Motorsport as a Technology Driver for Renewable Fuels in Transport

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Abstract: The Institute for Internal Combustion Engines and Powertrain Systems of TU Darmstadt, in cooperation with DMSB e.V. and funded by the ADAC Foundation, has intensively accompanied the determination of the technical requirements, testing and pilot introduction of non-fossil gasoline in motorsport. This study outlines the path to the first racing series in Germany powered by 100% fossil-free fuel, the ADAC XC Cup, as well as the technical feasibility and potentials of introducing renewable fuels for existing fleet vehicles. The project has successfully laid the foundation for access to climate-neutral drive technologies in junior and amateur classes.

The pilot application in motorsport was supported by preliminary investigations of a drop-in capable and non-fossil gasoline within the DIN EN 228 at the engine test bed. A 3-cylinder MPFI-engine from the powersport segment which powers the corresponding FIA XC Cross Car was used. Within the scope of the investigation the performance, efficiency, oil dilution and emission behaviour were analyzed and evaluated in comparison to conventional premium-grade gasoline. The tests were carried out at various operating points up to full load as well as in the legal certification cycle WMTC without changes to the engine's hardware or software. In addition, a life cycle assessment (LCA) has been carried out for the 100 % fossil-free fuel in cooperation between ASAP GmbH and P1 Performance Fuels GmbH.

The final result of the LCA showed that the (WTW) emissions of Eco100 Pro are reduced by 77.4% compared to fossil gasoline E5. The results at the engine test bench show that the non-fossil fuel achieves the same performance and efficiency level of its fossil counterpart across the entire map range. Increased wear as a result of engine oil dilution can also be ruled out with regard to the motorsport application under consideration. The moderate influence of fuel properties such as viscosity, which are not part of DIN EN 228, has been shown under full load as well as under cold start operation in WMTC. The emission results of the WMTC and the map measurement show possible potentials and highly recommend the application of the fuel in the powersports segment.

1 Introduction

The legal and social calls for sustainable mobility require the reduction of CO_2 and pollutant emissions in the transport sector. A central role has been taken by the political, media and social debate on renewable fuels as a possible pathway to achieve this goal. Drop-in capable and non-fossil gasoline within the DIN EN 288 offers the possibility of CO_2-neutral mobility with wide applicability and can significantly reduce atmospheric greenhouse gas emissions of existing fleet and new production cars [1]. In this context, demonstrating the technical feasibility of renewable fuels with existing engine technology is a key factor.

Detached from political discussions motorsport offers the ideal platform to develop, test and demonstrate renewable fuels under most demanding conditions and can also serve as a technology driver for the transfer to the transport sector. The introduction of alternative drive technologies and sustainability strategies in motorsport is also driven by social necessity as a public projection surface. In its long history, motorsport has paved the way for pioneering innovations in the automotive industry with its racing technologies. Numerous technologies and developments that originated in racing have found their way into road vehicles. The introduction of turbocharging and direct injection, for example, has helped to increase engine performance while reducing fuel consumption. In the 2000s, the Kinetic Energy Recovery System (KERS) was developed - initially in Formula 1 - which is now used in production vehicles, especially electric and hybrid vehicles, and significantly reduces fuel or energy consumption [3].

Today, motorsport is increasingly focusing on sustainability and the development of environmentally friendly technologies. Electric powertrains, fuel cell drives and renewable fuels are important areas where motorsport is currently driving innovation. The Deutsche Motor Sport Bund e.V. - DMSB as the responsible umbrella organisation for motorsport in Germany focuses on diversity with its sustainability strategy for alternative drive concepts. Only an approach to research and development in the mobility sector that is open to all technologies can reconcile sustainability, innovation, competition and social acceptance in a targeted manner.

Since 2021, the VKM of the TU Darmstadt has been running the research project "Replacement of fossil fuels by synthetic fuels in motorsport" with the DMSB, which was funded by the ADAC Foundation. In this context, the "ADAC XC Cup", the first racing series in Germany powered by 100% non-fossil fuel, could be introduced from 2022 by ADAC Motorsport and has successfully laid the foundation for access to climate-neutral drive technologies in junior and amateur classes. In addition, other racing series are gradually being run on synthetic fuels, e.g. the Porsche brand trophys (Porsche Super Cup and Carrera Cup), the German Kart Championship (100 % synthetic fuel from P1 Performance Fuels) or the DTM and the ADAC GT Masters, each of which uses 50% fossil-free fuel (Shell Blue-Gasoline 98) [4] [5] [6].

Overall, the move towards fossil-free fuels in motorsport signals a significant paradigm shift in the industry. It shows that motorsport can not only be focused on speed and technology, but also take a responsibility for the environment. This shift could not only enhance the image of motorsport, but also help create a more sustainable and future-proof direction for the entire sector. This paper presents the path towards the first racing series in Germany to run on 100% fossil-free fuel, as well as the technical feasibility and potential of introducing renewable fuels for existing fleet vehicles based on selected test bench results and an LCA consideration.

2 Pilot Introduction of an 100% fossil-free fuel in motorsport

The fundamental goal of the project was to launch the first amateur and junior racing series in Germany powered by 100% non-fossil fuel. Within the framework of a market and feasibility study, it was first assessed whether the development, testing and pilot introduction of synthetic fuels in amateur motor sports could be realised. Technical, economic and ecological boundary conditions were considered. Exemplary representatives of potentially renewable drop-in-capable synthetic hydrocarbon fuels and a C1 oxygenate fuel (DMC+) were investigated in comparison to conventional gasoline in preliminary tests at the engine test bench of the VKM of the TU Darmstadt. Based on this, the technical requirements for a potential fuel for the pilot application were detailed. This is initial basis for the results presented in this paper.

With P1 Performance Fuels GmbH, a fuel supplier could be found who has already developed a completely non-fossil fuel variant for the FIA WRC [1], which, however, does not fulfil DIN EN 228. The joint goal was to bring an EN 228-compliant variant into pilot application. Since ADAC Motorsport intended to launch the ADAC XC Cup as a low-cost amateur racing series run on climate-neutral fuels in the course of its promotion of young talent and sustainability premise, a cooperation could be realised together with DMSB e.V. The vehicles for the ADAC XC Cup are provided by LifeLive Germany GmbH. These are FIA-certified cross cars (XCs) with a 3-cylinder MPFI-engine from the powersport segment in accordance with the current EU5 emissions standard. The test bench investigations of the 100 % non-fossil fuel presented in this paper were performed at the VKM as well as the vehicle tests and technical support of the pilot application in the ADAC XC Cup. The life cycle assessment (LCA) has been carried out for the 100 % fossil-free fuel in cooperation between ASAP GmbH and P1 Performance Fuels GmbH.

