Advances in Fossil-Free Motorsports Fuels for Sustainable Transportation

A.Ferrari, D.Vrtiska, M.Popilka

R&D / Technology Department
P1 Performance Fuels GmbH
Salzufer 16, 10587 Berlin
alessandro.ferrari@p1fuels.com, dan@p1fuels.com,
martin@p1fuels.com

M.Schmidt, Prof. Dr techn. C.Beidl

Institute for Internal Combustion Engines and Powertrain Systems
Technical University of Darmstadt
Otto Berndt Straße 2, 64287 Darmstadt
Marvin.schmidt@vkm.tu-darmstadt.de, beidl@vkm.tu-darmstadt.de

Abstract: The topic of sustainable transportation has acquired a central position on the agenda of governments and industries globally. However, the discourse around which pathway to take to achieve sustainable mobility is sometimes incoherent, due to differing views and opinions from diverse stakeholders. This paper describes how it is technically possible to introduce drop-in carbon-neutral fuels (CNF) in ICEV and PHEV for fleets of vehicles, and how this immediately produces a reduction in well-to-wheel (WtW) greenhouse gas (GHG) emissions from the transportation sector. In particular, Berlin-based fossil-free fuel specialist P1 Performance Fuels GmbH has been developing various grades of sustainable fuel since 2018. It began introducing these products into international motorsport in 2020 and is currently transferring this technical know-how into the development of CNF for passenger vehicles. This paper describes the steps that allowed the introduction of CNF into motorsport, and the reasons why the motorsport arena is ideal for the development of sustainable fuel technologies.

1 Introduction

Global atmospheric concentration of greenhouse gases (GHG) such as carbon dioxide, methane, and other manufactured gases has increased significantly since the beginning of the industrial era. This is mainly due to human activities including industrial processes, agriculture, and the use of fossil fuels [1]. In Europe, the transportation sector contributes one-quarter of the region's total GHG emissions [2,7] and is one of the main causes of air pollution in cities. Since 1990 in Europe, other energy-consuming sectors have achieved a reduction of up to 40% in their GHG emissions, but this has not been matched by the transportation sector [3]. The priorities of the European Community (EU) in their effort to contain this trend and to achieve a reduction in emissions of 55% between 1990 and 2030 are:

- **Increasing the efficiency of the transport system**, including a larger implementation of digital technologies, as well as the use of lower-emissions transport modes, such as car sharing and bike sharing.
- **Speeding up the deployment of low-emission alternative energy for transport,** such as advanced biofuels, green hydrogen, and renewable synthetic fuels, and encouraging the electrification of transport.
- **Moving towards 'low-emission vehicles'** [3].

Since 2016 (Paris Agreement) — because of the penalties for the car manufacturers related to TtW CO_2 emissions, the car industry began seeking new strategies to reduce global emissions and striving toward a goal of 100% electric vehicle (EV) technology for passenger cars and light-weight transportation. This process is supported by the European legislation introducing a ban of the ICE from 2035, and public incentives for the consumers for the purchase of new EV.

While we all agree on the need to reduce transportation's carbon footprint quickly, the discussion around which is the best way of achieving this, is critical and instrumental in defining our future, and thus a scientific and pragmatic approach is required.

The reduction of transportation's GHG footprint must be attained by improvements in all processes, from vehicle manufacture to on-road use. In addition, the building of the infrastructure required by a new technology, and the environmentally friendly recycling of waste from that technology, need to be considered. E.g., vehicle electrification might not be the best solution for a rapid reduction of GHG in remote locations, regions with poor electrical infrastructure, and places where the only source of energy is fossil fuels. To attain our climate goals, and to cater for the different energetic, social, geographic, and economic characteristics of different areas in the world, it is important to evaluate and develop multiple technologies simultaneously to obtain a rapid reduction of GHG emissions. Reports like the FVV Fuels Study IV published in 2021 [12] argues that it will not be possible to meet the '1.5 degrees Celsius pathway' of the Paris Agreement without taking existing vehicles into account, and reducing urgently their emissions.

A competing GHG-reduction technology with wide applicability and potentially zero entry cost for end users is **fossil-free synthetic fuels**, also called **carbon-neutral fuels (CNF)**. These fuels can offer immediate GHG reduction with no need for roadside infrastructure development, and their application can potentially be extended to air and sea transportation.

Global GHG footprint reduction requires smart energy management and efficiency optimization in all phases of vehicle life and use — we cannot focus only on the energy source necessary to make the vehicle move, whether that is a battery or liquid fuel. To attain this goal, a technology agnosticism is required, allowing for an efficient mix of sustainable solutions applicable to the end users' needs. Motorsport is based on this same approach: the participants all compete under the same technical and sporting rules within a defined timeframe, and the team with the highest-efficiency mix of solutions wins the race, and in the long term, the championship. Starting in 2020, the *Fédération Internationale de l´Automobile* (FIA), the governing body of international motorsport, incentivized the use of **advanced sustainable fuels** by the FIA — and in 2022 published a new fuel technical regulation in the AppJ252.9, imposing a minimum fossil-free-components content for the fuel formulation of certain of its World Championships [4].

In 2021 and 2022, the cars of the FIA World Touring Car Championship (WTCR) ran successfully on a RON98 EN228 gasoline with 15% fossil-free components developed by P1 Fuels [5]. In 2021, P1 Fuels was appointed as sole fuel supplier to the FIA World Rally Championship (WRC) [6] for the seasons 2022-2024, with a 100%-fossil-free fuel formulation called **FossilFree100 WRC**. A few months after the announcement of the introduction of fossil-free fuel to the WRC, the F1 World Championship announced that it too will adopt these rules, from 2026.

The severe testing and racing conditions in motorsport challenge the development of both fuels and engines, enhancing the performance of the whole vehicle package. A fuel compliant with European EN228 automotive gasoline standards, developed by P1 Fuels with technology and manufacturing experience transferred from motorsport, is being tested and evaluated in cooperation with the Technical University of Darmstadt, with particular focus on drivability, emissions, and drop-in compatibility. The Institute for Internal Combustion Engines and Powertrain Systems of TU Darmstadt, in cooperation with *Deutscher Motor Sport Bund e.V.* (DMSB), is working intensively on the technical conditions, testing, and pilot introduction of drop-in-capable synthetic fuels in amateur motorsports. A drop-in fuel must work in an unmodified standard vehicle without any modification of the fuel system or engine, matching material compatibility and engine functionality.

2 Sustainability is a global matter

Electric vehicles (EVs) have grown in appeal in recent years because of their high energy conversion efficiency, and the fact that their CO_2 and emissions *at the tailpipe* are zero. However, this is only true because we are evaluating the *tank-to-wheel* (TtW) emission footprint, based on the transformation of electric energy stored in the batteries into kinetic energy used to move the vehicle. But, when we consider the *well-to-wheel* (WtW) footprint, including the GHG footprint during each step of the energy transformation into electric energy before reaching the batteries, the result is quite different, and is strongly affected by the emissions of the primary energy source (Figure 1). Moreover, the impact of mining the raw materials necessary to build the EV batteries cannot be neglected in the calculation of the GHG footprint, although this topic is not part of this paper. Of the 1.5 billion vehicles circulating worldwide in 2022, only 20 million (1.3%) are light-duty plug-in vehicles, and the sales of EV and plug-in hybrid electric vehicle (PHEV) passenger cars together achieved only a 9% market share of global new car sales in 2021 [10]. This growth is too slow to reach the GHG reduction goals set for 2030 and 2050, therefore actions to reduce the GHG of the existing fleet must be immediate [14]. Statistics and case studies highlight that the growing electrification of light-duty vehicles, sustained by large incentives from governments, might be the case in China and certain states in the EU and USA, however the largest part of the world is not ready for sustainable electrification [11]. In contrast, the introduction of carbon-neutral fuels (CNF), or low-carbon fuels, can **immediately** contribute to reducing the global GHG emissions from existing vehicles, aircraft and ships, and these fuels can be distributed using existing infrastructure.

