

Article

Assessing the Potential of Hydrotreated Vegetable Oil (HVO) for Transport Decarbonization: Experimental Results from Real-Driving Conditions in Local Public Transport

Angelo Robotto ¹, Cristina Bargerò ², Enrico Racca ^{3,*} , Enrico Brizio ³  and Secondo Paolo Barbero ³

¹ Regione Piemonte, 10127 Torino, Italy; angelo.robotto@regione.piemonte.it

² IRES Piemonte, 10125 Torino, Italy; bargero@ires.piemonte.it

³ ARPA Piemonte, 10135 Torino, Italy; e.brizio@arpa.piemonte.it (E.B.); s.barbero@arpa.piemonte.it (S.P.B.)

* Correspondence: e.racca@arpa.piemonte.it; Tel.: +39-011-19681431

Abstract

Advanced biofuels represent a key option for transport decarbonization, particularly in sectors where electrification is constrained by technical and economic barriers. Their compatibility with existing vehicle fleets and fuel distribution infrastructure enables rapid deployment without the need for major capital investments. In local public transport, biodiesel (FAME), hydrotreated vegetable oil (HVO), and biomethane are mature solutions capable of delivering greenhouse gas emission reductions of 60–90% compared with fossil fuels. Among these, HVO is particularly promising, as an extensive body of literature has consistently shown its potential to significantly reduce engine-out emissions, especially particulate matter (PM) and nitrogen oxides (NO_x). This study reports the results of an experimental campaign carried out on a diesel-powered local public transport bus equipped with a Euro III engine and lacking particulate matter and NO_x after-treatment systems. Emissions were measured using a portable emissions measurement system (PEMS) under real driving conditions, operating the vehicle with neat diesel, a 15% HVO blend, and a 70% HVO blend. Tests were conducted over urban and extra-urban routes. The results show that NO_x emissions decrease proportionally with increasing HVO content, with high-blend ratios (HVO70) yielding estimated reductions of approximately 13–18%, and up to 23% under carefully controlled and comparable urban driving conditions. Based on these findings and the existing literature, HVO proves to be a useful instrument to meet 2025–2030 climate and air quality targets (particularly NO_x and PM emission reductions), alongside electrification and modal shift measures, if used in public transport fleets.

Keywords: HVO; PEMS; NO_x



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1. Introduction

Biofuels represent one of the most promising alternatives for reducing the environmental impact of the transport sector. They are produced from renewable biomass sources, such as vegetable oils, agricultural residues, and organic waste. For this reason, they can significantly improve air quality compared with conventional fossil fuels.

Among them, advanced biofuels such as hydrotreated vegetable oil (HVO) are characterized by cleaner combustion and a favorable emission profile. HVO has chemical and physical properties similar to conventional diesel fuel. However, it differs because it is free of oxygen and aromatic compounds.

HVO offers several advantages. It has a relatively high lower heating value and cetane number. It also shows lower viscosity and a lower smoke point. In addition, it provides superior storage stability and improved cold-flow properties compared with FAME (fatty acid methyl esters) [1].

HVO can be used in diesel engines either as a neat fuel or in blends with conventional diesel [2]. Since HVO is a hydrocarbon, it behaves similarly to fossil diesel. Therefore, no engine modifications are required for blends up to about 30% [3].

To understand the regulatory framework of HVO in Europe, it is useful to refer to EN 590. This standard defines the specifications for automotive diesel fuel. It includes parameters such as density, viscosity, cetane number, flash point, sulfur content, and cold-flow properties. It also defines which components can be blended with diesel.

EN 590 allows the addition of up to 7% FAME by volume. HVO is not explicitly mentioned in the standard. This is not because it is prohibited, but because it does not belong to the ester family. Instead, it is a paraffinic hydrocarbon, which is chemically very similar to fossil diesel.

This similarity makes HVO fully compatible with EN 590. HVO is considered a “drop-in fuel,” meaning that it can be blended with diesel without altering its functional properties. At moderate concentrations (around 15%), the blend still complies with EN 590. This includes key parameters such as density, viscosity, and cetane number. As a result, no additional engine certification is required.

The situation is different for FAME biodiesel. The 7% limit in EN 590 reflects its different behavior compared with diesel. FAME is more hygroscopic and less oxidatively stable. It can also present compatibility issues with some materials. For these reasons, the standard imposes a strict limit. HVO, in contrast, does not show these drawbacks and is not subject to the same restriction.

In practice, diesel containing 15% HVO (HVO15) remains fully compliant with EN 590. At higher concentrations (above 30–40%), the blend may fall outside the density range specified by the standard. This is due to the lower density of HVO compared with fossil diesel. However, other fuel properties remain favorable.

For higher blending ratios, or for neat HVO (HVO100), another standard applies: EN 15940. This standard regulates paraffinic diesel fuels. Several vehicle manufacturers, especially in the heavy-duty sector, have already approved engines for fuels compliant with EN 15940. This allows the direct use of HVO100.

The use of HVO can reduce NO_x emissions compared with fossil diesel. This effect is due to both kinetic and thermodynamic factors. HVO consists mainly of linear and branched paraffins and contains no aromatics or sulfur. It also has a significantly higher cetane number than diesel (see Table 1).

These properties lead to a shorter ignition delay and a lower fraction of premixed combustion. In engines with a simple injection strategy, this reduces fuel accumulation before ignition. It also lowers the peak heat-release rate and reduces maximum combustion temperatures. Since NO_x formation depends strongly on peak temperature and residence time, a smoother combustion process results in lower engine-out NO_x emissions.

This benefit is more evident in older engines. These engines often lack pilot injection and advanced combustion control strategies. In such cases, the cetane number directly influences combustion.

In modern engines, the situation is different. Advanced systems such as multiple injections, closed-loop combustion control, and high EGR rates stabilize combustion temperature. As a result, the influence of the fuel is reduced, and the NO_x benefit of HVO becomes less pronounced.

Because of this complexity, NO_x reductions cannot be generalized. They depend on engine type, regulatory class, and test conditions. A systematic literature analysis is therefore required. This analysis must distinguish between vehicle categories (light-duty, heavy-duty, passenger cars), emission standards (Euro 3–6), and test methodologies (engine bench, chassis dynamometer, or real driving emissions). Only this approach allows a correct interpretation of results.

This study combines a structured literature review with experimental measurements. It includes a review of HVO use in internal combustion engines (Section 3); experimental results from a Euro III bus under real driving conditions (Section 4); and a discussion of the results (Section 5). The aim is to assess whether HVO can be effectively used in public transport fleets. It is considered a complementary measure to electrification and modal shift, contributing to 2025–2030 climate and air quality targets.

Table 1. Characteristics of the fuels used. Data for EN 590 diesel and HVO100 were obtained from [4]; properties of HVO15 and HVO70 were estimated based on their blending ratios.

Parameter	Unit	EN590 Diesel	HVO15	HVO70	HVO100
Density at 15 °C	kg/m ³	830.6	822.68	793.64	777.8
Kinematic viscosity	mm ² /s	2.969	2.921	2.743	2.646
Dynamic viscosity	Pa × s	0.00247	0.00241	0.00218	0.00206
Cetane number	-	54.6	58.4	72.1	79.6
Monoaromatic	%v/v	20.1	17.2	6.4	0.5
Polyaromatic	%v/v	3.0	2.6	0.9	0
Total aromatic	%v/v	23.1	19.6	6.9	0
Flammability	°C	74.0	72.0	64.6	60.5
Lower heating value	MJ/kg	42.7	42.9	43.8	44.35
Hydrogen	%m/m	13.7	13.9	14.6	15
Carbon	%m/m	85.7	85.6	85.2	85
Oxygen	%m/m	0.6	0.5	0.2	0
Sulfur	mg/kg	6.5	5.6	2.3	0.53
FAME	%v/v	5.0	4.3	1.5	0.05
Approx. formula	-	C ₁₃ H ₂₄ O _{0.06}	-	-	C ₁₃ H ₂₈

2. Materials and Methods

2.1. Preliminary Literature Review

This study investigates the potential of the alternative fuel HVO to reduce NO_x emissions from diesel vehicles under real driving conditions. As a first step, an extensive literature review was carried out to assess the current state of research on this topic.

The review considered the main scientific databases: Scopus, ScienceDirect, Springer Nature Link, ResearchGate, and JSTOR. Scopus is an abstract and citation database launched by Elsevier, providing access to a wide range of peer-reviewed scientific literature. ScienceDirect is a web-based bibliographic platform offering access to more than 4000 academic journals and 30,000 e-books published by Elsevier and several smaller academic publishers. Springer Nature Link is a research database comprising over 4000 academic journals and nearly 350,000 books, primarily published by Nature, Springer.com, BioMed Central, Scientific American, Heinrich Vogel Verlag, and SciGraph. ResearchGate is a European commercial social networking platform for scientists and researchers that enables the sharing of publications, collaboration, and discussion of research findings. Finally, JSTOR is a non-profit academic digital library founded in 1995 by Ithaka, providing access to more than 12 million documents, including journal articles, books, and other research resources, with extensive availability of retrospective journal collections, often starting from the first issue.

The following keywords were used in the search queries: “HVO”, “Green Diesel”, and “Hydroprocessed Renewable Diesel”. From the retrieved results, 113 scientific articles, conference proceedings, and book chapters were selected and reviewed in detail. Of these, 82 publications were found to be directly relevant and useful for the present study. Some of the excluded articles addressed other alternative biofuels, such as FAME biodiesel, farnesane, or Jatropha methyl ester; others focused on experimental studies in the aeronautical sector, which are outside the scope of this research. Additional works dealt with issues related to HVO production, storage, distribution, and life-cycle assessment, which were likewise not relevant to the objectives of this study. In summary, all articles that did not contribute to understanding the impact of HVO use on the exhaust emission performance of diesel vehicle engines were excluded. A diagram showing the method of the bibliographic search is shown in Figure 1.