3 Technical boundary conditions

In close coordination with the Deutscher Motor Sport Bund e.V. (DMSB), the technical boundary conditions for a potential fuel were derived from the findings of the market and feasibility study and the preliminary tests at the engine test bench. The DMSB is a member of the Federation Internationale de l'Automobile (FIA) and, as the umbrella organisation and holder of national sporting sovereignty, responsible for the technical regulation of German motor sport. In summary, the following fundamental technical requirements were defined:

- Compatibility with existing engine technology and compliance with existing fuel standards (FIA Appendix J, Art. 252.9; DIN EN 228 E10)
- Consideration of motorsport-specific requirements such as knock resistance (min. RON 98, max. RON 103) or high combustion rate (oxygen content)
- 100% renewable and non-fossil, hydrocarbon-based fuel using Advanced biofuel components (2nd generation, ISCC Plus /REDCert EU certified) and/or e-Fuel components

Retrofitting existing engine technologies is sustainable, cost-reducing, and a fundamental requirement in the short to medium term, especially in amateur motor sport. Adjusting the engine at software level to exploit fuel-specific efficiency and emission potentials was not assumed for the pilot application. However, co-optimisation of fuel and combustion engine should be considered in the future, as any efficiency and emission advantage will be important for the development of sustainable drive systems. In the course of stock compatibility, compliance with existing fuel standards in motorsport (FIA Appendix J, Art. 252.9) was also assumed. This permits to use the fuels without adapting the existing technical regulations. In addition, the predominant conformity with the European fuel standard for unleaded petrol DIN EN 228 enables a potential transfer to passenger car series application. Although compliance with this standard is not mandatory for use in international motor sports, it is already required for various racing series at national level, such as in the DMSB rally regulations [2]. The main differences between the conventional motorsport standard and DIN EN 228 are the increased permissible density value as well as the maximum values of the octane numbers for regulated competition. The distillation properties correspond predominantly to class C/C1 of EN 228, except for moderate differences at E70. [7] [8] In addition, in all DMSB competitions without FIA predicate, a maximum knock resistance of 103 octane must always be maintained. Specifically, to promote the use of renewable fuels, Advanced Sustainable (AS) Petrol was added to FIA Appendix J, Art. 252.9 [3] in 2021. This allows a higher oxygen and aromatics content which enables the use of ethanol contents up to 20 percent by volume. However, this deviates significantly from the EU standard, why this extension was excluded within the scope of the project.

In addition, motorsport-specific requirements were defined with regard to performance and efficiency aspects. Beyond the minimum value of the standards, a knock resistance of at least 98 octanes should be aimed for. Production fuels with RON 98 are already widely used in amateur motor sports up to the professional Touring Car sector in the FIA World Touring Car Cup (WTCR) [9]. With regard to the oxygen content in the fuel, the DIN EN 228 E10 standard, like the FIA standard, allows a higher ethanol and oxygen content compared to the conventional E5 standard.

The last essential requirement was defined as 100 % non-fossil raw material basis. The pilot application was intended to establish the first racing series in Germany to rely on completely non-fossil fuel and not only proportionally renewable components. This presented a separate challenge in terms of availability and economic aspects, but was nevertheless decisively supported by the DMSB e.V. and ADAC Motorsport. In addition, when using bio-components, only advanced 2nd generation components according to the Renewable Energy Directive (RED II) should be used and certified accordingly by the world's leading standards such as the International Sustainability and Carbon Certification (ISCC) Plus as well as REDCert.

4 Fuel Properties

The 100 % fossil-free fuel investigated and used for the pilot application is referred to below as "Eco100 Pro" in accordance with the naming convention of P1 Performance Fuels GmbH. An excerpt of the relevant characteristics of Eco100 Pro is shown in Table 1 in comparison with conventional premium grade gasoline "Super 98".

Table 1: Fuel Properties

Technical Characteristics		**Eco100 Pro**	**Super 98**	**Specification – EN 228**	
Parameter	Unit	Typical Value	Typical Value	Min	Max
Net Heating Value (NHV)	MJ/kg	41.0 – 41.4	42.25	-	-
Density (at 15 °C)	Kg/m³	760.0 – 763.0	754.0	720.0	775.0
RON	-	96.0 – 98.0	99.7	95.0	-
Aromatics	% V/V	27.0 – 30.0	33.8	-	35.0
Olefins	% V/V	< 7.0	11.6	-	18
Oxygen	% m/m	3.5 – 3.7	2.11	-	3.7
DVPE	kPa	48.0 – 52.0	55.7	45.0	90.0
E150 °C	% V/V	75.0 – 77.0	90.1	75	-
Final Boiling Point (FBP)	°C	205	190.9	-	210

Both fuels meet the requirements of DIN EN 228 for unleaded petrol. In detail moderate differences are noticeable. In particular, the lower share of aromatics and olefins, the higher oxygen content and the higher final boiling point as well as the lower evaporation rate with high-boiling fractions are to be mentioned for Eco100 Pro. The effects on mixture formation and the resulting combustion and emission behaviour are discussed in chapter 7.

5 Life Cycle Assessment (LCA)

A life cycle assessment (LCA) has been carried out for Eco100 Pro in cooperation between ASAP GmbH and P1 Performance Fuels GmbH, to investigate and compare the Eco100 Pro with a generic fossil fuel in order to determine the amount of GHG emissions that can be avoided by using 100% renewable hydrocarbons Eco100 Pro in place of fossil fuel. This model includes Well to Wheel (WTW) emissions which means the use-phase (combustion) of the fuel is taken into account [10]. The model includes all the greenhouse emissions from the production, conversion, and distribution of the fuel used to power the vehicle and including the manufacture of all the equipment and building required in the process. The LCA is according to DIN ISO 14040:2006 and ISO 14044:2006. The LCA framework adopted in this study consist of the following four phases.

5.1 Goal and Scope Definition

The objective, system boundary conditions and the level of detail is included in the scope. The first steps in carrying out an LCA involve defining the system, process, or product for which the LCA is being done, as well as the report's goals, parameters, functional unit, and boundaries for time, space, and the production chain. The analysis's elements, procedures, and life cycle stages are all defined as part of the system boundary specification. In order to obtain a clear frame of the LCA study scope, and determine the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA), the following assumptions have been taken into account:

- Determining of the direct impact of various parameters for Eco100 Pro and a reference gasoline on the WTT and WTW GHG emissions, relative to the functional unit applied (1 kg of Eco100 Pro or reference fossil gasoline).

