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ORIGINAL PAPER

Endurance results of a refuels fleet test in a real application based on directly comparable truck test pairs

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Abstract

Synthetic fuels from a renewable base are an essential part of a greenhouse gas-neutral mobility, especially in transport sector. While scaling production of e-fuels (fuels based on electrolysis hydrogen) is ongoing, HVO called paraffinic diesel fuels are already available. Their production is based on the hydrogenation of waste and residues and they are established as diesel substitute in several applications. With regard to the approval of these fuels in German regulation, the question repeatedly arises as to whether they can be used easily and what effects can be achieved. This article describes an application in a real logistics application, in which both the everyday use and the concrete comparability to a refueling with conventional gas station diesel were ensured. The use of several parallel active and different truck pairs has shown that the use of HVO in existing vehicles has achieved the desired CO_2 reduction. A detailed analysis of the engine oil also showed that no undesirable effects could be observed here either. From the perspective of this project, HVO fuels are ready for use for a significant greenhouse gas reduction in logistics.

Keywords reFuels · Regenerative fuels · HVO · Greenhouse gas reduction · Oil analysis · Fleet testing · Logistics

Abbreviations

BimSchV	Ordinance on the German Implementation of the Federal Immission Control Act
Bio-Fuel	Fuel from biogenic sources (conventional and advanced)
CFPP	Cold Filter Plugging Point
CO2e	Carbon dioxide equivalent
Diesel B7	Fossil diesel with a maximum of 7% FAME
e-Fuel	Synthetic fuel based on electrolysis hydrogen
EU	European Union

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FAME	Fatty acid methyl ester
HVO	Hydrogenated vegetable fat as an example of an advanced biofuel
ILUC	Indirect Land Use Change
JIS	Just-In-Sequence
Nox	Nitrogen oxides
REDII	Renewable Energy Directive Issue Two
reFuels	Synthetic fuels from renewable sources (e-fuels + bio-fuels)
GHG	Greenhouse gas
SO_2	Sulfur dioxide

1 reFuels as a building block on the way to greenhouse gas-neutral mobility

Reducing the concentration of greenhouse gas emissions is not only an important issue in principle, but also a very time-critical task due to the accumulation of CO_2. The European Union EU's "Fit for 55" action package (1) therefore contains numerous measures in all sectors. The longer the effect of these measures is delayed, the greater the reducing effect of measures must be in the remaining time until 2030, for example. In this context, the term "residual CO_2 budget" is often used (2).

Regarding mobility, many of the measures discussed are linked to a change of the vehicle fleet. However, such a fleet change also limits the effectiveness that can be achieved in a limited period of time. With a view to the above-mentioned residual budget, it is therefore important, to use all possible measures. One measure that leverages its effect with the volume of the existing fleet is the replacement of fossil fuels with fuels from renewable sources. As different types of synthetic fuels are named differently depending on the synthesis method and source raw material and the number of designations are confusing for end users and private individuals, the artificial term reFuels has been introduced in the past (3), which combines all fuels from renewable sources within the fuels standardized in the EU (petrol fuels according to DIN EN228:2017 (4), diesel fuels according to DIN EN590:2022 (5) and DIN EN15940:2023 (6)).

In order to be used quickly in the fleet, the corresponding synthesis paths need the corresponding technology maturity levels. Figure 1 shows the relevant material and synthesis pathways from today's perspective. For the group of e-fuels, fuels are based on electrolysis hydrogen and a carbon source extracted directly or indirectly from the atmosphere. Their scaling issue is based on the necessity of additional synthesis infrastructure and additional energy infrastructure from renewable sources in parallel. This infrastructure is installed at locations where energy from renewable sources is abundant and therefore foreseeably available without limitation, and without competing with other sectors. These new installations therefore enable low energy cost and product costs. This means that time scales of three to four years are realistic for a corresponding scaling step. Already available on the market today are the products shown in the left part of Fig. 1.

The most prominent example of these fuels is HVO fuel. The term HVO stands for hydrogenated vegetable oil and describes the first implementations of this technology. Today, the effects of indirect land use change have been taken into account for these fuels and the source materials have been adapted accordingly. In Germany, in accordance with the provisions of the 38th BImSchV (7), only organic residues and waste materials from traceable sources are used and potentially ILUC-critical (indirect land use change) resources such as palm oil are excluded. Publicly, the example of used cooking fat is often used here, but many other

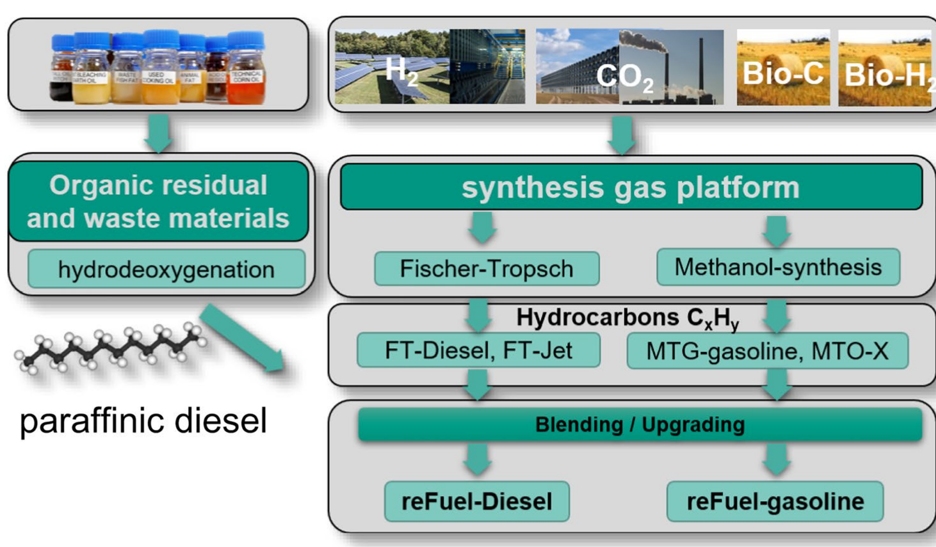

Fig. 1 Key material flows for reFuels synthesis paths for near-term use

residual and waste materials are used in production. Since 2023, the production facilities of all major European manufacturers have switched to corresponding raw materials.

The relevant differing physical characteristics of these diesel fuels are a slightly reduced gravimetric density and a slightly higher cetane number Compared to fossil diesel.

It is noticeable here that, with a comparable calorific value, the density is lower than specified in the standard for petrol station diesel and the cetane number is higher. As these parameters deviate from those of fossil diesel due to the process and similar values are also found in all diesel e-fuels synthesized using the Fischer–Tropsch process, we refer to paraffinic diesels, which are specified in the DIN EN15940:2023 standard.

The current version of the above-mentioned regulation is limited to the use of diesel in accordance with DIN EN590:2022, whereby the addition of the 10th BImSchV, which regulates filling station fuels (8) has already been decided (9) to be implemented nearby.