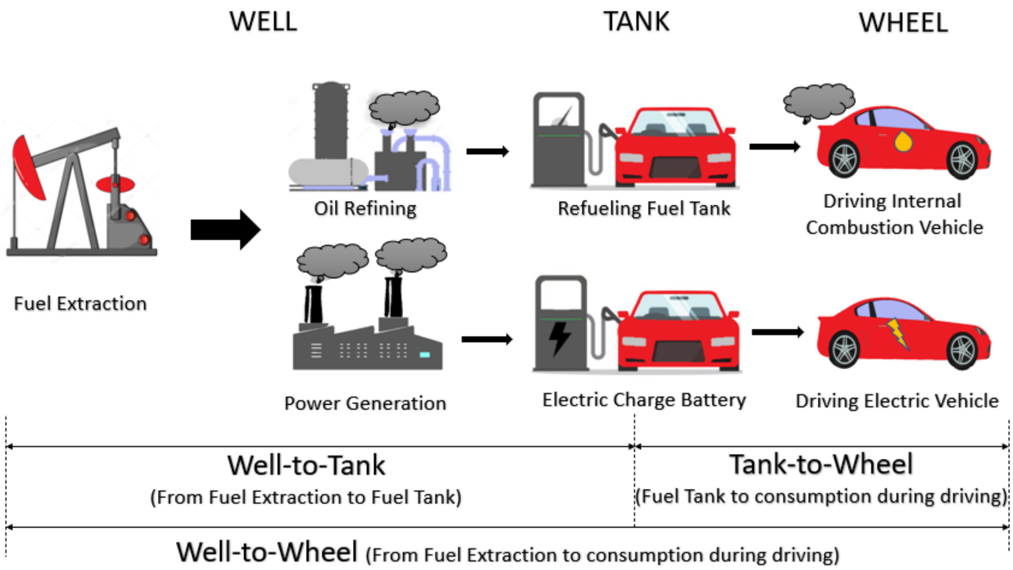


Figure 1: TtW and WtW scheme for an ICEV and EV

2.1 CNF – Carbon-neutral fuels: the way to store energy (and CO_2) in liquid form

CNF are part of a large family of partly- or fully-fossil-free synthetic fuels, blended from chemical components derived from either second-generation feedstock, (such as bio-alcohols generated from agricultural and urban-waste biomass), or from the industrial catalytic conversion of syngas ($CO + H_2$), generally known as *e-Fuels or Power to Liquid* (PtL) [9]. In both cases, every molecule of the blend has a non-fossil origin, so no new CO_2 is introduced into the atmosphere during its use, as shown in Figure 2. The carbon atoms in these fuels are captured from CO_2 already present in the atmosphere. The process of *carbon capture* can be natural, through photosynthesis of plants or algae, or artificial, for example, through direct air capture (DAC).

When an internal combustion engine (ICE) running on a 100% CNF transforms the energy stored in the fuel into mechanical work, it emits CO_2 that was originally captured from the atmosphere, and the resulting TtW footprint can be considered zero (neutral balance), as is the case for an EV. Figure 2 shows the circular path of CO_2 and water, which are released into the environment as combustion by-products, and become potential feedstock for reprocessing back into CNF, via either biosynthetic or PtL paths.

While the well-to-tank (WtT) footprint depends on the technical processes used (alcohol to gasoline, Fischer-Tropsch, Direct Air Capture for CO_2, etc.), as well as the energy mix adopted to produce the fuels, and the fuel transportation method, the TtW efficiency is directly related to fuel consumption, which can be improved by improving the fuel properties and the fuel/engine match.

Methanol (CH_3OH), the simplest alcohol molecule, containing one carbon atom. Because of its simple structure, producing methanol, synthetically or from biomass, is more straightforward than producing other fuels, and it is the simplest liquid energy carrier. Methanol can be used as a stand-alone fuel for certain applications such as ships, or as feedstock to produce more complex molecules for blending (e.g., ethers, gasoline, e-kerosene and e-diesel blend) [15]. Some of the synthetic gasoline manufacturing processes use alcohols as feedstock because the alcohol molecule contains all the necessary atoms to create a hydrocarbon blend [9] (see Figure 2). For these reasons, the authors believe that methanol (bio or synthetic) will have a central role in the future clean energy economy, and in CNF technology.

In summary, the advantages of CNF in transportation are:

- Replace fossil fuels in current vehicle fleet and reduce their WtW emissions.
- Keeping the existing refueling infrastructure and transportation assets (barges, storage depots, etc.).
- CNF can be used as drop-in fuels in vehicles (gasoline, diesel), aviation (kerosine), and ships (methanol), with only minor modification of the hardware.
- Endless availability of certain feedstocks, and *circular economy*.
- Feedstocks (including bio feedstocks) and renewable energy are potentially available in every region of the globe. This can allow local energy independence and a reduction of the environmental impact of long-haul fuel transport.

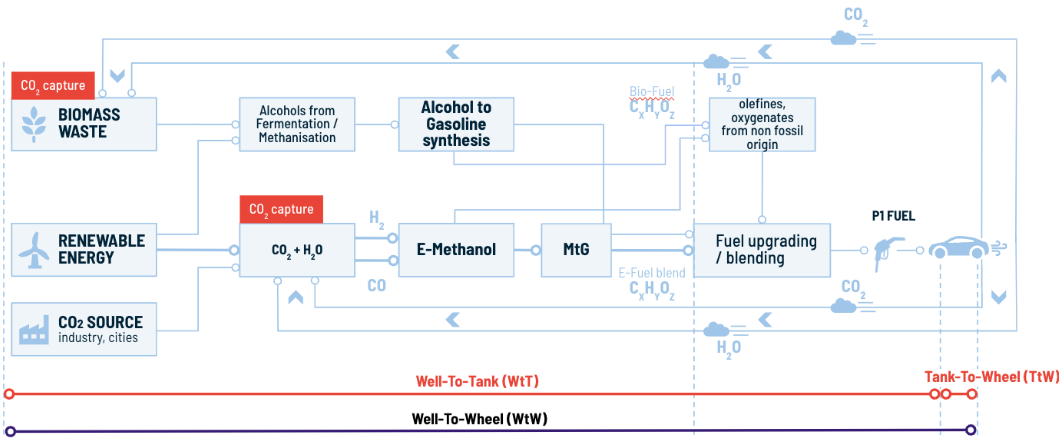


Figure 2: P1 Fuels Scheme of WtW and TtW footprint of the CNF production

2.2 P1 Fuels: removing 'fossil' from fuels as a mission

Since its establishment, P1 Fuels has developed innovative products for motorsport, which is traditionally a field requiring very rapid development of new solutions for efficient mobility.

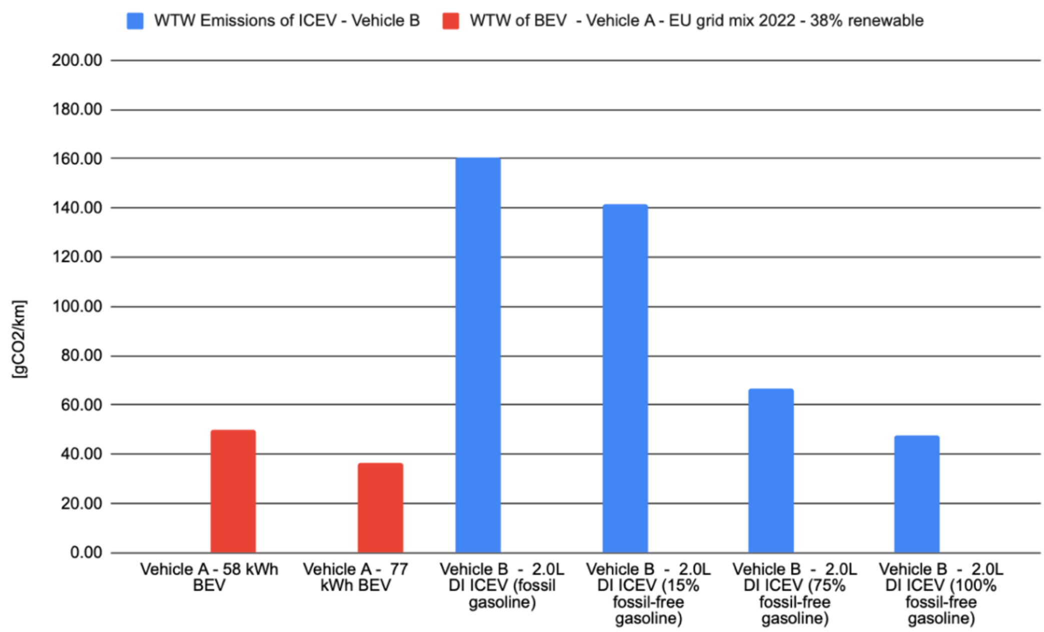
P1 has introduced sustainable racing fuel as early as 2016 and has been continuously innovating to increase the drop-in compatibility of the fuels as well as fuel performance. As part of the FIA working group P1 has collaborated on the definition of the Advanced Sustainable Fuel regulation which has led to the introduction of complete range of sustainable fuels with varying renewability contents.