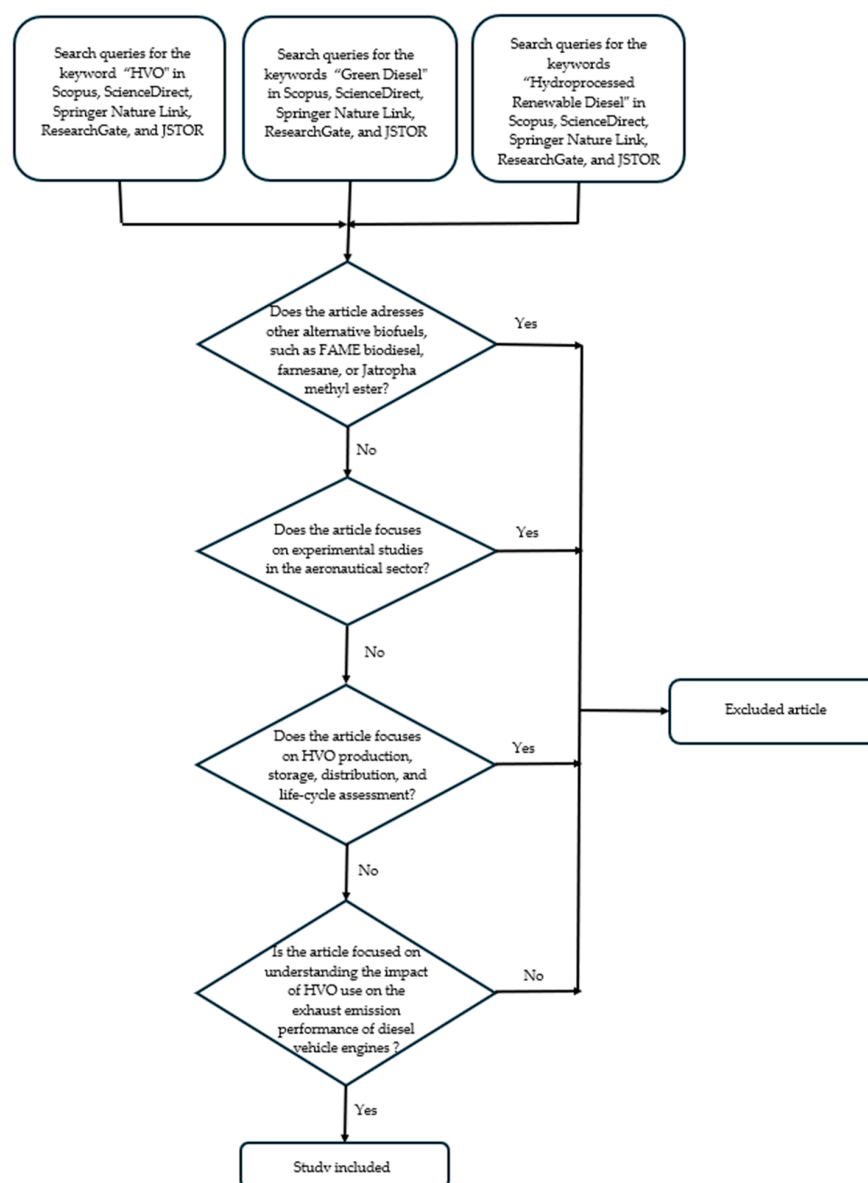


Figure 1. Bibliographic research scheme.

In calculating the mean, median, and standard deviation of the reduction in NO_x , PAHs, Tank-to-Wheel (TTW) CO_2 , Well-to-Wheel (WTW) CO_2 , and PM, non-peer-reviewed articles, studies reporting duplicate data, and tests conducted on non-representative engines or using fuels not comparable to those available in Europe were also excluded.

2.2. Experimental Setup

The experimental monitoring activities began in October 2025 at the local public transport operator Bus Company S.r.l. in Cuneo, northwestern Italy. During the measurement campaigns reported in this work, the focus was placed on emissions from a Euro III diesel vehicle (license plate CX562FZ, see Figure 2) not equipped with particulate matter or NO_x after-treatment systems and close to the end of its service life.



Figure 2. PEMS probe system connected to the exhaust of the Euro III bus used for road tests. The instruments were placed inside the bus (see Figure 3).

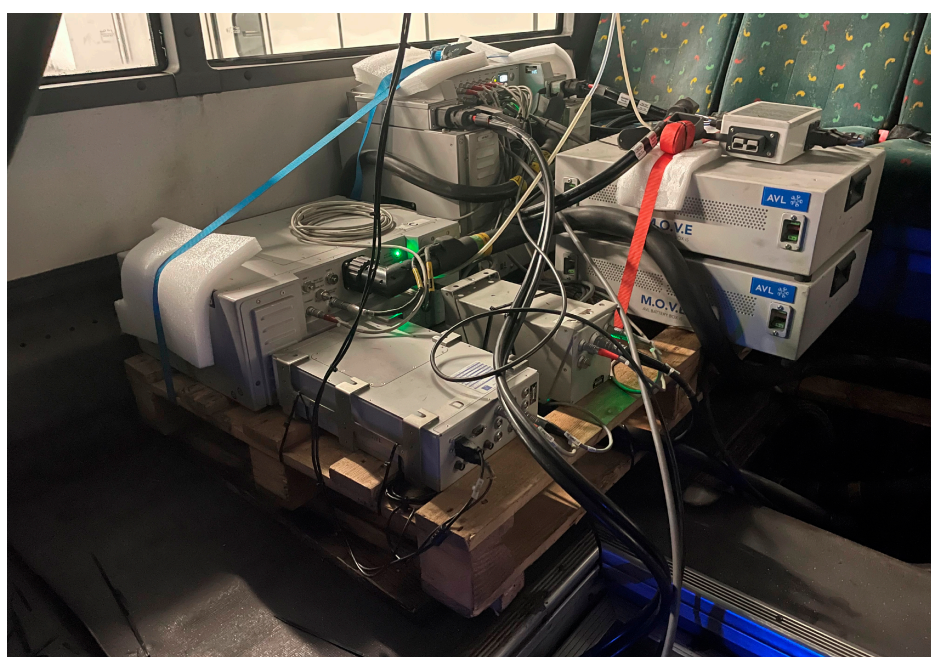


Figure 3. PEMS instruments inside the Euro III bus used for road tests.

Tests were carried out on extra-urban routes, urban routes, and under idling conditions (both cold and hot) to ensure that monitoring activity was as representative as possible of real-world vehicle operation. Both the stationary tests and the on-road measurements were carried out on the same vehicle and using the same AVL Portable Emissions Measurement System (PEMS) instrumentation, ensuring methodological consistency and comparability across all test conditions. No engine calibration or optimization was performed on the test vehicle when operating with HVO. For tests conducted on urban and extra-urban routes, comparability was ensured by controlling the duration of each test. Since each route always has the same length, maintaining the same travel time implied comparable average speeds. When this condition could not be achieved due to traffic conditions, correction factors were applied, as described in the following section. For stationary measurements, repeated test cycles were performed under controlled and reproducible conditions. Each cycle followed the same sequence of operations and had the same duration, including phases of acceleration and steady-state operation at idle engine speed.

The AVL PEMS that was used is a portable system designed to measure vehicle pollutant emissions under real driving conditions (Real Driving Emissions, RDE), overcoming the limitations of laboratory chassis dynamometer tests. The instrument used in this experimental campaign consists of three main units, as detailed in Table 2. The instruments used, which were placed inside the bus, are shown in Figure 3.

Table 2. Instrumentation of the PEMS used in this study. The measurement accuracy and the other characteristics are provided in [5].

Manufacturer Model	Pollutant Measured	Measurement Principle	Measurement Range	Measurement Accuracy
AVL M.O.V.E. Is + "GAS PEMS 492"	CO, CO ₂ , NO, NO ₂	NO, NO ₂ : NDUV (non-dispersive ultraviolet); CO, CO ₂ : NDIR (non-dispersive infrared)	NO: 0–5000 ppm NO ₂ : 0–2500 ppm CO: 0–5 vol. % CO ₂ : 0–20 vol. % N ₂ O: 0–2000 ppm	NO: ±5% NO ₂ : ±5% CO: ±5% CO ₂ : ±2% N ₂ O: ±5%
AVL M.O.V.E. Is + "PN PEMS 496"	PN (particle number, ≥10 nm)	Unipolar diffusion charging (corona discharge) followed by signal measurement with an electrometer in a Faraday cage	~1500–2.5 × 10 ⁷ [# / cm ³]	±25–35%
AVL M.O.V.E. Is + "EFM"	Exhaust flow rate and temperature	Differential pressure (Pitot tube) and thermocouple	~10–4000 kg/h (@100 °C; 2" to 6")	±2% of reading or ±0.3% of full scale, whichever is greater

The instrument used for particulate measurements is not capable of determining particulate matter mass, but instead counts the number of particles, including very fine particles, by means of an Advanced Diffusion Charger (ADC). The ADC principle estimates particle concentration by measuring the electric current generated by charged particles. In particular, the device measures very small, nanometric particles, which are typical of internal combustion processes in diesel and gasoline engines. Current regulations (e.g., Euro VI) require counting only particles larger than 23 nm (PMP standard), whereas with the introduction of Euro 7, particles larger than 10 nm will also need to be considered. The instrument used in this study is already capable of counting particles starting from a diameter of 10 nm.

2.3. Fuels Used in Experimental Campaigns

Emissions were measured while operating the vehicle with different fuels: conventional diesel fuel typically available at Italian fuel stations (B7, containing up to 7% FAME according to EN 590), HVO15 (Eni Diesel+, also available at Italian fuel stations, a blend with 85% diesel and 15% HVO), and HVO70 (a blend with 30% diesel and 70% HVO). This last one was obtained by blending conventional diesel fuel with neat HVO (HVO100), as available in dedicated fuel stations in Italy.

HVO in Italy is primarily produced at the biorefineries of Gela and Porto Marghera, both owned by the ENI group. These facilities were converted to biofuel production in 2019 and 2014, respectively. Additional conversion projects are currently under way, including partial upgrades of the refineries in San Nazzaro de' Burgondi (Pavia) and Priolo (Syracuse), the latter developed in collaboration with Q8. Plans are also in place for the construction of a new biorefinery in Livorno. Feedstocks are sourced from multiple regions. Used cooking oils (UCO), animal fats, and agro-industrial by-products are mainly supplied from Europe. However, large volumes of UCO are also imported from China and Southeast Asia. ENI has also initiated the development of agro-hubs in several African countries, including Kenya, Mozambique, and the Republic of Congo. These agro-hubs aim to produce vegetable oils from crops suitable for marginal or degraded land, thereby avoiding competition with food production. The objective is to cover up to 35% of the feedstock demand of ENI biorefineries by 2025. Recently, the first shipment of vegetable oil produced at the Makueni agro-hub in Kenya was delivered to the Gela biorefinery.