The deviations in the physical and chemical parameters give rise to the question of how existing engines and vehicles behave with these fuels in real-life applications. In 2020, the authors of this article launched an endurance run as part of the project "reFuels—Rethinking Fuels" to investigate this issue as closely as possible to the application and their use in daily business. Many comparative endurance runs in real-life applications are difficult to be evaluated, as the results are usually only available as the mean value of a large number of influencing factors. For this reason, in this case, up to five test pairs of two identical trucks each were operated comparatively with similar loads on the same route and day, and their results were analyzed. Seven further HVO-fueled vehicles were added during the project phase.

2 Motivation of transport logistics at Porsche for the research project

Porsche AG as a company aims to be CO_2 neutral across the entire value chain by 2030. This includes Porsche Logistics as a contributor. Porsche AG's logistics department is therefore endeavoring to exploit existing potential for CO_{2e} reduction. Numerous decarbonization and defossilization measures are continuously identified and implemented.

First and foremost in logistics are measures to avoid CO_{2e} emissions. One concrete example of implementation is the use of so-called long trucks for material delivery (inbound logistics) and finished vehicle transport (outbound logistics) or the use of rail (with electricity from renewable sources) instead of trucks. Using larger transport carriers for a volume to be transported, journeys can be saved completely.

In second place are measures to reduce CO_{2e} emissions in the inbound and outbound transport chain. Specifically, this can mean the use of more sustainable fuels (biogas instead of fossil gas; reFuels instead of diesel B7), as well as the use of alternative truck drive technologies (e.g., electric, fuel cell, etc. instead of diesel).

The heavy goods transport sector is currently only at the beginning of its transformation away from fossil diesel engines toward alternative solutions. For some time now, Porsche has left no stone unturned in its efforts to find technical and economical alternative solutions to defossilize transport. As truck transport in the articulated lorry sector still has to gain market penetration by means of electric and/or hydrogen drive, reFuels are an attractive and already usable solution for saving CO_{2e} emissions. Due to the fact that they are fundamentally based on an existing, proven and reliable diesel technology in heavy-duty transport, Porsche sees this as a piece of the puzzle for achieving the desired emissions target. In 2019, Porsche Logistics therefore decided to carry out a long-term project together with various strong partners under coordination of the KIT project "reFuels—Rethinking Fuels". Since 2020, up to a dozen trucks running on 100% reFuels (HVO) have been supplying the Stuttgart–Zuffenhausen site for series production of the sports cars and the Taycan. No laboratory conditions were deliberately created. This is reflected, among other things, in the fact that existing traffic and infrastructure are used for the endurance project. Reliable delivery according to fixed schedules had to be ensured over the entire project period. Unscheduled failures and/or delays had to be ruled out. Due to the realistic nature of the project, it can be scaled to other industries with similar framework conditions for automotive production.

3 Selection of test tracks and test vehicles

The endurance project was planned in 2020 and the first comparison pairs were started. All tests were carried out with conventional 40 t lowliner trucks of type S410 from Scania and the types TGX 18.510, TGX 18.430 and TGX 18.400 from MAN in regular operation at the project participating haulage company. In order to map all aspects of real delivery traffic, the following different routes were selected with differing focal points in the route profile.

3.1 a) Highway section—"Standard" production material

Route profile a) describes a shuttle service between the Ottmarsheim and Zuffenhausen locations. The route has a length of 70 km for the outward and return journey, 60 km of that is on the highway. Two Scania 40 t trucks were used on this route, which were refueled with filling station diesel fuel B7 and two identical vehicle units, which were refueled

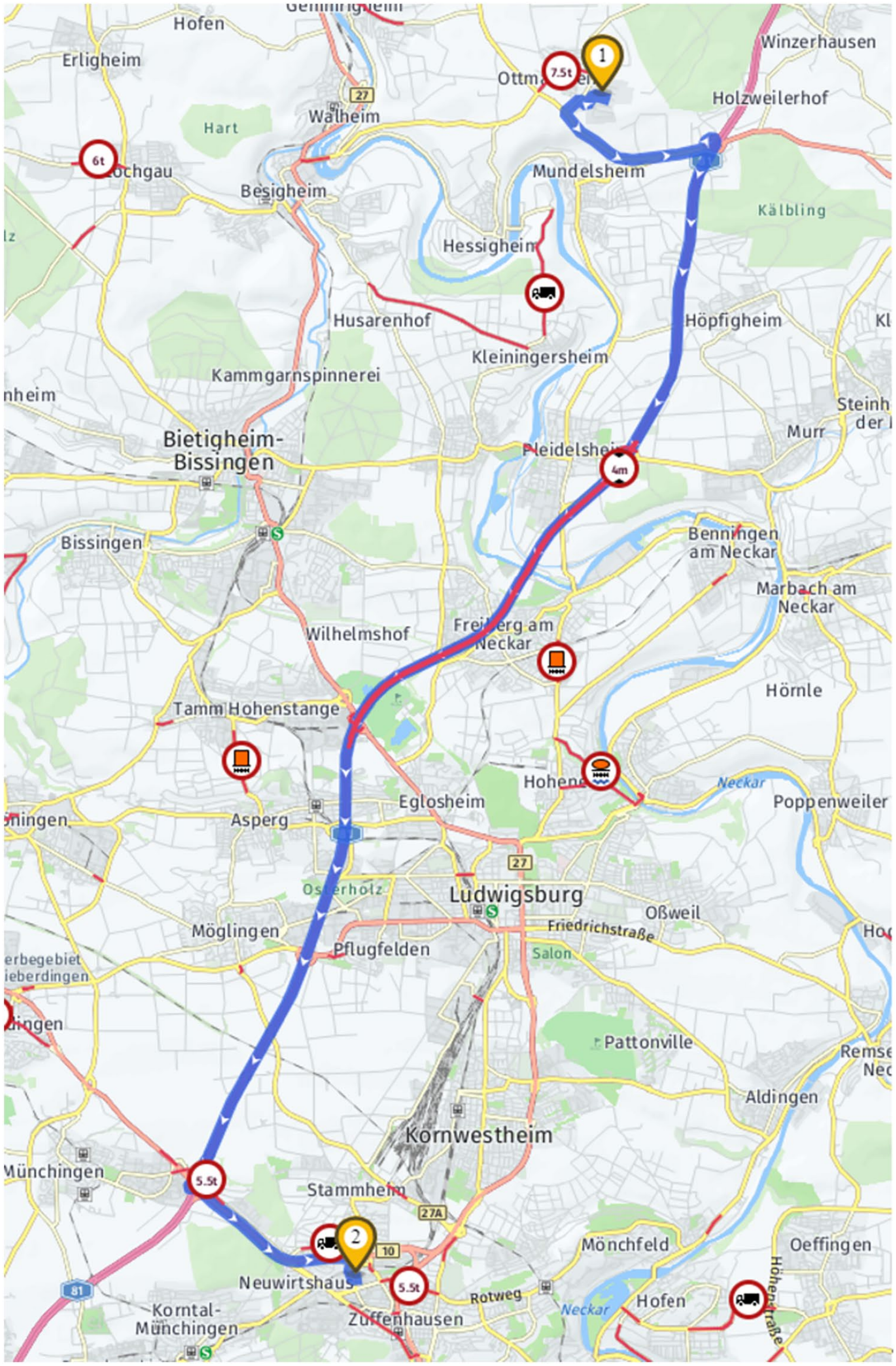

Fig. 2 Highway section—"Standard" production material

with HVO at the mobile filling station set up for the test. The goods to be loaded resulted in a medium load for the vehicles. Due to the use in regular logistics operations, it was possible to achieve a very high degree of comparability between the vehicles in operation with diesel B7 and in operation with HVO in terms of load weight, frequency, operating mode, and route. The corresponding route is shown in Fig. 2.