Table 1 is an overview of the estimated footprints of P1 Fuels' sustainable gasoline formulations comparing different levels of fossil-free rates, with the standard fossil gasoline. This evaluation is based on mass balance, where source data for fossil fuels and for the fossil-free components are coming from literature and from P1 Fuels internal calculations, based on GHG footprint of the raw materials adopted for the calculation of WtT footprint. Although the engine emits CO_2 at the tailpipe, in this approach the fossil-free part of the fuels adopted (15%-75%-100%) is considered to give a neutral contribution to the TtW footprint*. The resulting WtW CO_2 reduction range (right columns of Table 1) is based on the actual energy mix available in EU (2022) for the fuel manufacturing and a future scenario, when the 100% renewable energy mix will be available.

	Well-to-Tank (WtT) footprint	Tank-to-Wheel (TtW) footprint	Well-to-Wheel (WtW) footprint	WtW CO_2 reduction 2022	WtW CO_2 reduction future
	[gCO_2eq/MJ]	[gCO_2eq/MJ]	[gCO_2eq/MJ]		
100% Fossil	21.5	72.5*	94.0	-	
15% fossil-free	21.8	60.8*	82.6	10%	14%
75% fossil-free	20.5	18.5*	39.0	58%	71%
100% fossil-free	27.9	**0***	27.9	71%	92%

Table 1: P1 Fuels footprint evaluation for three different fossil-free gasoline solutions. *see description above the table.

The WtT footprint of each fuel is calculated via a mass-balance, using the footprint of each of the fuel's fossil-free components. Independent entities such as ISCC or REDcert, certify the origin of raw materials and give footprint values per energy (CO_2eq/MJ) for each fuel product's entire production transformation chain. P1 Fuels received REDcert certification in 2022, allowing it to issue *proof-of-sustainability* documentation quantifying the CO_2/MJ emissions of the fuels it produces. Based on this approach, it is possible to estimate the WtW footprint of fuels with different concentrations of fossil-free components, in gCO_2eq/km (Figure 3). This is compared to a standard fossil fuel and to BEV technology, considering the actual average electricity grid mix, ca. 38% renewable, in European countries [22]. The reference EV in this example is the 'Vehicle A', with both battery packs of 58 kWh and 77 kWh, while the reference ICE vehicle is called 'Vehicle B', 2.0L DI Gasoline. Both vehicle types have comparable mass and price, they are produced by the same car manufacturer and are available in the European market. This data shows that the introduction of 15% fossil-free fuels in gas stations could give a WtW CO_2 footprint reduction of ca. 10%–12%, corresponding in EU-27 to a reduction of 65.5 thousand Tons CO_2 yearly (data emissions in 2020) [13]. On the other hand, where a larger use of fossil-free rate is possible, for example for fleets of company cars, public administration, or service vehicles like police and ambulances, it is possible to reach a WtW footprint comparable to that of EVs during utilization, with the additional advantage of not producing new vehicles. According to this internal study, based on publicly available data, as well as the data from the proof of sustainability of the components adopted, with a 75% fossil-free gasoline it is possible to achieve a reduction of the WtW footprint of ca. 58%. With a 100%-fossil-free fuel the values of the gCO_2eq/km are comparable to those of today's EVs. In a future scenario where largely-renewable energy (solar, wind, etc.) is available for PtL production, and with an economy of scale in fuel logistics, a reduction in GHG emissions of up to 90%–92% (Table 1, right column) compared to fossil fuels is possible [8,9,23].



	Vehicle A		Vehicle B
Powertrain type	BEV		ICEV
Power [kW]	150	150	180
Torque [Nm]	310	310	370
Weight [kg]	1813	1936	1450
Tank capacity [L]	-	-	50
Energy capacity [kWh]	58	77	475
Autonomy (WLTP) [km]	335	550	990
Price	ca. 40k Euro	ca. 50k Euro	ca. 45k Euro

Figure 3: WtW emission evaluation for market-available EV and ICEV of same categories – P1 Fuels study

2.3 The main constraints on fuel development

This paper focuses on CNF (gasoline) and its application to spark ignition (SI) engines. However, similar considerations are also valid for diesel fuels. The development of the formulation of a high-performance fuel is a complex process, in which the chemico-physical properties have to satisfy specific requirements and meet the following constraints:

- **Fuel specifications:** these can be either EN228 for standard European gasoline, or the FIA AppJ Art.252.9 [4] for regulated motorsport competitions, or other technical customer specifications. Within the given technical specification, the optimization work aims to maximize the fuel performance, its knock resistance, flame speed, energy content, and fossil-free content. Fuel consumption is correlated to CO_2 TtW emissions, and HC and CO emissions are indicators of combustion efficiency, which is directly related to fuel characteristics.

- **Engine characteristics:** the engine design and its applications are important parameters in the design of the fuel. E.g., 2-stroke or 4-stroke, turbocharged or naturally aspirated, direct or port injection, engine target speed, etc. The target of a drop-in fuel is to make it work in the engine with minor changes (e.g., on engine calibration).

- **Material compatibility:** the fuel compatibility with the tank, filters, elastomers of the fuel line, and injector seals. This is one of the most relevant topics for the introduction of a new drop-in fuel.

- **Sustainability content of the fuel formulation**

- **Product stability and reproducibility:** in Motorsport, and in every application where the fuel plays a role in reaching high performance, the reproducibility of the production batches is fundamentally important. E.g., the high compression ratios and intake pressures of up to 2.5 bar in the FIA WRC require stable and reproducible fuel behavior, under all conditions. Quality control is fundamental to securing the reproducibility of the fuel and can be ensured using gas chromatography and infrared spectra comparison.

- **Product price:** offering a product that satisfies all mentioned constraints at an affordable price. Moreover, existing manufacturing technology and volumes still makes CNF more expensive than a comparable gasoline refined from crude oil.

About the last constraint, it must be said that in Europe, excise taxes are still as high for CNF as for fossil fuels — although it is hoped that this will soon change as an incentive to sustain scaling up, to be able to offer soon this innovation at an affordable price per litre.

3 100% Fossil-free racing fuel in the FIA WRC 2022

In 2022 the FIA WRC became the first FIA World Championship to adopt a 100%-sustainable gasoline called P1 *FossilFree100 WRC* (Figure 5). The inclusion of the Advanced Sustainable Fuel Standard in the FIA AppJ 252.9 facilitated the rapid introduction of racing fuels with a high renewable component content, either biosynthetic or PtL. In particular, the increase of the maximum oxygen concentration, from, for example, 3.7 % m/m as in the E10 EN228 spec., to 7.5% m/m (Table 2), is a major change in the technical regulations, which allows today to reach both a high level of renewability and good performance of the fuel.

According to the mass balance calculation as in Table 1, during the 2022 FIA WRC season, the introduction of the 100% CNF of P1Fuels contributed to a reduction of ca. 512 Tons of CO_2

Beyond the constraints of the 100%-fossil-free composition, the fuel *FossilFree100 WRC* has been designed to reach a level of performance like its fossil-based predecessor (called here WRC 2021, produced by a different fuel supplier), to be suitable for use in motorsport and the existing rally engines. All constraints described in chapter 2.3 were taken into account to supply the final product. During the development at P1 several fuel formulations have been evaluated with use of an internal ML (Machine Learning) development tool (it will be presented in future publications), allowing an efficient selection and screening of the possible solutions in short time, and limiting the number of physical laboratory measurements.

	P1 FossilFree100 WRC (2022)	FOSSIL WRC 2021 (different supplier)	FIA AppJ 252.9 standard (2022)	EN228 E10 standard
RON [-]	101.0	101.7	95.0 – 102.0	min. 95.0
MON [-]	88.5	88.4	85.0 – 90.0	min. 85.0
Density [kg/m3]	759.0	749.0	720 – 785	720 – 775
DVPE [kPa]	60 – 64	58.0	50 – 80	45.0 – 60.0 (s) 60.0 – 90.0 (w)
Final Boiling Point (FBP) [°C]	ca. 206	< 140	< 210.0	< 210.0
Evaporation at 100°C [% v/v]	64.0	71.0	46.0 – 72.0	46.0 – 71.0
Evaporation at 150°C [% v/v]	80.0	> 90.0	min. 75.0	min. 75.0
oxygen [% m/m]	7.3	3.5	7.5 (max.)	3.7 (max.)
Ethanol [% v/v]	< 1.0	ca. 7.1	-	max. 10
Stoich. A/F	13.4	13.9	-	-
Net Heating Value [MJ/kg]	39.6	41.2	-	-

Table 2: Overview of the WRC fuel characteristics (2021 vs. 2022) and the technical FIA AppJ 252.9, EN228 E10 specifications.

