



SZÉCHENYI ISTVÁN UNIVERSITY
AUDI HUNGARIA FACULTY OF
VEHICLE ENGINEERING

The Impact of Alternative Fuels on Emissions, Efficiency, and Performance of SI Engines

Author:

Zaid Mursi

BSc Vehicle engineering

Co-author:

Rafiul Hasan

BSc Vehicle engineering

Supervisor:

Nagy Gábor

Department engineer

Audi Hungaria Faculty of Vehicle Engineering

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Abstract

There is a strong move toward sustainable energy worldwide, and ethanol-blended fuels are considered a promising alternative to fossil fuels in the automotive industry. This Work analyzes and compares the performance, emissions, and fuel efficiency of ethanol-gasoline blends, specifically E10 (10% ethanol, 90% gasoline) and E34 (34% ethanol, 66% gasoline), in spark-ignition (SI) engines. This study evaluates the potential of using higher ethanol concentrations in automotive fuel systems by examining key engine performance metrics, including power output, thermodynamic efficiency, and emissions reduction.

The testing was performed on an AVL Dyno Spirit 450 test bench using a Volkswagen EA888 2.0 I4 engine in a controlled laboratory environment. The available data is adequate for conducting a precise assessment of fuel consumption, emissions, and overall engine performance. Steady-state and dynamic testing have been carried out at a wide range of operating conditions to compare E10 and E34 blends.

The results of our study demonstrate that E34 significantly improves the thermodynamic efficiency of the engine and reduces harmful emissions such as carbon monoxide (CO), and hydrocarbons (HC) due to ethanol's superior combustion properties. Furthermore, we had some success in reducing emissions of CO₂. Additionally, the higher ethanol content enhanced knock resistance, allowing the engine to operate at higher compression ratios, thus boosting performance. These improvements were achieved using fuel blends with the same RON number (95). These findings put E34 in a better position as a cleaner and more efficient option when compared to its lower ethanol blends and thus serve as a promising direction toward sustainable transportation solutions. The results obtained in this work will be very informative for policymakers and industrial stakeholders by providing further enhancement of the role ethanol can play in future green fuel strategies.

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Abbreviations

AHC	–	Aromatic Hydrocarbons
BSFC	–	Brake-Specific Fuel Consumption
C ₂ H ₄	–	Ethene
C ₂ H ₅ OH	–	Ethanol
CAN	–	Controller Area Network
CH ₃ CHO	–	Acetaldehyde
CH ₃ OH	–	Methanol
CH ₄	–	Methane
CO	–	Carbon Monoxide
CO ₂	–	Carbon Dioxide
COS	–	Carbonyl Sulfide
CPC	–	Condensation Particle Counter
CVS	–	Constant Volume Sampler
DOHC	–	Dual Overhead Camshaft
ETOH	–	Ethanol
FID	–	Flame Ionization Detector
FTIR	–	Fourier Transform Infrared
g/kWh	–	Grams per Kilowatt-Hour
GHG	–	Greenhouse Gases
GPU	–	Gas Preparation Unit
H ₂ O	–	Water
HCOOH	–	Formic Acid
IRD	–	Infrared Detector
LN ₂	–	Liquid Nitrogen
MEOH	–	Methanol
MEP	–	Mean Effective Pressure
MFC	–	Mass Flow Controller
MFM	–	Mass Flow Meter
MON	–	Motor Octane Number
NMHC	–	Non-Methane Hydrocarbon
NO _x	–	Nitrogen Oxides
O ₂	–	Oxygen
PMD	–	Paramagnetic Detector
PNC	–	Particle Number Counter
RON	–	Research Octane Number
RPM	–	Revolutions Per Minute
SI	–	Spark-Ignition
UN/ECE	–	United Nations Economic Commission for Europe

1. Introduction

There has been a hunt for more sustainable alternatives to fossil fuels in the automotive sector due to growing environmental concerns and the finite nature of these resources. The negative effects of burning fossil fuels on the environment, such as increased emissions of greenhouse gases (GHG) and the acceleration of global warming, have been more apparent in recent decades. The dominance of fossil fuels is unsustainable because of their limited availability and negative environmental impact. Biofuels have the potential to lessen the negative impact of the transportation sector on the environment, and this fact has prompted research into and use of alternative fuels (Atabani et al., 2012) [1].

Because of its renewable source and ability to drastically cut greenhouse gas emissions, ethanol has risen to the top of the biofuels developed so far. Plant resources, including corn, sugarcane, and other biomass, are the main ingredients in ethanol production. Because of this, it has an edge over traditional fossil fuels as they are nonrenewable and are considered one of the leading causes of pollution in the world. Ethanol, being a renewable energy source, could be integrated into relevant fuel systems currently in use by mixing with petrol. The output of such a process is a group of ethanol blends, which are gaining increased application in motor vehicles worldwide. Because it is an ecologically friendly fuel and one that would relieve the dependency on energy sources, ethanol looks like a promising area of future research. (Conțiu & Chiriac, 2024) [2]. More than any other sector, the car industry is a major source of global greenhouse gas emissions. It is therefore of great importance for the freight transport system to use less energy and provide fewer emissions. One way to solve this problem: use ethanol, it is a cleaner burning alternative than gasoline. Ethanol is a key component in the automotive industry's sustainable technology as it begins to wean off fossil fuels. (Costa & Sodr , 2016) [3].

Conventional spark-ignition (SI) engines can run on fuel mixes that include a certain percentage of ethanol, such as E10 (10% ethanol, 90% petrol). There has been a lot of research on the viability of using ethanol blends in SI engines, which are standard in passenger cars. Car makers can increase the performance of their engines by blending ethanol with petrol. This is because ethanol has a higher octane rating than base gasoline, allowing for increased compression. Ethanol, in this case, pairs with ethanol's higher compression ratio, essentially becoming a key part of green fuels. (Costa & Sodr , 2016) [3].

1.1. Problem Statement

While ethanol-blended fuels, like the popular E10 (10% ethanol, 90% gasoline), have become more common, there's still much we don't know about their long-term impact on engine performance, emissions, and fuel economy. Even with ethanol's widespread use, the science around how it affects these critical areas over time remains limited.

Researchers are studying E34, a 34% ethanol 66% gasoline fuel blend, to discover its impacts. They want to know if higher ethanol levels boost fuel economy without harming the environment. This research may reveal if higher-ethanol fuels are viable for engines and the environment.

One of ethanol's many virtues is the decreased amount of greenhouse gases it releases into the atmosphere. Blends such as E10 usually reduce emissions, but higher ethanol concentrations may not improve fuel efficiency. Because ethanol has less energy per gallon than gasoline, drivers may need to stop more often to refuel because they get worse fuel economy (Hansen et al., 2016) [4]. Ethanol blends help lower pollutants such as hydrocarbons (HC) and carbon monoxide (CO), but they may increase nitrogen oxides (NO_x), which contribute to smog and ozone formation (Jacobson, 2009) [5]. In terms of emissions, there is also a trade-off.

1.2. Objectives

The main goal of this study is to compare E10 and E34 ethanol blends in depth to see how they affect engine efficiency, emissions, and performance. By comparing the two, we can learn more about the costs and benefits of using larger quantities of ethanol and how they affect the environment. The study's stated goal is to:

- Focusing on power production, thermodynamic efficiency, and engine durability, assess the performance of current spark-ignition engines when operated on E10 and E34.
- Testing the environmental impacts of E10 and E34 mixtures.
- Assessment of the impact of E10 and E34 on fuel economy.
- To strike a compromise between the environmental benefits and the technical constraints associated with fuel economy and emissions management, suggest ways to optimize the percentage of ethanol in fuel mixes.

1.3. Research Questions

- How do ethanol blends, specifically E10 and E34, impact the performance of modern spark-ignition engines?

The effects of ethanol concentration on combustion efficiency, fuel economy, and engine power are the focus of this inquiry. Additionally, it will investigate whether increasing the concentration of ethanol can enhance thermodynamic performance while maintaining the longevity and reliability of the engine (Costa et al., 2021) [6].

- What are the comparative effects of E10 and E34 on greenhouse gas emissions, particularly CO₂, CO, and NO_x?

The study will assess the impact of increasing ethanol concentrations on greenhouse gas emissions and any unforeseen repercussions, such as a rise in nitrogen oxide (NO_x) emissions that are detrimental to air quality and public health (Singh & Agarwal, 2012) [7].

- What are the related trade-offs and how does using higher ethanol blends affect fuel economy?

Given ethanol's lower energy density than gasoline, this topic aims to investigate if using higher ethanol blends, such as E34, offers more environmental benefits than a negative effect on fuel efficiency (Hansen et al., 2016) [4]. Higher ethanol proportions in gasoline blends allow a sustainable mix of engine performance, fuel efficiency, and emissions lowering.

1.4. Scope of the study

This research shows a contrast between E10 and E34 in modern spark-ignition (SI) engines to investigate the effects of ethanol mixes on engine performance and environmental sustainability. SI engines found in passenger cars provide a subset of the whole fuel market for ethanol blends, so the emphasis is on them.

Research on the effects of ethanol blends on efficiency, emissions, and engine performance is underway. It will skip over diesel and natural gas as alternative fuels, and it will not get into the societal and economic effects of ethanol production, such as land use. In light of the study's conclusions, politicians, environmentalists, and car companies will need to think carefully about ethanol's role in future sustainable fuel initiatives.

2. Evaluating the Potential of Alternative Fuels

2.1. Overview of Alternative Fuels

2.1.1. Ethanol

The renewable resources and possible reduction in emissions of greenhouse gases (GHGs) have led to ethanol's rapid rise to prominence as an alternative fuel. The main sources of ethanol, which is subsequently combined with gasoline to generate fuels like E10 (10% ethanol) and higher ethanol blends like E20 and E34, are biomass feedstocks including corn and sugarcane. Especially in high-compression engines, the high-octane rating of ethanol in these blends increases combustion efficiency and helps to reduce engine knocking, hence improving engine performance (Atabani et al., 2012) [1].

The octane rating enhancement of ethanol fuels aids spark-ignition (SI) engines through a significant advantage. For example, experimental evidence shows in a fuel type comparison that ethanol-blended fuels (E10 and E20) have rather higher Research Octane Numbers (RON) than regular gasoline. When running blends like E20, which attain even higher values at around 99.0 RON, compared to E10's 97.2 RON, engines can run more effectively at greater compression ratios.

However given ethanol's lower energy density, its fuel efficiency is less than that of gasoline. More frequent refueling can result from this lower energy density, especially in higher ethanol concentrations such as E20 and E34 as Hansen et al. (2016) [4] have observed. Notwithstanding these issues, ethanol is still a sensible option for fulfilling rules aiming at the lower of GHG emissions since it benefits the environment (Costa & Sodré, 2016) [3].

2.1.2. Bioethanol

When it comes to achieving sustainable energy goals and lowering emissions, bioethanol a form of ethanol produced from renewable biological sources is indispensable. Extensive research on bioethanol's combustion properties has shown that fuels blended with ethanol help to reduce emissions of toxic byproducts such as hydrocarbons (HC) and carbon monoxide (CO), leading to a cleaner burn. Because of the oxygen in ethanol, which promotes more complete combustion, bioethanol blends (E10 and E20) enhance engine performance while reducing CO and HC emissions (Khuong et al., 2017) [9].

But bioethanol's effect on engine lubrication is a cause for concern. Researchers looking at the tribological characteristics of bioethanol-blended fuels found that engines using oils with a higher acid number saw faster corrosion and component wear when the ethanol percentage was higher. For instance, research on engine oils containing E20 and E30 mixes has shown that fuel dilution reduces oil viscosity by 30%. This, in turn, can worsen wear, especially when subjected to high loads (Khuong et al., 2017) [9]. Despite all these obstacles, bioethanol is still a preferred alternative fuel, particularly when it comes to cutting emissions. To satisfy more stringent environmental laws, ethanol is a good choice because it reduces emissions of particulate matter and carbon monoxide.

2.1.3. Ethanol blends and E34 performance

Recently revealed as a potential improvement over the popular E10 is another fuel mix, E34 (34% ethanol, 66% petrol). In 2019 Sathish Kumar et al. [10] study, E34 and other high-ethanol concentrations were examined on engine performance. According to their studies, ethanol mixes lower CO and HC emissions and raises brake thermal efficiency. Ethanol's lower energy density than gasoline means more fuel is needed to provide the same level of energy, so raising the ethanol content also raises fuel consumption. Better emissions and decreased fuel economy are traded off in determining the viability of more ethanol blends like E34 for general use.

Further study by Garlet et al. (2012) [11] shows that although ethanol blends like E34 can significantly lower CO₂ emissions, higher combustion temperatures cause a minor rise in NO_x emissions. Strict air quality criteria are difficult to reach in NO_x presence since it causes smog and ozone generation.

2.2. SI engine Fundamentals

The fundamental idea behind the operation of spark-ignition (SI) engines—which find great use in passenger cars is the controlled burning of air-fuel combinations. Ethanol offers SI engines various advantages like less knocking and improved fuel economy because of its high-octane rating. Because of their better combustion qualities, engines running E34, and other higher ethanol percentages may run at higher compression ratios without regard to pre-ignition.

Although ethanol improves engine performance, there are challenges related to fuel efficiency. Because ethanol has little energy content, especially in higher blends like E34 fuel economy suffers. Yang et al. (2024) [8] claim that this is a notable trade-off since vehicles running greater ethanol mixes need more frequent refueling than those running either pure gasoline or lower ethanol blends.

2.2.1. Oil diffusion and tribological characteristics

Particularly troublesome for internal combustion engine lubrication systems are the effects of ethanol-blended fuels diluting oil. Ethanol as a biofuel introduces complications that affect the tribological performance of engine oils. Studies on gasoline-bioethanol mixes carried out by Khuong et al. (2017) [9] revealed that engine oil fuel dilution rises as ethanol concentration in fuel rises. Fuel dilution causes the acid number of the oil to rise, which lowers oil viscosity and accelerates organic wear. Since the oil cannot provide enough lubrication, engine components are therefore more prone to suffer corrosion and wear.

Ajayi et al. (2016) [12] observed similar results in their investigation of bioderived fuel blends, supporting their conclusions. According to their studies, higher ethanol mixes like E34 dramatically lower engine oil viscosity. The decreased viscosity of the oil reduces its efficiency in forming a protective layer between the moving components, therefore worsening friction and wear in heavy loads. These results have major implications for the long-term dependability and durability of engines running ethanol-blended fuels because of the possible acceleration of wear on important engine components brought about by low lubrication efficiency.

