 5–10% compared to traditional diesel technologies. In the U.S., Toumasatos et al.'s [2024] conducted a recent study that found significant differences in CO_2 equivalents between conventional and LNG-powered HDVs. Their analysis across four route types (highway, urban, rural, and hilly terrain) showed an average difference of 10–15% in favor of natural gas HDVs. Global variation in emission values is observed, with highway and rural road CO_2 differences ranging from 8–15%, while urban settings show a 5–6% difference in favor of LNG. In our research, we minimized variability and ensured accurate results by first comparing simulations in controlled environments and then confirming these with real-world road measurements, achieving the smallest possible error margin for accurate results.

The aim of the research

The novelty of this study lies in the emission analysis methodology applied to HDVs used in long-distance transportation and freight logistics, conducted across simulation, test track, and real-world road environments. The primary objective is to investigate greener, more environmentally friendly alternatives and to propose solutions that remain competitive with traditional diesel-powered vehicles – particularly in terms of range – while achieving significant reductions in harmful emissions. Recent studies have explored the emission differences between diesel and LNG propulsion systems. Vermeulen et al.'s [2017] research identified an average difference of 5–15%, while Quiros et al. [2017] determined a 10% difference in highway conditions and 5% in urban settings, in favor of LNG technology, under uncontrolled conditions. Gnap and Dočkalik's [2021] study, based on long-distance European route tests, showed an average difference of 8% in varying environments. On a global scale, the results of reported by Di Maio et al. [2019] (from Europe), Ou and Zhang [2013] (from China), and Toumasatos et al. [2024] (from the United States) also indicated significant differences, with an average of 8–15% on highway and rural road sections and 5–6% in urban conditions, again favoring LNG propulsion. This study aims to address the gaps in these findings by applying controlled conditions to reduce emission discrepancies, with carefully defined routes that proportionally incorporate straight, downhill, and uphill segments. It contributes with a three-step test method that minimises emission differences through simulations (M1 – preparatory), test track (M2 – controlled) and public road (M3 – checking) measurements, and ensures accurate results between the two drive types. The research hypotheses:

- Replacing and integrating several system components could provide an energy-efficient and environmentally friendly solution in international road transport.

- Verification of the extent of emission reduction based on preliminary research and market feedback, considering controlled and variable environments.
- Validation of the emission measurement methodology (OBM procedure).

MATERIALS AND METHODS

To validate the research hypothesis, a vehicle combination consisting of a similarly configured diesel truck and an LNG truck was used as the basis. The testing lasted six days, five of which took place in controlled conditions on a test track, and one day under dynamically changing road conditions. Both vehicles came from the same OEM (Original Equipment Manufacturer), specifically equipped with 13.000 cm^3 engines, 12-speed automatic transmissions, and similar-sized tires (see Table 1). The trailers in the vehicle combinations were box-body semi-trailers, and in the case of the LNG vehicle, equipped with a solar-powered energy system (SolarOnTop System), which, along with the associated battery and control unit, added approximately 110 kilograms of extra weight. The remaining weight difference was compensated during the tests by appropriately distributing the personnel.

Regarding the testing methodology, the primary focus of the project was on the ZalaZONE Automotive Test Track (www.zalazone.hu, accessed on 9 September 2024). Here, the same driving cycle was run with both vehicles across five different elements, with the complete cycle consisting of 66 sub-segments. The simulation process prepared the results of this test, which were then validated and confirmed by the road test. The entire test cycle was varied from an environmental perspective, primarily focusing on simulating highway mode and rural road driving, supplemented with hills, slopes, and urban environments (see Fig. 1). There was also the possibility to conduct tests in complex, interconnected systems, maximizing the distance covered and utilizing a more extensive environment.

Similar to the study by Hao et al. [2023], the necessary data was extracted via OBD, providing a cost-effective and reliable procedure for our analysis. The recorded values during the measurements were sourced from the vehicle's CAN-bus (Controller Area Network) network, with real-time readings and subsequent processing. The vehicle's fleet management system (FMS) gateway provided the connection point for extracting CAN data at a bus speed of 250 kbit/sec, which is a standard access point and bus speed. By default, the messages are received in numeric or alphanumeric form, identified by a unique ID, broken down by bit and byte. The data decoding originated from the FMS standard unified identifier system (version 04, dated 17/09/2021), filtering out consumption-specific and influencing values (Table 2).

Table 1. 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	12TX 2210 TD	12TX 2010 TO
Tyre	315/70R22.5 Pirelli FH01/TH01 Proway	315/70R22.5 Michelin X Multi Energy Z/D
Fuel capacity	1190 liter	2 × 540 liter
Ad Blue tank	135 liter	–
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	12882 cm^3	12900 cm^3
Layout of cylinders	6 vertical in line	6 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
Compression ratio	20.5 ± 0.5 :1	12 ± 0.5 :1
Injection type	Direct	Indirect