P1 *FossilFree100 WRC* Fuel has been available from September 2021 for testing in rally engines of the Rally1, Rally2, and Rally3 cars in the WRC championship, for Toyota Motorsport, Hyundai Motorsport, M-Sport (Ford), Skoda Motorsport, and Stellantis, the major car manufacturers participating in the WRC events. Together with the manufacturers and the technical department of the FIA, P1 Fuels is investigating the fuel characteristics, and its interactions with the vehicle and engine parts, to understand its limits and what room for improvement is available for the next generation.

Figure 5: P1 Fuels as official supplier at WRC 2022.

Motorsport is the ideal field for the development of automotive technologies: historically, car manufacturers have invented and tested different applications, materials, and solutions in racing, before transferring them into large-scale application in consumer vehicles. This is happening today with CNF, as suppliers such as P1 develop fossil-free fuels for car manufacturers involved in professional motorsport, focusing on sustainability. P1 is transferring the know-how from motorsport to the blending of standard fuels with similar characteristics to what is available at commercial fuel stations, for example, DIN EN228 standard gasoline for Europe or JIS for the Japanese market.

3.1 Learnings from motorsport

Engine/Fuel performance:

Although the P1 *FossilFree100 WRC* fuel has a similar stoichiometric A/F ratio to its fossil predecessor, (it has a typical value of standard gasoline), which makes it a *drop-in fuel*, the net heating value, and particularly the distillation curve of the P1 *FossilFree100 WRC* are different. Indeed, the fossil fuel of the previous year had a much higher volatility at high temperatures, and a very low final boiling point (FBP) in the distillation curve (Table 2), because of the lower concentration of high boiling hydrocarbons, like aromatics.

The engine dynamometer measurements at wide open throttle (WOT) from one of the Rally1 car manufacturers involved in the WRC are shown in Figure 6 and Figure 7. (For confidentiality reasons, the values cannot be disclosed.) The engine is a 1.6 L, DI Turbocharged SI, with a maximum intake boost of 2.5 bar abs., a compression ratio of 12.5 and a 36 mm air restrictor diameter [4]. The Rally1 ICE have a declared power of ca. 280 kW, and the hybrid powertrain reaches a performance of more than 365 kW and 500 Nm. The measurements presented here (courtesy of the Toyota Gazoo Racing Team, TMG) were generated in September 2021, before the start of the first season with the fossil-free fuel, and include cylinder-indicated measurements, which give some insight into the combustion process.

The Rally engines in WOT operate under a rich air/fuel mixture to maximize the combustion efficiency and reduce the knocking tendency (Lambda = 0.80–0.85). The measurements show a relatively high knock sensitivity for the P1 *FossilFree100 WRC* at lower engine speed under these demanding operating conditions, which forces a reduction in ignition advance of ca. 1.0–1.5 °CA, depending on the engine speed. Enrichment of the mixture over a certain limit becomes counterproductive, reducing the indicated efficiency. On the other hand, in the restrictor area, the higher oxygen content in the fuel produces a slight advantage. The lower heating value of the P1 *FossilFree100 WRC* results in a slightly higher fuel consumption (3%–4%). The more recent performance development of the engine with this fuel cannot be reported in this work for confidentiality reasons. However, the indications from the dynamometer regarding the fuel development are quite clear. In direct comparison, the P1 *FossilFree100 WRC* and the previous WRC 2021 fossil fuel introduce a similar amount of energy into the combustion chamber (related to each stoichiometric A/F ratio). In addition, the knocking resistance indicators (RON/MON) are quite similar; however, the mixture formation and the fuel evaporation rate during injection are fundamental for creating the ideal conditions for ignition and combustion propagation. The latent heat of vaporization of the P1 *FossilFree100 WRC* is between 5% to 10% higher than the fossil fuel from 2021 — therefore a positive cooling effect of the mixture can be expected. On the other hand, the slower evaporation rate of the fossil-free fuel can produce a higher axial penetration of the spray, with a possible higher risk of cylinder wall impingement and consequent higher oil dilution. The results of the combustion test show a delay in the combustion start (ignition delay), although the combustion duration (10%–90% of burned mass) is comparable (See Figure 7). The ignition delay increases in the middle engine speed range and can be compatible with a poorer air/fuel homogeneity at the spark plug or with the need of a higher ignition energy. At this moment no more details are available.

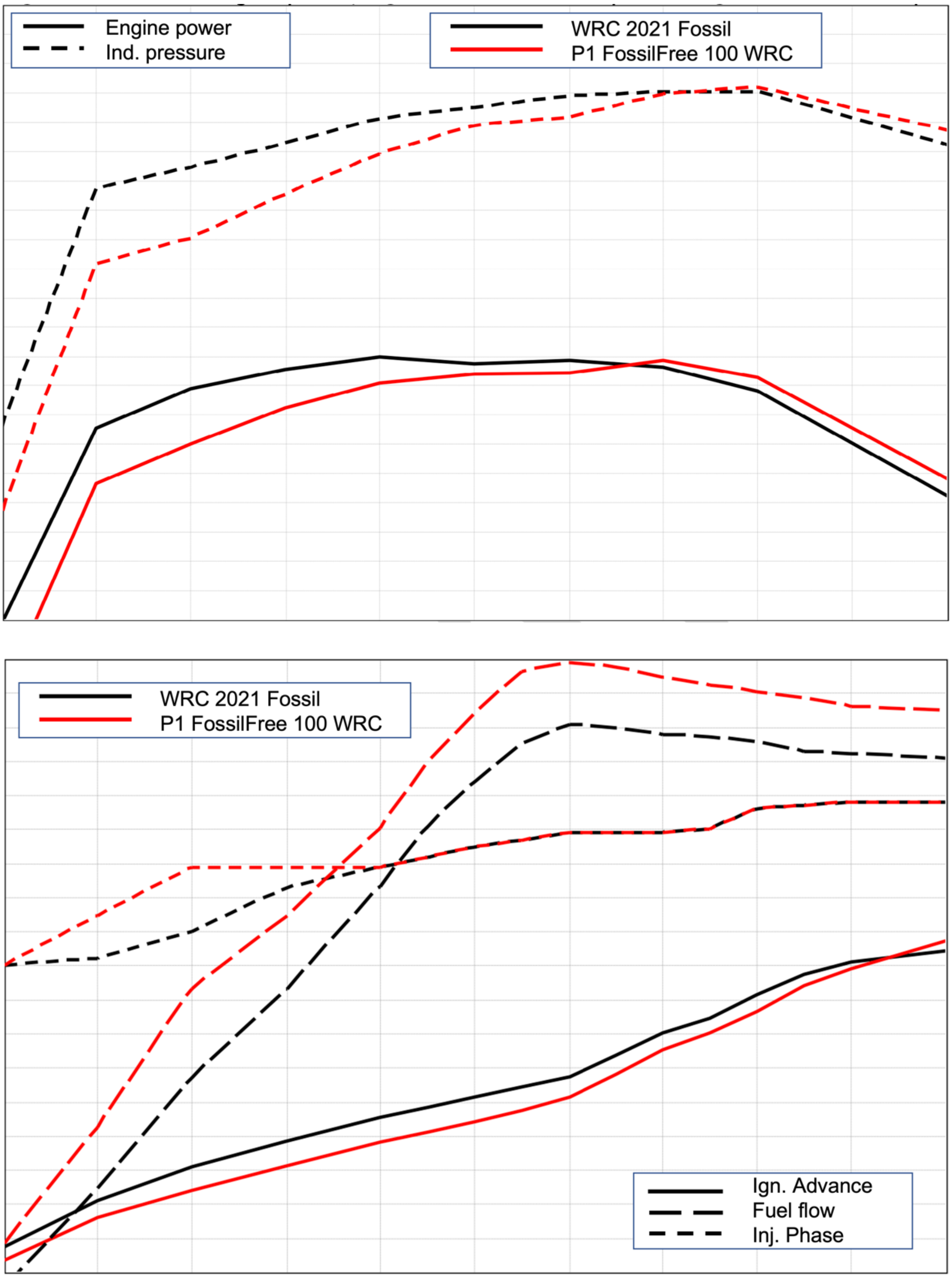


Figure 6: (upper) Torque/power comparison of the P1 *FossilFree100 WRC* fuel vs. the predecessor fossil-based fuel.
(lower) Ignition advance, fuel consumption comparison vs. engine speed (x-axis).