These challenges make adding more ethanol to gasoline blends quite difficult and call for careful consideration. Especially with higher ethanol mixtures like E34, it is imperative to maximize the balance between ethanol's environmental advantages and its influence on engine lubrication to prevent lowering engine system durability in the name of fewer emissions.

2.3. Rules and Regulations Regarding Emissions

To meet emission requirements that attempt to lessen the transportation sector's influence on the environment, there has been a push towards alternative fuels like ethanol. One approach to complying with these restrictions is to reduce CO₂ emissions through the implementation of ethanol blends, especially at higher percentages like E34. Reaching global warming targets set by accords such as the Paris Agreement depends on ethanol mixes lowering greenhouse gas emissions by as much as 34%, according to the Renewable Fuels Association (2020). Still, it's important to consider NO_x emissions given higher ethanol ratios like E34 could increase public health concerns and air pollution.

Jacobson (2009) [5] claims that optimal ethanol percentage in fuel mixtures should help to reduce CO₂ emissions without raising NO_x emissions risk. Future research will be necessary to identify the sweet spot between engine performance, pollutant reduction, and fuel efficiency using ethanol-blended fuels.

2.4. Chemical Properties of Ethanol and Bioethanol

Though they come from sustainable feedstocks like sugarcane, maize, or cellulosic biomass, bioethanol and ethanol share chemical similarities. However, the traditional method of producing ethanol uses resources derived from petroleum. Since the combined fuels have an oxygen content of about 35% by mass, they are both considered oxygenated.

In spark-ignition (SI) engines, this oxygenation improves combustion efficiency and lowers emissions of dangerous pollutants like carbon monoxide (CO) and unburned hydrocarbons (HC) (Demirbas, 2009) [14].

Table 1 Contains a comparison of key fuel properties for Gasoline, E10, E34, and Ethanol.

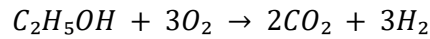
Table 1 Fuel Properties Comparison

Property	E10	E34	Gasoline	Ethanol
Research Octane Number (RON)	96.5	93.7	95.0	109.0 [20]
Density, g/cm ³	0.7536	0.7273	0.739	0.787 [20]
Heating Value, MJ/kg	42.04	40.23	44.4	26.8 [20]
Ethanol Content, V/V%	8.9%	29.8%	0%	100% [20]
Carbon content m/m%	83.27	74.06	87	52.14 [20]
Hydrogen content m/m%	13.32	14.6	13	13.13 [20]
Oxygen content, m/m%	3.41	11.34	2.0 - 2.7	34.73 [20]

2.4.1. Bioethanol production

Fermentation of sugars taken from biomass sources, including sugarcane and maize, yields bioethanol. Because the carbon dioxide (CO₂) absorbed by the plants during their growth balances the CO₂ released after combustion, this method is regarded as carbon neutral. Because of this, bioethanol is more environmentally friendly than ethanol derived from fossil fuels (Petersson et al., 2010) [16].

- The chemical combustion of ethanol can be represented as:



Given ethanol's higher oxygen concentration than gasoline, this reaction suggests that it burns more completely during combustion and produces fewer harmful pollutants. This reduces the CO and HC emissions (Heywood, 1988) [17].

2.4.2. Spark-ignition (SI) Engine Combustion Mechanisms

Phase of flame development: the interval between MFB 10 and MFB zero the interval between the spark plug firing and actual combustion. Ethanol's greater octane rating (~108) than gasoline (~95) increases its resistance to knocking, hence enhancing performance (Zhao, 2007) [13]. The flame front moves across the combustion chamber after ignition at rapid speed. The oxygen concentration of ethanol speeds flame propagation, therefore producing more thorough combustion.

While this faster combustion improves thermal efficiency, it could raise the heat load on engine components (Heywood, 1988) [17]. In this last phase, burnout, fuel oxidation is complete. Compared to gasoline (Zhao, 2007) [13]. Ethanol has less carbon content and generates less carbon emissions and particulate matter (PM).

2.4.3. Emission Characteristics

SI engine emissions are strongly influenced by ethanol and bioethanol, with PM, HC, CO, NO_x, and CO₂ being the primary pollutants from these engines. High oxygen content in ethanol helps to reduce emissions and increase combustion efficiency. However, ethanol's lower energy density than other fuels means that more fuel is needed to generate the same amount of power, therefore somewhat offsetting the decrease in CO₂ emissions. Bioethanol is seen as carbon-neutral since the CO₂ collected by biomass during growth balances the CO₂ emitted during combustion (Demirbas, 2009) [14]. Gasoline CO₂ emissions are ~73 g CO₂/MJ, while ethanol CO₂ emissions are ~51 g CO₂/MJ (Petersson et al., 2010) [16]. Ethanol maximizes combustion efficiency, hence lowering CO emissions, which is particularly helpful in cold starts and transitory engine settings since incomplete combustion of gasoline sometimes results in increased CO emissions (Zhao, 2007) [13]. Emissions of nitrogen oxides (NO_x) depend on pressure and combustion temperature, and ethanol's higher latent heat of vaporization (~840 kJ/kg) cools the intake air, therefore lowering peak combustion temperatures and lowering NO_x emissions from gasoline. In some circumstances, though, if the engine settings are not properly calibrated, ethanol's quicker combustion rate may raise NO_x emissions (Heywood, 1988) [17]. Emissions of hydrocarbon (HC) come from incomplete combustion, but the oxygen component of ethanol helps to attain more complete combustion, hence lowering HC emissions. Further reducing unburned hydrocarbons (Zhao, 2007) [13] is ethanol's quicker flame speed. Because ethanol's carbon content is lower and soot precursors like aromatics and polycyclic aromatic hydrocarbons (PAHs) are absent, it generates less PM emissions than gasoline. Using ethanol or bioethanol in SI engines offers one of the main environmental benefits—a decrease in PM emissions (Pundir, 2010) [15].

2.4.4. Performance Measures and Efficiency

Fuel octane rating, combustion characteristics, and energy content are a few elements influencing SI engine performance and efficiency. The ability of the engine to convert fuel energy into useful work is known as thermal efficiency, and because ethanol improves octane rating, which increases thermal efficiency, higher compression ratios are achievable. Since ethanol has a lower energy density, more fuel is needed for the same amount of power, though. Because of ethanol's rapid combustion rate and resistance to banging, which results in a 1-3% boost in thermal efficiency for optimal engines (Heywood, 1988) [17], Brake Specific Fuel Consumption (BSFC) is the fuel used to generate a particular power output. The lower energy density of ethanol results in greater BSFC values than that of gasoline, but ethanol can get a competitive fuel economy (Pundir, 2010) [15] with correct engine tuning. Gasoline BSFC is 0.25–0.30 kg/kWh, while ethanol BSFC is 0.32-0.35 kg/kWh (Zhao, 2007) [13]. A greater octane rating of ethanol helps engines to run at more aggressive ignition timing and higher compression ratios, therefore producing more power output. Studies on engines using ethanol blends reveal that they provide 5-10% more power than gasoline-powered engines (Demirbas, 2009) [14].

3. Experimental setup

3.1. Test case

The test case examined an EA888 2.0 I4 engine, manufactured by Volkswagen Group and provided by Audi Hungaria. Detailed engine specifications are shown in Table 2. The test is taking place in the laboratory of Széchenyi István University campus at the BMT building in Győr, Hungary. The objective of the test is to study the effects of different ethanol-gasoline blends on emissions, fuel efficiency, and overall performance of the EA888 engine compared to the standard Ethanol gasoline (E10). Three people were attending the test. Professor Nagy Gábor from Audi Hungaria Faculty of Vehicle Engineering as a department engineer, and two Bachelor vehicle engineering students: Zaid Mursi, a Vehicle Engineering student from Jordan, is currently undertaking his final semester of study, and Rafiul Hasan from Bangladesh, is undertaking his fifth semester of study. This Team will be responsible for running the test smoothly and with the best results possible throughout the measurement time.

Table 2 Engine Specification

Specification	Value
Configuration	Inline-4 cylinder
Displacement	2.0 liters (1984 cc)
Valvetrain	16 valves, DOHC (dual overhead camshaft)
Fuel System	Direct injection
Aspiration	Turbocharged
Bore x Stroke	82.5 mm x 92.8 mm
Compression Ratio	12.2:1
Power Output	150 kW
Output	320 Nm @ 2000 – 4000 rpm

3.2. Test Apparatus

To begin the measurements, it is necessary to have certain equipment, tools, and machines for conducting the test, starting with the EA888 2.0 I4 engine, which is manufactured by the Volkswagen Group and provided by Audi Hungaria. The detailed engine specifications can be found in Table 2 Above. The test bench that will be used is the AVL Dyno Spirit 450 Testbench as illustrated in Figure 1, with some limits of application mentioned in Table 3. Which consists of three rooms: the control room, where the automation and control system is located. The test room, which contains the test bench mechanics as well as measuring and conditioning devices containing the torque measuring flange with specific technical data as shown in Table 4, and the technical room on the upper floor, which houses the building services, the converter cabinet, and other measuring and conditioning devices.

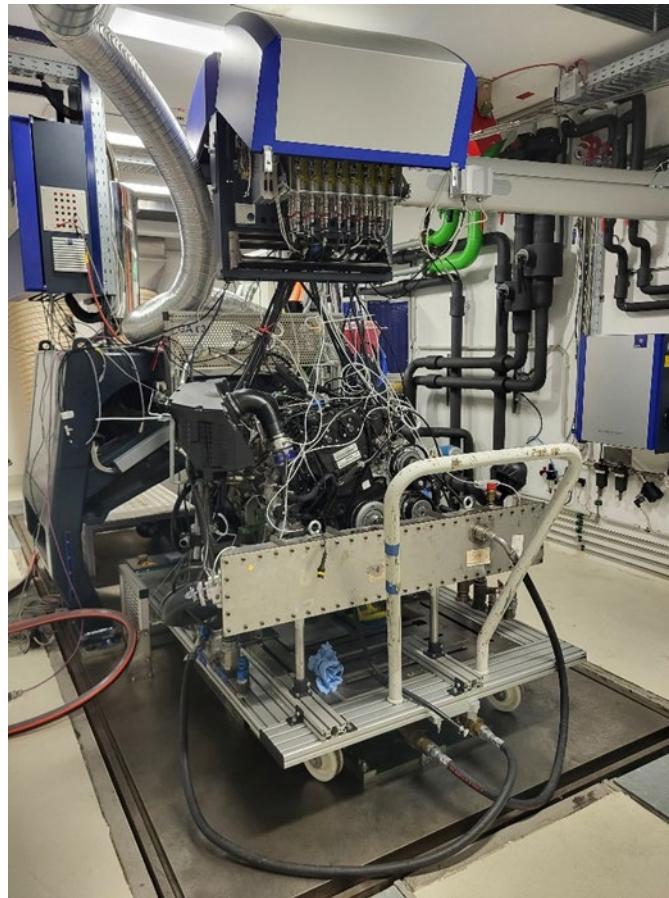


Figure 1 AVL Dyno Spirit 450 Testbench with engine assembled

Table 3 Limits of the scope of application

Temperature range in the test cell	22 °C
Intake air temperature	25 with 50% rel humidity
Charge air after intercooler	30 °C
Coolant inlet to the engine	60 °C

Table 4 Technical data of the torque measuring flange

Technical data of the torque measuring flange T12HP 2 kNm	
Rated speed	12000 rpm
Nominal torque	2000 Nm

3.2.1. Emission measurement instrument SESAM

The AVL SESAM i60 FT SII is classified as an advanced exhaust gas analysis equipment that can measure the gaseous pollutants emitted from petrol or diesel engines. This cutting-edge device is mainly found in engine and vehicle test cells where it permits emission testing under various working conditions as highlighted in Table 5. One of the key reasons for its high secondary reliance is the capability of the analyzer to give precise readings of the contaminants that are critical in ensuring compliance with the stringent pollution laws and the enhancement of green engine technologies.

Table 5 AVL SESAM i60 FT SII Datasheet

Ambient temperature	5 – 30 °C
Rel. humidity	5 – 80 % non-condensing
Gas cell temperature	50 °C
Gas cell pressure	800 mbar absolute
Detector cooling	Liquid nitrogen (LN2)
LN2 consumption	50 ml/h
LN2 refill interval	12 – 16 h
Purge gas	Synthetic air or N2
Purge gas consumption	1,0 – 2,0 l/min – steadily

3.2.1.1. Fourier Transform Infrared Spectroscopy (FTIR)

The FTIR spectrometer is the core element of the apparatus. A constant and uniform radiation in the range between 4000-400 cm⁻¹ (wavenumber) = 2.5-25 µm (wavelength) is produced with an infrared source and beamed into the interferometer optic via deflection mirrors. An interferometer is an optical attachment that is used to separate light bundles (waves), to move them against each other spatially, and to overlay them again.

An interference pattern is produced which contains all spectral information with time resolution. In the interferometer, the radiation as a signal of the frequency is converted into a signal of the time (interferogram), with the benefit of higher measurement accuracy and measuring speed. The outgoing signal from the interferometer then passes through the gas sample to be analyzed in the gas measurement cell and is acquired by a highly sensitive MCT detector. It is quite sensitive and accurate making it possible to recognize and measure several constituents of exhaust gases such as carbon monoxide (CO), carbon dioxide (CO₂), water (H₂O), nitrogen oxides (NO_x), and hydrocarbons (HC). The gas cell of the spectrometer is kept at a temperature of 191 degrees Celsius to enhance the measurement by avoiding any possibility of condensation. Table 6 Provides a comprehensive overview of the Fourier Transform Infrared (FTIR) Spectroscopy setup employed in this study. The instrument utilizes nitrogen or synthetic air as a zero/purge gas with a flow rate of 1.5 l/min, and the detector is cooled using liquid nitrogen at 50 ml/h. The spectrometer operates at a sampling rate of 5 scans per second, generating data for all measured gas components at 5 Hz with a rapid response time of 110 to 190 ms (300 ms for the fast response version). A sample flow of 8 l/min is passed through a gas cell heated to 191 °C to facilitate analysis. The FTIR spectrometer is capable of both measuring and calculating a wide range of gas components, including various hydrocarbons, nitrogen oxides, alcohols, aldehydes, and other compounds relevant to combustion and emission analysis. This detailed information on the FTIR setup and its capabilities ensures transparency and reproducibility of the experimental methodology.