- The Eco100 Pro is a fossil-free second-generation biofuel (sourced from biomass waste). It is produced inside the EU and transported by lorry EURO6. The input data and inventory are based on the POS (Proof of Sustainability) of each material certified by REDCert EU and ISCC Plus. If there weren't specific input data, the input data were taken from Ecoinvent 3.8 (2021).

- The system boundary to determine the environmental impacts of the fuel is Cradle-to-Gate emissions which include all the greenhouse emissions from the production, conversion, and distribution of the fuel used to power the vehicle and include the manufacture of all the equipment and building required in the process. In road transport, LCA studies Cradle-to- to-Gate is equivalent to Well-to-tank (WTT). Additionally, a second model with an extended system boundary has been created. This model also includes the Cradle-to-grave emissions which means the use-phase (combustion) of the fuel is taken into account. Cradle-to-grave emissions are also called Well-to-wheel (WTW) in terms of road transport.

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- The Umberto LCA+ 10.0.3 life cycle assessment modeling software is used to develop and link primary unit processes.

- The impact assessment method used is IPCC 2013 GWP 100a, with the impact categories climate change expressed in kg CO_{2eq}.

- The allocation method used in this LCA is energy-based allocation already used in input data from the suppliers.

5.2 Inventory Analysis

The life cycle inventory analysis (LCI) phase involves compiling the input and output data related to the system under Assessment. The LCI phase entails identifying each input (materials and energy resources) and output (emissions and waste to the environment) for the product system or process that is being investigated. Each process within the system boundary has input and output data gathered and collected, including flows of raw materials, energy, products, co-products, wastes, and emissions into the air, soil, and water. The main data are collected from:

- The POS (Proof of Sustainability) of each material certified by REDCert EU and LCA calculations of suppliers.
- The Ecoinvent 3.8 (2021), the global leading LCI database which contains over 16.000 unique datasets.
- The JEC Well-To-Wheels report V5 from the EU Joint Research Centre (JRC) [11].

Raw Material

All the components are made from food waste (cut-off approach) which means there are no emissions from land use change, cultivation, etc. taken into account from the feedstock of these components like explained in the RED II [10]. During the growth of the biogenic feedstocks, all the carbon in the main components is bound from the air in the form of Carbon (C). As a result, no fossil CO_2 is emitted during fuel combustion, only CO_2 that has been removed from the atmosphere. The CO_2 equivalents from combustion are therefore equal to zero due to the carbon sequestration of the biogenic feedstock.

Production

The fuel blending plant is placed in a country in western Europe, for this process the electricity is provided from the European grid. Additionally, for a RED II conform calculation, a petroleum refinery is considered as a reference plant for this process. The impact of the petroleum refinery is based on one kilogram of fuel of the total production capacity of the entire plant lifetime.

Distribution

The Transport of the final product Eco100 Pro includes the lorry transport from the plant in Europe to a customer in a neighborhood country. The transport distance is calculated with an online map service.

Use

The use phase of the Eco100 Pro is the combustion in a vehicle. The measured emissions are 3.031 kg CO2eq/kg fuel. The result of the measure is validated with a calculation. The calculated emissions amount to 3.035 kg CO2eq/kg fuel and have been calculated using fossil reference values from JEC Well-To-Wheels report V5.

Fossil Fuel Comparator

The Directive (EU) 2018/2001 (RED II) defines a fossil fuel comparator of 94 g CO_{2eq}/MJ fuel (3.8728 kg CO_{2eq}/kg fuel) [10]. This includes all cradle-to-grave emissions.

5.3 Impact Assessment

The purpose of the life cycle impact assessment phase (LCIA) is to provide further information to assess the environmental consequences of a product system. The life cycle impact assessment is based on the IPCC 2013 GWP (100a) method [12] [13]. The IPCC 2013 GWP (100a) is calculated with the LCA modeling tool Umberto LCA+ 10.0.3.

5.4 Interpretation

Life cycle interpretation is the process of summarizing and analyzing the findings of an LCI, LCIA, or both in order to derive conclusions, make recommendations, and make decisions that are in line with the aim and scope description. The total cradle-to-gate emissions to produce 1 kilogram of Eco100 Pro is 0.8783 kg CO_{2eq}.

The final result of the LCA showed that the (WTW) emissions of Eco100 Pro is 0.8780 kg CO_2/kg fuel. If we compare this result with Fossil Gasoline E5 that has (WTW) emissions of 3.8728 kg CO_2/kg fuel [11], the GHG emissions reduction for Eco100 Pro is 77.4%. The LCA has been critically reviewed by SGS Institut Fresenius GmbH as they confirmed that it has been carried out largely in accordance with the international standards ISO 14040:2006 and ISO 14044:2006 and can be regarded as scientifically and technically correct.

6 Experimental Setup and Test Procedure

The unit under test is an 890 cm^3 three-cylinder gasoline engine with intake manifold injection and conventional three-way catalytic converter (TWC) with binary lambda control. The engine from the powersports segment is certified according to the current Euro 5 emission standard. Table 2 summarises the key technical characteristics.

Table 2: Technical engine data

Technical Characteristics	**Property**
Engine Type	3 cylinder MPFI-gasoline engine
Displacement	890 ccm
Max. Power	87,5 kW/119 hp at 10.000 1/min
Transmission	6-speed-manual
Exhaust gas aftertreatment	3-way-catalyst
Emission standard	EU 5

The engine corresponds in its configuration and application to the drive unit intended for the FIA XC Cross Car, which is used in the ADAC XC Cup. A Woolich Racing Log Box D-CAN and a Zeitronix ZT-3 Wideband Package were installed to record the essential data from the engine control unit and for future potential adjustment of the ignition, fuel and throttle maps. The additional wideband lambda sensor enables the lambda values to be recorded. The engine itself, however, is controlled by the standard binary lambda sensor. The standard fuel pump is used. Fuel consumption is determined with an AVL KMA Mobile. The gaseous exhaust components are measured by an AVL FTIR i60 upstream of the three-way catalytic converter (TWC) and an AVL AMA i60 downstream of the TWC. In addition, the particle number concentrations (PN) are measured upstream of the TWC using an AVL Particle Counter (APC).

6.1 Map Measurement

To analyse the oil dilution, efficiency, performance and emission behaviour, both fuels are subjected to a map measurement in the course of the investigations. The aim is to evaluate the engine performance without any adjustments to the engine control when using Eco100 Pro in comparison to conventional Super 98. The engine speeds are run through in steps of 2000 rpm up to a maximum speed of 10.000 rpm with constant throttle valve positions. The throttle positions (TPS) themselves are approached in 10 % steps up to the maximum opening (100 %). The operating time at the respective stationary points is identical for both fuels under steady state conditions. The engine is examined at operating temperature. The ambient conditions and the relevant fluid temperatures are kept comparable.