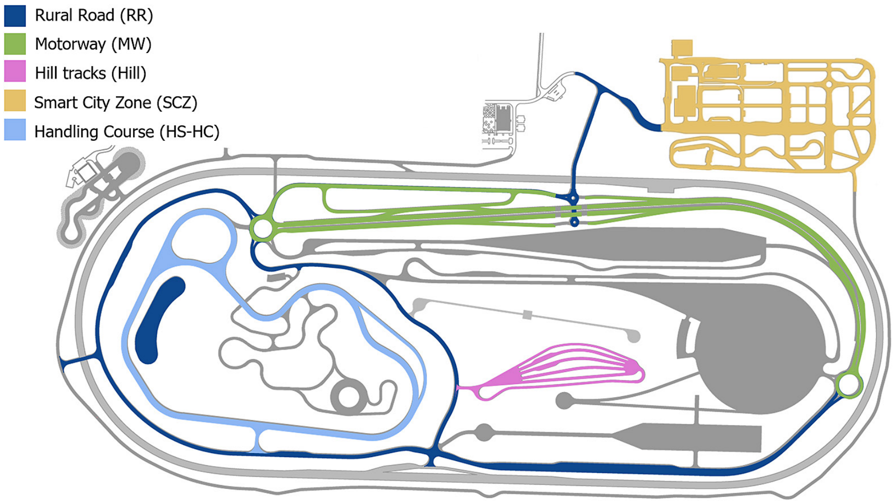

Figure 1. The map of the ZalaZONE test track

Table 2. FMS standard data and their units of measurement

ID	Message	Signal	Unit
0x0CFE6CEE X	Tachograph: TCO1	Vehicle speed	[km/h]
0x0CF00400 X	Electronic engine control #1: EEC1	Engine speed	[rpm]
0x0CF00400 X	Electronic engine control #1: EEC1	Engine torque	[%]
0x0CF00300 X	Electronic engine control #2: EEC2	Accelerator pedal pos.	[%]
0x18F00503 X	Electronic gearbox control. #2: ETC2	Selected/current grade	[-1, 12]
0x18F0010B X	Electronic brake control #1: EBC1	Brake pedal pos.	[%]
0x18FEFC21 X	Dashboard #1: DD1	Fuel level 1–2	[%]
0x18F00010 X	Electronic retarder control #1: ERC1	Torque mode / current torque	[0-16];
0x18FEE900 X	Fuel consumption (liquid): LFC	Total fuel consumed	[l]
0x1CFEAF00 X	Fuel consumption (gaseous): GFC	Total fuel consumed	[kg]
0x18FEC1EE X	High resolution distance: VDHR	Mileage	[m]
0x18FEE6EE X	Time/Date: TD	Timestamp	[y-m-d-h-m-s]

Initially, the data was read and processed using a CAN-based telemetry system (see Fig. 2a) for testing purposes, which included the following elements: Kvaser Memorator R SemiPro CAN USB (Universal Serial Bus) interface (Mölndal, Sweden), 120 Ω terminating resistor (Palmdale, CA, USA), CL-CAN contactless CAN data sensor (Budapest, Hungary), and a 12 V power supply. During the live measurements, the number of devices was reduced. The only device required was the Kvaser Memorator R-SemiPro CAN-bus interface (Fig. 2b), which featured a D-SUB 9-pin

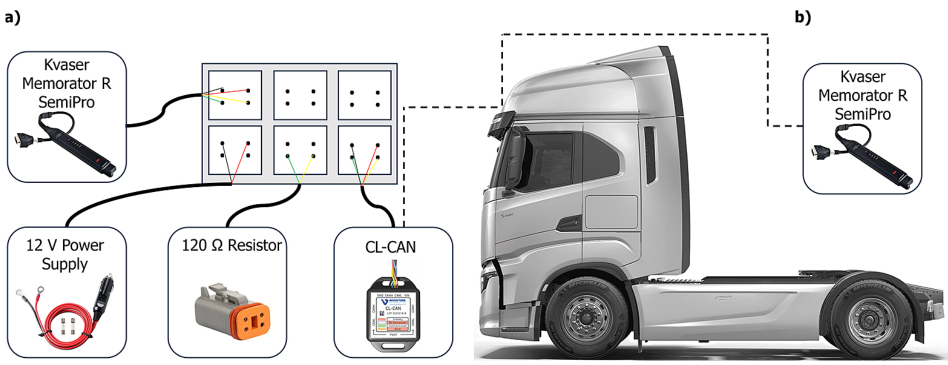

Figure 2. Application of telemetry system to read CAN messages: a) test process, b) measurement process

connector integrated with CAN-Low, CAN-High, +12 V power, and protective grounding. Therefore, only a USB connection was necessary for the measurements.

During the driving cycles, the speed of both vehicles was measured at a sampling rate of 100 Hz. The amount of fuel consumed was measured in each sub-section, and the CO_2 equivalent emissions were calculated based on the following Equation 1 for LNG and Equation 2 for diesel, was described in the literature by Dezsényi, Emőd, and Finichiu [1999].

- In case of LNG:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (1)$$

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 from the combustion of 1 kg CH_4 becomes 2.75 kg CO_2 equivalent emission.

- In case of diesel:

$$C_{16}H_{34} + 49/2O_2 \rightarrow 16CO_2 + 17H_2O \quad (2)$$

In Equation 2 diesel molecular formula the Hexadecane ($C_{16}H_{34}$) 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 CO_2 equivalent emission. For the OBM system-based study, we used the Kvaser CanKing software (version V6.24.510) for data reading and recording. The decoding of CAN messages was made by a .dbc extension file (a text file that contains information for decoding raw CAN bus data to 'physical values'), for which the CANdb++ software (version 3.1.), was utilized.

RESULTS AND DISCUSSION

The evaluation of the project's results was divided into three stages. The first step was the simulation process (M1), which prepared and supported the execution of the subsequent milestones with its results. The second step followed with the measurement series conducted at the ZalaZONE Automotive Test Track (M2), which was the primary focus of the project. The test track provided a closed, controlled test structure, eliminating various external influencing factors. Finally, the series of tests concluded with the public road measurement procedure (M3), which served as a verification step, providing real-world feedback to the results.