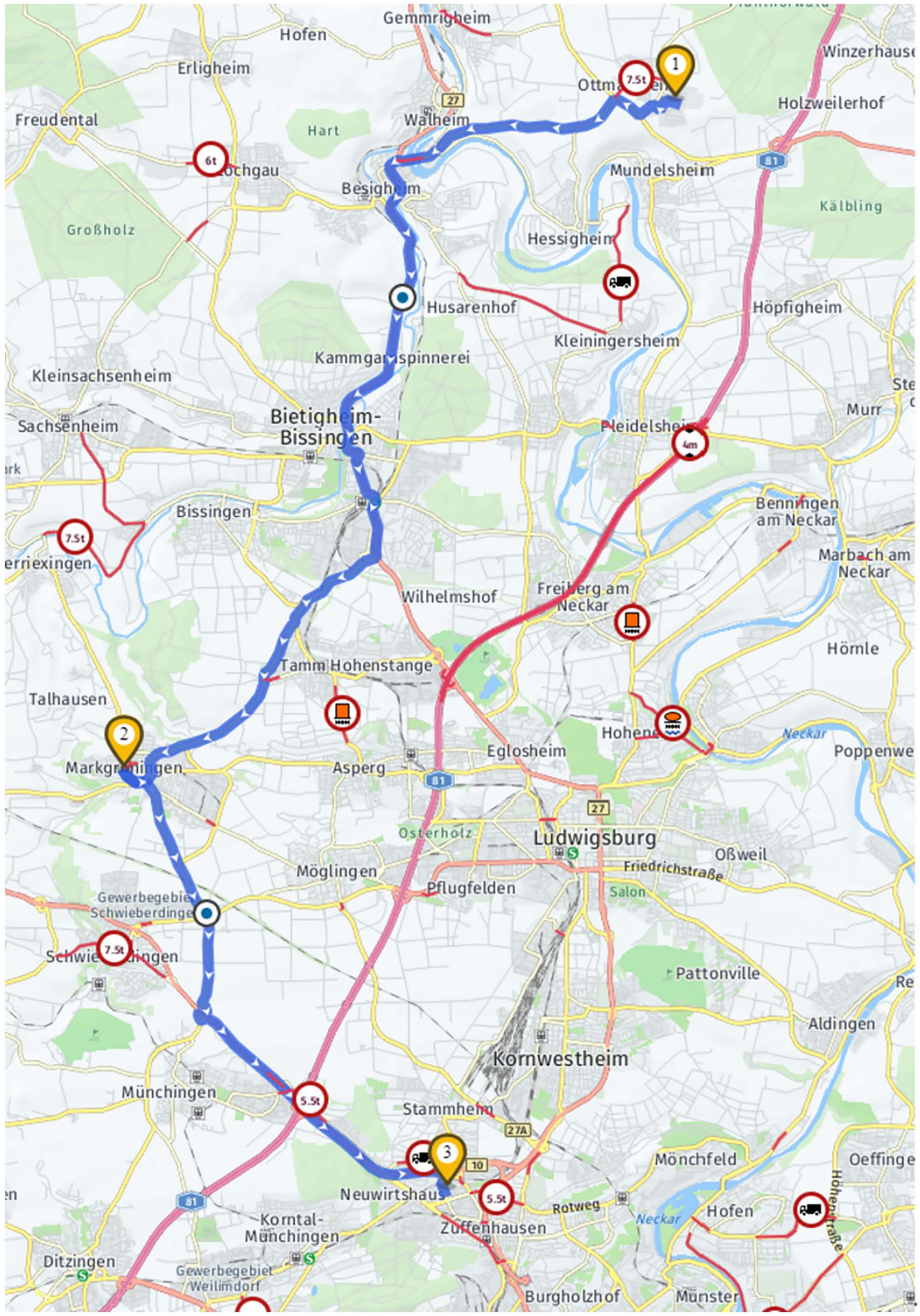

Fig. 3 Overland route—production material JIS

3.2 b) Overland journey—production material "time-critical"

The second route profile examined differs from the first route profile in almost all characteristics. The Shuttle service from Ottmarsheim via Mark-Gröningen and Zuffenhausen to Ottmarsheim does not include any highway operation at all over a distance of 85 km, but does include overland operation and the load can be described more as a light load (high volume per load weight). Of particular importance for the driving behavior is the fact, that the goods in question are just-in-sequence (JIS) deliveries. This particularly time-critical delivery excludes highway operation and other risk elements that are difficult to plan, but nevertheless requires a fast and reproducible driving style. A pair of Scania trucks and a pair of MAN trucks were used on this route. As with route profile a), the parallel use of the pairs also guarantees a high degree of comparability of the results. The corresponding route profile is shown in Fig. 3.