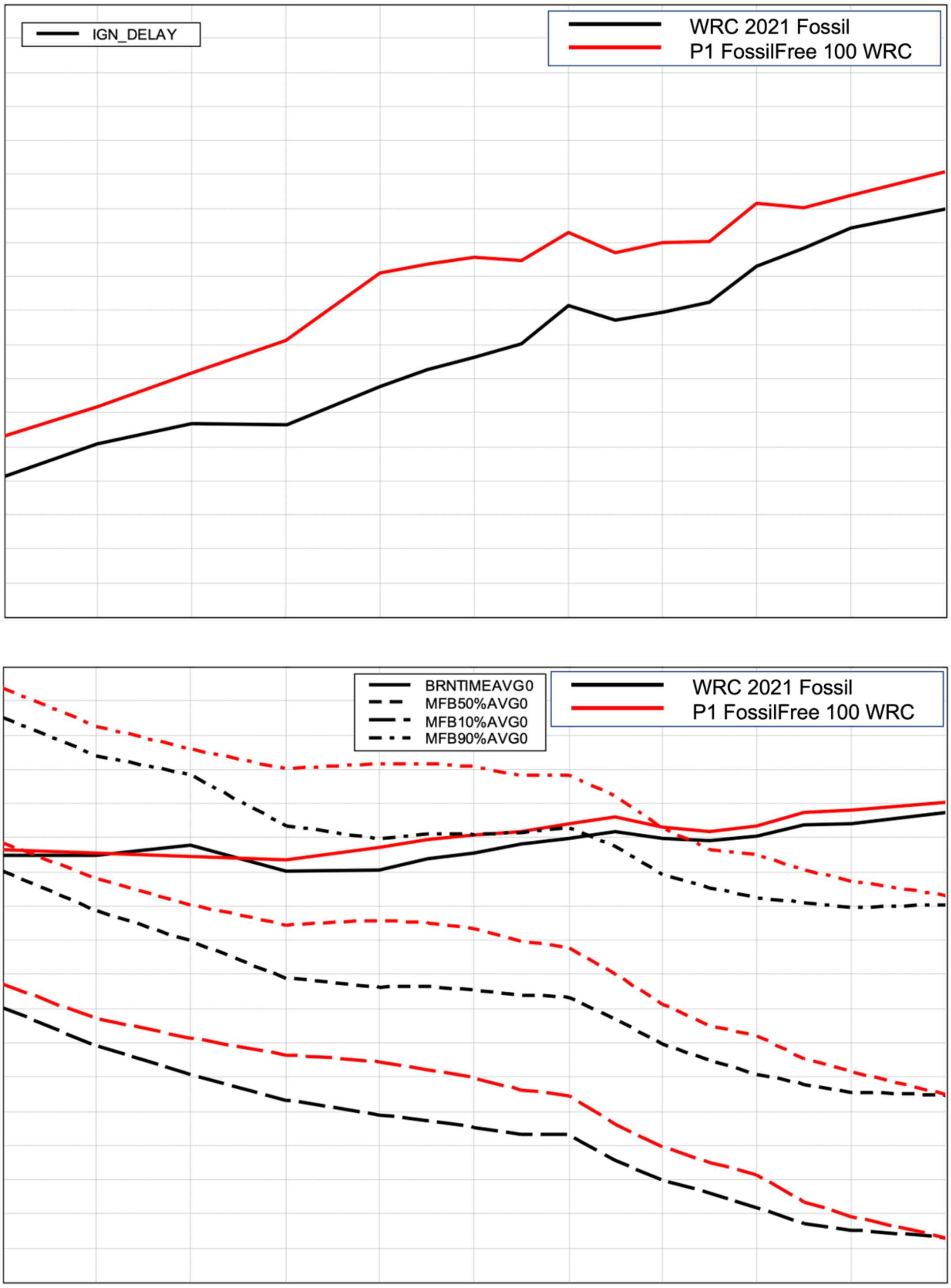


Figure 7: Ignition delay comparison of the P1 *FossilFree100 WRC* fuel vs. the predecessor fossil-based fuel (upper). Combustion duration comparison (lower).

Oil dilution:

Increased oil dilution has been observed when using fossil-free fuel, in particular in direct injection spark ignition (DISI) engines, suggesting the need for further investigation of cylinder wall impingement and spray penetration. These experiments on spray injection have been conducted by P1 Fuels at the French Institute of Petroleum and new energies (IFPen) in Paris, together with the FIA, and the results are reported in Figure 8-9. Different tests have been conducted on a multi-hole gasoline injector (8-holes Delphi solenoid injector) at different temperatures and injection pressures to compare the axial penetration of the fossil-free fuel with the fossil version of the previous year. The measurements have been conducted into a 1.4 L cell at a pressure of 1 bar, the temperature of the fuel was of 90°C, while the air temperature in the cell was of 150°C. The fuel injection pressure tested was of 100 and 200 bar (Figure 9). The results of the tests show that, due to its higher volatility and lower FBP compared to the fossil-free fuel, WRC 2021 fossil fuel builds a more homogeneous droplet distribution during injection. Because of its faster evaporation (see lower FBP and heat of vaporization), the fossil fuel spray has an easier dispersion and a reduced axial spray penetration. As consequence the wall impingement and the oil dilution are lower.

It should be noted that the engine design of the intake ports, combustion chamber and the injectors (homologated parts, which cannot be modified within three years), in the Rally1 cars have been optimized for the use of the previous fuel, while for the lower categories of Rally2 and Rally3, it is mandatory to use standard production injectors [6]. Therefore, it is not possible to intervene in the engine hardware design to improve the fuel injection and mixing process, and the solution must come (almost) exclusively from fuel development, just like drop-in fuels in passenger cars that are already on the roads.

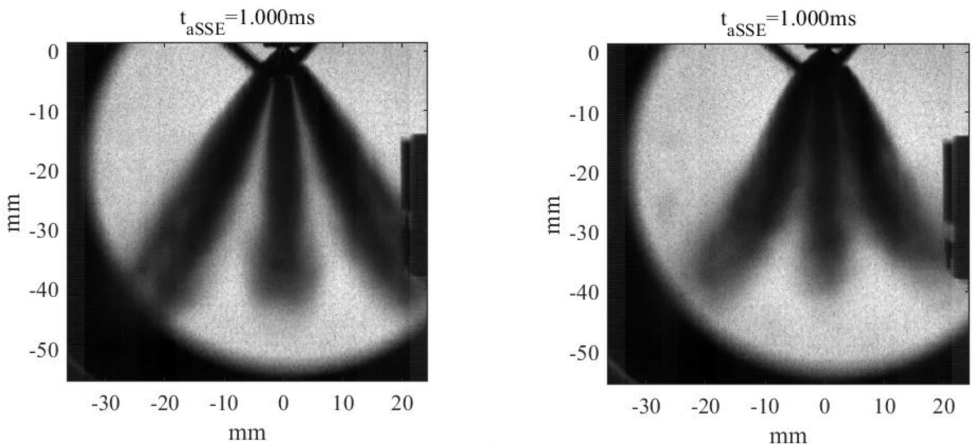


Figure 8: Fuel Injection at 200 bar, 150°C testing cell temperature after 1,0 ms. (Left) P1 *FossilFree100 WRC* fuel. (Right) WRC 2021 (fossil fuel).