Table 6 FTIR technical data

Fourier Transform Infrared (FTIR) Spectroscopy			
Zero / purge gas	Nitrogen, synthetic air, 1.5 l/min		
Detector cooling	Liquid nitrogen, 50 ml/h		
Sampling rate	5 scans per second		
Data rate	All measured gas components at 5 Hz		
Response time	t ₁₀ to t ₉₀ within 1 second (fast response version with 300 ms)		
Sample flow	8 l/min		
Measurement cell	Gas cell heated to 191 °C (375.8 °F)		
Measured gas components			
CO - Carbon monoxide CO ₂ - Carbon dioxide H ₂ O - Water NO - Nitrogen monoxide NO ₂ - Nitrogen dioxide N ₂ O - Nitrous oxide NH ₃ - Ammonia	CH ₄ - Methane C ₂ H ₂ - Acetylene C ₂ H ₄ - Ethene C ₂ H ₆ - Ethane C ₃ H ₆ - Propylene C ₃ H ₈ - Propane C ₄ H ₆ - Butadiene	C ₂ H ₅ OH - Ethanol CH ₃ OH - Methanol CH ₃ CHO - Acetaldehyde HCHO - Formaldehyde HCOOH - Formic acid SO ₂ - Sulfur dioxide IC ₅ - iso-Pentane	NC ₅ - n-Pentane NC _{2s} - n-Octane HNCO - Isocyanic acid HCN - Hydrogen cyanide COS - Carbonyl sulfide AHC - Aromatic HC
Calculated Gas Components			
HCG - Hydrocarbon Gasoline HCD - Hydrocarbon Diesel HCE - Hydrocarbon Ethanol		NMHC - Non-Methane Hydrocarbon NOX - Sum Nitrogen oxides (NO + NO2)	

3.2.1.2. Flame Ionization Detector (FID)

This type of analyzer is designed particularly to quantify the amount of hydrocarbons present in the exhaust gases. In its operation, as shown in Figure 2, carbon atoms are ionized in a hydrogen flame creating an electrical current that is dependent on the amount of hydrocarbons present. The FID i60 HH device used in the SESAM i60 FT SII overcomes the challenge of measuring low as well as high hydrocarbon concentrations allowing measurement in different types of engines and their operating conditions.

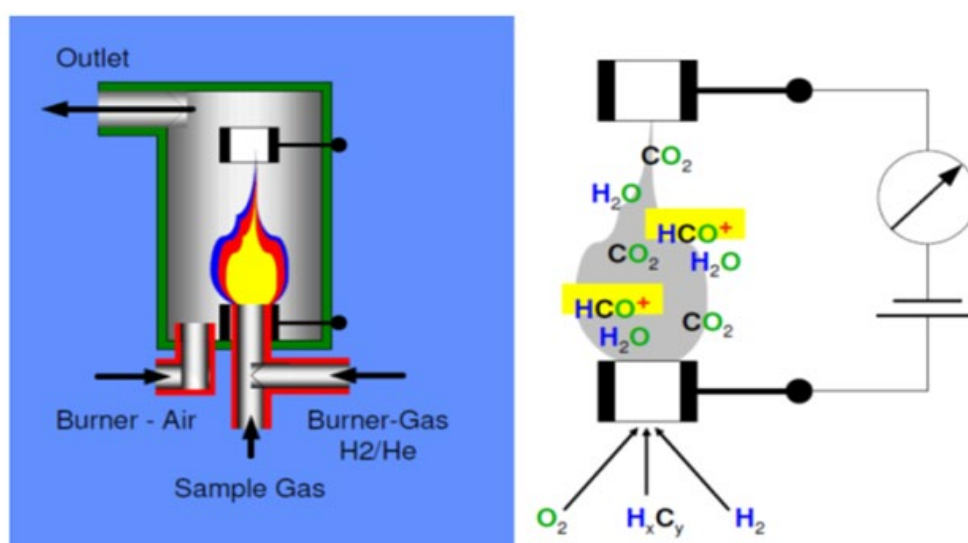


Figure 2 FID working principle

3.2.1.3. Paramagnetic Detector (PMD)

The PMD analyzer is used to measure the concentrations of oxygen (O₂) by taking advantage of the paramagnetic nature of oxygen (O₂). A magnetic field is used to verify the concentration of oxygen and an electrical signal is generated that is henceforth relatable to the concentration of the oxygen. The addition of PMD i60 to the framework helps in understanding the combustion process and the performance of the emission control systems better. Table 7 Shows the required gases for the operation of the PMD i60 analyzer.

Table 7 Required gasses for the operation of the PMD

Use	Gas type
Zero gas	Nitrogen N ₂
Span gas	Oxygen O ₂ in N ₂

3.2.2. Particle Counter

AVL Particle Counter is a technical device used mainly for the measurement of particulate matter emissions from different vehicles in motion Figure 3. This device is crucial in ensuring compliance with tough regulatory requirements such as the United Nations Economic Commission for Europe Regulations No. 83 and No. 49 particles that exceed the size of 23 nm are measured with an efficiency of $50 \pm 12\%$ as shown in Table 8, which limit the particulate number emissions of light and heavy-duty vehicles respectively. How the AVL Particle Counter works by first measuring and diluting exhaust samples before counting the grown particles using a Condensation Particle Counter (CPC). This functionality allows policymakers and research fellows to evaluate and control the damage caused by particulate emissions on the environment, making it possible to develop cleaner and more efficient transportation systems.



Figure 3 AVL particle counter

Table 8 AVL Particle Counter technical data

Confirmed standards	UN/ECE-R83 (Rev.5), UN/ECE-R49 (Rev.6)	
Field of application	Diluted measurement (CVS), partial flow dilution (PFDS) raw exhaust measurement	
Measuring components	Particle number concentration of non-volatile particles (p/cm ³)	
Lower particle size limit	23 nm (50% ±12% eff.), 41 nm (>90%)	
Mean instrument response time (t₉₀)	4.5 s	
CPC butanol consumption	5 ml/h	
Ambient temperature conditions: operation	5 °C ... 35 °C (up 45 °C with optional cooling trolley)	
Exhaust gas conditions	Exhaust temperature: ≤600 °C Up to 1000 °C with high-pressure option	Exhaust pressure: ±200 mbar Up to 2000 mbar with high-pressure option
Sample flow rate	5 l/min (diluted) 4–7 l/min (raw)	
Compressed air consumption	<40 l/m	

3.2.2.1. Particle Counter Measuring Technologies

3.2.2.1.1 Condensation Particle Counter (CPC)

The core component of the device is its CPC check Figure 4, which is a technology used to identify as well as count the presence of nonvisible particles in the size range of 23 nm and below. The working principle consists of pushing the exhaust sample into a chamber filled with butanol vapor. The sample is allowed to cool, and, since the butanol vapor is now rinsed off the vapor dome, it now condenses on the surfaces of the particles, which in turn increases their volume considerably. These larger particles then pass through a laser beam and scatter laser light that is detected by a photodetector. The pulse of light represents a single particle, and thus the device can measure particle number concentration and its associated size. It is important to mention that butanol was considered as a working fluid meaning that advantages in condensation and Particle growth could be achieved when using butanol.

3.2.2.1.2 Primary Diluter

The AVL Primary Diluter uses a new patented perforated disk design that includes two circles of holes to facilitate the adjustment of dilution ratios without replacing the disk. This could be regarded as a modification that looks to provide solutions to different measurement conditions. Primary bodies of a patented shape that are heated may also assist in the better flow of sample and dilution air.

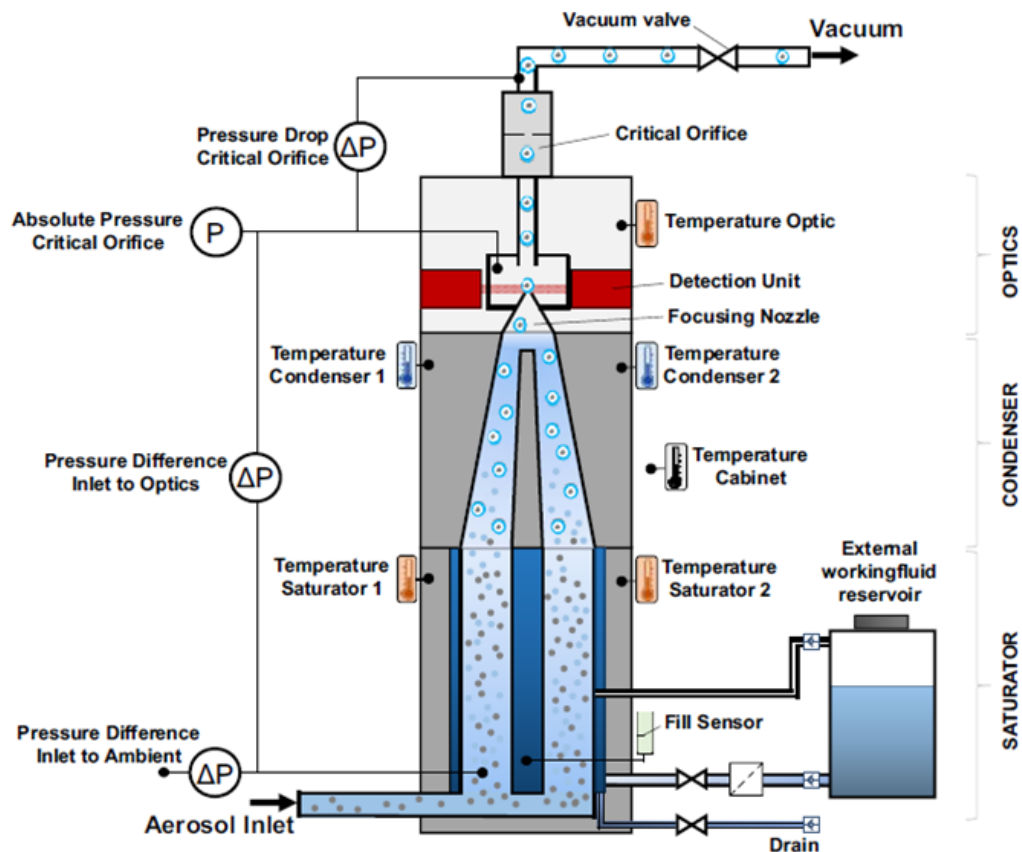


Figure 4 Condensation Particle Counter (CPC)

3.2.2.1.3 Secondary Diluter

After completing the first stage of dilution, the sample is subjected to further dilution through a porous tube diluter. This design seeks to reduce particle loss involving dilution, thus enabling measurement of the actual number of particles present in the effluent within the limits of the exhaust itself. The efficiency of the secondary diluter is critical for measurement purposes especially where particle concentration is low.

3.3. Fuels

This study will use two fuels with individual properties to assess their impact on engine performance. Conventional gasoline, with a 10% ethanol blend (E10), will serve as the baseline fuel due to its widespread availability and established use in internal combustion engines. The alternative fuel, E34, comprises 34% ethanol and 66% gasoline produced especially to these measurements, representing a significantly higher biofuel content. This choice allows for a direct comparison between a standard petroleum-based fuel and a renewable alternative with the potential to reduce greenhouse gas emissions. The distinct chemical and physical properties of these fuels, particularly the higher oxygen content and latent heat of vaporization of ethanol, are expected to influence combustion characteristics, engine efficiency, and exhaust emissions.

Table 9 Presents a comparative analysis of the key properties of two gasoline blends, E10 and E34, with varying ethanol content. As expected, the E34 blend, containing 29.8% ethanol, exhibits a higher oxygen content (11.34 m/m%) and hydrogen content (14.6 m/m%) compared to the E10 blend (3.41 m/m% and 13.32 m/m% respectively). This increase in oxygen and hydrogen content is attributed to the molecular structure of ethanol (C_2H_5OH). Contrariwise, the E34 blend shows a lower carbon content (74.06 m/m%) and heating value (40.23 MJ/kg) than E10 (83.27 m/m% and 42.04 MJ/kg respectively), which can be attributed to the lower energy density of ethanol compared to conventional gasoline hydrocarbons. While the research octane number (RON) is slightly lower for E34 (93.7) than for E10 (96.5), both blends fall within the acceptable range for use in modern spark-ignition engines.

The data highlights the trade-offs associated with increasing ethanol content in gasoline, particularly the impact on energy density and carbon emissions.

Table 9 Fuel Properties

Property	E10	E34
Research Octane Number (RON)	96.5	93.7
Density, g/cm ³	0.7536	0.7273
Heating Value, MJ/kg	42.04	40.23
Ethanol Content, V/V%	8.9%	29.8%
Carbon content m/m%	83.27	74.06
Hydrogen content m/m%	13.32	14.6
Oxygen content, m/m%	3.41	11.34

3.4. Methodology

3.4.1. Steady-state measurement

To ensure consistency and reliability, a standardized test procedure was implemented. Before starting the engine, the fuel system was drained and refilled with the appropriate E10 fuel for the test. The engine was then brought to its optimal operating temperature through a two-stage warm-up procedure, initially running at 1500 RPM with 9.5% throttle, followed by operation at 2000 RPM with 15% throttle.

This preconditioning ensured that all engine components attained thermal stability before the start of experimental runs. Subsequently, a comprehensive series of steady-state measurements were conducted across 115 operating points, spanning an engine speed range of 1000 to 6000 RPM and a mean effective pressure (MEP) range of 2 to 20 bar.

The steady-state measurement sequence proceeded as follows: The engine speed was initially set to the desired value (e.g., 1000 RPM), followed by the application of the lowest load point (2 bar MEP). A period of stabilization was observed until steady-state operating conditions were achieved. Subsequently, a 30-second measurement period was initiated, ensuring that momentary fluctuations in measured values did not excessively influence the final results. Upon completion of the measurement, the engine speed was maintained while the load was incrementally increased by 2 bar MEP, if possible, and the measurement process was repeated.

This iterative process continued until the maximum load capacity of the engine was attained at that specific engine speed. Subsequently, the engine was allowed to cool down at a low speed, low load operating point before the engine speed was incremented to the next higher value (e.g., 1250 RPM after completing measurements at 1000 RPM full load). The engine was then allowed to reach its operating temperature at the new speed and a 2 bar MEP load, and the measurement sequence was repeated. This comprehensive measurement protocol was continued until full load operation at the maximum engine speed (6000 RPM) was achieved. Throughout the testing process, meticulous records were maintained of torque, power output, fuel consumption, and emissions (CO, CO₂, NO_x, and unburned hydrocarbons) using AVL SESAM i60 Ft SII exhaust gas analyzer that includes FTIR detector for CO₂, CO and NO_x emission – FID for unburned HC – PMD for residual O₂, and key engine operating parameters, including intake air temperature, coolant temperature, exhaust gas temperature, and cylinder pressure using AVL IndiCOM cylinder pressure indication system, implemented with Kistler 6045 piezo sensors. Upon completion of the tests with E10, the fuel system was thoroughly drained and flushed before being filled with E34, and the identical test procedure, including the warm-up and steady-state measurement sequence, was repeated to ensure a direct comparison of engine behavior under identical operating conditions for both fuels.