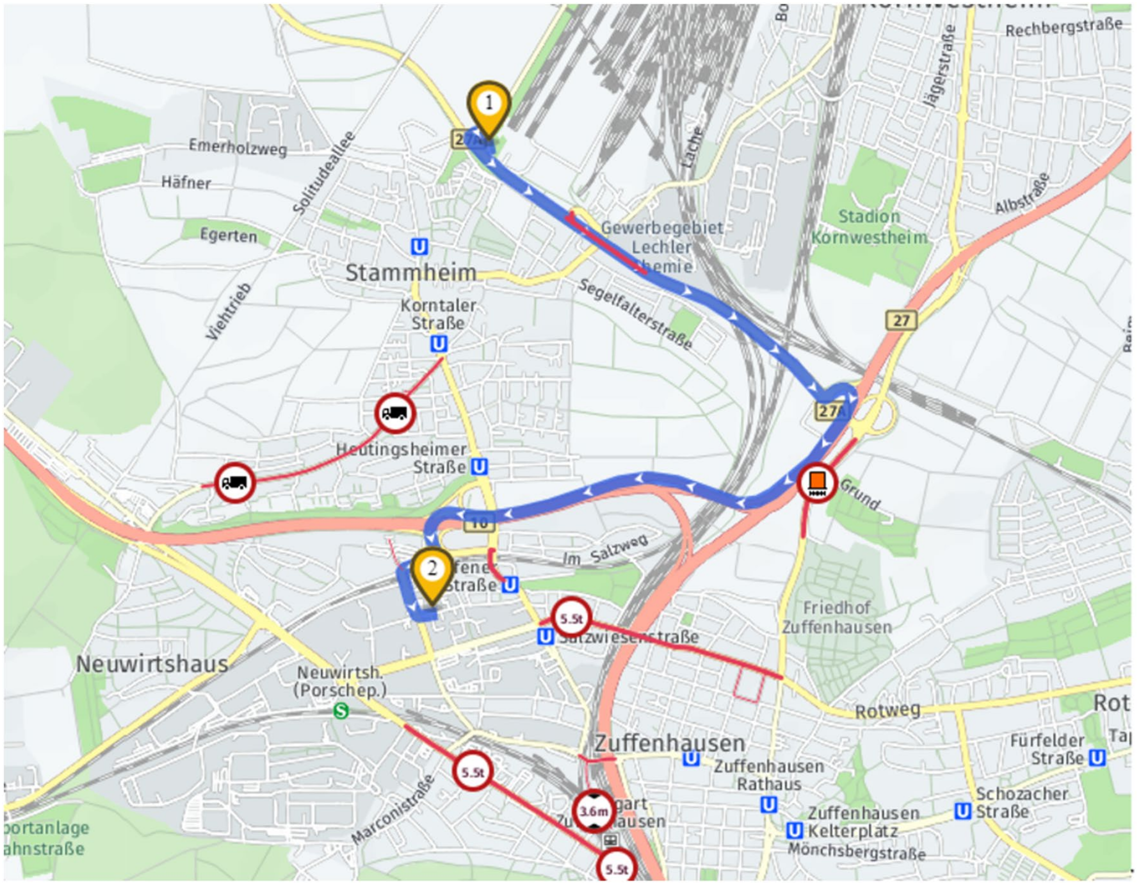

Fig. 4 Short-haul—"Standard" production material

After good results were achieved on the routes described above in 2020 and 2021, a further short route was added in test operation in 2022.

3.3 c) Short-haul—"Standard" production material

The third route profile examined is characterized by a relatively short shuttle service between the Kornwestheim and Zuffenhausen locations. This approximately 10 km long route is characterized by a high proportion of urban traffic and multi-shift operation. This 50% multi-shift operation was carried out with 4 pairs of articulated trucks, half of which were refueled with B7 diesel from the filling station and the other half with HVO from the yard filling station. The corresponding route profile is shown in Fig. 4.

The entire test procedure was carried out with an approximately equal mix of used and new vehicles in order to rule out potential special influences from new vehicles.

4 Fuel

The fuel used is Neste MY Renewable Diesel™ from the Finnish company Neste. The following statements relate exclusively to this product. It is categorized as HVO fuel and is made from 100% renewable raw materials. This includes residual materials and waste such as used cooking oil. The fuel meets the requirements of the fuel standard DIN.

EN 15940:2023 for paraffinic diesel fuels. Neste MY Renewable Diesel can reduce greenhouse gas emissions (GHG or CO_{2e}) by up to 90 percent over the life cycle of the fuel compared to diesel B7[1] (see also Fig. 5). Neste calculates the carbon footprint of its products and solutions over their entire life cycle: from the production of the raw materials to the end of use of the end product.

With its proprietary NEXBTL™ technology, Neste has developed a process to convert a wide range of fats and oils into high-quality renewable products (see Fig. 6) (10).

[1] *The method for calculating life cycle emissions and emission reductions corresponds to the EU Renewable Energy Directive II (2018/2001/EU).*

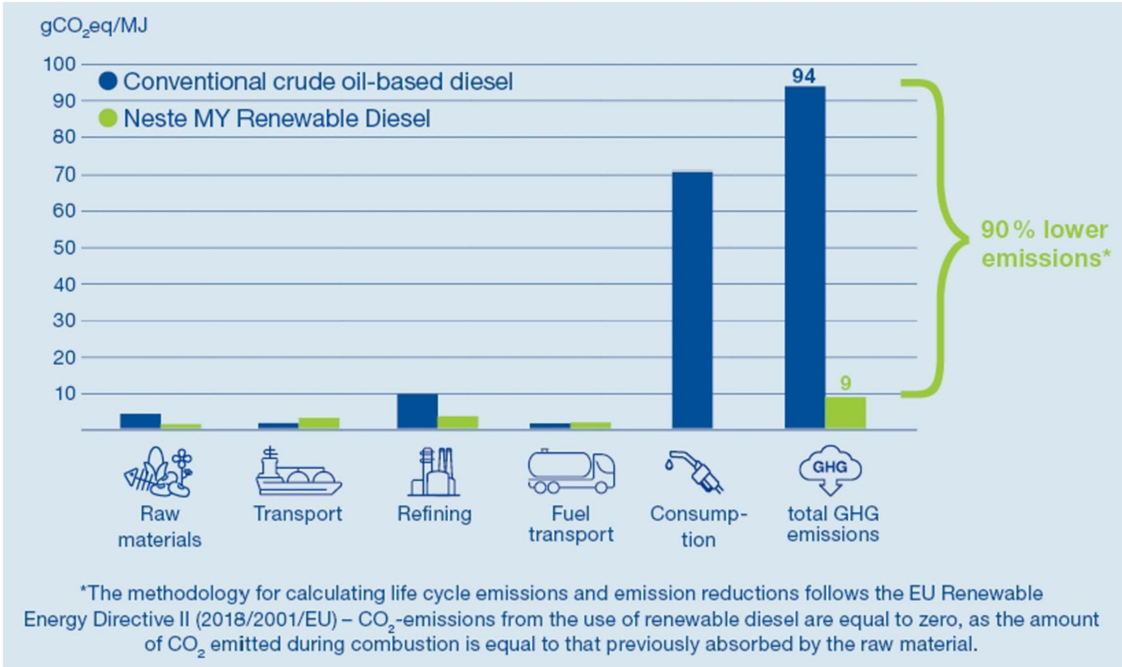

Fig. 5 Calculation of life cycle emissions and emission reduction (source: Neste)

Fig. 6 Starting materials for HVO synthesis (Source: Neste)

Neste started producing 'renewable diesel' at its refinery in Porvoo, Finland, back in 2007. For the production of its renewable products, Neste uses a variety of feedstocks from over 60 countries worldwide. The raw materials comply with the RED II regulation.

Thanks to pre-treatment, e.g., cleaning capacities, waste and residues of lower quality can also be used as raw materials. Regardless of the raw materials used, Neste's HVO is characterized by a consistently high quality.

Neste continuously invests in research and development to expand the existing portfolio of renewable raw materials and to develop further renewable raw material sources, while at the same time expanding the existing pool. Algae, lignocellulosic biomass, and municipal solid waste, for example, offer considerable scaling potential.

Neste's renewable diesel is not to be confused with biodiesel (also known as fatty acid methyl ester or FAME) and differs from it not only in the type of raw materials used. Compared to biodiesel, Neste MY Renewable Diesel offers a higher energy density and better low-temperature properties, which prevents clogging of the fuel filter and problems with cold starts (s. Table 1). Due to the high paraffinic content and less polycyclic aromatic hydrocarbons, HVO offers significantly reduced particulate emissions during combustion (see Fig. 7).