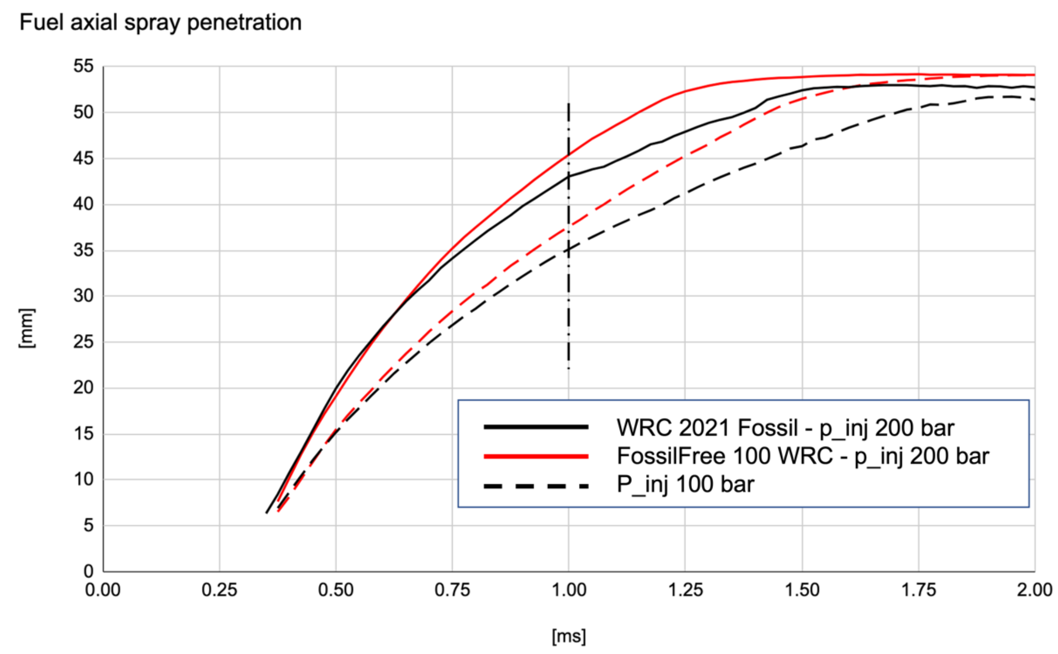


Figure 9: Fuel axial spray penetration comparison at different injection pressure: P1 *FossilFree100 WRC* vs. WRC 2021 (fossil fuel)

The reduction of oil dilution by fossil-free fuel is one of P1 Fuel's highest priorities, as this is not only relevant to the loss of oil viscosity and consequently engine mechanical reliability, but also impacts engine efficiency, as the energy of the fuel impinged onto the cylinder walls cannot be released during combustion. Moreover, under some circumstances, this might create undesirable soot formation and facilitate knocking — however, this last aspect requires deeper investigation, beyond the scope of this work.

4 From racing to standard gasoline

In motorsport, the introduction of new technical regulations has allowed for CNF development, and this knowledge can be transferred towards developing drop-in fuels for commercial applications, where a revision of the fuel road standards (e.g., EN228 in Europe) could facilitate this process.

Valuable experience in CNF development gained in motorsport has been transferred without delay into the development of CNF for standard car applications. P1 Fuels has developed EN228 (European gasoline standard) and JIS (Japanese fuel standard) fuels with different levels of fossil-free components, from 15% up to 100%, based on the same technologies and approach as for the racing fuels. The fuel compatibility with passenger cars fuel line components like sealings and elastomers, as well as the reduction of the oil dilution were the main constraints for the fuel design. In collaboration with prominent car and engine manufacturers, P1 Fuels has developed drop-in solutions which have been successfully implemented for multiple applications, for example, in vintage engines (e.g., the demonstration with the 1922 *Green Pea* Aston Martin with Sebastian Vettel at the French F1 Grand Prix, or with the 1992 F1 Williams car, as well driven by Sebastian Vettel at a demonstration drive in Silverstone in 2022), in GT and touring car engine applications, motorbikes, karting, etc.

At the moment the current legislative framework in Europe does not facilitate the utilization of CNF, and incentives are dedicated only for the purchase of new EV. The ban of ICE from 2035, limiting the necessary investments so scale up CNF. A reduction of the excise taxes for CNF — e.g., correlated with WtT emissions — would be a useful incentive to sustain the development of this market, and facilitate investments by major energy companies and technology owners. Taking the example of what has happened in motorsport, a good first step would be the introduction of a mandatory, affordable minimum level (e.g., 10% - 15%) of fossil-free content in the fuels, with a revision of the technical specification standards.

4.1 Testing the EN228 CNF in a passenger car

Despite conformity with existing fuel standards such as DIN EN 228, the chemical formulation of a fuel has a decisive influence on its evaporation and combustion properties. In order to ensure future use in existing and new production cars, engine oil dilution in gasoline direct-injection engines and compliance with current emissions legislation are important issues which must be managed in the development of synthetic fuels. With this in mind, an advanced EN228 gasoline based on 100%-fossil-free components, called P1 *Eco100Pro*, is analyzed in comparison with conventional premium-grade gasoline, and evaluated under Real Driving Emissions (RDE) boundary conditions. Tailpipe emissions, oil dilution, and drivability tests are carried out at the Institute of Internal Combustion Engines and Powertrain Systems at TU Darmstadt, using an existing fleet production car with a gasoline direct injection engine.

4.2 Experimental setup

A representative C-segment passenger car with homogeneous direct injection and Euro 6c emissions standard is used as the test vehicle. A detailed overview is presented in Table 3.

Research vehicle	
Euro car segment	C
Engine type	3-Cylinder gasoline direct injection
Charging	Exhaust gas turbocharging
Displacement	1000 cc
Max. power	88 kW (120 hp)
Transmission	6-speed manual
Exhaust aftertreatment system	Controlled three-way catalyst
Emission standard	Euro 6c

Table 3: Characteristics of the test vehicle

For the test series, P1 *Eco100Pro*, with 100% fossil-free components, is examined, in comparison with conventional fuel station *Super 95* gasoline. The main properties of the P1 *Eco100Pro* are summarized in comparison to DIN EN228 in Table 4. [18]

P1 *Eco100Pro* technical characteristics			**Specification** – EN 228	
Parameter	Unit	Typical Value	Min	Max
Net heating value (NHV)	MJ/kg	41.0 – 41.4	-	-
Density (at 15 °C)	Kg/m³	760.0 – 763.0	720.0	775.0
RON	-	96.0 – 98.0	95.0	-
DVPE	kPa	48.0 – 52.0	45.0	90.0
Final boiling point (FBP)	°C	ca. 205	-	210

Table 4: Fuel properties

4.3 Test procedure

The testing procedure proposed in this work is based on the following key points:

- At the beginning of the respective measurement series with Super 95 or P1 Eco100Pro, the fuel filter, oil filter and engine oil (SAE 5W30) are replaced.
- The test series with both fuels are each divided into two different real driving profiles.
- A total of eight cold starts are made in urban short trip operation (5.5 km each, Figure 10), followed by a total of eight cold starts on one of the legally compliant RDE routes developed by the Institute (77 km each, Figure 11).
- Before each start, the vehicle is conditioned to 23 °C.
- To determine the fuel content in the engine oil (DIN 51454 :2015) as well as the viscosity curve (ASTM D7042 :2020) over the course of the measurements, oil samples are taken after defined distances have been covered.
- The RDE trips are also used to evaluate the emissions behavior in an existing fleet production car regarding the current Euro 6d legislation.

The cold-started urban short trip in the inner-city low-load range is used to determine the fuel input into the engine oil before the engine is fully warmed up and higher-boiling fuel components can evaporate. The maximum oil temperature after the urban short trips reaches 78 °C. Oil samples are taken after the first (5.5 km total), fifth (27.5 km total), and the last short distance trip (44 km total). The last one is also the initial sample for the following measurements on the RDE route. The oil is not changed in between the two different real driving profiles. The removed quantity is directly replaced with fresh oil at each step. The urban short trip (5.5 km) through the city of Darmstadt and an exemplary speed curve can be seen in Figure 10.