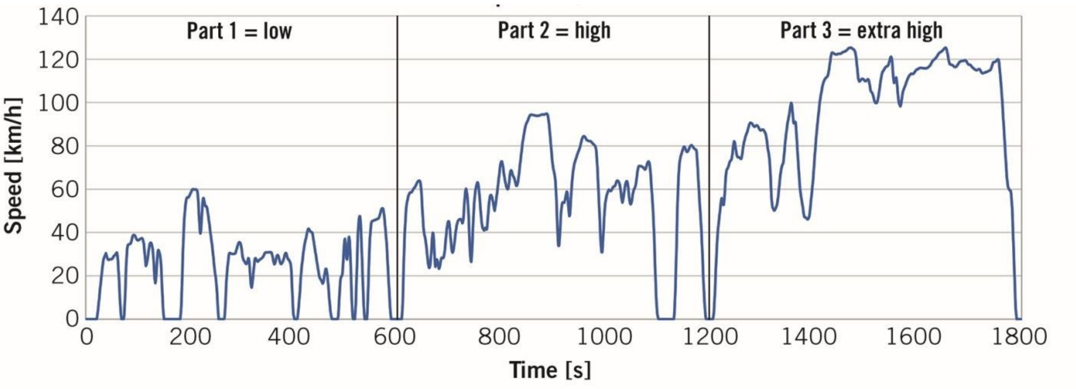
To determine the fuel input into the engine oil, an oil and filter change is conducted before the map measurement of the two investigated fuels. In accordance with the ADAC XC Cup, fully synthetic engine oil RAVENOL Racing 4-T Motobike SAE 110W-40 is used. After the respective map measurement has been carried out, a sample of the engine oil is taken. The oil samples are subsequently tested for their fuel content (DIN 51454 :2015) and kinematic viscosity at 100 °C (ASTM D7042:202).

6.2 Flow measurement

The viscosity of a fuel is not regulated in DIN EN 228. As the engine under investigation is operated in higher load and speed ranges outside the lambda control range, a change in viscosity may have an effect on the lambda value and thus on the engine performance with the same opening time of the injection valve and a constant injection pressure. Using an external injector (Bosch 0 280 158 191), the flow of both fuels is investigated at constant injection pressure (3.5 bar), an opening time of the injection nozzle of 180 s and at three different fuel temperatures (between 22°C and 30°C) in order to draw conclusions about potential differences in dynamic viscosity. The flow volume is determined via an AVL KMA Mobile and the fuel mass calculated with Table 1 is validated via weighing. The injector does not correspond to the injector of the test engine and is only used to estimate possible viscosity differences.

6.3 World Motorcycle Test Cycle (WMTC)

In order to assess the transfer potential to series application, the emission behaviour under transient and cold-start conditions is being investigated at the engine test bench based on the Euro 5 homologation cycle WMTC [14]. Results of the application in a direct-injection passenger car have already been presented in [1]. Figure 1 shows the velocity curve as well as the distances and average speeds of the three phases of the WMTC.



Cycle part	Duration (from-to) [s]	Average speed [km/h]	Distance [km]
Part 1	1-600	24.395	4.066
Part 2	601-1200	54.673	9.112
Part 3	1201-1800	94.424	15.737

Figure 1: Speed Profile WMTC L3e 3-2 [15]

For the carry-over to the engine test bench, the WMTC was retraced in accordance with Regulation EU 134/2014 (L3e 3-2) on a certification chassis dynamometer using a motorbike with identical engine hardware and software. The corresponding resistance coefficients were determined using Appendix 5-1 from Regulation EU 134/2014. The resulting TPS profile was subsequently transferred to the engine test bench. As the delivered break mean effective pressure is comparable for both fuels, a specific emission comparison can be made. In analogy to the map measurement, the cold-starts are carried out under standard conditions in the test cell. Three tests are carried out with each fuel.

7 Experimental Results

7.1 Oil Analysis

Dilution of engine oil with fuel can significantly reduce an oil's lubricating and load carrying capabilities. The causes of oil dilution are predominantly due to wetting of cylinder running surfaces with fuel and blowby gases, especially in direct-injection engines. [1] [16] In the application case of an intake manifold injection, increased wall wetting may also occur. The extent depends on the injection strategy, e.g. with an open valve injection (OVI) or with a closed valve injection (CVI). [17] Figure 6 shows the results of the gravimetric fuel content in the engine oil analysis after 440 minutes of operation in all map ranges.

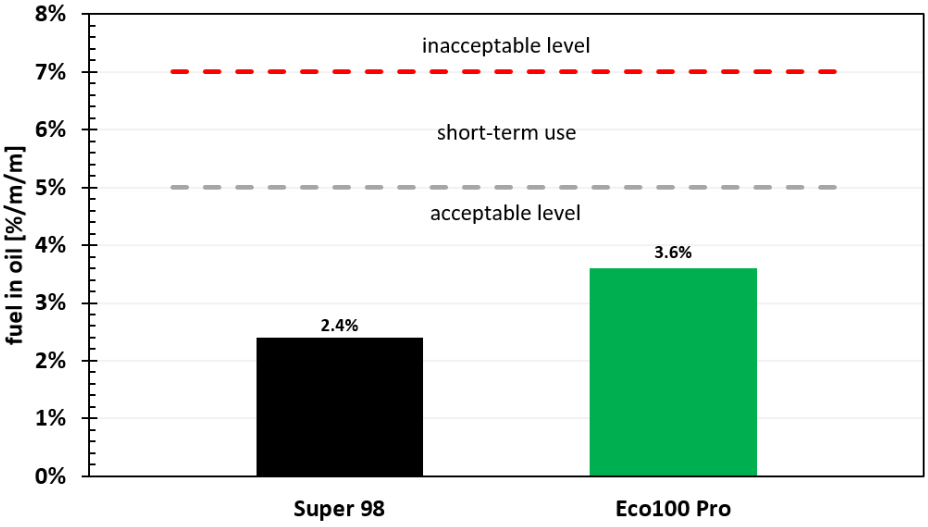


Figure 2: gravimetric fuel content in engine oil after 440 minutes of operation

The maximum fuel content in the engine oil is 2.4 % (m/m) with Super 98 and 3.6 % (m/m) with Eco100 Pro. As a result, after 440 minutes of operation in all map ranges including full load, an increase in oil dilution can be seen with the Eco100 Pro. Nevertheless, this is not to be considered critical, as the gravimetric fuel content in the oil is < 5 % (m/m). Above 5 % (m/m), only short-term use is recommended, as both the flash point and the oil film stability decrease progressively. Above 7 % (m/m) oil should be changed. [18] The kinematic viscosity at 100 °C also confirms that the Eco100 Pro is at an acceptable level. According to SAE J 300, the oil's viscosity of 12.41 mm^2/s is marginally below the limit viscosity values at 100 °C for fresh 10W40 oil (>12.5 mm^2/s) [19]. In addition, with a driving time of approx. 60

minutes per race weekend in the ADAC XC Cup and scheduled oil change intervals after each event, increased wear mechanisms can be ruled out through the use of the Eco100 Pro in the motorsport application considered. Whether a saturation point has already been reached must be investigated in further tests under dynamic operating conditions. Approaches in the further development of the fuel (Super Eco100 Pro) by lowering the final boiling point and an increase in the evaporation rate for high boiling fractions are already promising. In the same test procedure, the same level as for Super 98 was measured with this fuel at 2.3 % (m/m).