According to Neste, the fuel is fully compatible with all diesel engines and the existing distribution infrastructure and can be used in its pure form without the need for any modifications to the diesel vehicles or engines. The largest manufacturers of heavy commercial vehicles, such as Liebherr, Volvo Trucks, John Deere, Caterpillar, Scania, Mercedes Benz, DAF, and MAN, have approved pure HVO for use. The high cetane number ensures efficient and clean combustion. Neste MY Renewable Diesel has good cold

Table 1 Relevant physical parameters of diesel fuels according to EN 590 and EN15940

	Fossil diesel according to DIN EN590:2022	HVO diesel according to DIN EN 15940:2023	Biodiesel (FAME) according to DIN EN 14214:2019
Calorific value	not part of the norm ~42 MJ/kg usual	not part of the norm ~44 MJ/kg usual	> 35 MJ/kg
Cetane number	> 51	> 70	> 51
Density	820–860 g/L	740–760 g/L	860–900 g/L
CFPP	0 °C to − 20 °C	+ 5 °C to − 20 °C	0 °C to − 20 °C
E250	< 65% Vol	< 65% Vol	–
E350	≥ 85% Vol	≥ 85% Vol	–
T95	≤ 360,0 °C	≤ 360,0 °C	–
polycyclic aromatic hydrocarbons	< 8% (m/m)	< 1% (m/m)	
Raw material	Crude oil	Waste and residual materials	Vegetable oil and animal fats
Technology used	Traditional reffineration	Hydrotreating	Esterification
Chemical composition	$C\,H_{n2n+2}$ + aromatics	$C\,H_{n2n+2}$	O ‖ H C–O–C-R_3

Fig. 7 Neste MY Renewable Diesel burns cleaner than fossil diesel (Source: Neste)

Fig. 8 Example of a reFuels truck from Müller—Die Lila Logistik in use for Porsche AG (Source: Müller—Die Lila Logistik)

resistance and is therefore suitable all year round for very low temperatures of − 22 °C and below (11). In addition, this fuel is free of sulfur, oxygen, and aromatics and can be stored for long periods without loss of quality or increase in water content.

4.1 Refueling the vehicles

A mobile 5000-L diesel filling station with installed remote monitoring ensured the continuous supply of the test vehicles by the Neste Channel partners EDi Hohenlohe GmbH and Tool Fuel Services GmbH at all times. The filling station is located at the ground of Lila Logistik in Ottmarsheim (See Fig. 8).

5 Results of the multi-year test phase

5.1 Comparability of the routes

The results were achieved in the years 2020–2023. In total, distances of more than 1 million kilometers were driven with filling station diesel B7 and with HVO diesel. As the journeys in 2020 were still significantly influenced by the restrictions in connection with the COVID-19 pandemic, Fig. 9 shows the journeys from 2021 with > 750,000 km for the period 2021–April 2023.

When averaging the values recorded for the individual vehicle pairs, it is noticeable, that the average consumption of the vehicles fueled with HVO is even slightly lower than the consumption of the vehicles fueled with diesel B7. This means that the additional volumetric consumption expected due to the lower density cannot be measured. The project team attributes the lower consumption to the drivers' awareness that they are using an ecological fuel and that they are driving more consciously.

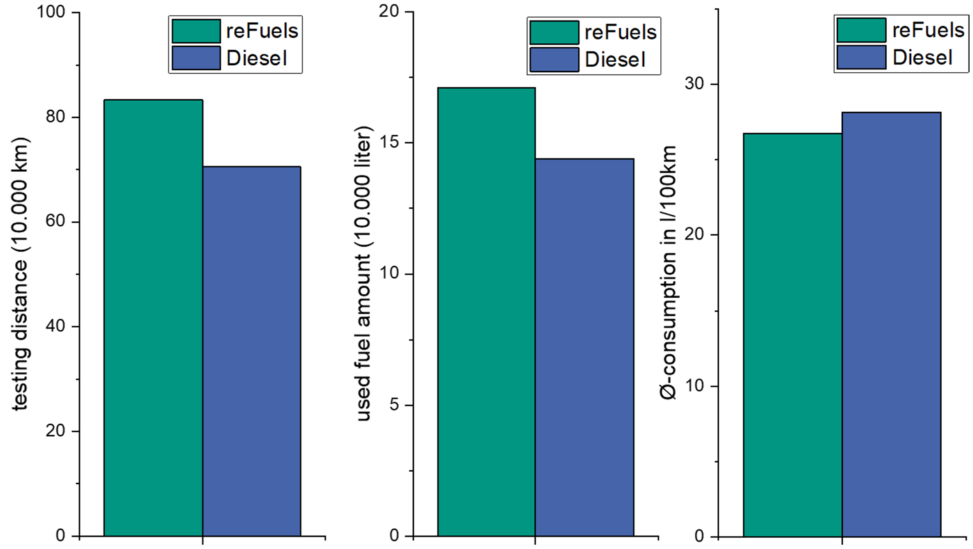

Fig. 9 Overview of the distance traveled, consumption and average consumption

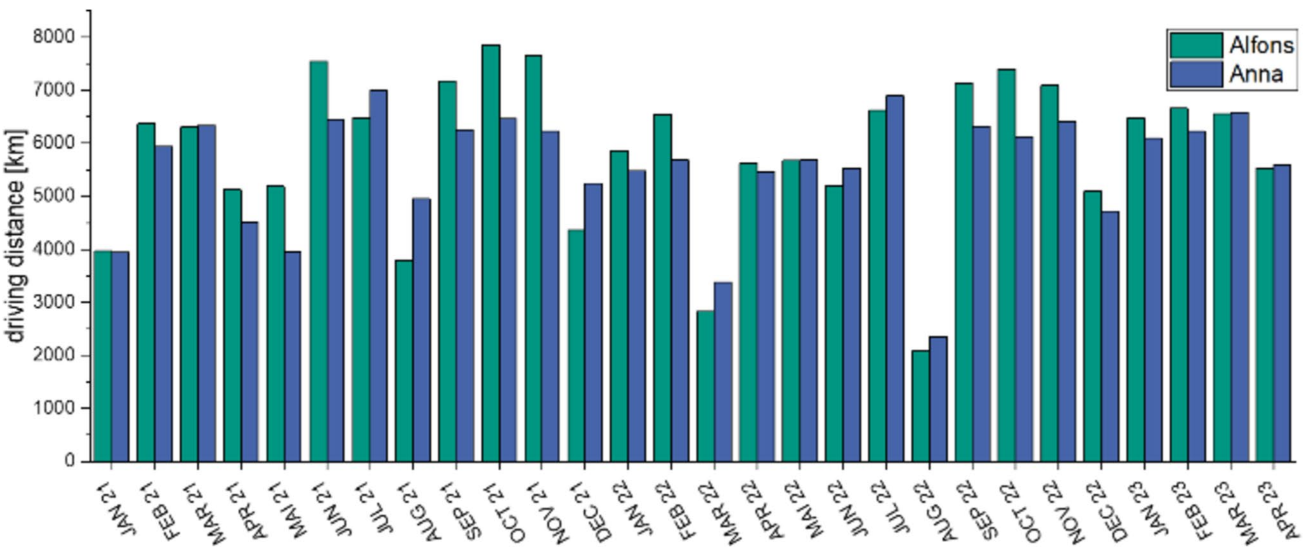

Fig. 10 Monthly routes of the two vehicles anonymously designated as "Alfons" and "Anna" over the evaluation period

In order to investigate the above thesis, the consumption data stored in the fleet management system of the vehicles was evaluated. The vehicles are evaluated anonymously as pairs, each of them drove the same route profile and comparable load. Alfons" refers to the HVO-fueled variant and "Anna" to the B7 diesel-fueled variant. The quality of the comparability of the data can be seen, for example, in the monthly presentation of the routes in Fig. 10.