3.4.2. Dynamic measurements

Following the completion of the steady-state measurements, a series of dynamic tests were conducted to assess the engine's transient response and emissions behavior in a real-world driving environment. The objective of this dynamic testing phase was to evaluate how the engine responds to rapid changes in demand, moving beyond steady-state operations to better understand its performance and emissions under more realistic conditions.

An AVL 450 dynamometer was used to perform a specific drive cycle designed at the University. This unique cycle, however, was not based on the WLTP and was created specifically to mirror the driving behavior and conditions in the real world. It presents a mixture of driving conditions, including urban, rural, and highway conditions driving at different speeds and acceleration, hence covering the engine's drive dynamics.

During this specialized cycle, the dynamometer precisely controlled the engine speed and load, adhering to the defined profile and accurately simulating real-life driving conditions with fluctuations in operational parameters.

Measurements were conducted five times for both E10 and E34. During this testing process, the emission values and the total amount of gas emitted, as well as overall fuel consumption, were recorded. The final results reflect the sum of these emitted and consumed fuels. Subsequently, the five cycles were averaged, and both the minimum and maximum values were determined, allowing us to calculate the standard deviation. This approach of taking five measurements was implemented to minimize the risk of any erroneous results affecting the overall outcome. Throughout the dynamic test, continuous monitoring and recording of critical parameters were performed. These included instantaneous engine speed and torque, fuel flow rate, and emissions of CO, CO₂, NO_x, and unburnt hydrocarbons. Additionally, other essential engine operating parameters, such as intake air temperature, coolant temperature, exhaust temperature, and cylinder pressure levels, were continuously collected. This comprehensive data acquisition enabled a thorough analysis of the engine's response to transient conditions and its ability to maintain performance and minimize emissions during dynamic operation.

The dynamic measurements were conducted for both E10 and E34 fuels, allowing for a direct comparison of their influence on the engine's transient behavior. By analyzing the dynamic response and emissions data alongside the steady-state results, a complete understanding of the engine's overall performance characteristics and the impact of fuel composition was achieved. This approach provided valuable insights into the engine's suitability for real-world operation and its potential to meet stringent emissions standards while maintaining satisfactory drivability and performance.

4. Results

The results presented in this study stem from a comparative analysis of engine performance parameters derived from an Audi 2.0 I4 E888 engine, which was fueled with both E10 and E34, maintaining identical octane ratings (RON 95 and MON 85). The analysis centered around specific operating points that encompassed a range of engine speeds and loads, strategically selected to represent various driving conditions and to provide a comprehensive understanding of how fuel composition impacts engine behavior. These points included low-speed/low-load conditions (1500 rpm, 6 bar), mid-range operation (2500 rpm, 10 bar, and 3000 rpm, 12 bar), high-speed/high-load scenarios (4500 rpm, 20 bar), and high-speed operation under varying loads (3500 rpm, 10 bar; 6000 rpm, 14 bar; and 6000 rpm, 2 bar). This selection ensured a thorough evaluation of engine performance across its operational map, capturing the intricacies of combustion behavior, emissions, and efficiency under different driving conditions. The analysis included key performance indicators such as cylinder pressure, lambda values, exhaust gas temperatures, brake-specific fuel consumption (BSFC), mass fraction burned (MFB) at different stages, NO_x emissions, particulate matter (PM) emissions, and rapid burn duration. This comprehensive approach facilitated a detailed comparison of engine behavior and emissions when utilizing E10 versus E34, underscoring the complex interplay between fuel properties, combustion characteristics, and engine calibration in optimizing performance and achieving the desired outcomes.

4.1. Static measurements

4.1.1. Fuel consumption

An analysis was performed on fuel consumption data derived from engine maps, as illustrated in Figures 5 and 6, for an Audi 2.0 I4 E888 operating on both E10 and E34 fuels. Notably, both fuel types exhibited identical Research Octane Number (RON) ratings of 95.

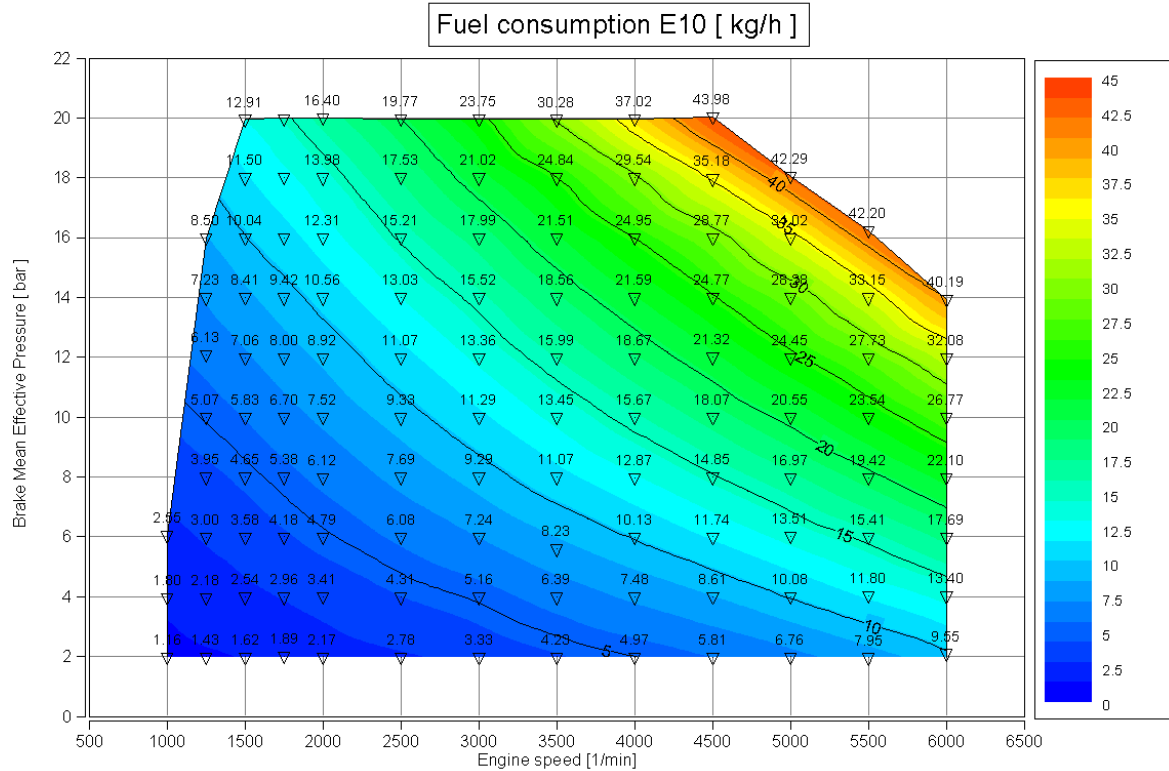


Figure 5 E10 Fuel Consumption

The results consistently showed that E10 fuel provided superior fuel efficiency across various operational parameters. Although ethanol has a lower energy density than gasoline, E10 showed better fuel efficiency at various operating conditions, such as low-speed/low-load at 1500 rpm, 6 bar, midrange at 2500 rpm, 10 bar, and high-speed/high-load at 3500 rpm, 10 bar and 4500 rpm, 20 bar.

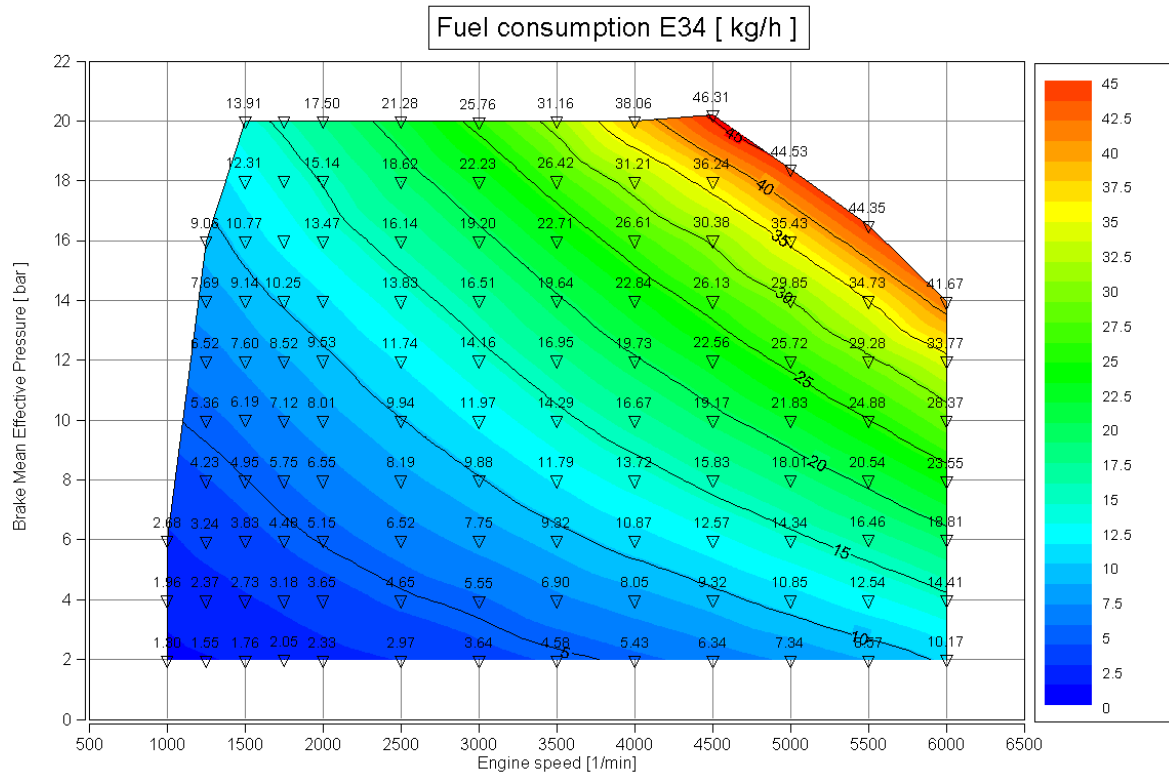


Figure 6 E34 Fuel Consumption

The higher fuel usage seen with E34 is explained by the fact that ethanol has less energy, requiring more fuel to generate the same power output. Its higher renewable content makes it more environmentally friendly, although its fuel consumption rate makes E10 a more cost-effective option.

Table 10 E10 & E34 Fuel consumption operating points

Operating Point	E10 Fuel Consumption (kg/h)	E34 Fuel Consumption (kg/h)	Difference (%)
1500 rpm, 6 bar	3.58	3.83	+7.0%
2500 rpm, 10 bar	9.33	9.94	+6.5%
3500 rpm, 10 bar	13.45	14.29	+6.24%
4500 rpm, 20 bar	43.98	46.31	+5.3%
6000 rpm, 14 bar	40.19	41.67	+3.7%
Average			+5.7%

E34 consistently exhibits higher fuel consumption across all analyzed engine operating conditions, as demonstrated in the comparison engine map (Figure 7). This difference is quantified as the percentage increase in fuel consumption when E34 is used instead of E10. At lower speeds and loads (1500 rpm, 6 bar), the difference is a moderate 7%. Even at higher speeds and loads (4500 rpm, 20 bar), E34 still consumes more fuel than E10, with an increase of 5.3%. This indicates that the reduced energy density of E34 results in greater fuel consumption compared to E10, particularly across a majority of engine conditions. On average, E34 experiences a 5.75% increase in fuel consumption relative to E10 for the operation conditions considered.

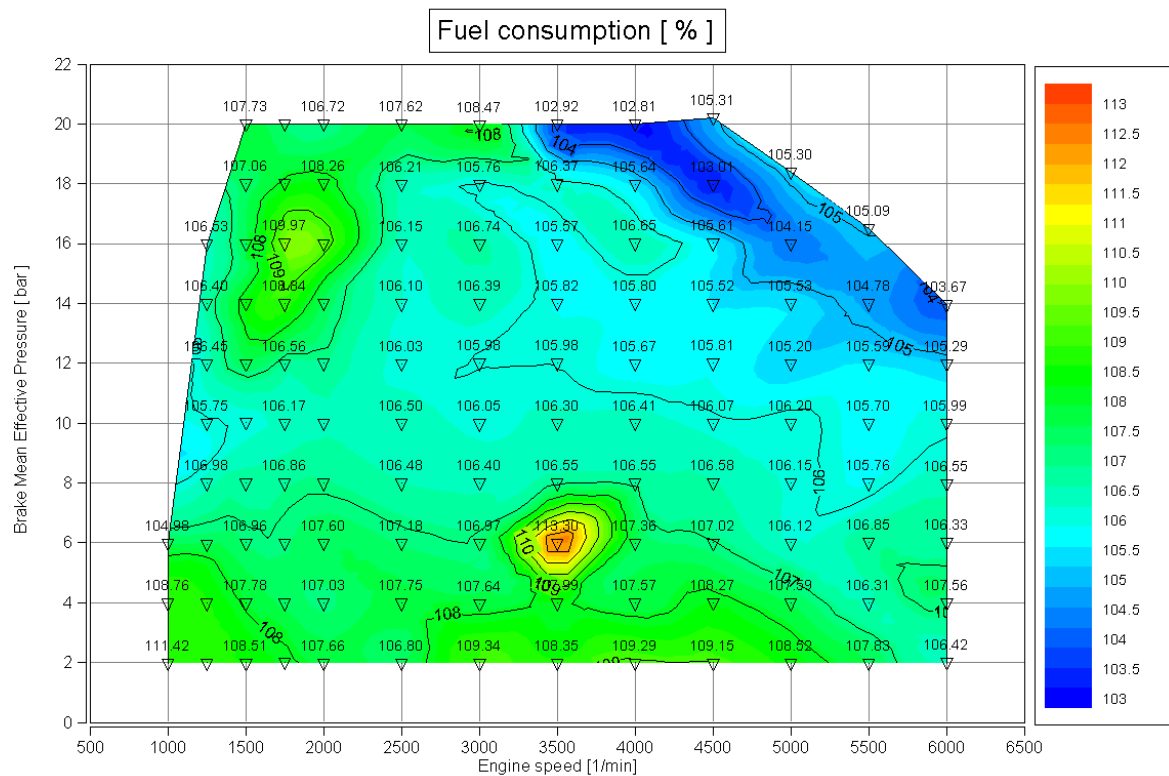


Figure 7 Comparison E10 & E34 engine map

4.1.2. BSFC

Analysis of brake-specific fuel consumption (BSFC) reveals a clear advantage for E10 fuel in terms of fuel economy.