7.2 Speed Variation at Part-Load

At partial load at 40 % throttle position (TPS) the same map-based engine parameters, such as injection duration and ignition angle, are set by the engine control in the entire speed range independently of which fuel is used. At the load points under consideration in the low to medium speed range (2000 to 7000 rpm), there is already a transition from binary Lambda control to map-based application. The resulting air-fuel ratios (Lambda) and the brake mean effective pressures (BMEP) of both fuels are shown in Figure 3.

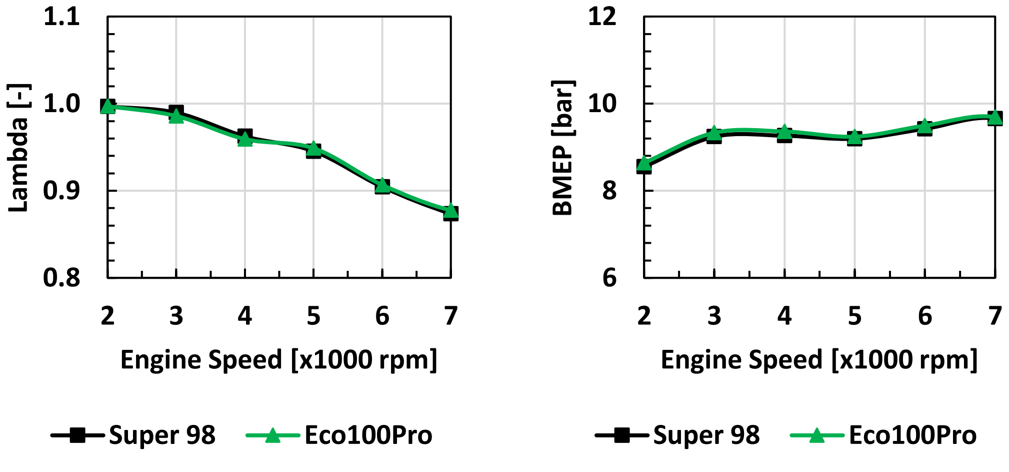


Figure 3: Air-fuel ratio and effective mean pressure at 40 % TPS

Comparable air-fuel ratios (λ) and brake mean effective pressures (Δ BMEP < 1 %) follow from the same map-based engine parameters for both fuels. The same applies to the exhaust gas temperatures and specific volumetric fuel consumption (SVFC) in Figure 4.

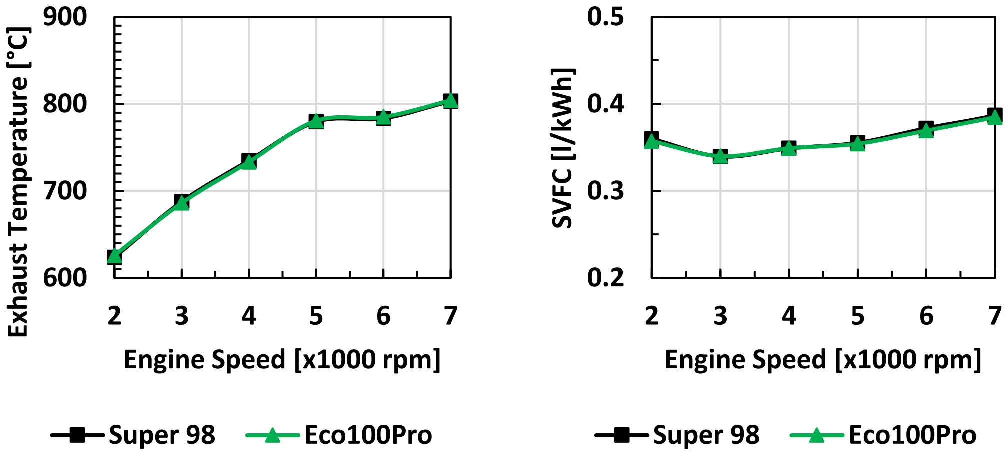


Figure 4: Exhaust gas temperature pre TWC and specific volumetric fuel consumption at 40 % TPS

The results show a consistent engine performance and efficiency for the Eco100 Pro at part load and in the low to medium speed range, due to the comparable chemical properties to conventional gasoline within DIN EN 228. The differences between the slightly higher density and the moderately lower calorific heating value of the Eco100 Pro balance each other out in terms of volumetric fuel consumption. Contrary to the FIA Formula 1, for example, it is not the fuel mass that is decisive in the ADAC XC Cup, but the amount of fuel carried.

The consistent engine performance with the engine at operating temperature and under stationary conditions allows a direct comparison in terms of emission behaviour. The correlations continue by looking at the CO and NO_X raw emissions in Figure 5.

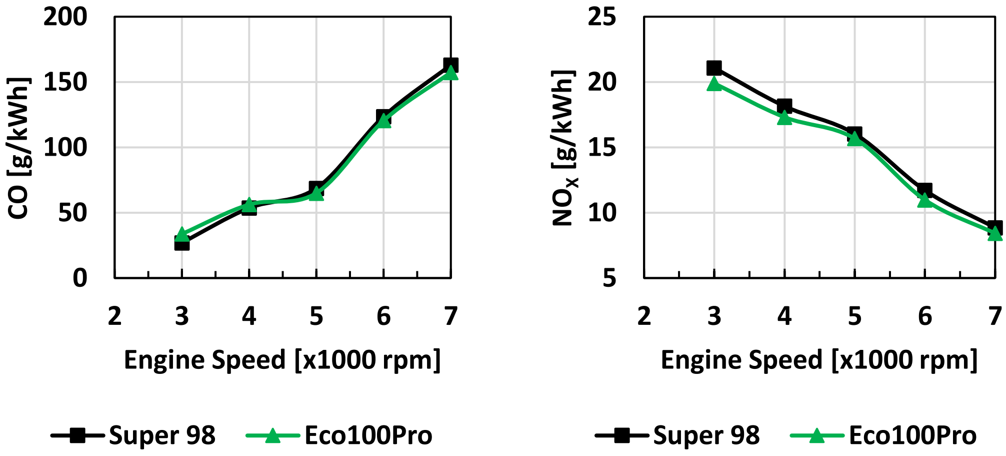


Figure 5: specific CO and NO_X raw emissions at 40% TPS

With Eco100 Pro, the CO raw emissions show no significant difference compared to Super 98. The same applies to the NOx raw emissions, which even show a moderate trend towards a reduction by up to 6.5%. The trend towards emission reduction is clearly seen in the THC raw emissions and the particle number concentrations in the range > 10 nm (PN10) in Figure 6.