5.2 a) Influences on fuel consumption

Using the test pair "Alfons" and "Anna" as an example, the slight reduction in consumption is constant across all months. This means that one-off, strongly deviating events can be ruled out, as can temperature and climatic influences on consumption are the same. Fuel consumption variations over the year have been influenced by traffic situations, construction influences, and driver behavior.

The analysis of driving behavior on fuel consumption is only possible to a limited extent (on a monthly base see Fig. 11) for data protection reasons. As a strong indicator of a more or less restrained driving profile, the fleet management system counts the events referred to as so-called "strong acceleration". These events describe the use of the vehicle in the characteristic map ranges that correspond to significantly stronger acceleration. However, these events are themselves strongly influenced by traffic. Journeys with a lot of roadworks traffic (April–December 2021) causes an accumulation of these events, as shown in Fig. 12 can be seen.

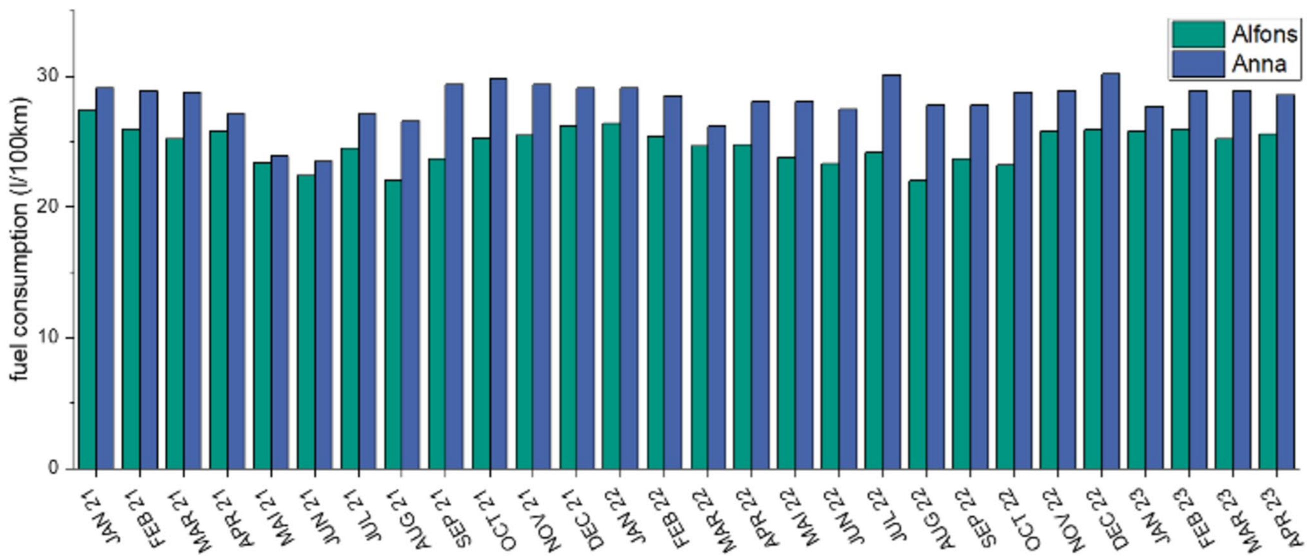

Fig. 11 Monthly consumption of the test pair "Alfons" and "Anna", with "Alfons" HVO refueling and "Anna" diesel B7 refueling

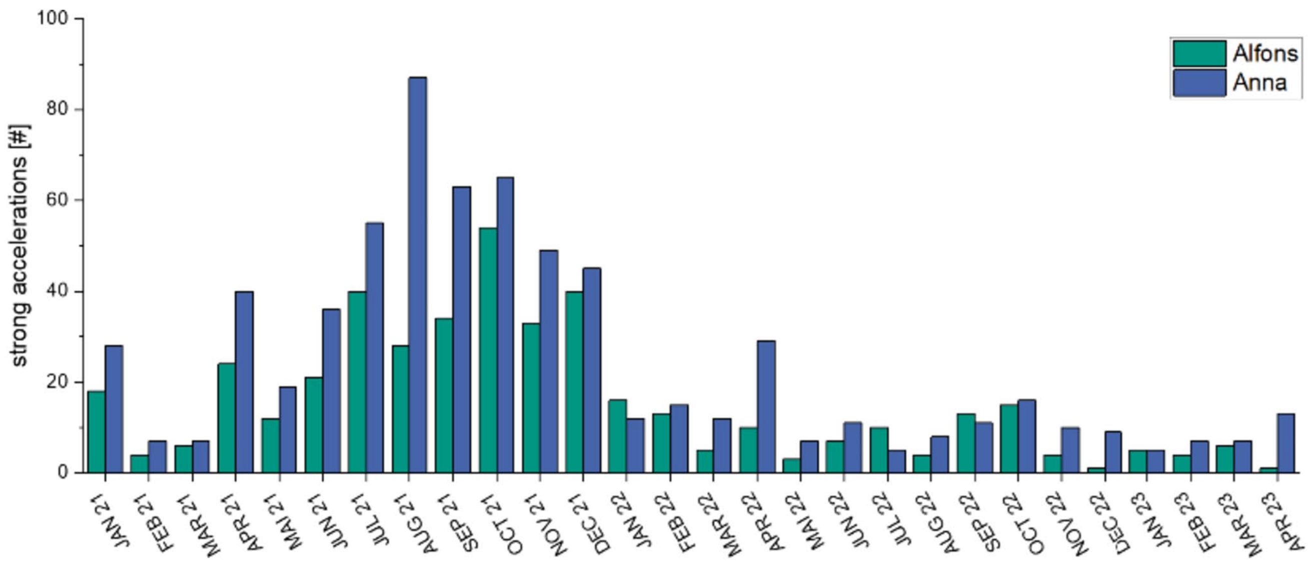

Fig. 12 Monthly representation of the events marked as "strong acceleration" by the fleet management system

Figure 12 shows a restrained driving profile with reduced fuel consumption for the HVO fueled trucks over several months. The higher number of "strong acceleration" events may have caused the slightly higher fuel consumption of the B7 diesel-fueled vehicle.