Regarding HVO distribution in Italy, ENI remains the dominant supplier, but other market players are also present. These include Kuwait Petroleum Italia S.p.A., (Q8 brand, Rome, Italy), Costantin S.p.A. (Borgo Veneto, Italy), Socogas Group (Fidenza, Italy), and EKOpaint (Bergamo, Italy). In addition, UTA Edenred (Kleinostheim, Germany) supplies HVO for professional transport fleets. The HVO sold at these stations is either produced by ENI or sourced from other European producers. For the ENI share of the market, which is currently predominant, HVO production is largely based on waste and residue feedstocks. However, the company plans to increase the share of oils from dedicated energy crops to approximately 35% of total feedstock supply. The characteristics of the three fuels used in the experimental campaign are reported in Table 1.

3. Literature Review on the Use of HVO in Internal Combustion Engines and Its Effect on Emissions

The use of HVO in internal combustion engines of homologated vehicles and its effects on atmospheric emissions have been extensively investigated over the past 15–20 years. A comprehensive and recent review of the state of the art regarding HVO can be found in [1,2,6–10].

3.1. NO_x Emissions Reduction

Reduction in NO_x emissions represents a key advantage of HVO compared to both biodiesel and fossil diesel, and this effect has been experimentally confirmed in numerous publications. According to the different types of vehicles involved, it is possible to find references showing NO_x reduction for HVO use in buses [11–13], Heavy-Duty Vehicles (HDV) [14–16], Light Commercial Vehicles (LCV) [17–19] and passenger cars. For this last type of vehicles, it is particularly important to distinguish between different regulatory classes, since up to Euro 6 a, b, c, the aftertreatment system, including Selective Catalytic Reduction (SCR), was not compulsory. In the present study, we classified three different types of passenger cars: Euro 3 and 4, Euro 5, and Euro 6a, b, c. A significant reduction in NO_x emissions has been shown for all the three categories: for Euro 3 and 4 vehicles

in [20,21], for Euro 5 vehicles in [22–24] and for Euro 6a, b, c vehicles in [25–27], among the others. Considering all the 81 references found to be useful for the present work [1–4,6–82], the mean and median of all quantifiable emission reduction data both indicate a 10.0% decrease. A second-level screening of the sources—excluding non-peer-reviewed articles, studies reporting duplicate data, and tests performed on non-representative engines or using fuels not comparable to those available in Europe—yields an average reduction of 11.9% (standard deviation 6.8%). Within this scope, Euro 5 passenger cars exhibit an average reduction of 10%, while Euro 6 a/b/c vehicles show an average reduction of 12.6%. Euro 5 LCV report a reduction of 13%, and Euro 6 ones approximately 10%. Among all the articles considered, some report emission reductions well above these average values. Several bench tests on Euro 6d LCV engines [28–30] document NO_x reductions up to 15% when using HVO instead of fossil diesel (with potential increases up to 60% when engine recalibration is applied). Reference [25] reports a 21% reduction for neat HVO in a Euro 6b passenger car equipped with a Low-NO_x Trap (LNT).

3.2. Particulate Matter Emissions Reduction

Regarding particulate matter (PM) emissions, all the considered 81 references, from [1] to [4] and from [6] to [82], report an average reduction of 43% (standard deviation 16%), with peak values up to 70%. Reductions from 30 to 65% have been reported for buses and HDV in [1,11,12,14] and [13], among others, whereas reductions from 33 to 46% were found for LCV [17,19,28,29]. Studies on passenger cars report a reduction in PM emissions from 27 to 70%, and the vehicles considered range from Euro 3 to Euro 6 a and b [22,23,25].

3.3. Polycyclic Aromatic Hydrocarbons Emissions Reduction

Polycyclic aromatic hydrocarbons (PAHs) are a class of organic compounds consisting of two or more fused benzene rings, composed exclusively of carbon and hydrogen. They are called “aromatic” because their rings exhibit aromatic electronic stability and “polycyclic” because they contain multiple rings. PAHs are mainly formed during incomplete combustion processes involving fuels that contain aromatic structures or aromatic precursors. In conventional diesel engines operating on fossil diesel, PAHs are formed through a complex network of pyrolytic and radical-recombination reactions involving aromatic intermediates and unsaturated species formed during combustion. The use of HVO in diesel engines is associated with a significant reduction in PAH emissions. This phenomenon is attributable both to the molecular composition of the fuel—which lacks aromatic compounds—and to its combustion characteristics. Fossil diesel typically contains 15–35% vol. aromatic species (mono-aromatics, diaromatics, and traces of PAHs). These molecules act as direct precursors for the formation of more complex polycyclic structures during combustion. HVO, on the other hand, consists almost exclusively of linear paraffins and iso-paraffins (saturated C₁₅–C₁₈ alkanes). The hydrotreatment process eliminates double bonds and aromatic structures, producing a mixture free of aromatic and sulfur compounds. From a kinetic perspective, PAH formation requires the presence of aromatic rings or unsaturated species (e.g., acetylene, dienes, benzyl radicals) that act as growth nuclei through mechanisms such as HACA (Hydrogen Abstraction–C₂H₂ Addition) and radical cyclization/condensation pathways. Because HVO contains neither aromatics nor olefins, the availability of such precursors is greatly diminished, limiting the nucleation of polycyclic structures. Regarding HVO combustion characteristics, its significantly higher cetane number compared to conventional diesel improves ignition quality and combustion kinetics, resulting in shorter ignition delay, more controlled combustion, and a reduction in fuel-rich zones. High-temperature fuel-rich regions promote pyrolysis and aromatic nuclei formation, which are key steps in PAH and soot formation. By reducing such con-

ditions, HVO limits PAH formation pathways. The considered references, from [1] to [4] and from [6] to [82], indicate that HVO yields an average PAH emissions reduction of 68.2% (standard deviation 18.2%), with peak reductions of 100% (notably in [31]). Studies that separately evaluate vapor-phase and particle-bound PAHs reveal additional insights: vapor-phase PAHs are reduced by more than 80%, while particle-bound PAHs decrease by approximately 30% [16,32]. Consequently, HVO combustion provides a dual emission reduction benefit: reduced particulate mass (on average 43%, with peak reductions of 70%) and reduced PAH content in the emitted particulate. The reduction in PAH content in particulate emissions from HVO-fueled engines directly lowers the toxicity of the emitted particles. Reference [33] reports the mutagenicity outcomes obtained via Ames testing on particulate collected from the exhaust of three different biofuels. HVO demonstrates a 68% reduction in particulate mutagenicity. The selection criteria for the articles considered remain consistent with those outlined previously; thus, non-peer-reviewed articles, duplicate studies, and tests conducted on engines not representative of real-world driving conditions were excluded.

3.4. Tank-to-Wheel and Well-to-Wheel CO₂ Emissions Reduction

Assessment of CO₂ emissions associated with transport systems can be conducted using different system-boundary definitions. Among the most common approaches are the TTW and WTW analyses, which differ in the scope of the energy chain considered. TTW emissions include only the direct CO₂ emissions generated during the vehicle-use phase, that is, from the conversion of fuel energy into mechanical traction. In this approach, the tank represents the vehicle fuel tank, and the analysis boundary includes only combustion in the internal combustion engine. WTW emissions take a broader perspective, including the entire energy supply chain from feedstock production to end-use in the vehicle. WTW CO₂ emissions comprise two contributions: (1) WTT emissions associated with extraction, production, refining, processing, and distribution of the fuel or electricity; (2) TTW emissions: the direct-use emissions described above. Thus, $WTW = WTT + TTW$. This approach enables consistent comparison among different propulsion technologies (internal combustion, electric, hybrid, hydrogen), as well as evaluation of their overall climate impact, accounting for the energy mix used to produce fuel or electricity. For example, an electric vehicle has zero TTW emissions, but WTW emissions depend on the carbon intensity of the national electrical grid. A biogenic fuel such as HVO exhibits significantly lower WTW CO₂ emissions than fossil fuels due to the characteristics of the carbon cycle, feedstock origin, and methodological boundaries used for emissions accounting. The fundamental difference between fossil and biogenic fuels lies in the origin of the carbon they contain. In fossil fuels, the carbon released as CO₂ during combustion originates from geological reserves isolated from the natural carbon cycle for millions of years; its oxidation results in a net increase in atmospheric CO₂. In biogenic fuels such as HVO, the carbon originates from biomass (vegetable oils, waste oils, animal fats), which previously absorbed atmospheric CO₂ through photosynthesis. The WTT phase for HVO includes biomass cultivation or collection, raw material transportation, hydrotreatment and refining processes, and production of the hydrogen used during processing. WTT emissions can be very low when the feedstock consists of residues and waste (e.g., used cooking oils), avoiding emissions associated with land use. An analysis of references from [1] to [4] and from [6] to [82] reveals that HVO already exhibits lower TTW CO₂ emissions than fossil fuels, due to both its slightly higher H/C ratio (i.e., lower carbon content per MJ) and to improved engine combustion efficiency (higher cetane number and improved ignition quality, potentially reducing specific fuel consumption). On average, the reduction is 3.3% (standard deviation is 1.8%). A 4% reduction has been reported in [18] for LCV, whereas

for passenger cars TTW CO₂ reduction ranges from 3.1 to 6% [21,25,34]. Much larger reductions occur for WTW CO₂ emissions, consistent with the biogenic nature of HVO. Scientific publications from [1] to [4] and from [6] to [82] report an average WTW reduction of 68.6% (standard deviation 7.7%), with peaks of 77.5%. The article selection criteria were the same as described earlier—non-peer-reviewed articles, duplicate studies, and tests on engines not representative of real-world operating conditions were excluded, and lead to a reduced number of articles, among which [10,11,27] are particularly significant.

The mean, median, standard deviation, minimum, and maximum values reported in peer-reviewed publications—excluding results duplicated across multiple studies—for PM, NO_x, TTW CO₂, WTW CO₂, hydrocarbons (HC) and PAH are summarized in Table 3.

Table 3. Mean, median, standard deviation, minimum, and maximum values of decrease reported in references from [1] to [4] and from [6] to [82]—excluding results duplicated across multiple studies and non-peer-reviewed articles—for PM, NO_x, TTW CO₂, WTW CO₂, HC, and PAH in exhaust gas emissions. -5% value means a net increase in NO_x measured in reference [35].