Simulation process (M1)

In terms of the simulation process results, estimated consumption and emissions values were calculated for the given track elements and heavy-duty vehicles. The first step was constructing a schematic vehicle model, using the technical data of the vehicle and trailer. This model was created in the IPG CarMaker (version 13.1) simulation software (Fig. 3).

To calculate the fuel consumption and emission values, a consumption map was created based on processed literature from Kulikov et al. [2020] and the technical specifications of the diesel (Fig. 4a) and the LNG (Fig. 4b) tractor's drivetrain. The brake-specific fuel consumption (BSFC) maps were then integrated into the IPG software alongside the schematic model for the diesel tractor (Fig. 4c), and for the LNG tractor (Fig 4d).

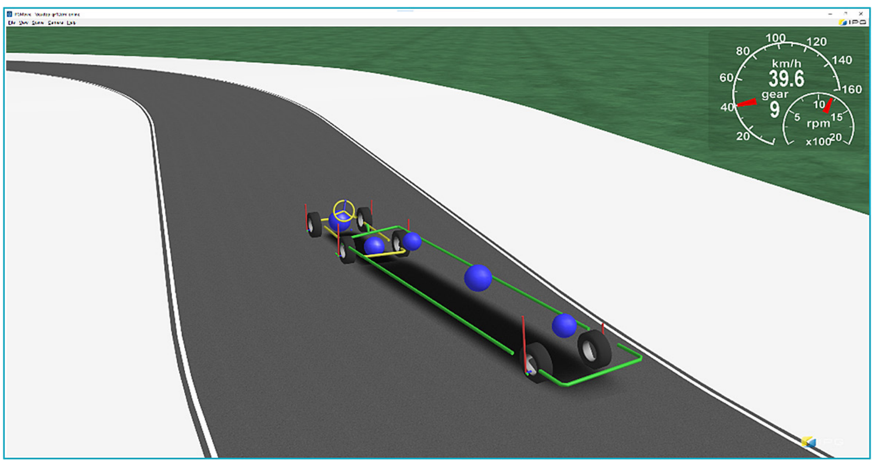

Figure 3. The vehicle and the attached trailer schematic model in the IPG CarMaker software

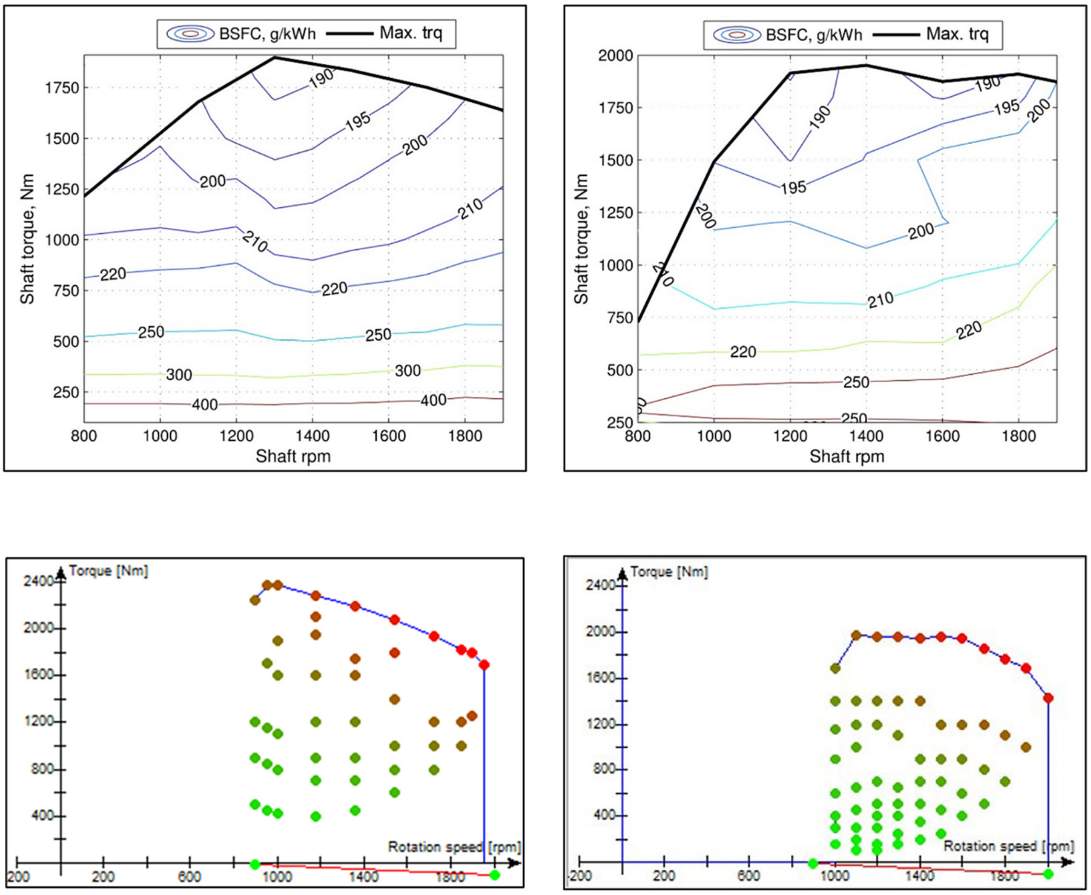

Figure 4. Brake-specific fuel consumption (BSFC) maps in different heavy-duty truck (HDV) powertrains: a) diesel BSFC in the specialized literature, b) LNG BSFC in the specialized literature, c) the analysed diesel HDV BSFC points in the software, d) the analysed LNG HDV BSFC points in the software