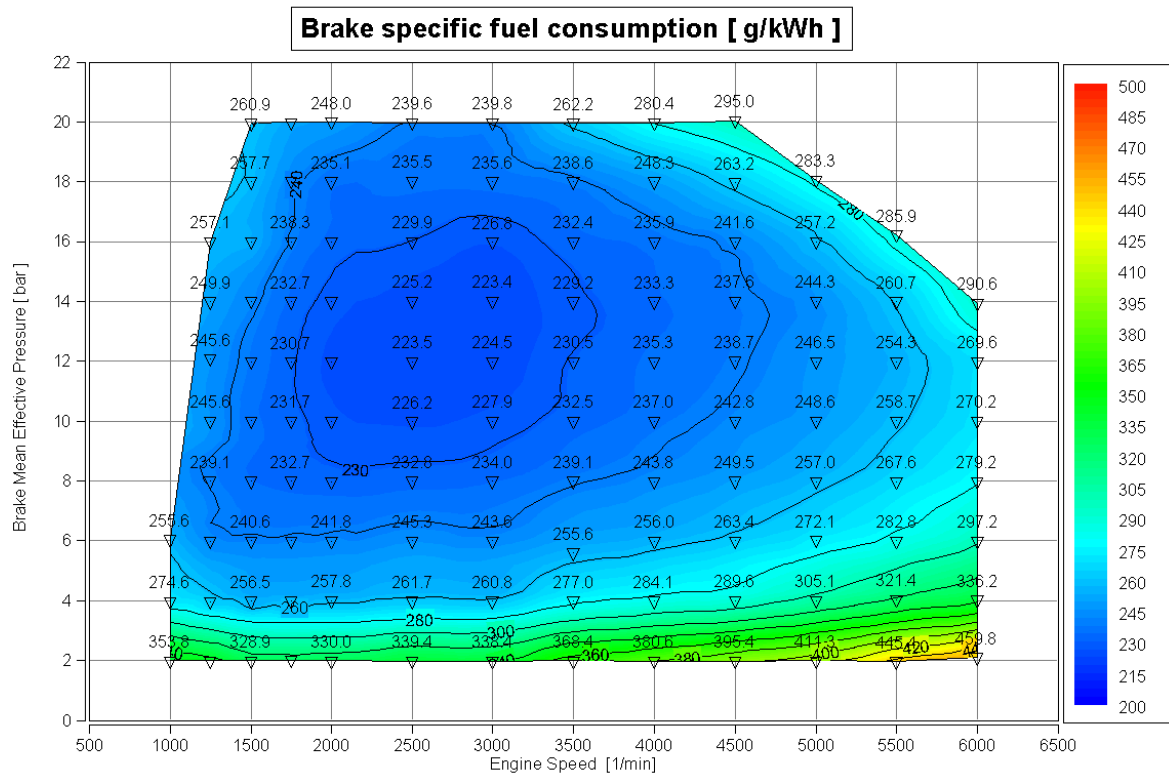


Figure 8 E10 brake-specific fuel consumption

Figure 8 shows the BSFC plot for the Audi 2.0 I4 E888 engine operated on E10 fuel. In this context the term BSFC stands for brake-specific fuel consumption which refers to the amount of fuel burnt for every unit power produced by the engine. Lower values of BSFC are therefore more desirable as they reflect a better fuel economy. In Figures 8 and 9, the contour lines are drawn to denote the engine brake-specific fuel consumption and thus show how the fuel consumption changes with the engine speed and load. The areas with blue and green lower BSFC regions show that E10 is being more efficiently used in those operating conditions. Such a figure is useful to assess engine performance and assists in determining the best operating points while using E10 fuel.

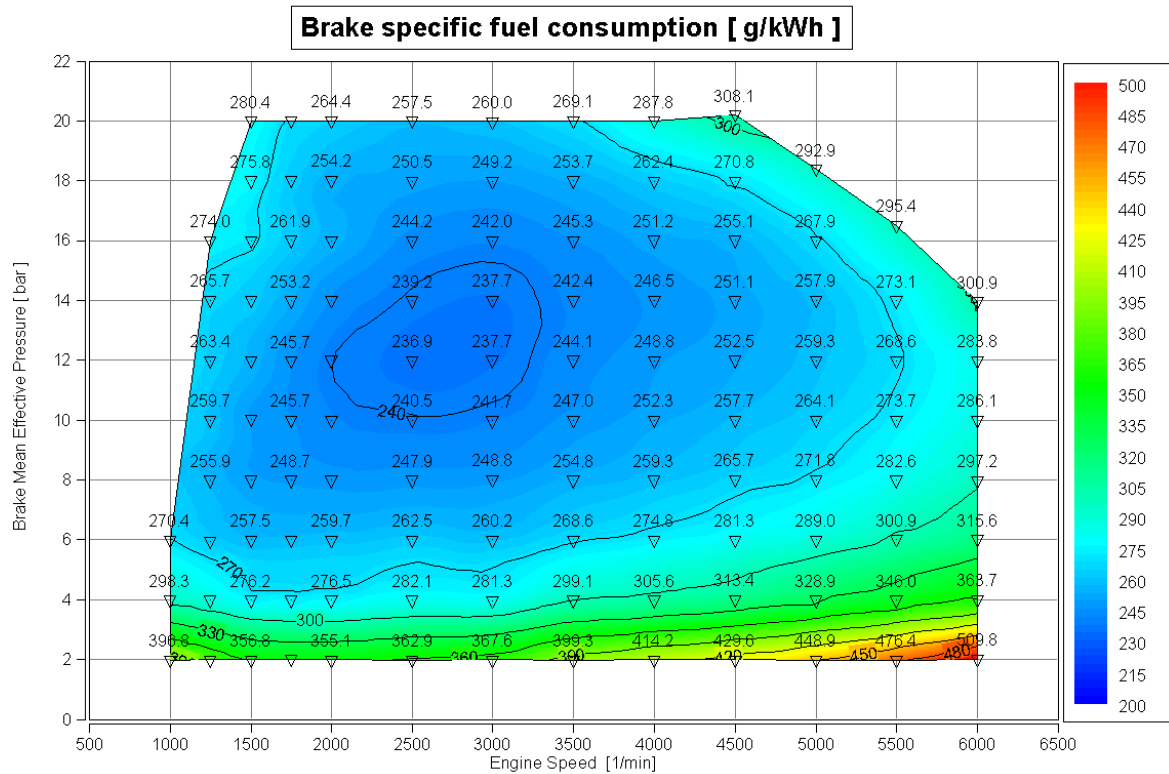


Figure 9 E10 brake-specific fuel consumption

Figure 9 depicts the BSFC map for the same engine when fueled with E34. Comparing Figure 8 with Figure 9 allows for a direct assessment of the impact of fuel composition on engine efficiency. As demonstrated in the contour plots and the data presented in Table 11, E10 consistently exhibits lower BSFC values than E34 across a range of operating conditions, from low-speed, low-load (1500 rpm, 6 bar) to high-speed, high-load scenarios (4500 rpm, 20 bar). This difference is particularly pronounced at higher engine speeds and loads, with E10 demonstrating significantly lower BSFC at 4500 rpm, 20 bar and 6000 rpm, 2 bar. This superior fuel economy with E10 translates to a higher brake thermal efficiency, as evidenced by the calculations based on the provided BSFC values and the lower heating values of each fuel. E10 consistently demonstrates higher efficiency across all operating points. This indicates that E10 not only consumes less fuel but also converts the fuel energy into useful work more effectively.

Table 11 E10 & E34 BSFC operating points

Operating Point	E10 BSFC (g/kWh)	E10 Thermal Efficiency (%)	E34 BSFC (g/kWh)	E34 Thermal Efficiency (%)	Difference (%)
1500 rpm, 6 bar	240.6	35.6	257.5	34.8	+0.8%
2500 rpm, 10 bar	226.2	37.9	240.5	37.2	+0.7%
3000 rpm, 12 bar	224.5	38.1	237.7	37.6	+0.5%
3500 rpm, 10 bar	232.5	36.8	247	36.2	+0.6%
4500 rpm, 20 bar	295	29.0	308.1	29	0.00%
6000 rpm, 14 bar	290.6	29.5	300.9	29.7	-0.2%
6000 rpm, 2 bar	459.8	18.6	509.8	17.6	+1%
Average					+0.49%

According to the results shown in Table 11, E10 exhibits elevated thermal efficiency at most of the studied operating points with an average increase of 1.68% compared to E34. This means that E10 not only burns less fuel but also makes better use of the fuel's energy. This enhanced performance is because gasoline has a greater energy density than ethanol, and potentially also due to differences in combustion efficiency, the mechanism by which gas is burned, and how flames react to different fuels in terms of speed, duration, or heat release.

E34 will provide better results only in certain working conditions, such as the case when efficiency is measured at 6000 rpm and 14 bar where E34 is higher than other fuels, however the general trend indicates better thermal efficiency of E10 in the tested engine.

4.1.3. Exhaust temperature

An examination of the exhaust gas temperatures, using E34 and E10 fuels, showed that E34 fuel always produces lower exhaust gas temperatures than E10 when the engine is operating under different conditions.

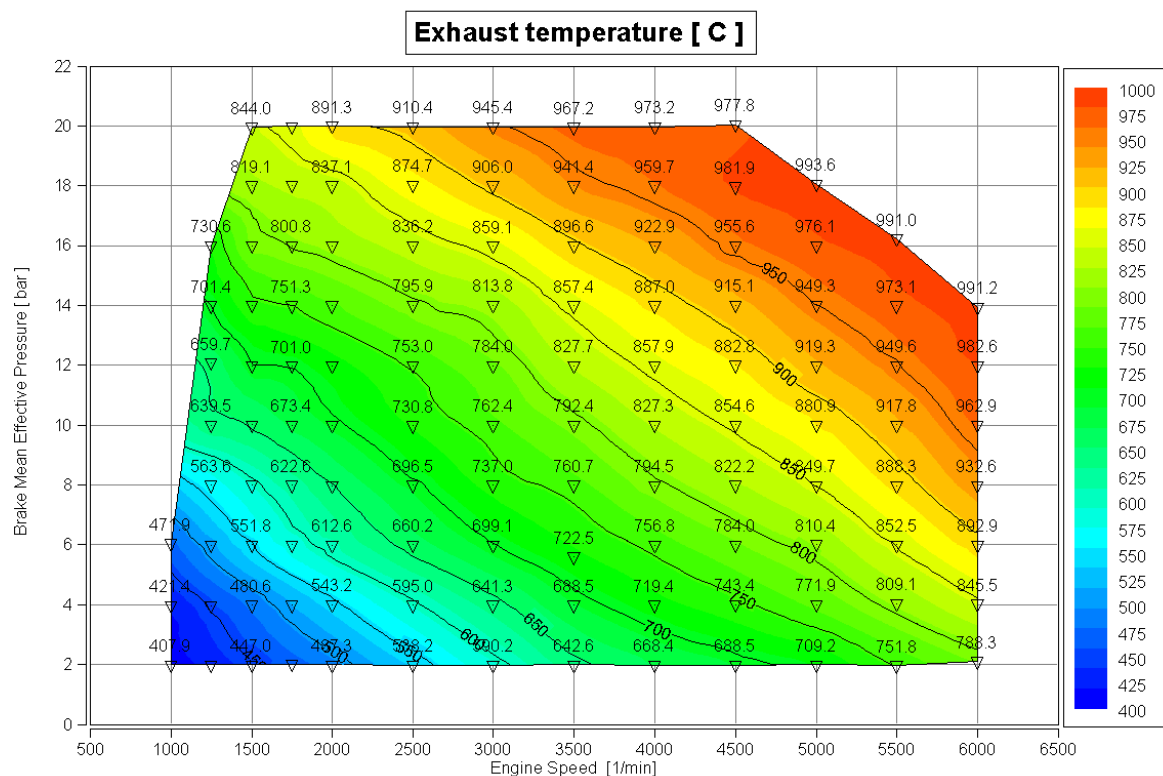


Figure 10 E10 Exhaust Temperature

This is well shown in the contour diagrams in Figures 10 and 11 as well as the information provided in Table 12. Whereby E34 has a lower exhaust gas temperature at all the operating situations that were evaluated such as 1500 rpm, 6 bars; 2500 rpm, 10 bars; 3500 rpm, 10 bars; 4500 rpm, 20 bars; and 6000 rpm, 14 bars. Many reasons can explain the differences, which are more significant at higher speeds and loads of the engine. First of all, the high heat of vaporization of ethanol induces a cooling effect in the intake manifold, which reduces the peak combustion temperatures and therefore the temperatures of the exhaust gases. This impact is especially true for E34 which contains more ethanol (34% vs 10% in E10).

In addition, secondary exhaust gas emissions could be a result of different engine calibrations for each fuel, for example using slightly richer air-fuel mixtures with E10 at high loads leading to excess unburned fuel in the exhaust pipeline. Finally, even if both fuels have identical octane scores, upper combustion limits at given engine operating parameters could still be affected by ethanol and petrol flame velocities given that the two fuels have the same octane rates. The low calorific value of Ethanol, for example, makes combustion less effective and exhaust gas temperature relatively high because excess heat is lost through the exhaust system.