	PM	NO _x	CO ₂ TTW	CO ₂ WTW	HC	PAH
mean	43%	11.86%	5.6%	68.6%	42.99%	68.20%
median	38%	12.35%	3.7%	64.3%	42.00%	60.00%
standard deviation	16%	6.80%	7.4%	7.7%	13.46%	18.02%
min	16%	−5%	0.0%	64.0%	24%	57%
max	70%	30%	26.3%	77.5%	68%	100%

4. Results of the Experimental Campaigns

In total, 13 measurement tests were conducted on 22 October, 31 October, and 14 November 2025: seven idling tests, divided between hot and cold engine start conditions, using diesel, HVO15, and HVO70; two extra-urban tests on the same route (Cuneo–Magliano Alpi), one with diesel and the other with HVO15; and four urban tests on the same route (Cuneo–Borgo San Dalmazzo–Fontanelle–Cuneo), comparing the performance of diesel and HVO70. It should be noted that, during the tests performed on 14 November 2025, only some sections of the entire route could be considered due to the specific test conditions, as they will be discussed later. The characteristics of each measurement are summarized in Table 4. Measurements under idling conditions were performed both at steady idle speed and following a protocol based on a structured sequence of variable engine speeds, designed to reproduce, in a controlled manner, the dynamic conditions encountered during real driving.

Table 4. Monitoring campaign on the use of HVO in public transport vehicles.

Test n.	Date	Test Type	Route	Length (km)	Fuel
1	22 October 2025	Cold idling	stationary test	-	Diesel
3	22 October 2025	Cold idling	stationary test	-	HVO15
3	22 October 2025	Extra-urban	Cuneo–Magliano Alpi	12	Diesel
4	22 October 2025	Hot idling	Cuneo	12	Diesel
5	31 October 2025	Extra-urban	Cuneo–Magliano Alpi	12	HVO15
6	31 October 2025	Hot idling	stationary test	-	HVO70
7	14 November 2025	Urban	Cuneo–Borgo San Dalmazzo–Cuneo	12	HVO70
8	14 November 2025	Urban	Cuneo–Borgo San Dalmazzo–Cuneo	12	Diesel
9	14 November 2025	Hot idling	stationary test	-	Diesel
10	24 November 2025	Urban	Cuneo–Borgo San Dalmazzo–Cuneo	12	Diesel
11	24 November 2025	Hot idling	stationary test	-	Diesel
12	24 November 2025	Urban	Cuneo–Borgo San Dalmazzo–Cuneo	12	HVO70
13	24 November 2025	Hot idling	stationary test	-	HVO70

It is important to clarify from the outset that ensuring the proper comparability of measurements carried out on the same vehicle using different fuels is a critical requirement for the correct interpretation of the resulting data. Comparability depends not only on the selected route—which must be identical for both fuel types—but also on the speed at which the route is driven, as emissions are strongly influenced by this parameter, as clearly illustrated in Figure 4. Furthermore, it is equally essential that comparisons be performed under engine “temperature” conditions that are as similar as possible, so as to avoid cold-start effects masking the influence of the fuel type on atmospheric emissions.

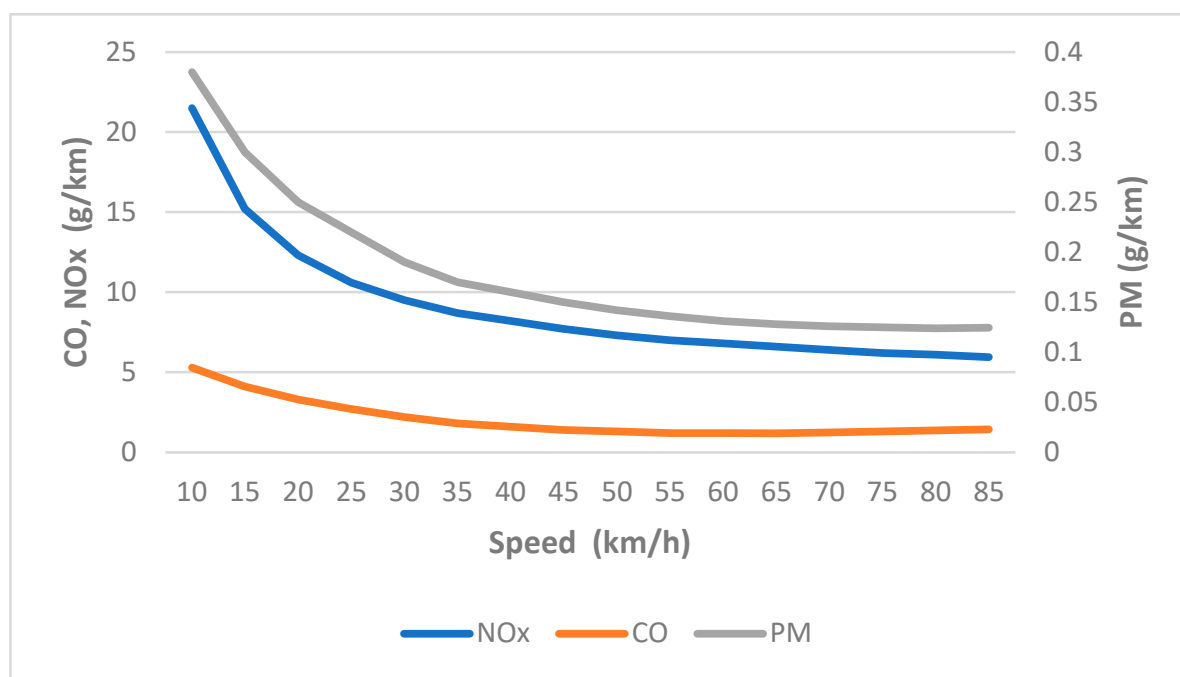


Figure 4. Effect of speed on emissions from a Euro III diesel bus (data from EMEP/EEA air pollutant emission inventory guidebook 2023—update 2025).

An additional aspect that must be considered is the following: while parameters such as carbon monoxide, nitrogen oxides, oxygen, and carbon dioxide can be quantified in terms of mass (i.e., emissions expressed in g or kg per unit of time), this is not possible for particulate emissions. The available instrumentation measures the number of particles contained in a given volume, but it does not provide information on particle size and therefore, even indirectly, on their mass. This implies that comparing the number of particles emitted per unit of time when using different fuels may not accurately reflect the actual particulate mass flows emitted under different operating conditions. Indeed, when switching from diesel fuel to HVO, the mechanism by which the engine generates particles changes substantially. Since HVO contains very low levels of aromatic compounds, it tends to produce significantly less “classical” soot, resulting in markedly lower particulate mass emissions. However, HVO combustion may release, under certain conditions, a greater number of ultrafine particles—below 50 nm associated with nucleation processes, compared with conventional diesel fuel. In such cases, the total particulate mass may decrease while the total particle number increases or behaves less predictably, precisely because the nature of the particulate matter formed changes fundamentally.

With regard to the tests conducted on 22 and 31 October 2025, Table 4 shows that several stationary tests were performed under both cold-start and hot-engine conditions, in addition to measurements carried out along the extra-urban Cuneo–Magliano Alpi route. The tests conducted on the extra-urban route allow for a comparison of nitrogen oxide

emissions between pure diesel and HVO15. The comparison was valid only for the return segment (Magliano Alpi–Cuneo) due to excessively rapid departures with insufficient engine warm-up on both testing days.

Figure 5 presents the comparison of nitrogen oxide emissions (NO + NO₂, expressed as NO₂), showing that the HVO15 blend leads to a reduction of more than 2% in tailpipe nitrogen oxide emissions. This reduction confirms that the beneficial effect of the alternative fuel is proportional to its blending ratio.

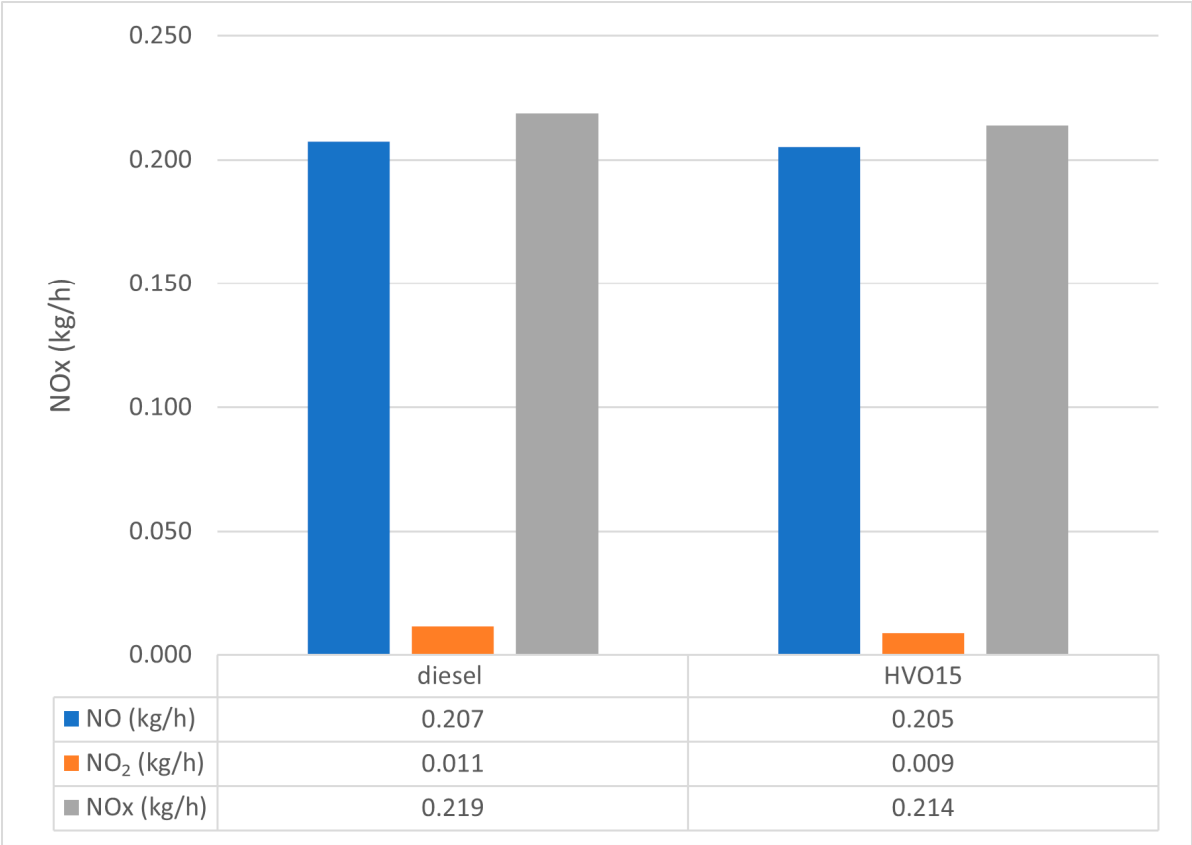


Figure 5. Emission comparison between diesel and HVO15 on an extra-urban route (Cuneo–Magliano Alpi). The measurements were carried out on 31 October 2025. See Section 4.2 for the whole numerical results.