As a result of the simulation, the estimated consumption values were determined in liters (Fig. 5) and kilograms (Fig. 6), along with the CO_2 equivalent calculated emission (Fig. 7) based on the literature from Dezsényi, Emőd and Finichiu [1999]. In the software, the high-speed handling course (HS-HC) of the ZalaZONE Automotive Test Track was used. Regarding fuel consumption, the differences arising from density and calorific value are clearly visible. In liters, there is almost a two times difference between the fuel types, while converting to kilograms changes the curve's behavior. The CO_2 equivalent calculated during the simulation process clearly shows the difference between the two drivetrains. For the handling course, the results indicate nearly a 1-kilogram CO_2 difference for the approximately 2.3-kilometer section, which represented completing one full lap. This difference is not representative of the reality, it is only relevant for simulation comparisons without any external influencing factors, but the results have been used in the live test preparation.

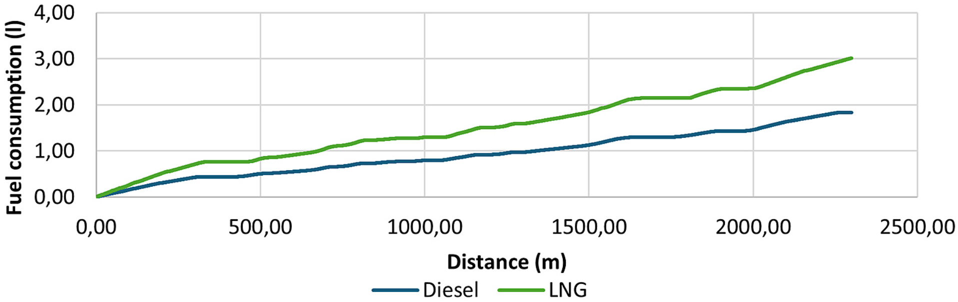

Figure 5. Simulated fuel consumption in different HDV powertrains on the HS-HC test track

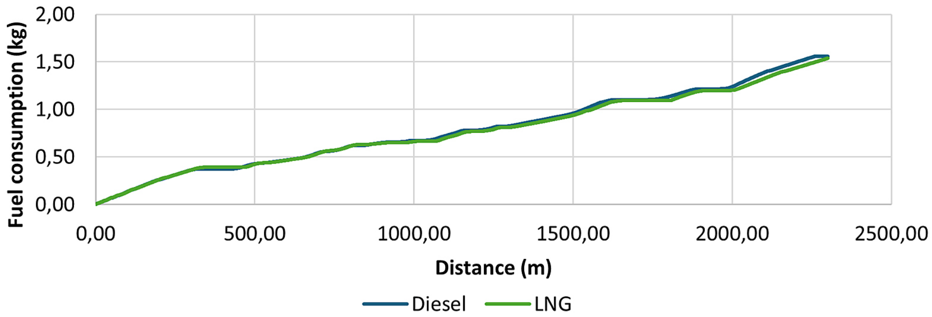

Figure 6. Simulated fuel consumption in different HDV powertrains on the HS-HC test track

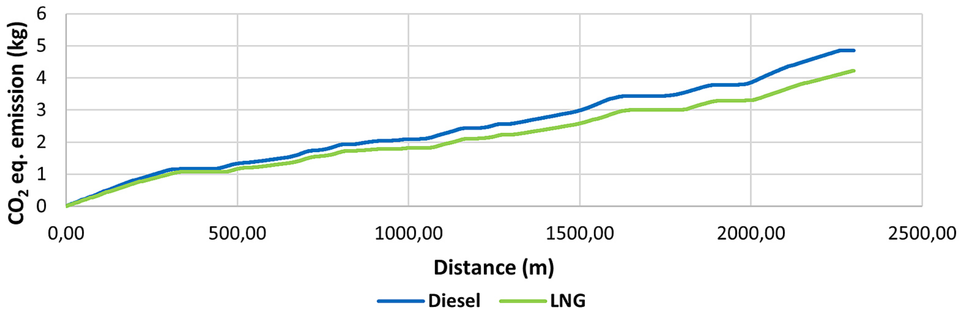

Figure 7. Simulated CO_2 equivalent emission in different HDV powertrains on the HS-HC test track

Test track measurements (M2)

To uncover the exact differences in fuel consumption and emissions between the two tractors, a test track providing controlled conditions was used. The series of tests conducted on the track minimized external influencing factors, offering reproducibility, various environments, test types, and precise results. During the tests, 90% of the measurement ran on track elements representing highways and main roads, while the remaining 10% was conducted in urban settings, on inclines and declines, and on a handling course. This distribution approximately simulated the route and environment encountered by a long-haul heavy-duty vehicle. The results are presented in Table 3, which summarizes the total distance traveled, the amount of fuel consumed (expressed in liters for diesel and in kilograms for LNG), and the calculated CO_2 equivalent emissions.