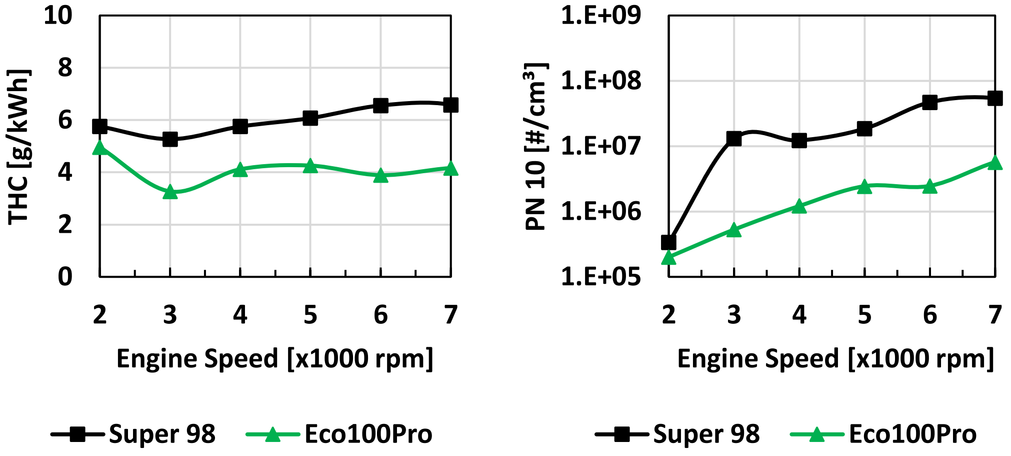


Figure 6: specific THC and PN10 raw emissions at 40% TPS

The reduction of THC raw emissions is at a maximum of 40.6 % at 6000 rpm. For PN10, this results in a significant reduction potential by up to 95.9 %. The reduction potential of the THC- and PN10 raw emissions is measured in a wide range of the map at engine operating temperature. This is where the lower aromatics and olefin content, the higher oxygen content and slightly lower C/H ratio of Eco100 Pro may have an effect [20]. In addition, if the vapour pressure is not reached, the fuel can evaporate abruptly (flash boiling), which could increase the particle emissions of Super 98. Due to the lower boiling temperatures and the negative pressure when injecting the fuel. [21] [22]

7.3 Full-Load Performance

For the motorsport-specific application, the full-load behaviour is considered in particular. The results of the brake power and brake torque of both fuels within the map measurement are shown in Figure 7.

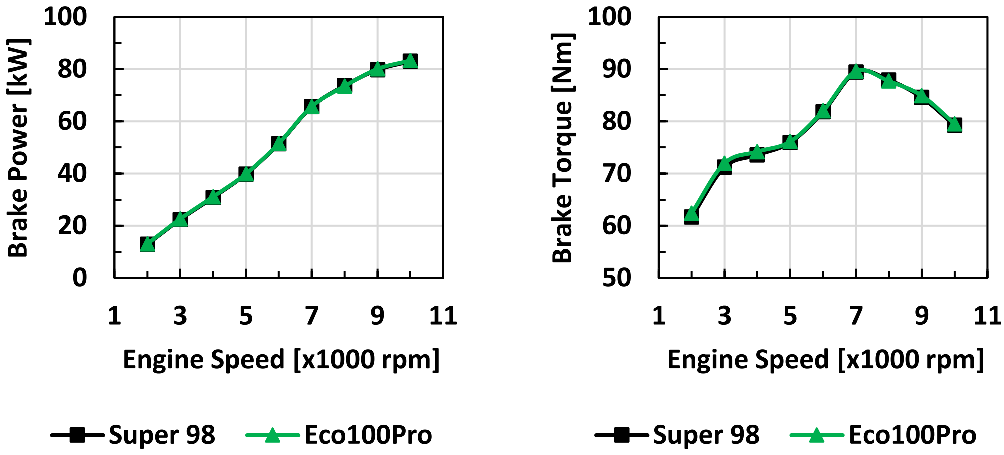


Figure 7: Power and torque with WOT and speed variation

Without any adjustment to the engine control, the maximum deviations in power and torque are less than 1 % over the entire speed range. As a result, the same level of performance is achieved with the non-fossil fuel as with conventional Super 98. In similarity to the part-load tests, the map-based engine parameters such as injection duration and ignition angle are predominantly the same at full load. However, it is noticeable that slightly different λ-values result for the same brake mean effective pressure (BMEP) at wide open throttle (WOT).

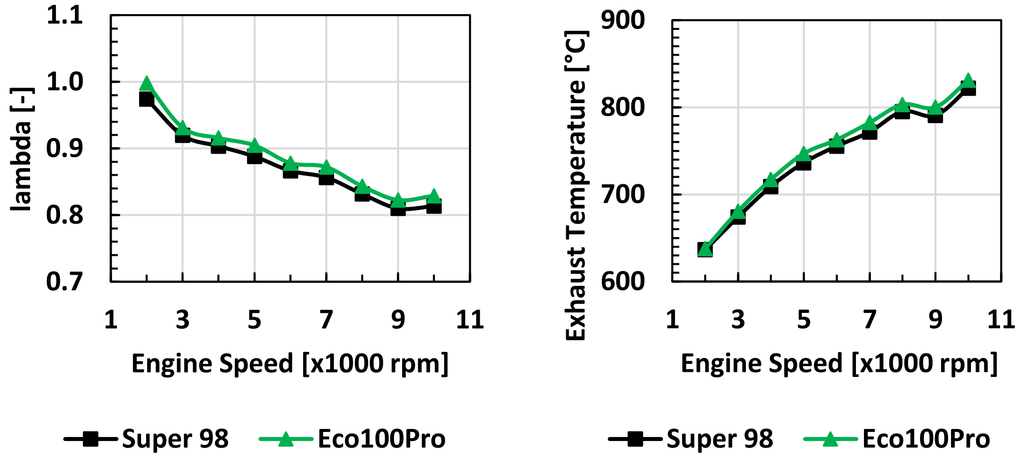


Figure 8: lambda and exhaust temperature at WOT and speed variation

Figure 8 shows the slightly lower full load fuel enrichment across the entire speed range with the Eco100 Pro based on Lambda and the exhaust temperature in the manifold pre TWC. The injection pressures (IP) are similar for both fuels (Figure 9). The higher lambda value is accompanied by an increase in exhaust gas temperatures of 10.8 °C at maximum. Consequently, the excess fuel with Super 98 is primarily used for cooling, as there is no increase in performance compared to the Eco100 Pro. Any effects on increased component wear are therefore not to be expected. Especially in the use case of the ADAC XC Cup due to the short race distance, the high maintenance intervals and the limited full-load shares in the Auto-Cross area.