On the same dates, 22 and 31 October 2025, it was possible to measure emissions under different fueling conditions during stationary operation, both immediately after engine start and under fully warmed-up conditions. Although such comparisons are not representative of the mass flows emitted during real-world driving, they are nonetheless extremely valuable for assessing the potential benefits associated with the use of advanced biofuels, even when the engine is not yet at operating temperature and under fully comparable conditions.

Tables 5 and 6 present the results of these tests for pure diesel, HVO15 and HVO70. The results are reported in relative terms. Additional comparisons between stationary tests under hot-engine conditions will be carried out during the measurement campaigns scheduled for 14 and 24 November 2025 and will be discussed in the following sections.

Table 5. Ratio between mass flows emitted during cold-start idling phase by Euro III buses powered with diesel and HVO15.

Cold Idling	Diesel	HVO15	$\Delta\%$
CO	100	48	−52%
NO	100	90.1	−10%
NO ₂	100	93	−7%
NO _x	100	90.4	−10%
PN	100	71.9	−28%

Table 6. Ratio between mass flows emitted during hot-start idling phase by Euro III buses powered with diesel and HVO70.

Hot Idling	Diesel	HVO70	$\Delta\%$
CO	100	59.2	−41%
NO	100	86.1	−14%
NO ₂	100	67	−33%
NO _x	100	83.9	−16%
PN	100	68.5	−32%

On 14 November 2025, measurements were conducted on the same public-transport vehicle along a more typically urban route, namely the Cuneo–Borgo San Dalmazzo–Fontanelle–Cuneo loop. The objective of this measurement campaign was to compare vehicle operation on conventional diesel with operation on HVO70.

During this campaign, the same route was driven at significantly different average speeds: specifically, the first run, carried out with HVO70 blend, was driven at a substantially lower average speed than the second run performed with traditional diesel. As previously noted, this condition compromises the comparability of the measured emission flows. As shown in Figure 5 for the specific vehicle used (data derived from the COPERT model employed in the EMEP/EEA air pollutant emission inventory guidebook 2023—update 2025), within the relevant operating range, higher vehicle speed is associated with lower specific emissions expressed in g/km.

Despite the inconvenience encountered, several sections of the overall route were analyzed—each fully corresponding between the two fueling conditions (same starting point and same end point), one on the outbound leg and one on the return leg—in which the average driving speeds were less dissimilar, although a noticeable deviation in favor of the diesel-fueled run was still observed (see Tables 7 and 8). As highlighted, in the sections analyzed, the use of an advanced biofuel at high blend ratios provides emission benefits both for nitrogen oxides—albeit marginal—and more markedly for particle number emissions. However, when accounting for the emission disadvantage associated with the lower driving speed of the HVO run (reported as a percentage at the bottom of the tables), the actual reduction in nitrogen oxide emissions would have been substantially higher and fully consistent with the scientific literature, where reductions of approximately 20% in NO_x emissions are expected for operation on pure HVO. The approach is based on the emission factor curves reported in Figure 5, which describe the relationship between vehicle speed and emission factors for the investigated pollutants. By using the average speeds recorded during the tests performed on the same route with diesel and HVO blends, it is possible to enter the diagram shown in Figure 5 and derive the corresponding emission factors for each operating condition. This allows the calculation of relative emission factors and their percentage ratio. These ratios were reported in Tables 7 and 8 as the ones to be used to correct the measured values, thereby reducing the influence of differences in driving dynamics.

Table 7. Emission comparison between diesel and HVO70 on a Euro III diesel bus on part of the urban route Cuneo–Borgo San Dalmazzo–Cuneo loop (San Rocco Castagnaretta–Fontanelle section, tests of 14 November 2025).

Time Interval [s]	Fuel	Speed [km/h]	Flow Rate [m ³ /s]	CO [kg/h]	CO ₂ [kg/h]	NO [kg/h]	NO ₂ [kg/h]	NO _x [kg/h]	PN [G#/h]
1010	HVO70	28.40	0.094	0.090	17.956	0.266	0.009	0.275	5,346,719
870	diesel	33.14	0.103	0.109	19.594	0.273	0.009	0.281	7,207,141
–14.3%				–18.8%	–8.4%	–2.5%	9.6%	–2.1%	–25.8%
Correction for speed difference				–16.8%				–10.8%	–13.6%
Reduction after speed correction				–35.6%				–12.9%	–39.4%

Table 8. Emission comparison between diesel and HVO70 on a Euro III diesel bus on part of the urban route Cuneo–Borgo San Dalmazzo–Cuneo loop (Borgo San Giuseppe–Cuneo section, tests of 14 November 2025).

Time Interval [s]	Fuel	Speed [km/h]	Flow Rate [m ³ /s]	CO [kg/h]	CO ₂ [kg/h]	NO [kg/h]	NO ₂ [kg/h]	NO _x [kg/h]	PN [G#/h]
630	HVO70	22.22	0.08	0.083	15.28	0.224	0.011	0.235	4,475,314
490	diesel	27.73	0.088	0.056	16.205	0.226	0.012	0.238	5,302,854
–19.9%				+49.9%	–5.7%	–0.9%	–10.5%	–1.4%	–15.6%
Correction for speed difference				–25.0%				–16.6%	–18.4%
Reduction after speed correction				+24.9%				–18.0%	–34.0%

On the same date, 14 November 2025, an additional hot-engine stationary test using diesel fuel was performed upon completion of the second run along the selected route. On 24 November, the test on the Cuneo–Borgo San Dalmazzo–Fontanelle–Cuneo route was repeated, taking particular care to ensure both proper engine warm-up and closely matched driving speeds. This approach was adopted to obtain a long-duration test that is fully comparable to the two fueling conditions under investigation. Table 9 presents the results of the measurements carried out on that day along the designated urban route. Also on 24 November 2025, hot-engine stationary tests were performed following a predefined sequence of varying engine speeds. Figures 6–9 illustrate the minute-by-minute emission trends of CO, NO_x, particle number, and CO₂ for both fueling configurations on the Cuneo–Borgo San Dalmazzo–Fontanelle–Cuneo route.

Table 9. Emission comparison between diesel and HVO70 on a Euro III diesel bus on the full length of urban route Cuneo–Borgo San Dalmazzo–Cuneo (tests of 24 November 2025).

Time Interval [s]	Fuel	Speed [km/h]	Flow Rate [m ³ /s]	CO [kg/h]	CO ₂ [kg/h]	NO [kg/h]	NO ₂ [kg/h]	NO _x [kg/h]	PN [G#/h]
2750	HVO70	29.24	0.087	0.083	14.905	0.226	0.010	0.235	4,957,839
2650	diesel	30.31	0.091	0.128	17.017	0.294	0.012	0.306	5,718,193
–3.5%				–34.9%	–12.4%	–23.3%	–17.1%	–23.0%	5.1%

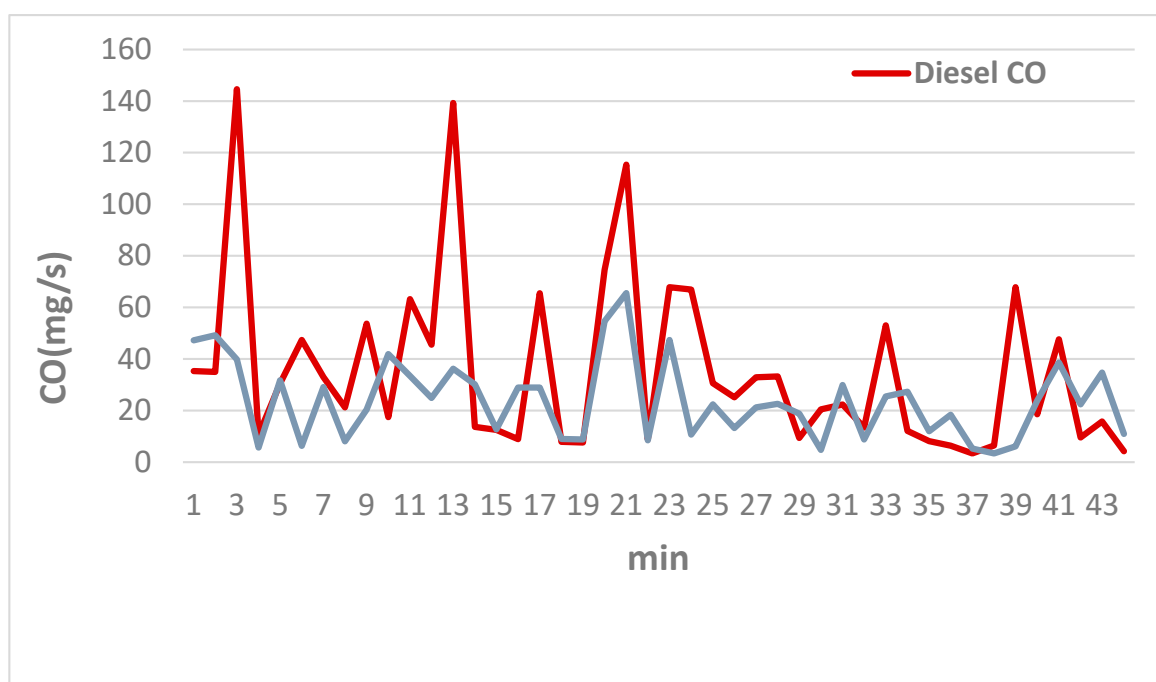


Figure 6. Comparison of CO emissions between traditional diesel (red line) and HVO70 blend (blue line) for a Euro III diesel bus on an urban route (Cuneo–Borgo San Dalmazzo–Fontanelle–Cuneo).