The aggregated results clearly demonstrate the differences in consumption (14% reduction) and CO_2 emissions (10% reduction) in favor of the LNG tractor. The results were broken down by day, with averages based on recorded consumption (Fig. 8) and emissions (Fig. 9). The track elements for each test day were as follows:

- T1: Motorway + rural road (public road)
- T2: Rural road (public road)
- T3: Smart city zone (urban area)
- T4: Motorway + Rural road (public road)
- T5: Hill (ascent/slopes) & motorway + rural road (public road)
- T6: High speed – handling course (test track)

Table 3. Results of the test track measurement

Summary	M2: Test track measurements		
Type	Diesel	LNG	Difference
Distance travelled [km]	487.4	488.2	
Total fuel consumption [diesel in l; LNG in kg]	166.0	147.0	←Δ 14%
Average fuel consumption [l/100km; kg/100km]	34.1	30.0	
Total CO_2 emission [kg]	440.0	404.0	←Δ 10%
Average CO_2 emission [kg/100km]	90.3	82.7	
* SolarOnTop system: 11 kWh – further CO_2 saving ≈ 35 kg for a given period (04/09/2023–08/09/2023).			

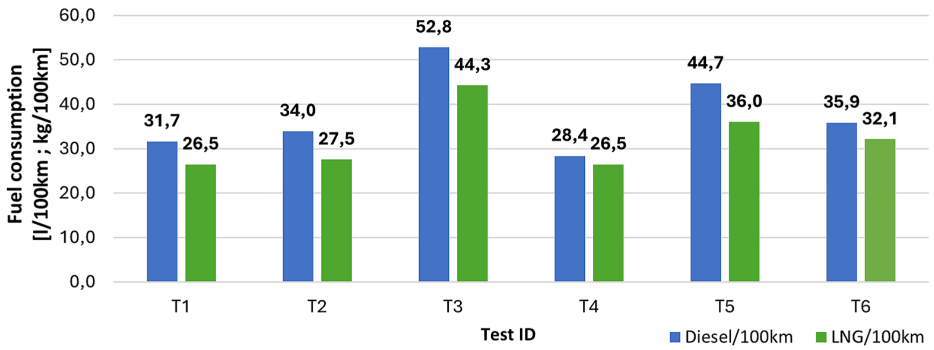

Figure 8. Summary of consumption for test days (04/09/2023–08/09/2023)

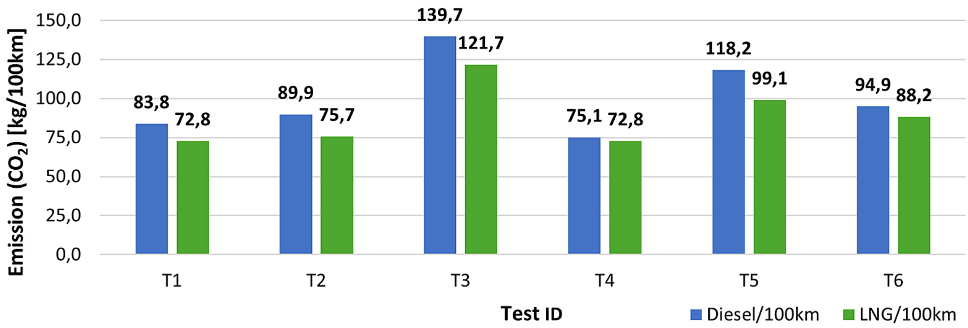

Figure 9. Summary of CO_2 equivalent emission for test days (04/09/2023–08/09/2023)

Public road tests (M3)

The third stage of the study involved a series of measurements conducted in real-world road conditions. To validate the hypotheses, we chose a dynamically changing environment, which included a combination of standard roads, urban sections, main roads, and highways. Based on the recorded and processed data, feedback was obtained regarding the consumption and CO_2 emission differences between the two tractors, further confirming the accuracy of the test method. For road measurements, data was recorded along two routes: the first part on highways HU-76 and HU-86, between ZalaZONE Automotive Test Track (Zalaegerszeg) and Vép (Fig. 10a), and the second part on the HU-M86 motorway between Vép – Sárvár – Szombathely – Vép (Fig. 10b).

During the tests, the LNG tractor and semi-trailer combination participated, and the results showed a more normalized fuel consumption and emissions value (Table 4), which accurately reflects reality using the OBM system.

For further confirmation, the performance of both tractors was also examined during active operation, with a similar route and work type.

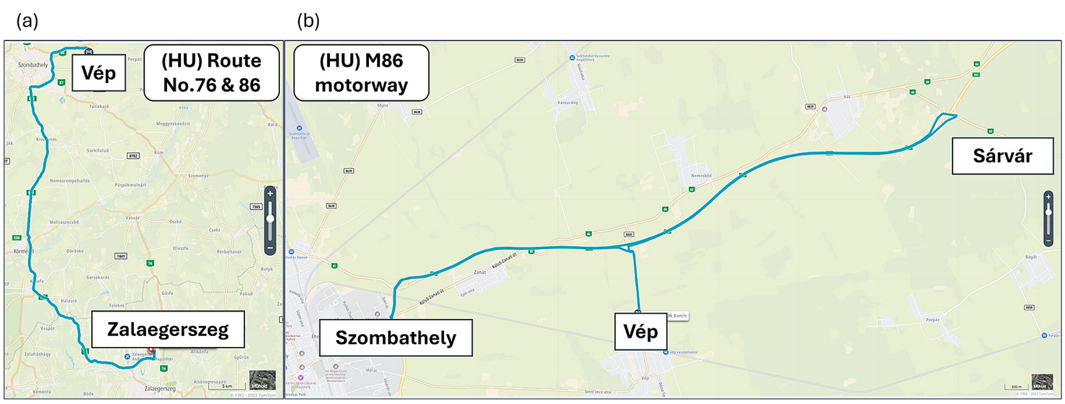

Figure 10. Performed public road tests in Hungary (HU): a) in case of No. 76 & 86 main roads, b) in case of the M86 motorway

Table 4. Results of public road tests in case of LNG truck

Details	LNG
Distance travelled [km]	95.6
Total fuel consumption [diesel in l; LNG in kg]	22.0
Average fuel consumption [l/100km; kg/100km]	23.0
Total CO_2 emission [kg]	60.5
Average CO_2 emission [kg/100km]	63.3

However, data collection was carried out via an online telematics system. This method operates similarly to the OBM system but records fewer vehicle-specific values with a lower sampling rate. The results of the study are shown in Table 5, summarizing the distance travelled on the route, the amount of fuel consumed (expressed in liters for diesel and kilograms for LNG), and the calculated CO_2 equivalent emissions.