The moderate higher lambda of the Eco100 Pro at WOT can be traced back to the fact that slightly less fuel is introduced into the intake manifold with the same fuel pressure and the same opening time of the injector. Figure 9 shows the corresponding volumetric fuel consumption (VFC) at WOT as well as the injection pressure (IP) on the left. The results of the flow measurement at different fuel temperatures and constant injection pressure (3.5 bar) are presented on the right-hand side.

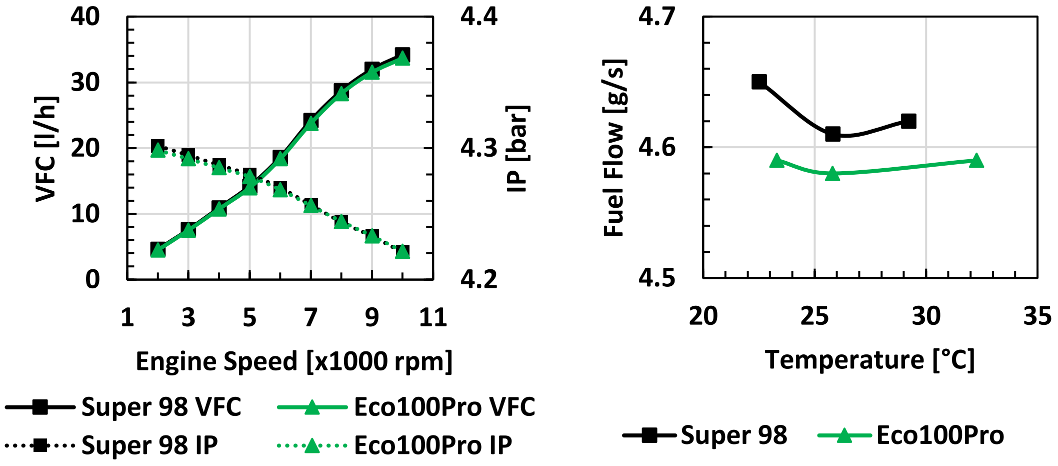


Figure 9: volumetric fuel consumption at WOT and speed variation (left); flow measurement at different fuel temperatures and 3.5 bar injection pressure (right)

The volumetric fuel consumption is on average 1.5 % lower with Eco100 Pro. The results of the flow measurement confirm the observation of the slightly lower fuel input in the order of magnitude, taking into account the minor density differences. This can be attributed to a moderate higher dynamic viscosity of the Eco100 Pro. The viscosity is not regulated in DIN EN 228 but nevertheless has an influence on the injection behaviour. As the viscosity of the fuel increases, a higher injection pressure is required [23]. At part load, this relative difference is not noticeable due to the lower fuel mass introduced overall.

Looking at the emission behaviour at WOT, it can be determined that the NO_X and CO raw emissions behave in the same way as already shown in the partial load tests. However, it is noticeable that the THC and particulate raw emissions of both fuels converge at high engine speeds in Figure 10, although advantages for the Eco100 Pro were detected in the low to medium speed range and the lambda value is even lower than with Super 98.

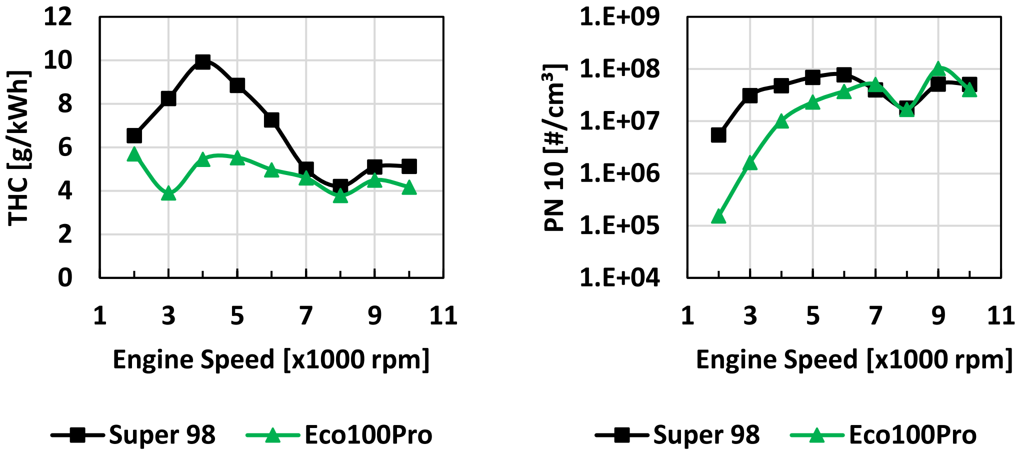


Figure 10: specific THC and PN10 raw emissions at WOT and speed variation

This can be attributed to the higher final boiling point, the higher share of high boiling fractions and the lower vapour pressure of the Eco100 Pro in combination with the lower time for mixture preparation, which compensates the advantages of the fuel in the lower speed range [21] [22] Nevertheless, even at WOT, the Eco100 Pro shows consistent or even improved emission results compared to conventional Super 98. A further development of the fuel (Super Eco100 Pro) with lowered boiling point suggests potentials that are part of further investigations.

7.4 WMTC

The following results discussed are based on the cold-started WMTC in order to evaluate the potential of a series application in the powersports segment. Figure 11 shows the legally relevant [14] specific gaseous tailpipe emissions of the WMTC in relation to Super 98. The particulate mass is only regulated for direct-injection engines and therefore not part of this assessment. Part 2 of the WMTC was double-weighted according to equation 2-54 of Regulation EU 134/2014 for the performance classes L3e/L4e. In addition, fuel consumption as well as (WTW-)CO_2 emissions are shown.