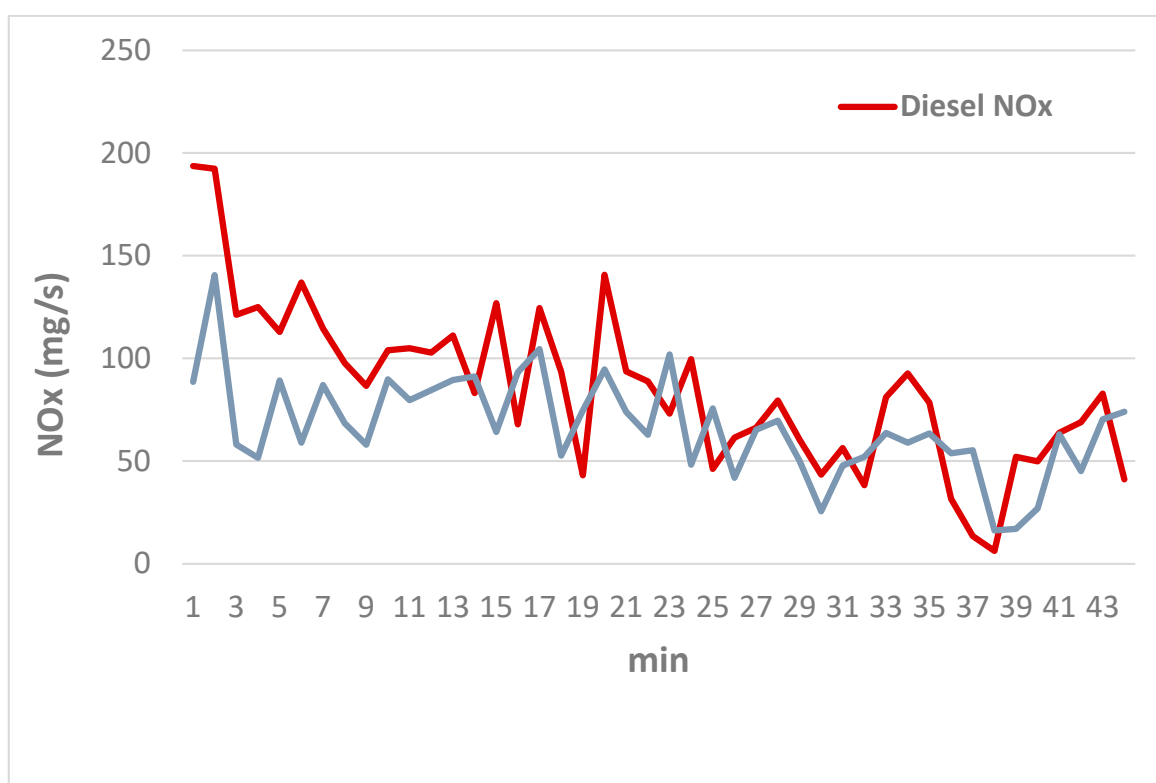


Figure 7. NO_x emissions comparison between traditional diesel (red line) and HVO70 blend (blue line) for a Euro III diesel bus on an urban route (Cuneo–Borgo San Dalmazzo–Fontanelle–Cuneo).

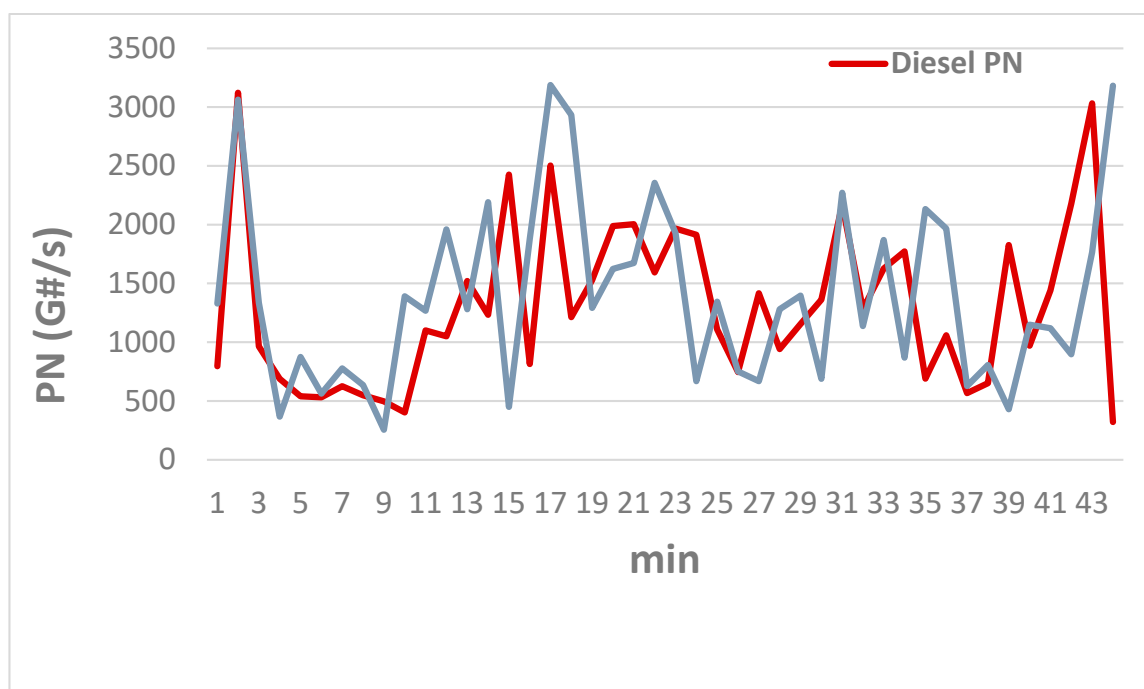


Figure 8. PN emissions comparison between traditional diesel (red line) and HVO70 blend (blue line) for a Euro III diesel bus on an urban route (Cuneo–Borgo San Dalmazzo–Fontanelle–Cuneo).

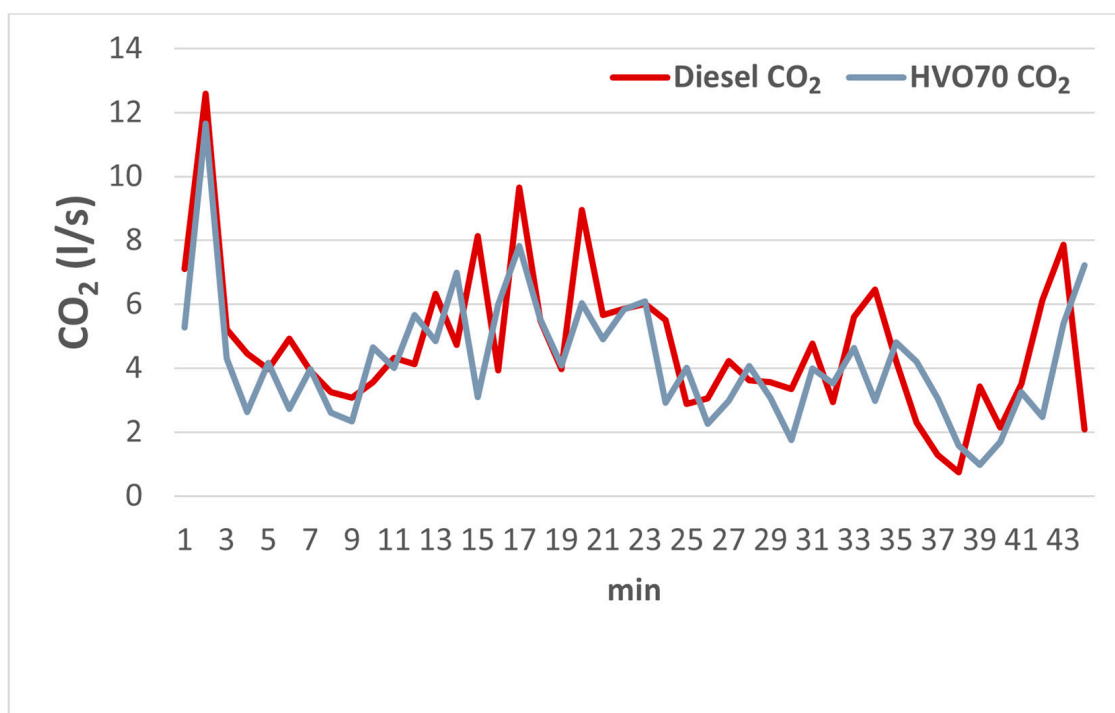


Figure 9. CO₂ emission comparison between traditional diesel (red line) and HVO70 blend (blue line) for a Euro III diesel bus on an urban route (Cuneo–Borgo San Dalmazzo–Fontanelle–Cuneo).

4.1. Engine Idle Phase Measurements

In the following sections, the data and graphs related to the emission performance measured during stationary tests—carried out using diesel fuel, HVO15, and HVO70—will be presented. Data are reported in Table 10.

Table 10. Emission comparison between diesel, HVO15, and HVO70 for a Euro III diesel bus in different stationary phases.

Cold Idling 22 October 2025									
Time Interval [s]	Fuel	Speed [km/h]	Flow Rate [m ³ /s]	CO [kg/h]	CO ₂ [kg/h]	NO [kg/h]	NO ₂ [kg/h]	NO _x [kg/h]	PN [G#/h]
626	diesel	-	0.039	0.132	6.965	0.168	0.021	0.189	2,525,540
1013	HVO15	-	0.031	0.063	5.619	0.151	0.020	0.171	1,816,878
Hot Idling 22 October 2025 (diesel), 31 October 2025 (HVO70) and 14 November 2025 (diesel)									
2758	diesel	-	0.031	0.019	2.625	0.069	0.009	0.078	718,760
1426	HVO70	-	0.031	0.011	2.556	0.059	0.006	0.065	492,373
1375	diesel	-	0.031	0.013	2.733	0.074	0.008	0.082	581,651
Hot Idling (high revs.) 24 November 2025									
360	diesel	-	0.085	0.039	7.543	0.121	0.018	0.139	2,837,382
360	HVO70	-	0.051	0.018	3.93	0.062	0.008	0.070	1,051,543

The results of the stationary tests show an overall favorable behavior of HVO compared to conventional diesel, with clear differences for certain pollutants and more nuanced variations for others. Starting with carbon monoxide, CO emissions are consistently lower when using HVO under all engine operating conditions. This effect is particularly evident during the cold-idle phase, where combustion is naturally more challenging: even at a blend ratio as low as 15%, HVO—thanks to its higher cetane number and absence of aromatic compounds—promotes more complete combustion, thereby reducing the formation of intermediate products such as CO. In the hot-idle phase and at higher engine speeds, the paraffinic fuel, this time at higher blend levels (HVO70), continues to ensure cleaner combustion, resulting in systematically lower CO levels than those recorded for fossil diesel.

The behavior of nitrogen oxides is more complex. NO_x emissions are always reduced when HVO is used, even at low blending ratios (such as HVO15 in the cold-idle test). Greater reductions can be observed under hot-idle conditions and see a more notable decrease at higher engine speeds, although in this latter case the observed difference may depend not only on the intrinsic properties of the fuel but also on slight variations in operating conditions during the tests (load, EGR rate, exhaust gas temperature). The NO_x emission behavior clearly reflects the characteristics of this advanced biofuel: its higher cetane number leads to a shorter ignition delay, a more gradual combustion process, and a lower peak temperature in the combustion chamber.