Analysed route: Szombathely, HU – Weil am Rhein DE – section part

- Diesel: HU-9700 Szombathely – AT-4676 Aistersheim section
- LNG: HU-9700 Szombathely – AT-4774 Sankt Marienkirchen bei Schärding section

As seen in the telematics data in Table 5, the difference in the calculated average CO_2 emissions for 100 kilometers between the conventional diesel and LNG tractors is 6,7 kilograms. When this difference is scaled to 100,000 kilometers, the average value translates to 6,7 tons. According to our market research, a tractor can cover approximately 18,000 kilometers per month, from which the annual CO_2 emission difference can be calculated, significantly exceeding 6,7 tons. In the following example, the annual CO_2 difference for an average long-haul tractor is shown. Example based on the average CO_2 emission difference for the diesel and LNG tractors we studied:

- 100 km = 6.7 kg
- 18.000 km = 1.206 kg (average monthly mileage)
- 18.000 km × 12 months = 216.000 km (average annual mileage)
- 216.000 km = 14.472 kg ≈ 14.5 t (average annual CO_2 emission difference)

In summary, it can be seen that, for an average difference value, close to 14.5 tons of CO_2 emissions can be saved annually with the integration of an LNG tractor, assuming a distance of 200.000 km per year.

Data check and validation

During the comparison of the results, we contrasted the test track measurements with the public road measurements. Regarding the controlled (M2) and dynamically changing (M3) environments, the difference in CO_2 equivalent emissions was found to be 1% (Table 6), indicating that heavy-duty vehicles can be reliably examined in both controlled and variable environments.

Table 5. Results of public road tests in international transportation

Summary	M3: Public road tests		
Type	Diesel	LNG	Difference
Distance travelled [km]	342.7	387.1	
Total fuel consumption [l; kg]	84.2	82	←Δ 16%
Average fuel consumption [l/100 km; kg/100 km]	24.6	21.2	
Total CO_2 emission [kg]	223.0	225.5	←Δ 11%
Average CO_2 emission [kg/100 km]	65.0	58.3	

Table 6. Results of public road tests in case of LNG truck

Summary	M2: Test track measurements			M3: Public road tests		
Type	Diesel	LNG	CO_2 difference	Diesel	LNG	CO_2 difference
Distance travelled [km]	487.4	488.2		342.7	387.1	
Total fuel consumption [diesel in l; LNG in kg]	166.0	147.0		84.2	82	
Average fuel consumption [l/100 km; kg/100 km]	34.1	30.0		24.6	21.2	
Total CO_2 emission [kg]	440.0	404.0		223.0	225.5	
Average CO_2 emission [kg/100 km]	90.3	82.7	←Δ10%	65.0	58.3	←Δ11%

CONCLUSIONS

In this study, we compared two heavy-duty vehicle technologies, both offering solutions for long-distance transportation, primarily from the perspective of emissions and fuel consumption. The comparison was carried out at several levels, with a primary focus on comparing the vehicles in a controlled environment on the test track, followed by simulation preparation and real-world road measurements.

- The OBM-based emissions testing method provided cost-effective and accurate results during the measurements.
- The results of the simulation process highlighted the extent of potential differences and helped in preparing for further tests (which track elements to use, what types of tests to conduct).
- In the literature reviewed, the range of CO_2 emissions differences was estimated between 5–15%, depending on the environment in which the tests were conducted. Our own tests resulted in an average of 10% CO_2 equivalent in favor of the LNG tractor, which could mean a saving of up to 15 tons of CO_2 emissions annually.
- The results determined from the public road measurements confirmed the accuracy of the testing method used and the extent of the emissions differences between the two tractors.
- The findings confirmed that LNG is a viable environmentally friendly alternative in long-distance transportation, as this drivetrain can compete in both range and energy efficiency.
- An innovative three-stage testing procedure was applied, providing preparation, controlled environmental testing, and feedback verification of results during the research, based on predefined routes.
- With the help of the SolarOnTop power supply system, further cost and emissions reductions can be achieved, depending on the system's usage, efficiency, and weather conditions. To determine the precise impact of this system, further measurements are needed, which can be calculated after real-world usage. We plan to conduct long-term measurements on this in the future.