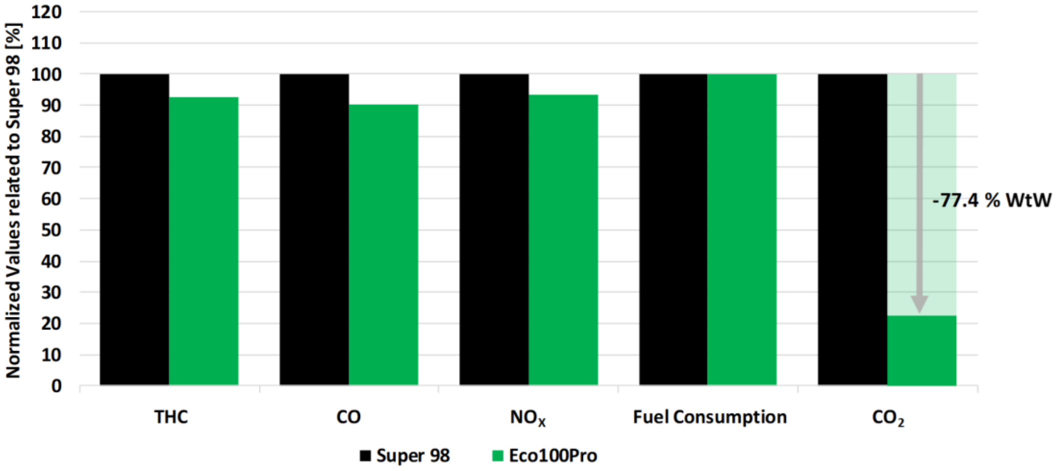


Figure 11: gaseous tailpipe emissions, fuel consumption and WTW-CO_2 at WMTC

For the gaseous exhaust gas components, a trend towards reduction is seen for all 3 species considered. In particular 8.6 % for THC, 9.7 % for CO and 6.8 % for NO_x. Volumetric fuel consumption and tailpipe CO_2-emissions are at the same level for both fuels. Considering the WTW-emissions as shown in chapter 5, the reduction potential of 77.4 % becomes visible.

Looking at the cold start in part 1 of the WMTC conclusions can be drawn about the engine behaviour and the differences in gaseous emissions for both fuels. Figure 12 shows the lambda values measured with the wideband O_2 as an average for each fuel up to 5 s and 10 s after engine start up and the corresponding exhaust gas temperatures before TWC. In contrast to the results in 7.2 and 7.3, the binary lambda control is predominantly active in the WMTC. However, it takes a few seconds for the lambda sensor to be activated, and in cold start operation rich conditions ($\lambda < 1$) are set for the first 20 seconds at idle to ensure safe operation. Since the standard binary lambda only enables control by lambda ~1.0, injection and ignition are purely pre-controlled during this time.

	Mean λ after 5 s	Mean λ after 10 s
Super 98	0.99	0.95
Eco100Pro	1.02	0.98

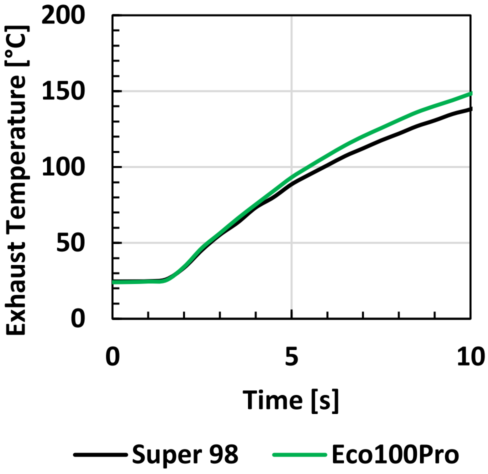


Figure 12: mean lambda value and exhaust temperature pre TWC during cold start

It can be seen that higher mean lambda values result from the pilot control 5 s and 10 s after the start-up process with the Eco100 Pro. The engine runs under slightly lean conditions for the first few seconds. In the second idling phase of the WMTC after the cold start phase has been completed (110 s), a lambda of 1.0 is adjusted for both fuels. Accordingly, the moderate differences in fuel properties influence cold-start operation until the control loop is active. For example a higher viscosity reduces the flowability and pumpability as well as the atomisation behaviour of the fuel [24]. In the case of engine concepts with gasoline direct injection and wideband lambda sensor as in [1], the moderate differences can be compensated for even under rich conditions by adjusting the injection pressure and duration as soon as the lambda sensor is active. The resulting effects on the starting behaviour and the smooth running under slightly leaner conditions for the engine concept considered, must be clarified in further investigations especially at low ambient temperatures.

Figure 12 also shows that the exhaust gas temperatures pre TWC increase more quickly with the Eco100 Pro due to the leaner mixture compared to Super 98 as well as the late ignition angles at the start up. Thus, the TWC heat up slightly faster. This leads to a faster conversion of gaseous emissions in part 1 of the WMTC. Apart from the influences in the starting behaviour, the results also show that the fuel-specific advantages of the Eco100Pro are visible when the engine is at operating temperature in particular in phase 3 of the WMTC. This confirms the results in Chapter 7.2 and in [1].

8 Conclusion and Outlook

The project has supported the introduction of the first racing series in Germany powered by 100% fossil-free fuel and has successfully laid the foundation to climate-neutral drive technologies in junior and amateur classes. By using fossil-free fuel, the CO_2 footprint of the racing series could be significantly reduced. The final result of the LCA showed that the (WTW) emissions of Eco100 Pro are reduced by 77.4% compared to fossil gasoline E5. Accordingly, a use in series application can make a decisive contribution to achieving the climate targets.

The results of the engine test bench show that the same level of performance and efficiency is achieved with the non-fossil fuel as with conventional Super 98 without any adjustments to the engine control unit. Increased wear mechanisms as a result of engine oil dilution by fuel can be ruled out in the motorsport application under consideration. The behaviour under dynamic boundary conditions should be investigated beyond. The results confirm the observations made in [1] with a gasoline direct-injection production car.

The results have also shown that the kinematic viscosity of the fuel should be taken into account, even if it is not specified in DIN EN 228. Although the moderate influences have no significant effect on engine operation under full load. When transferring it to series development, the starting behaviour at low temperatures as well as smooth idle should be part of further investigations due to the slight leaning with pilot-operated injection under cold start operation.

From an emissions point of view, the results of the WMTC and the map measurement indicate that the application of the fuel in the powersports segment for engines with manifold injection is highly recommended. In this respect, advantages can be expected, as the results of the gaseous emissions and [1] confirm. The behaviour in cold start operation with a direct injection gasoline engine is part of further investigations as well as the effects on mixture formation and oil dilution due to the reduction of the final boiling point with the further development called Super Eco100 Pro.

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