5.3 b) Oil analysis as a long-term sensor

The piston rings do not completely seal off the combustion chamber from the crankcase and the oil circuit in a gas-tight manner. As a result, combustion gasses enter the crankcase as so-called blow-by gasses and come into contact with the engine oil. Some of the exhaust gasses are returned to the combustion chamber via the crankcase ventilation and exhaust gas recirculation, while another part condenses and mixes with the engine oil as a liquid. This effect is stronger when the engine is cold and running at partial load than at full load. The liquid mixed to the oil consists mainly of water, which is produced when the hydrocarbons react with the oxygen in the air. Acidic combustion residues produce a weak acid that has a corrosive effect on metals, among other things. Unburned fuel components deposit on the cylinder wall and thus also enter the engine oil. This effect is also relevant during cold starts, under partial load and especially

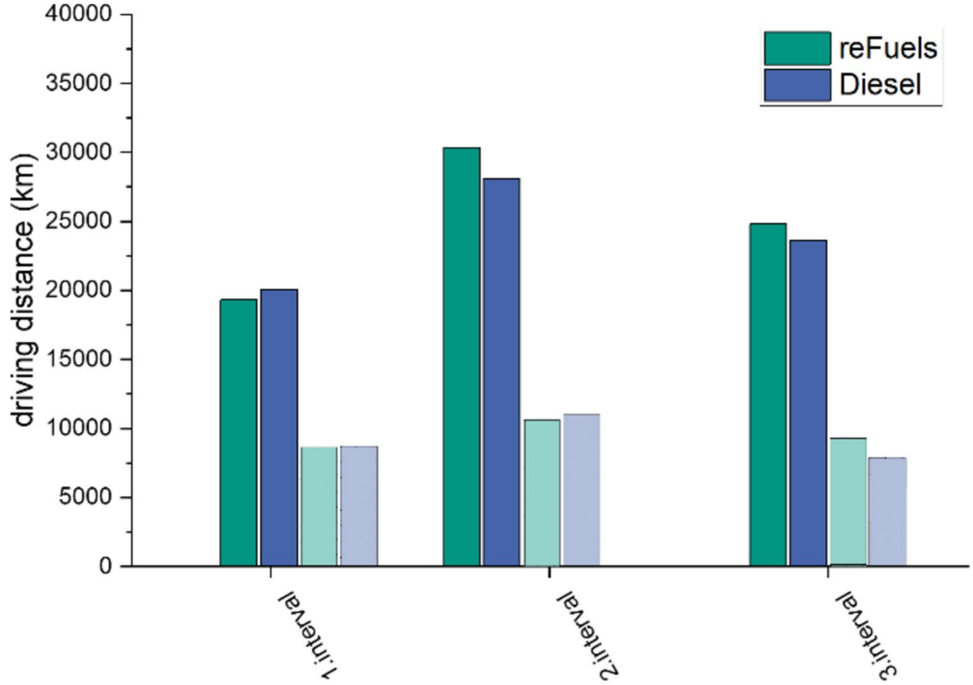

Fig. 13 Driving distance overview engine oil detailed analysis in test intervals of two different driving profiles. Not shaded shows results from route profile a) and lighter bars show results from route profile c)

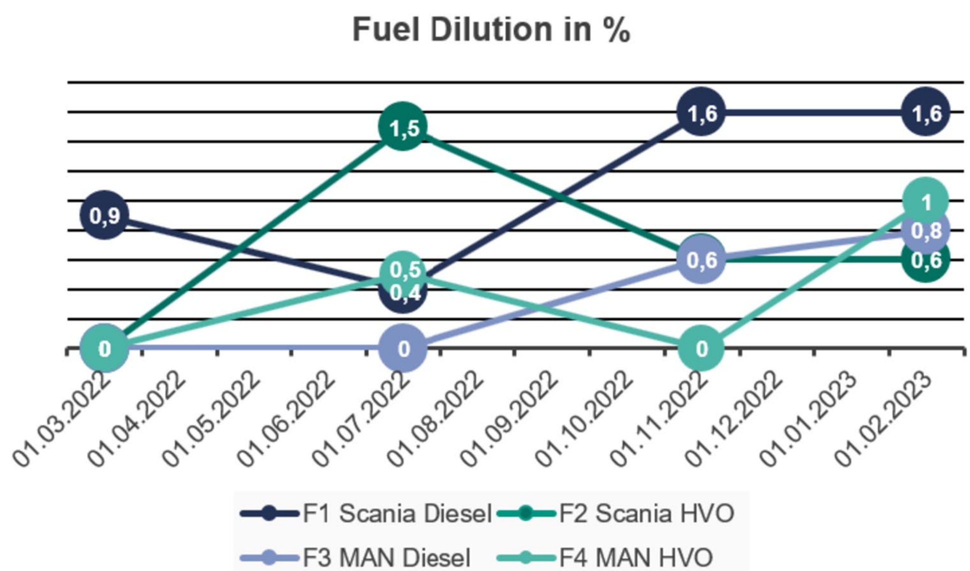

Fig. 14 Fuel dilution of selected vehicle pairs in long-haul transport (Scania) and short-haul transport (MAN), each in % by weight

during post-injection to regenerate the particulate filter. Fine soot particles produced during combustion can also get into the engine oil and lead to oil thickening.

The engine oil is therefore a kind of permanent sensor and reacts to any combustion changes caused by the fuel. Two representative vehicle pairs were selected with the aim of representing as many different vehicle manufacturers, operating conditions, and mileages as possible. The boundary conditions for the two vehicles to be compared with conventional diesel and HVO diesel should be as similar as possible in order to obtain reliable comparisons (see also Fig. 10).

To analyze the corresponding effects, samples were taken at three intervals (s. Figure 13) and analyzed in Neste's-certified oil laboratory. In order to obtain as much information as possible regarding the influences on the oil, the vehicles were filled with fresh oil in 03/2022 and an oil sample was taken approx. every 6 months (07/22; 11/22 and 02/23). Particular care was taken to ensure that these samples were not contaminated during sampling. The oil change intervals were reduced, compared to the manufacturer's specifications in order to be able to analyze any temporal influences that may occur. Over the period between two oil change intervals, exhaust gas components,

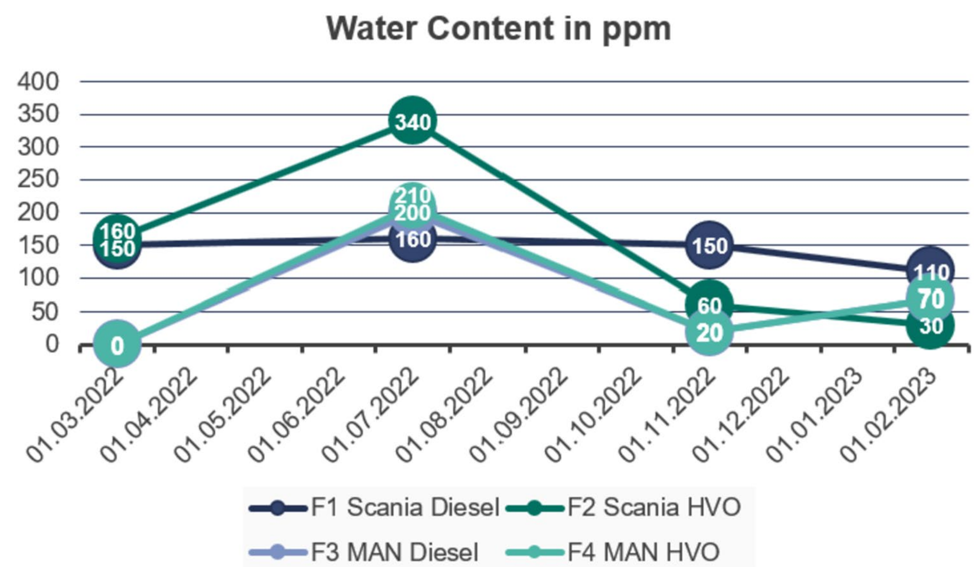

Fig. 15 Dilution of the engine oil with water in a selected pair of vehicles in long-distance operation (Scania) and short-distance operation (MAN). The water content of the 1st, 3rd and 4th samples of the MAN vehicles lies on top of each other within the measurement uncertainty