The reduction in particle number (PN) emissions with the biofuel is particularly pronounced. In the stationary tests performed, HVO consistently produces a lower particle number than diesel fuel, both in cold- and hot-idle conditions, and up to the highest load levels. This behavior is expected for paraffinic fuels, which contain no aromatic compounds and therefore tend to form less soot during combustion. It is, however, important to recall that PN measures the number of particles rather than their mass: it is therefore not possible to automatically infer a proportional reduction in particulate mass concentration (mg/m³), as mass depends on particle size, structure, and composition. Nevertheless, the observed decrease in PN remains a clear indicator of cleaner combustion with respect to particulate formation under the conditions analyzed. Figure 10 summarizes all the previous results.

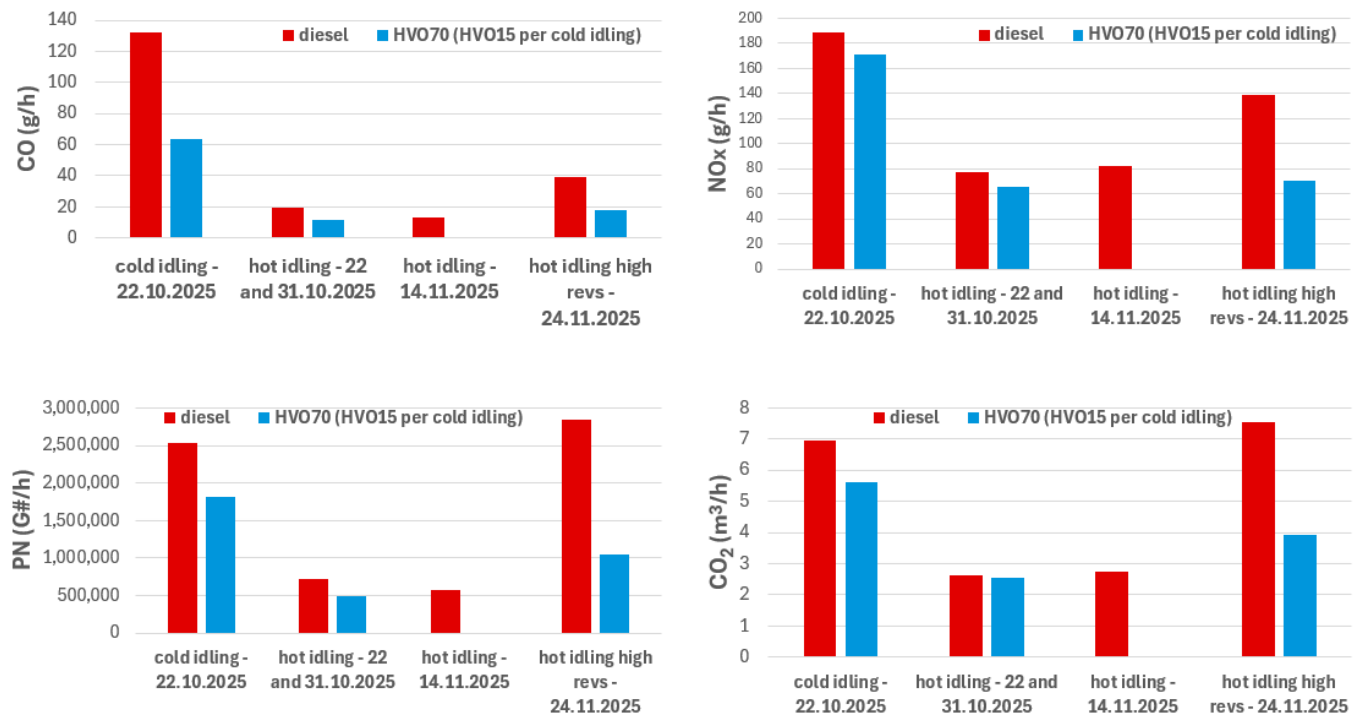


Figure 10. CO₂, CO, PM and NO_x emission comparison between traditional diesel and HVO70 (HVO15 in the first cold test) for a Euro III diesel bus during stationary tests.

Perhaps the most interesting result concerns CO₂. Here, as well, HVO shows lower values under all operating conditions. In this case, however, the interpretation is not related to the biogenic origin of CO₂ (which is not the focus of the test), but rather to the energy behavior of the system. HVO has a slightly higher energy content than diesel on a mass basis, but due to its lower density, its volumetric energy density is lower (8100 kcal/L versus 8600 kcal/L for diesel). For the same power demand, the engine would therefore be expected to consume a larger volume of HVO—approximately 2–5% more—than the corresponding amount of diesel. This would suggest that CO₂ emissions from HVO should be higher than those from diesel, were it not for the fact that one liter of HVO contains roughly 10% less carbon than one liter of diesel. As a result, CO₂ emissions from HVO should be approximately 5% lower than those of diesel for the same duty cycle. The same conclusion can be reached by comparing the carbon content per unit of fuel energy (68.7 g/kWh for HVO versus 72.5 g/kWh for diesel).

If the measurements show a reduction greater than 5%, this indicates that—in that specific test—HVO performed better than expected from an energy standpoint, consuming less fuel than predicted. The smaller differences observed under hot-idle conditions are entirely plausible, while the more pronounced decrease at higher engine speeds may be the combined result of an actual difference in fuel consumption and slight operational variations between the two test runs.

4.2. Real Driving Measurements

In the following sections, the data and graphs related to the emission performance of diesel fuel and HVO—blended at 15% and 70%—as measured during the driving tests (real-drive conditions) will be presented. See Table 11 for the data.

Table 11. Emission comparison between diesel, HVO15, and HVO70 for a Euro III diesel bus in different real-driving conditions.

Extra-Urban Route Cuneo–Magliano Alpi 31 October 2025									
Time Interval [s]	Fuel	Speed [km/h]	Flow Rate [m ³ /s]	CO [kg/h]	CO ₂ [kg/h]	NO [kg/h]	NO ₂ [kg/h]	NO _x [kg/h]	PN [G#/h]
3974	diesel	39.31	0.096	0.060	15.078	0.207	0.011	0.219	4,690,535
4023	HVO15	40.26	0.092	0.121	16.711	0.205	0.009	0.214	5,367,884
Urban Route Cuneo–Borgo San Dalmazzo–Cuneo 14 November 2025 (partial)									
870	diesel	33.14	0.103	0.109	19.594	0.273	0.009	0.281	7,207,141
1010	HVO70	28.40	0.094	0.09	17.956	0.266	0.009	0.275	5,346,719
Urban Route Cuneo–Borgo San Dalmazzo–Cuneo 14 November 2025 (partial)									
490	diesel	27.73	0.088	0.056	16.205	0.226	0.012	0.238	5,302,854
630	HVO70	22.22	0.080	0.083	15.280	0.224	0.011	0.235	4,475,314
Urban Route Cuneo–Borgo San Dalmazzo–Cuneo 24 November 2025									
2650	diesel	30.34	0.091	0.128	17.017	0.294	0.012	0.306	4,718,193
2750	HVO70	29.39	0.087	0.083	14.905	0.226	0.010	0.235	4,957,839

The results of the on-road tests show an overall pattern consistent with what was observed under stationary conditions, although there are some variations attributable to real-world operating conditions, which in the case of on-road testing can significantly influence emissions.

With regard to carbon monoxide, the behavior of the vehicle running on HVO is less linear than in the stationary phase. In the first extra-urban segment (Magliano Alpi–Cuneo), CO emissions are higher with HVO than with diesel. This deviation, however, can be explained by the specific circumstances of the initial tests: the vehicle started from a cold engine state, and the initial phase was not fully controlled. In the following two urban segments, CO levels are in one case higher and in another lower for HVO compared to diesel; however, it should be noted that in both segments the HVO-fueled runs were driven at substantially lower speeds—14% and 20% lower, respectively—than the corresponding diesel runs. If one accounts for the worsening effect that lower speed typically has on CO emissions (as well as on NO_x and particulate emissions), as suggested in Table 6, the resulting emission performance would be favorable to HVO, in line with what was found in the stationary tests.

NO_x emissions in the real-driving tests fully confirm the expectations from the literature, which estimate a 20% reduction in emissions when using neat HVO. Indeed, even the use of HVO at low blend ratios (HVO15) results in a proportional reduction compared to the benchmark associated with HVO100: in the first Magliano Alpi–Cuneo segment, emissions decrease by about 2.2%, a value corresponding to an estimated 15% reduction if extrapolated to HVO100 configuration. In the subsequent urban segments, the emission benefits of HVO70—after adjusting for the reduced average speed relative to conventional diesel—fall within the range of 13–18%. Finally, in the last segment, conducted at controlled speed and with the engine operating at full load for both fuels, the NO_x reduction attributable to HVO reaches 23%.

Regarding particle number (PN), it is not possible to draw unequivocal conclusions in favor of one fuel over the other. It remains important to reiterate that PN reflects the number of emitted particles, not their mass; a reduction in PN therefore indicates a lower formation of nuclei but does not directly quantify changes in the total particulate mass generated. Figure 11 summarizes all the previous results.