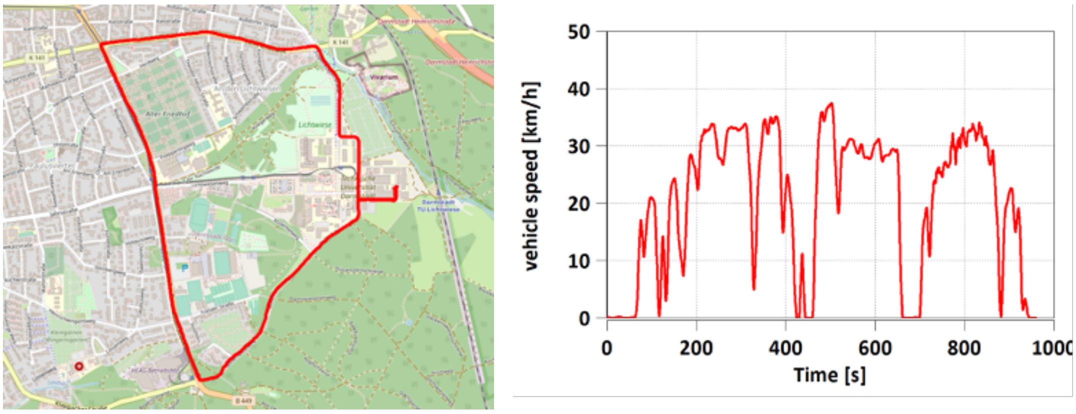


Figure 10: Urban short trip and exemplary speed profile (© TU Darmstadt)

The subsequent RDE route (77 km) meets the requirements of the EU Commission regarding route characteristics in the RDE legislation and is composed of urban, rural and motorway sections [17]. In addition to the environmental conditions and route characteristics, the requirements of the RDE regulation regarding driving dynamics are also met. It will be investigated how oil dilution evolves with higher engine oil temperature compared to short-distance operation, due to a thermally more demanding load profile. The maximum oil temperature after the RDE trips is up to 105 °C. Oil samples are taken after the first (121 km total), fifth (429 km total), and last RDE trip (660 km total). In addition to determining the oil dilution, the RDE trips are used to evaluate the emissions behavior in an existing fleet production car regarding the current Euro 6d legislation. The measurement of the gaseous exhaust gas components (CO_2, CO, NO_X), as well as the particle number (up to 23 nm), are carried out via an AVL M.O.V.E GAS PEMS iS. When evaluating the gaseous exhaust components as well as the particle number, it must be considered that, in the RDE procedure, different boundary conditions are created for the operating state of the engine as well as the exhaust aftertreatment system. This is caused by varying driver characteristics, the influence of traffic, and different ambient conditions. The ambient temperatures during the RDE runs vary from a minimum of 6 °C to a maximum of 25 °C. In addition, production cars such as the Euro 6c test vehicle, which were certified before 1 September 2017, were still tested in standardized test cycles on the chassis dynamometer in a conditioned environment according to the

Worldwide Harmonized Light Vehicles Test Procedure (WLTP) [17]. The application of the RDE legislation only applies to vehicles certified according to Euro 6d-Temp or Euro 6d. The presented results are nevertheless compared to the current Euro 6d RDE 4 legislation in order to assess the usability of the P1 *Eco100Pro* for existing fleet and new production cars under real driving conditions.

The RDE route as well as an exemplary speed curve can be seen in Figure 11.

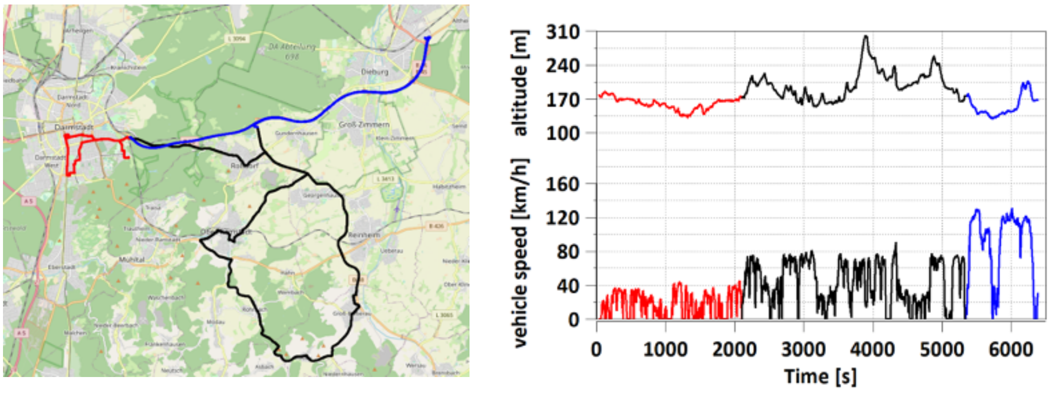


Figure 11: RDE route and exemplary speed profile (© TU Darmstadt)

4.4 Results

The dilution of engine oil with gasoline fuel has a decisive influence on its lubricating properties and consequently on friction and wear of the engine components. Furthermore, with increased oil dilution, lubricant oxidation also increases [19]. Figure 12 shows the change in the fuel content in the engine oil and the kinematic viscosity (at 40 °C and 100 °C) over the mileage for the urban short-trip operation and the subsequent RDE trips.

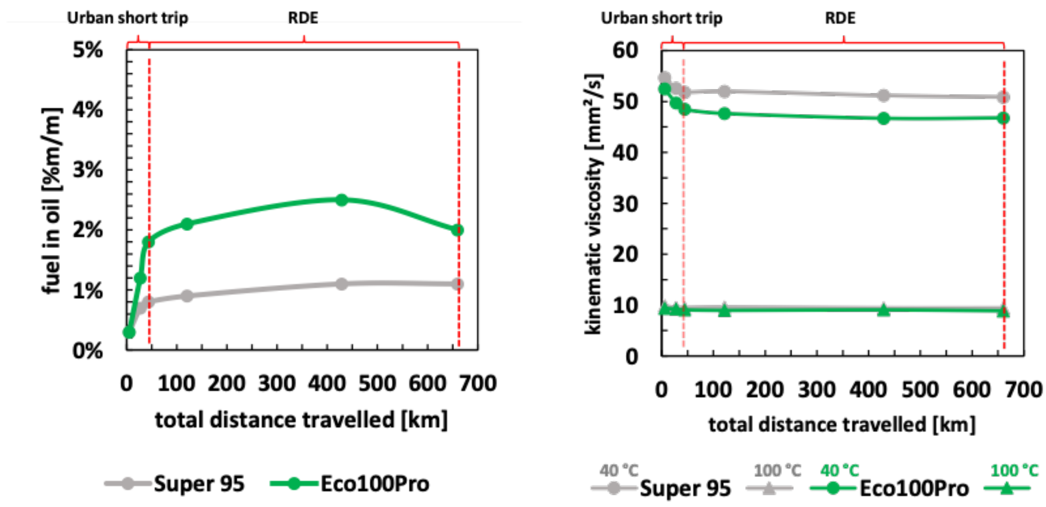


Figure 12: Gravimetric fuel content in engine oil (left) and kinematic viscosity (right) for urban short-trip operation and RDE trips

Most of the oil dilution through fuel occurs in cold-start urban short-trip operation (44 km in total). Especially during cold starts, the fuel condenses on the cold cylinder walls and pistons and reaches the oil sump through the piston rings. Evaporation of the higher-boiling components of the fuel only takes place when the engine is at operating temperature. The low temperature of the cold start urban short-trip operation leads to an increase in oil dilution. In the subsequent RDE runs, only a slight increase is detected, which ends at a maximum of 2.0 % (m/m) for the P1 *Eco100Pro* and 1.1 % (m/m) for *Super 95* after 660 km in total. (The reasons for the higher oil dilution measurable with the P1 *Eco100Pro* in comparison to the fossil fuel are described in chapter 3.1, discussing spray measurements of the racing CNF.)

The measurements for P1 *Eco100Pro* show an evaporation of the fuel content in the oil, which reduces the oil dilution from 2.5 % (m/m) after 429 km to 2.0 % (m/m) after 660 km. For the RDE trips, the steady state point of oil dilution seems to have already been reached at a relatively low dilution level, and no significant increase in oil dilution is expected with continued operation in this load profile. The kinematic viscosity curves at 40 °C for the cold-start relevant range, and at 100 °C for the engine at operation temperature, behave analogously to the oil dilution rate. Similarly, a reduction of the kinematic viscosity in short-distance operation can be seen here, as well as convergence to the steady-state point in the RDE runs.

As investigated in [21], with a maximum fuel content of 2.0 % (m/m) in the oil, no increased wear is to be expected using the P1 *Eco100Pro* compared to *Super 95* in an RDE load profile. Whether an increase in oil dilution occurs during exclusively cold-start short-distance operation over a longer period must be observed in further investigations.

The results of the emission tests on the RDE Route compared to the current Euro 6d RDE4 legislation are presented below. Figure 13 shows the distance-related CO and NO_X tailpipe emissions for a total of eight valid RDE test runs for each fuel.