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REFERENCES

1. Anderhofstadt, B., and Spinler, S. [2020]. Preferences for autonomous and alternative fuel-powered heavy-duty trucks in Germany. Transportation Research Part D: *Transport and Environment, 79*. https://doi.org/10.1016/j.trd.2020.102232
2. Arteconi, A., Brandoni, C., Evangelista, D., and Polonara, F. [2010]. Life-cycle greenhouse gas analysis of LNG as a heavy vehicle fuel in Europe. *Applied Energy, 87*(6), 2005–2013. https://doi.org/10.1016/j.apenergy.2009.11.012
3. Aryanpur, V., and Rogan, F. [2024]. Decarbonising road freight transport: The role of zero-emission trucks and intangible costs. *Scientific Reports, 14*(1). https://doi.org/10.1038/s41598-024-52682-4
4. Askin, A. C., Barter, G. E., West, T. H., and Manley, D. K. [2015]. The heavy-duty vehicle future in the United States: A parametric analysis of technology and policy tradeoffs. *Energy Policy, 81*, 1–13. https://doi.org/10.1016/j.enpol.2015.02.005
5. Bishop, G. A., Stedman, D. H., Bishop, G. A., and Stedman, D. H. [2012*]. Remote Measurements of On-Road Emissions from Heavy-Duty Diesel Vehicles in California*; Year 5, 2012. Retrieved from Denver website: https://digitalcommons.du.edu/feat_publications
6. Caban, J., and Ignaciuk, P. [2018]. Technical-economic aspects of cng gas usage in Buses of Urban communication. *Engineering for Rural Development, 17*, 2129–2133. https://doi.org/10.22616/ERDev2018.17.N483
7. Cunanan, C., Tran, M. K., Lee, Y., Kwok, S., Leung, V., and Fowler, M. [2021, June 1]. A review of heavy-duty vehicle powertrain technologies: diesel engine vehicles, battery electric vehicles, and hydrogen fuel cell electric vehicles. *Clean Technologies*, *3*, 474–489. https://doi.org/10.3390/cleantechnol3020028
8. Di Maio, D., Beatrice, C., Fraioli, V., Napolitano, P., Golini, S., and Rutigliano, F. G. [2019]. Modeling of three-way catalyst dynamics for a compressed natural gas engine during lean-rich transitions. *Applied Sciences (Switzerland), 9*(21). https://doi.org/10.3390/app9214610
9. European Commission. [2023]. European Green Deal: Commission proposes 2030 zero-emissions target for new city buses and 90% emissions reductions for new trucks by 2040. Retrieved from https://ec.europa.eu/commission/presscorner/detail/en/ip_23_762
10. European Parliament: [2019]. Regulation (EU) 2019/1242 of the European Parliament and of the Council of 20 June 2019 setting CO2 emission performance standards for new heavy-duty vehicles and amending Regulations. *Official Journal of the European Union, 62*. Retrieved from https://eur-lex.europa.eu/eli/reg/2019/1242/oj