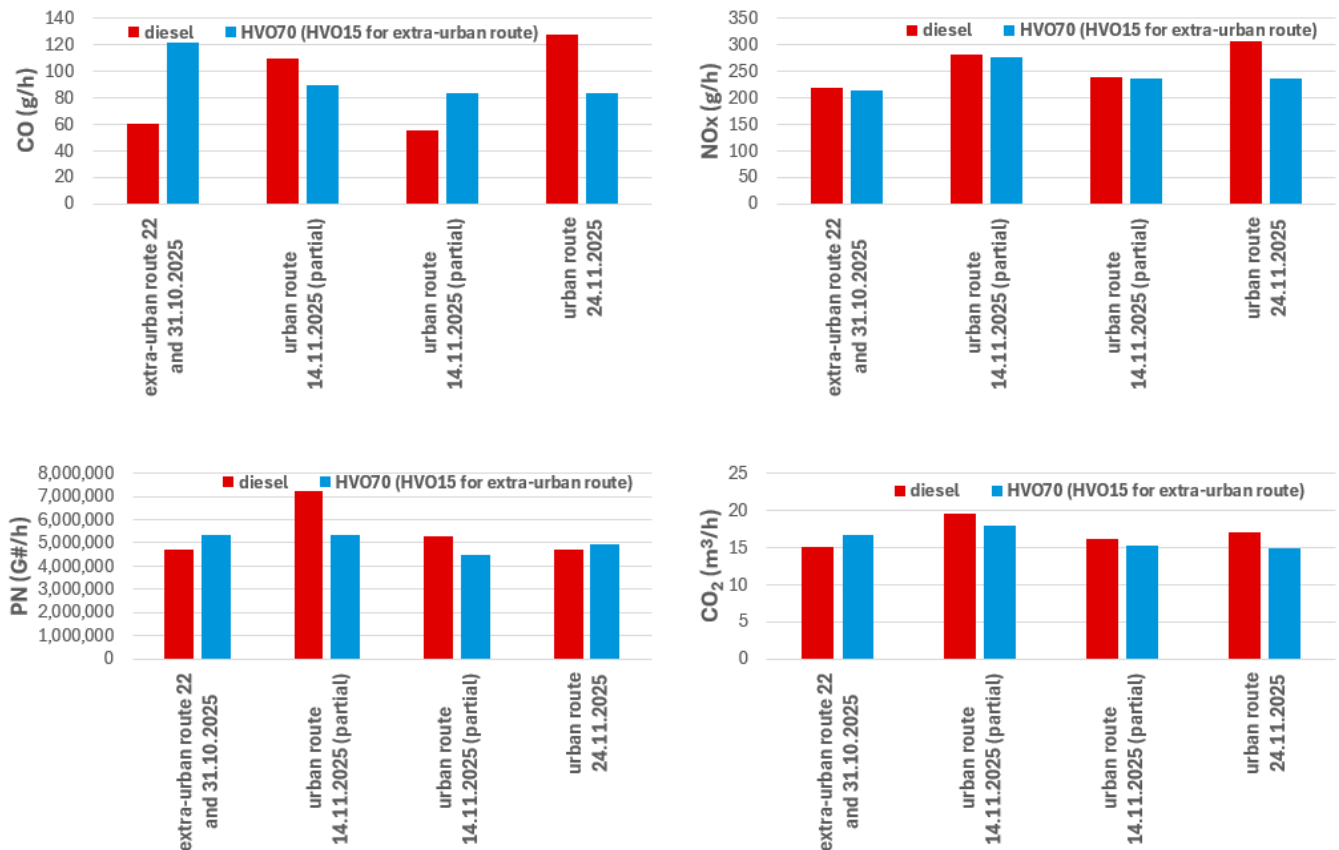


Figure 11. Emission comparison between traditional diesel and HVO70 (HVO15 is used in the first extra-urban section) for a Euro III diesel bus during on-road tests.

For completeness, it should be noted that the particle concentrations measured during the October–November 2025 campaigns on the Euro 3 diesel vehicle approaching end of life—ranging between 11 and 16 million particles per cm³—were approximately twice as high as those recorded in previous regional measurement campaigns on Euro 2, Euro 3 and Euro 5 buses not equipped with particulate filters (Figure 12).

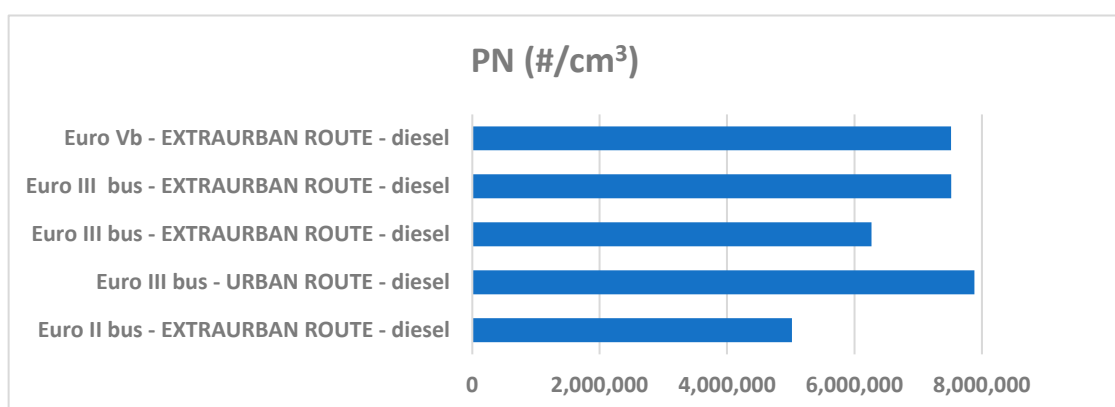


Figure 12. Particulate matter emissions from vehicles without particulate filters.

Finally, CO₂ shows an overall trend similar to that observed under stationary conditions, although attenuated by the transients inherent to real-world driving. Only in the first extra-urban measurement does CO₂ increase with HVO, once again reflecting the atypical conditions associated with the cold start and the uncontrolled initial segment of the route. In the subsequent urban segments, CO₂ emissions decrease by 6–12% when operating

on HVO70, suggesting a possible improvement in the energy efficiency of the advanced biofuel.

Overall, the results are consistent with what can be expected from a paraffinic fuel such as HVO: more complete combustion, a tendency to reduce CO and particulate emissions, and lower nitrogen oxide emissions. A potential improvement relative to expected fuel consumption—indirectly inferred through CO₂ emissions—also appears plausible. A holistic interpretation therefore confirms the superior “emission performance” of HVO compared with diesel under the tested conditions. This conclusion is further reinforced by the fact that the tests were conducted without any prior engine calibration aimed at optimizing or enhancing the combustion characteristics of the advanced biofuel; moreover, HVO was used in blends still far from its neat form (HVO70 rather than HVO100), leaving room for additional potential improvements.

5. Conclusions

The measurement campaign conducted with PEMS instrumentation on an urban public transport vehicle of Euro III category made it possible to evaluate, under real-world driving conditions, the emission effects associated with the use of fuels containing HVO, both at low blend ratios (HVO15) and high blend ratios (HVO70), in comparison with conventional diesel fuel. While the analysis is based on a limited number of vehicles and test cycles, it provides useful, indicative insights into the potential emission behavior of such fuels under operational conditions.

The results obtained appear to be broadly consistent with the framework outlined in the available scientific literature, which attributes to HVO an overall more favorable emission profile than fossil diesel. At the same time, it should be noted that most studies are based on engine bench testing or standardized chassis cycles, and that experimental evidence under RDE conditions remains relatively limited.

The stationary tests, although not representative of total emissions under RDE, indicate potential benefits of HVO in terms of combustion quality. Under all conditions examined—cold engine, warm engine, and high-speed operation—the use of HVO was associated with a reduction in carbon monoxide emissions, consistent with its higher cetane number and lack of aromatic compounds, which promote more complete combustion. Nitrogen oxide emissions were also generally lower than those of diesel, with more pronounced reductions at higher HVO blend ratios and under warm engine conditions, in line with findings reported in the literature for paraffinic fuels.

The reduction in PN observed during the stationary tests, both in cold and warm operation, is also noteworthy. This result is consistent with the chemistry of HVO, which tends to limit soot formation compared to traditional diesel. However, it is important to reiterate that PN quantifies only the number of particles, not their mass: a reduction in particle count cannot be directly translated into a proportional reduction in particulate mass, although it remains an indicator of a potentially different—and often more favorable—mechanism of PM formation.

The measurements performed under RDE conditions represent the most relevant component of the campaign, as they allow for a direct comparison of the emission performance of the various fuels in a context representative of the vehicle’s actual daily service. Nevertheless, some limitations were present—such as differences in driving speed and cold-start conditions during the initial test days, as well as the limited number of repetitions—which should be taken into account when interpreting the results. Despite these constraints, the overall trends observed are generally consistent with theoretical expectations and laboratory evidence from the available scientific literature.

In particular, the NO_x emissions measured during the urban and extra-urban routes suggest a reduction potential associated with HVO use. Even the use of HVO15 is associated with a decrease in NO_x emissions, while high-blend usage (HVO70), after accounting for differences in average driving speed, leads to estimated reductions ranging from approximately 13% to 18%. In the final urban test, conducted under carefully controlled and comparable conditions for both fuels, the NO_x reduction reaches 23%. While this value is higher than the average 10.0% reductions reported in the literature for neat HVO, it should be interpreted with caution given the limited dataset.

The behavior of PN during RDE is more variable, reflecting the complexity of particulate formation mechanisms under dynamic conditions and the sensitivity of PN to driving transients. As such, no definitive trend can be established based on the available measurements alone.

Regarding CO₂, the measurements show a generally favorable trend for HVO, particularly in the controlled urban tests. This result can be interpreted, in this context, not in terms of carbon renewability, but as an indirect indicator of fuel consumption. Given the lower volumetric energy density of HVO compared to diesel, the observed CO₂ reductions—sometimes greater than 5%—may suggest a potential improvement in energy efficiency under the tested conditions, although further investigation would be required to confirm this effect.

Overall, the measurement campaign indicates that the use of HVO, even in blended form and without engine calibration specifically optimized for this fuel, may provide emission benefits on a Euro III diesel vehicle not equipped with advanced after-treatment systems. The results obtained under RDE conditions are broadly aligned with laboratory evidence reported in the literature, while also offering preliminary operational validation. However, given the limited experimental scope, these findings should be considered indicative rather than conclusive.

In light of these findings, it can be hypothesized that further improvements could be achieved through the use of neat HVO and through specific engine calibration, especially for older vehicles. Within these boundaries, HVO may represent a potentially effective and readily deployable option in strategies aimed at improving air quality in local public transport systems as well as in private vehicle use, although additional studies on larger samples and more extensive test cycles would be beneficial to strengthen these conclusions.

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Abbreviations

The following abbreviations are used in this manuscript:

HVO	Hydrotreated Vegetable Oil
FAME	Fatty Acid Methyl Esters
TtW	Tank-to-Wheel
WtW	Well-to-Wheel
PEMS	Portable Emissions Monitoring System
RDE	Real Driving Emissions
EGR	Exhaust Gas Recirculation
ADC	Advanced Diffusion Charger
HDV	Heavy-Duty Vehicle
LCV	Light Commercial Vehicle
LNT	Low-NO _x Trap
PM	Particulate Matter
PAH	Polycyclic aromatic hydrocarbons
HACA	Hydrogen Abstraction–C ₂ H ₂ Addition
HC	Hydrocarbons
PN	Particulate Number
RED	Renewable Energy Directive
RFNBO	Renewable fuels of non-biological origin

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