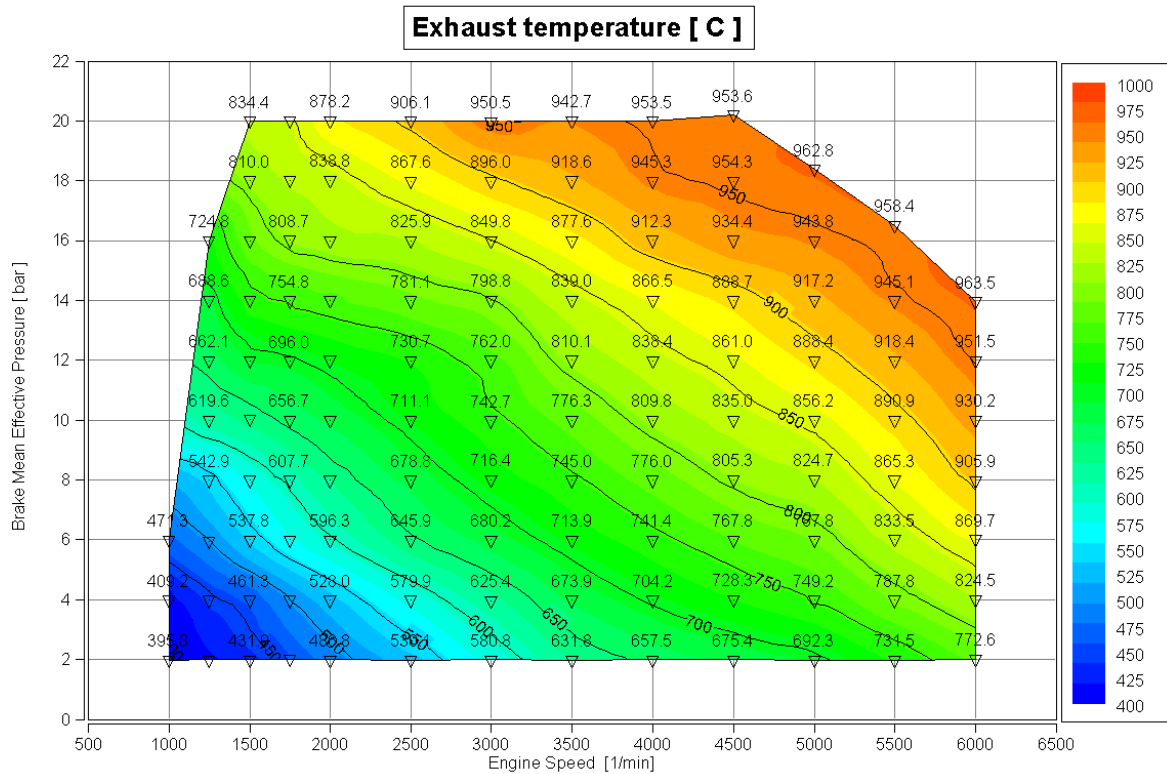


Figure 11 E34 Exhaust Temperature

Table 12 E10 & E34 Exhaust Temperature operating points

Operating Point	E10 Exhaust Temp (°C)	E34 Exhaust Temp (°C)	Difference (%)
1500 rpm, 6 bar	551.8	537.8	-2.54%
2500 rpm, 10 bar	730.8	711.1	-2.70%
3500 rpm, 10 bar	792.4	776.3	-2.03%
4500 rpm, 20 bar	977.8	953.6	-2.47%
6000 rpm, 14 bar	991.2	963.5	-2.79%
Average			-2.51%

According to the data shown in Table 12 Obtained from the engine maps, one conclusion is drawn: all E34 exhaust gas temperatures at all analyzed points of operation are lower than those of E10 as illustrated in Figure 14. This difference is calculated in relation to E10 as a lowering in temperature expressed in percentage. For instance, at low engine speed and low engine load conditions (1500 rpm, 6 bar), it is 2.54% but the difference is more emphasized at high engine speed and high engine load conditions, 2.79% at 6000 rpm and 14 bar. One can notice that on average E34 results in 2.51% lower exhaust gas temperature than E10.

4.1.4. Cylinder pressure

A study comparing cylinder pressure as shown in Figure 15 using E10 and E34 fuels shows how fuel composition, burning behavior, and engine settings interact. The E34 consistently produces slightly higher pressures inside the cylinders across different engine speeds and loads. This is because ethanol in E34 burns faster and can reach higher pressures compared to the gasoline in E10. This difference averaged 1.78%.

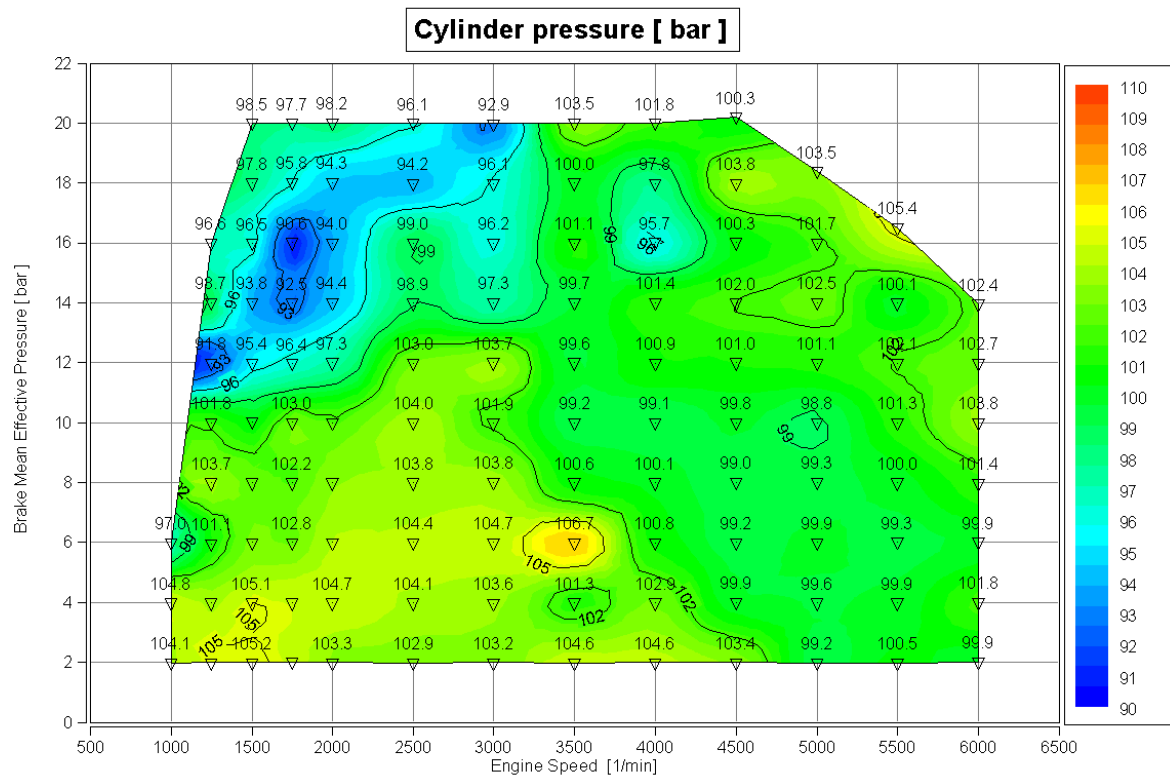


Figure 12 E10 & E34 Cylinder pressure comparison

4.1.5. Rapid Burning Phase

As outlined in Heywood's [17] "Internal Combustion Engine Fundamentals" The rapid burning phase is a pivotal stage in the combustion process during which a substantial portion of the fuel-air mixture is consumed. This phase significantly impacts engine performance, efficiency, and emissions. The analysis, which draws upon data obtained from contour plots and is summarized in Table 13, examines five operating points that span a range of engine speeds and loads.

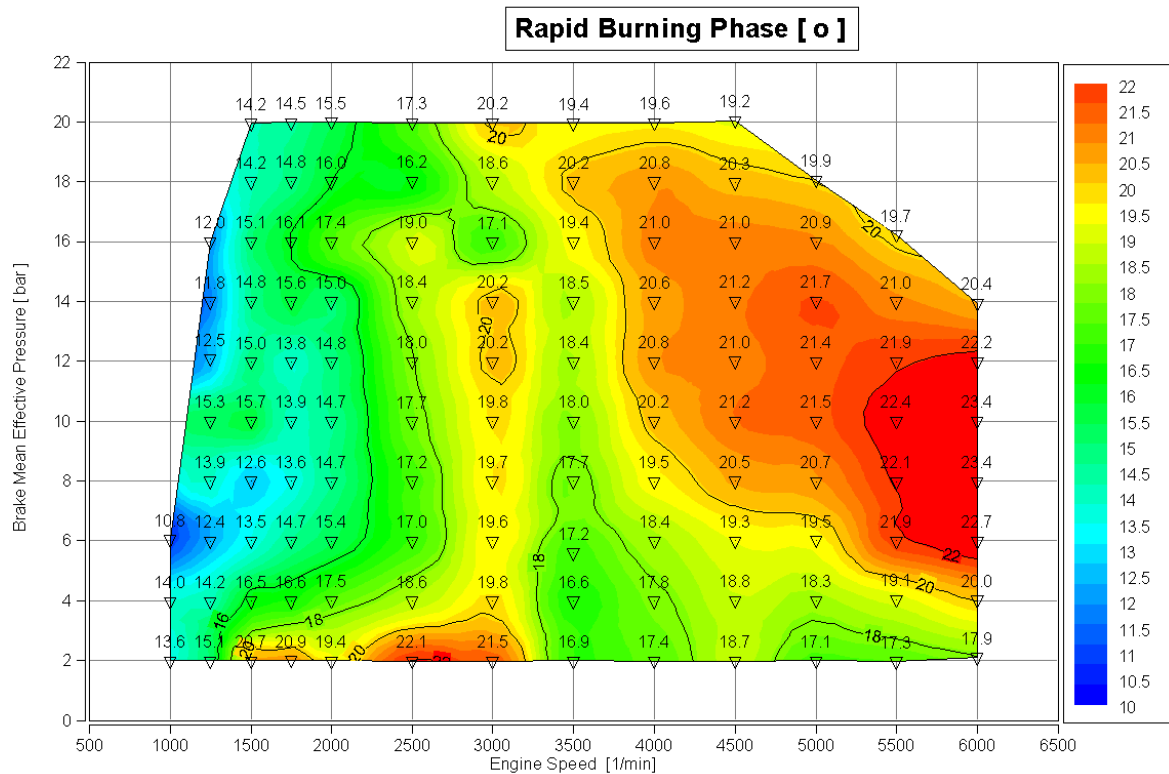


Figure 13 E10 Rapid Burning Phase

E34 typically demonstrates a slightly shorter duration of the rapid burning phase compared to E10 across various operating points, indicative of faster combustion characteristics associated with the higher ethanol blend. This observation is consistent with the principles outlined in Heywood's text, which emphasizes the impact of fuel properties on combustion phasing. Ethanol, known for its higher flame speed and shorter ignition delay in comparison to gasoline, plays a significant role in facilitating quicker combustion and reducing the rapid burn duration. For instance, at 1500 rpm and 6 bar BMEP, E34 shows a rapid burn duration of 13.0 °CA, while E10 exhibits a duration of 13.5 °CA. Similar patterns are evident at other operating points, including 2500 rpm at 10 bar and 4500 rpm at 20 bar, where E34 consistently demonstrates slightly faster combustion.

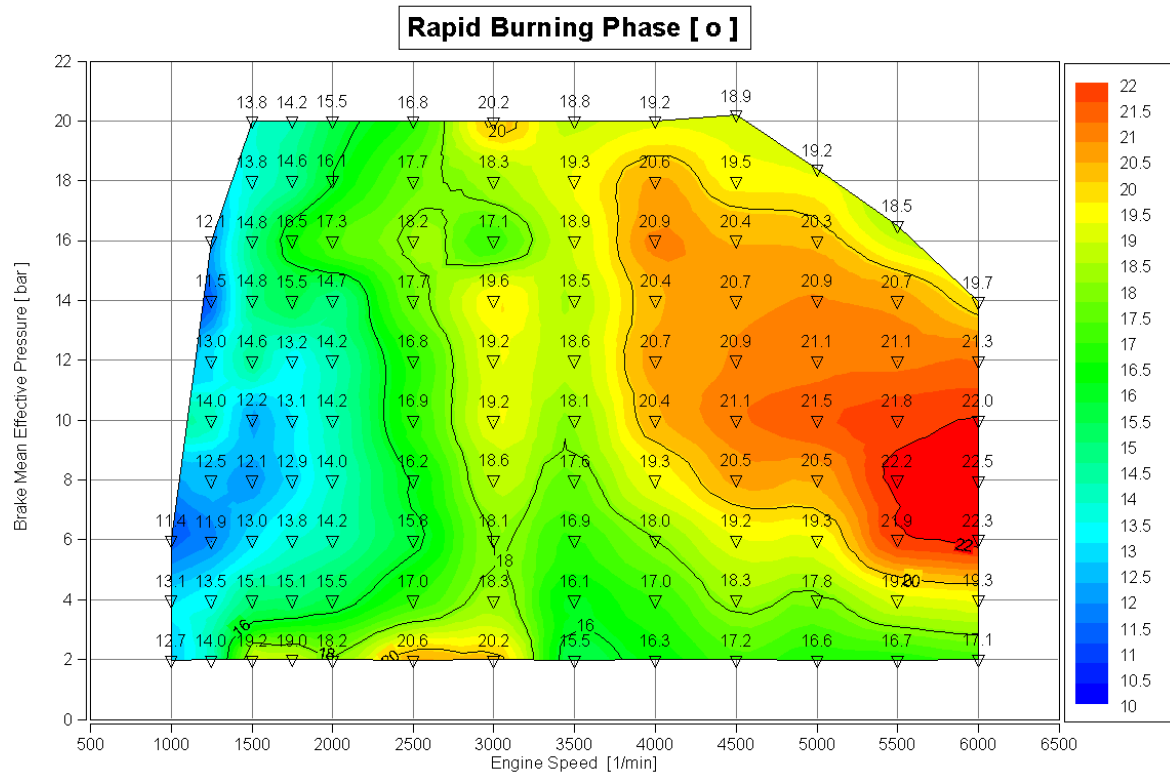


Figure 14 E34 Rapid Burning Phase

The marginally quicker combustion rate associated with E34 may impact engine performance and efficiency. This accelerated combustion can result in higher peak pressures and potentially improve thermal efficiency, as outlined in Heywood's book. However, it is crucial to evaluate these effects alongside other considerations such as fuel consumption and emissions to comprehensively understand the implications of using E34 in comparison to E10.

Table 13 E10 & E34 Rapid Burning Phase Operating Points

Operating Point	E10 Rapid Burn (°CA)	E34 Rapid Burn (°CA)	Difference (%)
1500 rpm, 6 bar	13.5	13	-3.70%
2500 rpm, 10 bar	17.7	16.9	-4.52%
3500 rpm, 10 bar	18	18.1	+0.56%
4500 rpm, 20 bar	19.2	18.9	-1.56%
6000 rpm, 14 bar	20.4	19.7	-3.43%
Average			-2.33%

4.1.6. Mass Fraction Burn 50 (MFB 50)

An examination of 50% mass fraction burned (MFB50) data reveals the significant difference in burning behavior exhibited by the two fuels, E10 and E34. MFB50 is an important combustion characteristic that is defined as the crank angle at which 50 percent of the burned fuel mass is reached and is used to derive burning rate and burning timing information. Using the information presented in contour plots in Figure 18 and Figure 19 and their corresponding summary in Table 14, the study has addressed five operating EGT limits on multiple engine speeds and loads.