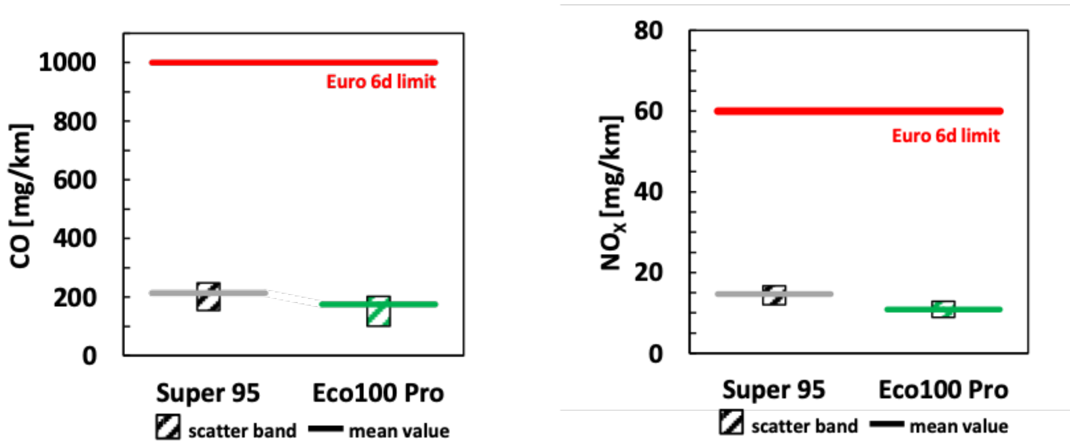


Figure 13: Distance-related CO and NO_X emissions in RDE valid test runs

For both CO and NO_X emissions, the P1 *Eco100Pro* shows comparable results to the *Super 95* after the three-way catalyst. As expected, the respective Euro 6d limits are met by a wide margin. On average, there is even a slight reduction in the CO and NO_X results. This result is to be validated in further investigations on the 4x4 chassis dynamometer of the TU Darmstadt, under defined laboratory test conditions in the Worldwide Harmonized Light Vehicles Test Cycle (WLTC). In addition, the THC emissions, which do not have to be measured in real driving according to the RDE regulation [17], are to be evaluated on the chassis dynamometer in order to obtain a more precise statement about the combustion behavior.

Figure 14 shows the distance-related tailpipe particle number (PN) for the legally relevant detection limit up to 23 nm. On the left of the figure are the entire RDE runs (77 km each), and on the right are the urban part, broken down individually (21 km each). In addition, the Euro 6d limit is shown as well as the permitted limit in real driving conditions, considering the conformity factor (CF). This includes measurement tolerances (0.5), which explains why the permitted laboratory value for PN may be exceeded by a factor of CF max = 1.5 [17]. It has to be considered that the EU 6c certified test vehicle does not have a gasoline particulate filter (GPF), as is already state-of-the-art for an EU 6d production car.

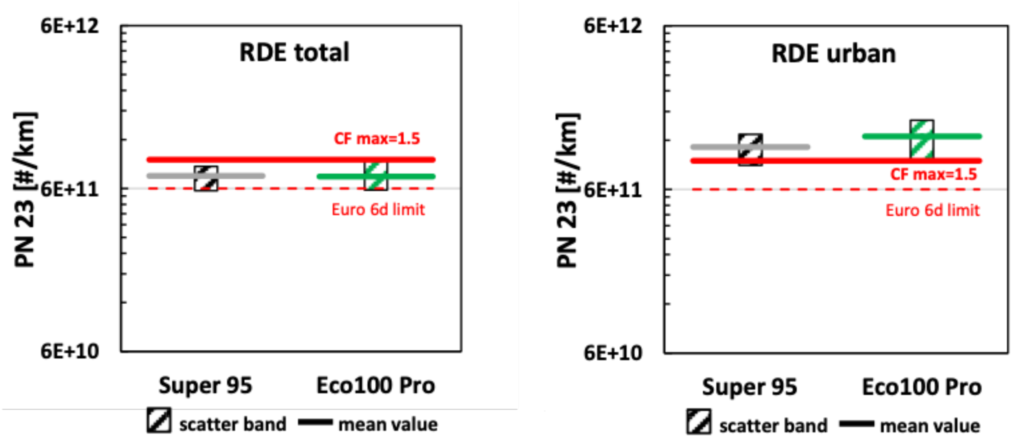


Figure 14: Distance-related particle number (PN 23) in RDE total and urban only

For the mean distance-related particle number considered over the total of eight RDE trips (RDE total), the P1 *Eco100Pro* is at the same level as *Super 95*. Furthermore, the limit values are complied with in all journeys, considering a CF max of 1.5. In the RDE procedure, particulate emissions in the urban part are also assessed individually (RDE urban). With the high proportion of cold starts in relation to the RDE total, the Euro 6d limits are not met in the urban section only, even when applying the conformity factor. As shown in [20], with a gasoline particulate filter (GPF), the Euro 6d limits for the particle number are expected to be met by both fuels within the RDE boundary conditions.

A comparison of the distance-related fuel consumption and the distance-related tank-to-wheel (TtW) CO_2 emissions, over the total of eight RDE trips, are plotted in Figure 15. Both mean fuel consumption and TtW CO_2 emissions are, on average, at the same level due to the comparable carbon content of the fuels. An accurate determination of the fuel consumption without the influence of traffic and the environment must be carried out under laboratory conditions on the chassis dynamometer. As already described in chapter 2.1, the 100%-fossil-free raw material basis of the P1 *ECO100Pro* produces a neutral TtW CO_2 footprint compared to its fossil counterpart.

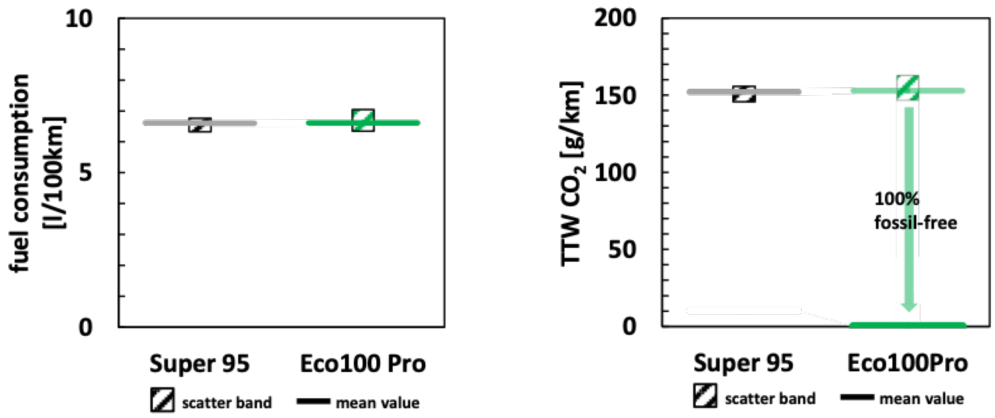


Figure15: Distance-related fuel consumption and CO_2 emissions in RDE valid test runs

The presented results show the potential for the application of an EN228 advanced gasoline fuel based on 100% fossil-free components in existing and new series production cars. The Euro 6d limits for CO and NO_X in the RDE procedure are met by a wide margin, and are slightly lower than for conventional gasoline-station fuel. In addition, P1 *Eco100Pro* fuel tested in a Euro 6d vehicle with a GPF is also expected to comply with RDE limits under all boundary conditions. In further investigations on the chassis dynamometer and at the engine test bench, the fuel's potential for standard vehicle application is to be highlighted, and more in-depth investigations are to be carried out regarding combustion and emission behavior, as well as performance and efficiency.

5 Conclusions and Outlook

The transportation sector is required to make an extraordinary effort to reduce its GHG emissions, and this pressure to achieve the EU government's goals paradoxically leads to significant incentives to use only one technology, the battery EV (BEV) or plug-in hybrid technology (PHEV). However, the path towards sustainable mobility has to take into account social, economic and geographic factors, and we must choose multiple relevant technical solutions in order to maximize the benefit. Fossil-free synthetic fuels can quickly contribute to significant WtW emissions reductions for the majority of currently circulating vehicles worldwide, since 99,5% of them have an internal combustion engine [10]. P1 Fuels recently introduced the first carbon-neutral fuel (CNF) into international motorsport, combining both biosynthetic and PtL solutions with the approach 'now or never', and bringing existing technologies to the market at an affordable price. The FIA WTCR and WRC are the first FIA World Championships in history to use CNF. The transfer of know-how from motorsport to standard fuels like EN228 (European gasoline standard) is underway. In this paper, the results of emissions and drivability tests, conducted on 100%-fossil-free EN228 gasoline, show that the fuel is already a viable drop-in fuel, with comparable performance to the fuel available from commercial gas stations, in terms of emissions, material compatibility and consumption.

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