11. Giuliano, G., Dessouky, M., Dexter, S., Fang, J., Hu, S., and Miller, M. [2021]. Heavy-duty trucks: The challenge of getting to zero. Transportation Research Part D: *Transport and Environment, 93*. https://doi.org/10.1016/j.trd.2021.102742
12. Gnap, J., and Dočkalik, M. [2021]. Impact of the operation of LNG trucks on the environment. *Open Engineering, 11*(1), 937–947. https://doi.org/10.1515/eng-2021-0096
13. Gy. Dezsényi, I. Emőd, and L. Finichiu. [1999]. *Internal Combustion Engines Design and Testing* (Dr. Dezsényi György, Ed.). Budapest: National Textbook Publisher.
14. Hao, L., Ren, Y., Lu, W., Jiang, N., Ge, Y., and Wang, Y. [2023]. Assessment of heavy-duty diesel vehicle NOx and CO_2 emissions based on OBD data. *Atmosphere, 14*(9). https://doi.org/10.3390/atmos14091417
15. International Energy Agency (IEA). [2023, June 26]. *Global CO2 emissions from trucks and buses in the Net Zero Scenario*. Retrieved 26 March 2024, from https://www.iea.org/data-and-statistics/charts/global-co2-emissions-from-trucks-and-buses-in-the-net-zero-scenario-2000-2030
16. Isermann, R. [2014]. Engine modeling and control: Modeling and electronic management of internal combustion engines. In *Engine Modeling and Control: Modeling and Electronic Management of Internal Combustion Engines 9783642399343*. https://doi.org/10.1007/978-3-642-39934-3
17. Jahaniaghdam, T., Mamdoohi, A. R., Kheyrabadi, S. A., Mehryar, M., and Ciari, F. [2023]. Preferences for alternative fuel trucks among international transport companies. *World, 4*(4), 795–815. https://doi.org/10.3390/world4040050
18. Jin, T., Lu, K., Liu, S., Zhao, S., Qu, L., and Xu, X. [2017]. Chemical characteristics of particulate matter emission from a heavy-duty diesel engine using ETC cycle dynamometer test. *Aerosol and Air Quality Research, 17*(2), 406–411. https://doi.org/10.4209/aaqr.2016.06.0264
19. Krause, J., Arcidiacono, V., Maineri, L., Broekaert, S., and Fontaras, G. [2023]. Calculating heavy-duty vehicle CO2 emission reduction costs for Green Deal scenarios: Extension of the DIONE model. *Transportation Research Procedia, 72*, 2597–2603. https://doi.org/10.1016/j.trpro.2023.11.788
20. Kulikov, I., Kozlov, A., Terenchenko, A., and Karpukhin, K. [2020]. Comparative study of powertrain hybridization for heavy-duty vehicles equipped with diesel and gas engines. *Energies, 13*(8). https://doi.org/10.3390/en13082072
21. Kumar, S., Kwon, H. T., Choi, K. H., Lim, W., Cho, J. H., Tak, K., and Moon, I. [2011]. LNG: An eco-friendly cryogenic fuel for sustainable development. *Applied Energy, 88*, 4264–4273. https://doi.org/10.1016/j.apenergy.2011.06.035
22. Littera, D., Cozzolini, A., Besch, M., Carder, D., and Gautam, M. [2017]. Effect of turbulence intensity on PM emission of heavy duty diesel trucks - Wind tunnel studies. *Atmospheric Environment, 162*, 31–44. https://doi.org/10.1016/j.atmosenv.2017.05.013
23. Schwarzkopf M.E. [2019]. *Investigating the introduction of alternative tractor-trailers in Hungary (Thesis)*. Budapest University of Technology and Economics, Budapest, Hungary.
24. Osorio-Tejada, J. L., Llera-Sastresa, E., and Scarpellini, S. [2017]. Liquefied natural gas: Could it be a reliable option for road freight transport in the EU? *Renewable and Sustainable Energy Reviews, 71*, 785–795. https://doi.org/10.1016/j.rser.2016.12.104
25. Ou, X., and Zhang, X. [2013]. Life-cycle analyses of energy consumption and GHG emissions of natural gas-based alternative vehicle fuels in China. *Journal of Energy*, 1–8. https://doi.org/10.1155/2013/268263
26. Pfoser, S., Schauer, O., and Costa, Y. [2018]. Acceptance of LNG as an alternative fuel: Determinants and policy implications. *Energy Policy, 120*, 259–267. https://doi.org/10.1016/j.enpol.2018.05.046
27. Quiros, D. C., Smith, J., Thiruvengadam, A., Huai, T., and Hu, S. [2017]. Greenhouse gas emissions from heavy-duty natural gas, hybrid, and conventional diesel on-road trucks during freight transport. *Atmospheric Environment, 168*, 36–45. https://doi.org/10.1016/j.atmosenv.2017.08.066
28. Ribberink, H., Wu, Y., Lombardi, K., and Yang, L. [2021]. Electrification opportunities in the medium- and heavy-duty vehicle segment in Canada. *World Electric Vehicle Journal, 12*(2). https://doi.org/10.3390/wevj12020086
29. Robin Vermeulen, A., Verbeek, R., and van Goethem, S. [2017]. *Emissions testing of two Euro VI LNG heavy-duty vehicles in the Netherlands: tank-to-wheel emissions.* Retrieved from www.tno.nl
30. Rodrigues Teixeira, A. C., Borges, R. R., Machado, P. G., Mouette, D., and Dutra Ribeiro, F. N. [2020]. PM emissions from heavy-duty trucks and their impacts on human health. *Atmospheric Environment, 241*. https://doi.org/10.1016/j.atmosenv.2020.117814
31. Šarkan, B., Kuranc, A., Sejkorova, M., Caban, J., and Loman, M. [2022]. Comparison of the exhaust emissions of heavy-duty vehicle engines powered by diesel fuel (DF) and natural gas (LNG) in real operation conditions. *Przemysł Chemiczny, 1*(1), 39–43. https://doi.org/10.15199/62.2022.1.2
32. Selleri, T., Gioria, R., Melas, A. D., Giechaskiel, B., Forloni, F., Villafuerte, P. M., … Suarez-Bertoa, R. [2022]. Measuring emissions from a demonstrator heavy-duty diesel vehicle under real-world conditions—moving forward to Euro VII. *Catalysts, 12*(2). https://doi.org/10.3390/catal12020184
33. Smajla, I., Sedlar, D. K., Drljača, B., and Jukić, L.

[2019]. Fuel switch to LNG in heavy truck traffic. *Energies, 12*(3). https://doi.org/10.3390/en12030515

34. Sugihara, C., Hardman, S., and Kurani, K. [2023]. Social, technological, and economic barriers to heavy-duty truck electrification. *Research in Transportation Business and Management, 51*. https://doi.org/10.1016/j.rtbm.2023.101064
35. Thiruvengadam, A., Besch, M., Padmanaban, V., Pradhan, S., and Demirgok, B. [2018]. Natural gas vehicles in heavy-duty transportation – A review. *Energy Policy, 122*, 253–259. https://doi.org/10.1016/j.enpol.2018.07.052
36. Toumasatos, Z., Zhu, H., Durbin, T. D., Johnson, K. C., Cao, S., and Karavalakis, G. [2024]. Real-world particulate, GHG, and gaseous toxic emissions from heavy-duty diesel and natural gas vehicles. *Atmospheric Environment, 327*. https://doi.org/10.1016/j.atmosenv.2024.120512
37. Van Kranenburg, K., Van Delft, Y., Gavrilova, A., De Kler, R., Schipper, C., Smokers, R., Verbeek, M., and Verbeek, R. [2020]. *E-Fuels: Towards a More Sustainable Future for Truck Transport, Shipping and Aviation.* Retrieved from https://www.tno.nl/publish/pages/3735/vankranenburg-2020-efuels.pdf
38. Wang, X., Song, G., Zhai, Z., Wu, Y., Yin, H., and Yu, L. [2021]. Effects of vehicle load on emissions of heavy-duty diesel trucks: A study based on real-world data. *International Journal of Environmental Research and Public Health, 18*(8). https://doi.org/10.3390/ijerph18083877
39. Williams, M., and Minjares, R. [2016]. *A technical summary of Euro 6/VI vehicle emission standards*. Retrieved from www.theicct.org
40. Zhao, Q., Huang, W., Hu, M., Xu, X., and Wu, W. [2021]. Characterizing the economic and environmental benefits of lng heavy-duty trucks: A case study in shenzhen, china. *Sustainability (Switzerland), 13*(24). https://doi.org/10.3390/su132413522