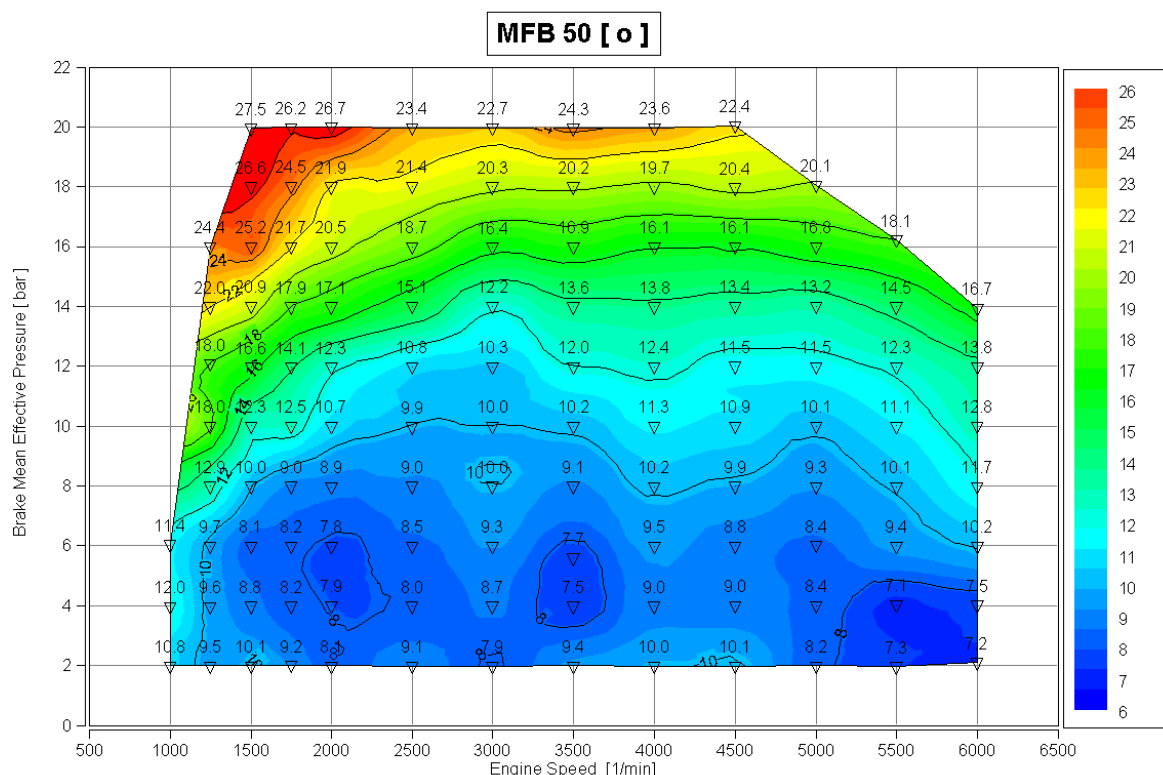


Figure 15 E10 MFB 50

E34 typically has lower MFB50 values in comparison to E10 at most of the operating points, especially at low engine speeds and high loads. This indicates that E34, which has a higher content of ethanol, can combust more rapidly than E10. Ethanol exhibits this behavior due to its superior combustion characteristics, such as its short ignition delay and high flame speed as compared to gasoline. Even though both fuel levels are rated at RON 95, the higher ethanol content of the fuel E34 may provide a greater resistance to knock enabling the use of more advanced ignition timing which is a process that assists in faster combustion as well.

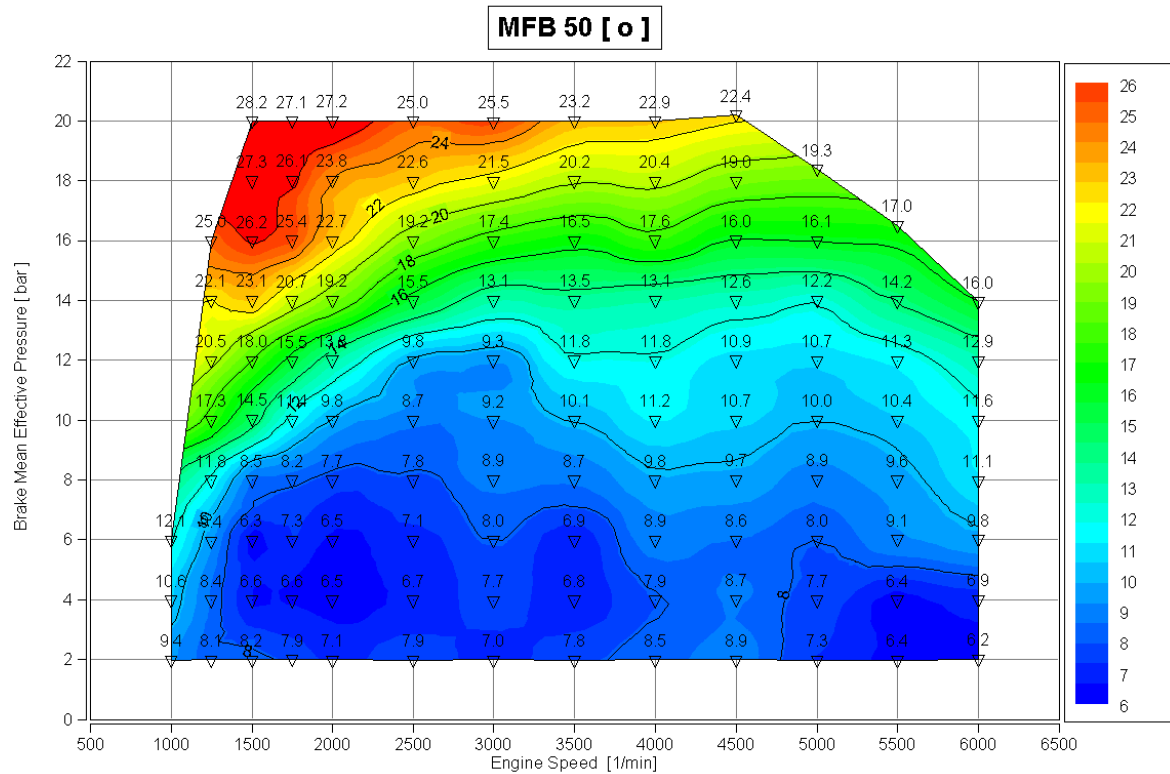


Figure 16 E34 MFB 50

The faster combustion observed with E34 can have implications for engine performance and efficiency. Faster combustion can lead to higher peak pressures and potentially better thermal efficiency, although this needs to be considered in conjunction with other factors like fuel consumption and emissions.

Table 14 E10 & E34 MFB 50 operating points

Operating Point	E10 MFB 50 (°CA ATDC)	E34 MFB 50 (°CA ATDC)	Difference (%)
1500 rpm, 6 bar	8.1	6.3	22.22%
2500 rpm, 10 bar	9.9	8.7	12.12%
3500 rpm, 10 bar	10.2	10.1	0.98%
4500 rpm, 20 bar	22.4	22.4	0.0%
6000 rpm, 14 bar	16.7	16.0	4.19%
Average			7.9%

4.1.7. MFB (90,50,10) comparison

The analysis of the mass fraction burned (MFB) at 10%, 50%, and 90% fuel levels for E10 and E34 offers valuable insights into the combustion characteristics of each fuel type. MFB is a crucial indicator of combustion phasing and burn rate, representing the crank angle at which a specific percentage of the fuel mass has been consumed. By examining MFB10, MFB50, and MFB90, the team obtained a comprehensive understanding of the entire combustion process, spanning from ignition initiation to the conclusion of the main burning phase. This analysis, based on data extracted from contour plots and summarized in Table 15 and Table 16 Focuses on five operating points that encompass a variety of engine speeds and loads. This approach facilitates a thorough comparison of the combustion behavior between E10 and E34.

Table 15 MFB 10, 50, 90 Operating points

Operating Point	E10 MFB 10 (°CA ATDC)	E34 MFB 10 (°CA ATDC)	E10 MFB 50 (°CA ATDC)	E34 MFB 50 (°CA ATDC)	E10 MFB 90 (°CA ATDC)	E34 MFB 90 (°CA ATDC)
1500 rpm, 6 bar	2.1	0.9	8.1	6.3	15.7	13.9
2500 rpm, 10 bar	3.5	2.7	9.9	8.7	21.2	19.6
3500 rpm, 10 bar	3.9	2.5	10.2	10.1	21.9	21.8
4500 rpm, 20 bar	13.7	13.8	22.4	22.4	32.9	32.7
6000 rpm, 14 bar	8.2	7.8	16.7	16	18.6	27.5

E34 consistently exhibits faster combustion across all stages, as evidenced by lower MFB10, MFB50, and MFB90 values in most cases. This faster combustion is attributed to the inherent properties of ethanol, which has a higher flame speed, shorter ignition delay, and higher laminar burning velocity compared to gasoline. The higher ethanol content in E34 (34% versus 10% in E10) allows it to leverage these properties more effectively, leading to quicker flame development and shorter burn durations.

Table 16 MFB crank angle differences

Operating Point	E10 (MFB50 - MFB10) (°CA)	E34 (MFB50 - MFB10) (°CA)	E10 (MFB90 - MFB50) (°CA)	E34 (MFB90 - MFB50) (°CA)	E10 (MFB90 - MFB10) (°CA)	E34 (MFB90 - MFB10) (°CA)
1500 rpm, 6 bar	6	5.4	7.6	7.6	13.6	13
2500 rpm, 10 bar	6.4	6	11.3	10.9	17.7	16.9
3500 rpm, 10 bar	6.3	7.6	11.7	11.7	18	19.3
4500 rpm, 20 bar	8.7	9	10.5	10.3	19.2	19.3
6000 rpm, 14 bar	8.5	8.2	1.9	11.5	10.4	19.7

Analyzing the crank angle differences between MFB10, MFB50, and MFB90 provides further insights into the different stages of combustion. Early Flame Development (MFB50 - MFB10): This difference represents the duration it takes for the initial 10% of the fuel mass to burn and then reach 50% mass fraction burned. A smaller difference indicates faster initial flame development and a quicker transition to the main combustion phase. E34 generally shows smaller differences in this metric, suggesting that the early flame propagation and establishment of a stable flame kernel are faster with E34 compared to E10. For example, at 1500 rpm and 6 bar, E34 shows a difference of 5.4°CA between MFB50 and MFB10, compared to 6.0°CA for E10. Main Combustion Phase (MFB90 - MFB50): This difference represents the duration of the main combustion event, where the bulk of the fuel mass is consumed.

A smaller difference indicates a faster main burn, potentially leading to higher peak pressures and more efficient energy release. E34 often exhibits smaller differences in this metric as well, suggesting a faster main combustion phase compared to E10. For instance, at 2500 rpm and 10 bar, the difference between MFB90 and MFB50 is 10.9°CA for E34 and 11.3°CA for E10. Total Burn Duration (MFB90 - MFB10): This difference represents the overall duration of the combustion process, from the initial ignition to the point where 90% of the fuel mass is burned. A smaller difference indicates faster overall combustion, which can influence engine performance, efficiency, and emissions. E34 consistently demonstrates a faster total burn duration across all operating points, confirming that the entire combustion event is generally faster with E34 compared to E10. There are specific operating points where these trends differ. Notably, at 6000 rpm and 14 bar, E34 exhibits a slower late combustion phase (MFB90) compared to E10, despite having faster early and main combustion phases. While faster combustion can potentially lead to improved engine performance and efficiency, it is crucial to consider its overall impact in conjunction with other factors such as fuel consumption and emissions.

4.1.8. CO₂ emissions

The two fuel blends, E10 (10% ethanol, 90% gasoline) and E34 (34% ethanol, 66% gasoline), were tested under varying engine speeds (1000–6000 RPM) and loads (2–20 bar). CO₂ emissions were carefully measured using an AVL SESAM i60 FT SII exhaust gas analyzer. The engine was subjected to identical operating conditions for both fuels, ensuring an accurate and direct comparison of their emission outputs.

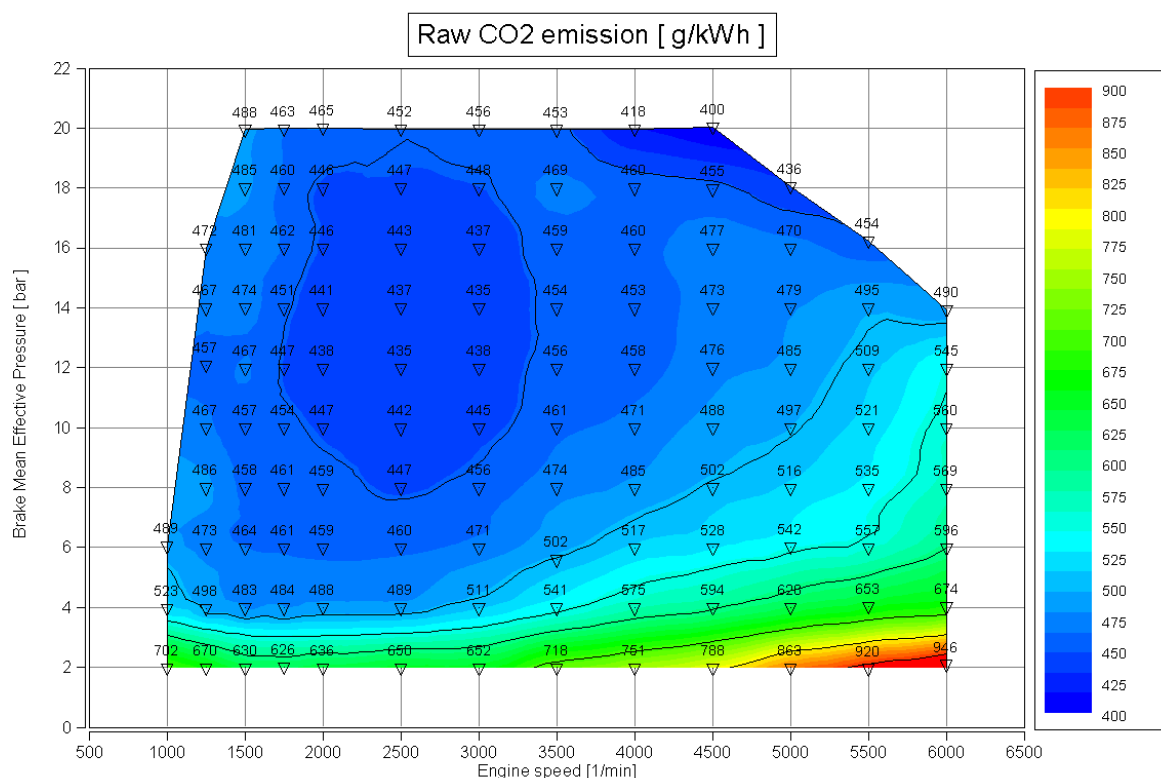


Figure 17 E10 CO₂ emissions

The results show that E34 regularly lowers CO₂ emissions more efficiently than E10 because of its higher ethanol percentage. Because ethanol contains oxygen, it improves combustion and lowers CO₂ emissions by allowing a more complete fuel burn. Oxygenation increases combustion efficiency, therefore lowering unburned hydrocarbons and hence carbon dioxide emissions.