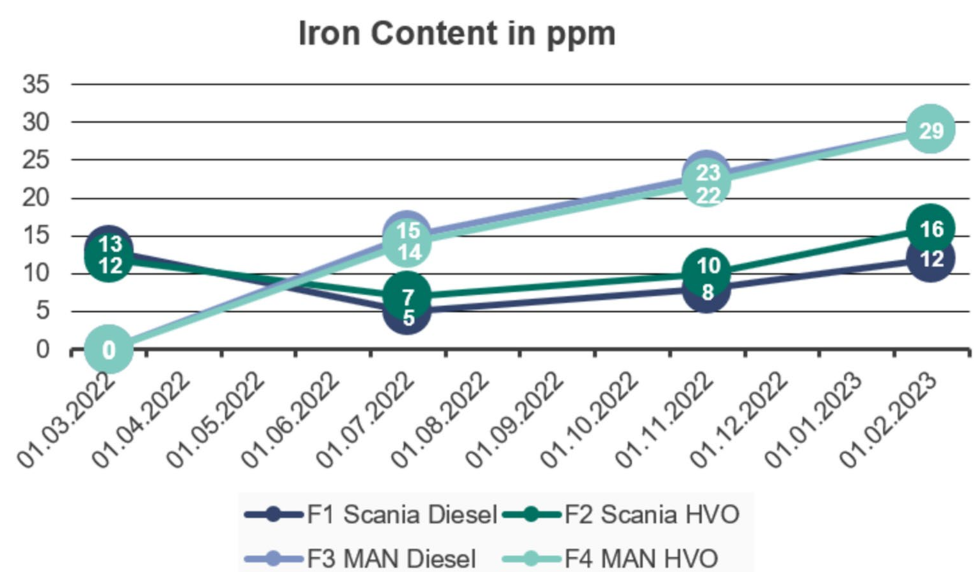

Fig. 16 Iron content of engine oils for selected vehicle pairs in long-haul operation (Scania) and short-haul operation (MAN) in ppm

condensation water from combustion and soot can accumulate in the engine oil and cause interactions with the engine oil. The amount of foreign substances introduced by the blow-by gasses is a good indicator of the quality of the fuel used, especially when assessing it as a 1:1 replacement for the existing B7 petrol station diesel.

In addition, there is the so-called oil dilution caused by unburned fuel, which enters the engine oil during particulate filter regeneration, for example. Elements of the fuel can accumulate there, e.g., if the fuel has an unfavorable boiling behavior. If fuel jets hit the liner, possible mixing of the fuel with the oil during continuous operation is crucial for maintaining viscosity and therefore lubricity (s. Figure 14).

The dilution of the engine oil with water reacts less sensitively to part-load operation, as shown in Fig. 15. Neither the water content nor the fuel dilution are outside the usual ranges; there are no fuel-related abnormalities.

Another important element that can be observed with the oil analysis is soot deposition. Its values are also at a very low level and indicate normal combustion and soot emissions. Fuel-related deviations are not detectable.

Further influences on the wear behavior can be caused by acid formation, e.g., in connection with nitrogen oxides NOx and SO_2 in the raw emissions. The combustion of paraffinic diesel HVO is accompanied by reduced soot formation, as several analyses have shown (12). Increased nitrogen oxide emissions were also not observed in the “reFuels—Rethinking Fuels” project and without sulfur as a fuel component, SO_2 emissions are also below the measurement limit (3).

Effects in a changed wear behavior can be detected very well by the metal content in the oil, here exemplified by the iron content in the oil samples taken (see Fig. 16).

The iron content increases as expected over the duration of the test, but at a maximum of 30 ppm is a very low, good level and does not indicate increased wear. The curves between the reference vehicles with conventional diesel B7 and the test vehicles with HVO diesel run parallel at the same level. The same applies to the aluminum values at an even lower level.

Two pairs of vehicles were tested over a period of one year, one vehicle with conventional diesel and one vehicle with HVO diesel. The Scania with conventional diesel covered 116,939 km during the test period, the one with HVO diesel 123,104 km. Both vehicles were in long-distance operation. All oil parameters tested were within the expected permissible range and no indication of fuel-related differences in operating behavior can be observed.

The MAN vehicles tested in short-haul traffic covered 26,001 km (vehicle with conventional diesel B7) and 26,726 km (vehicle with HVO diesel), and here too there was no indication of fuel-related operating differences.

Over an operating period of one year and mileages of around 26,000 km (MAN in short-haul traffic) and 120,000 km (Scania on long-haul routes), HVO diesel demonstrated its unrestricted suitability for this application. In particular, the problems of oil dilution and soot thickening observed with some alternative fuels could not be observed.

6 Summary of the results

The suitability of HVO fuel as an element of greenhouse gas reduction in logistics was proven in the endurance test of five pairs of trucks plus additional HVO-fueled vehicles. Each pair of trucks consisted of two identical vehicles of the same age, one of them was fueled with diesel B7 filling station fuel and one with HVO fuel. The fact that each pair of trucks was used on the same route on the same day and with a comparable load meant that a previously unattainable level of data quality could be achieved for a comparison.

The evaluation of the HVO fuel consumption versus the B7 fuel consumption showed, that a slight reduction in fuel consumption could be observed, which, according to the indicators examined (e.g., number of "heavy acceleration" events), indicates a stronger influence of driving behavior than of fuel effects.

An analysis of oil samples has also demonstrated that no fuel-related combustion emissions have led to significant changes in the oil.

In summary, the result of the endurance run in the real application of a freight forwarder is that the vehicles analyzed in daily logistics operations have confirmed the possibility of using HVO fuel as a tool for significant greenhouse gas reduction.

Author contributions OT, TW and TK provided the scientific support of the project the general manuscript, while MF provided the intercompany logistics demands and the organisation, CR provided test route definition and organisation of the daily transports, SD provided the evaluation of the oil analysis, AS and RW provieded the fuel logistics and JH and CB the fuel performance and oecological data. The number of authors is caused by the complexity of the fuel and logitics supply chain.We thank the companies Scania and MAN for providiung access to the fleet and vehicle data.

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Data availability Data sets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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