E34 shows 5.82% lower CO₂ emissions than E10 at 2500 RPM at 10 pressure as shown in Table 17. Mostly explaining this difference, the extra ethanol in E34 improves the combustion conditions. Reducing emissions and increasing combustion efficiency follow from higher ethanol concentration. Because ethanol's oxygen concentration is higher than that of other fuels, especially at moderate engine loads, it promotes more complete burning.

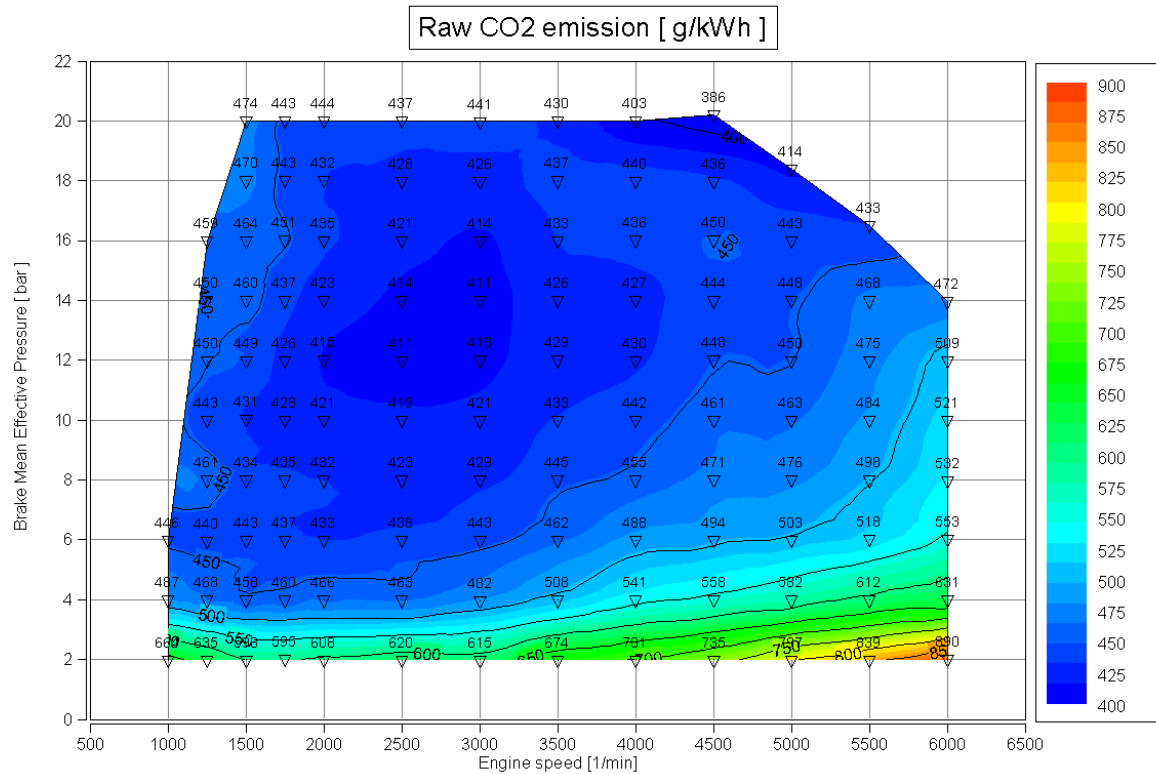


Figure 18 E34 CO2 emissions

Relative to E10, E34 reduces CO₂ emissions by 6.07% at 3500 RPM. This is a great accomplishment. Particularly under high engine loads, the characteristics of ethanol help to expedite flame propagation and improve combustion, therefore producing a more notable reduction. Ethanol's fast flame speed helps complete combustion, reducing remaining fuel and producing a cleaner burn. Because E34 has lower pollution emissions, it is a more fuel-efficient option at high speeds.

Table 17 E10 & E34 CO₂ operating points

Operating Point	E10 CO ₂ Emission (g/kWh)	E34 CO ₂ Emission (g/kWh)	Improvement
1500 rpm, 6 bar	464	443	-4.53%
2500 rpm, 10 bar	447	421	-5.82%
3500 rpm, 10 bar	461	433	-6.07%
4500 rpm, 20 bar	400	386	-3.50%
6000 rpm, 14 bar	490	472	-3.67%
Average			-4.72%

Ethanol helps to reduce greenhouse gas emissions; E34 lowers CO₂ emissions on average by 4.72% in all the studied environments. The higher oxygen concentration of ethanol improves fuel combustion, therefore reducing emissions. By improving combustion efficiency and greatly reducing environmental effects, the E34 characteristic makes it a more ecologically friendly substitute for the conventional E10 blend.

4.1.9. CO emissions

The higher ethanol content in E34 as shown in Figure 22 contributes to better combustion and thus from the results obtained, considerably reduces CO emissions when compared to E10 see Figure 23. Carbon monoxide emissions are reduced at all ranges of engine speed and load due to the improvement of fuel oxidation by this oxygenated fuel blend. The E34 at 1500 RPM and 6 bar showed a quite remarkable 26.6% reduction of CO emissions compared to that of E10.

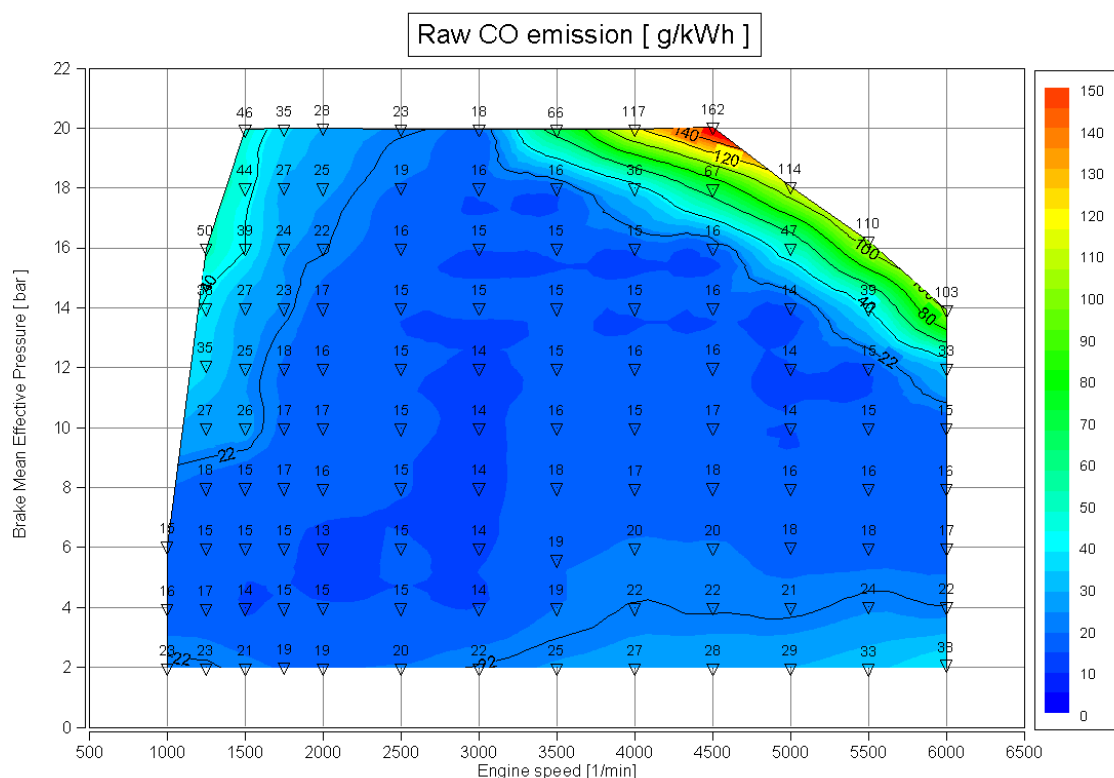


Figure 19 E10 CO emissions

Due to the oxygen-rich nature, E34 ensures better fuel combustion with enhanced combustion efficiency, therefore accounting for this noticeable drop. At such low engine speed and load, the engine can optimize the combustion process and can give fewer emissions because of an enhanced amount of oxygen in E34. The E34 blend also continues to perform satisfactorily in emissions reduction of CO, even at increased speed and load. The E34 continued this trend of improved combustion, reducing CO emissions by 13.3% at 2500 RPM and 10 bar due to its inherently higher ethanol content. The improved oxygen concentration of the fuel blend directly results in lower CO emissions due to increased efficiency in oxidation.

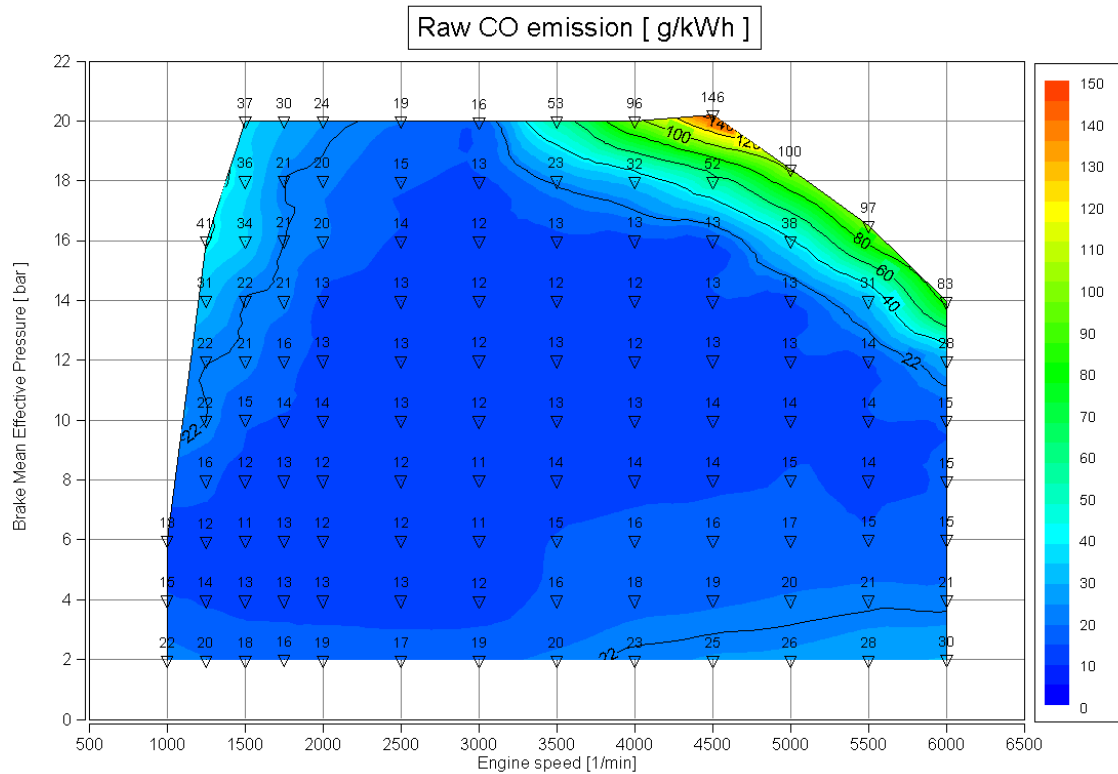


Figure 20 E34 CO emissions

Notably, at 3500 RPM with 10 bar, E34 decreased CO emissions by 18.7%. It showed this much bigger difference in emissions as compared to the E10. This reduction occurs because ethanol has superior combustion properties which thereby provide more efficiency during higher usage of engine loads. Increased combustibility and flame speed due to ethanol provide more time for complete combustion of the air-fuel mixture at higher RPMs, thus making carbon monoxide emissions lower. With the 9.8% reduction in CO emissions at 4500 RPM and 20 pressure, it is proven that E34 works even under high load. If the demand on the engine's operation for pressure is higher, E34 still promotes efficient combustion and less emissions. In continuous reduction of carbon monoxide emissions across the operating test situations, 14 bar was reduced at the maximum tested speed of 6000 RPM. E34 resulted in a decent reduction in CO emission, which varied in a range from 9.8 to 26.6% of the engine load and speed as illustrated in Table 18.

These results show how well E34 works as an environmentally friendly fuel and contributes to a reduction in carbon monoxide emissions, further facilitating the use of environmentally friendly fuel.

Table 18 E10 & E34 CO operating points

Operating Point	E10 CO Emission (g/kWh)	E34 CO Emission (g/kWh)	Improvement by using E34
1500 rpm, 6 bar	15	11	-26.6%
2500 rpm, 10 bar	15	13	-13.3%
3500 rpm, 10 bar	16	13	-18.7%
4500 rpm, 20 bar	162	146	-9.8%
6000 rpm, 14 bar	103	83	-19.4%
Average			-17.56%

4.1.10. NOx emissions

All the findings indicate that E34 considerably reduces NOx emissions when compared to E10, mainly because of the higher content of ethanol in its blend. Since ethanol has a high heat of vaporization, the combustion temperature is reduced during its phase change from liquid to gas. NOx emissions are directly proportional to the increase in combustion temperature; therefore, the cooling effect of ethanol will directly impact NOx production due to reduced peak combustion temperatures. E34 produced NOx 11.25% lower than E10 at 1500 RPM at 6 bar. It is important to note that at low speeds of the engine, the reduction of NOx emissions recorded testifies to the fact that the cooling effect of ethanol serves to minimize combustion temperatures and lower conditions under which NOx would be produced. On the other hand, E34 proved that it could further reduce NOx at moderate engine load with an 8.6% reduction at 2500 RPM and 10 bar. Because ethanol cools the combustion process, it cuts emissions regardless of speed or load inside the engine. Its distinctive properties allow combustion temperature to drop always and, therefore, provide constant NOx emission reduction whatever operating conditions are.

The most obvious improvement was the E34 NOx emissions at 3500 RPM and 10 bar were reduced by 12.17%. Since larger engine loads create more heat and thus accelerate NOx generation, the cooling qualities of ethanol are especially vivid in this load. Even under these extreme conditions, E34 still manages to cool the combustion process a lot and reduces NOx emissions significantly. With the NOx reduction peak of 26.66%, E34 was at its peak at 4500 RPM, which is at 20 bar; this indeed shows good efficiency of E34 at high-load conditions where the generation of NOx is usually higher by temperature. Really, because of its high vapor pressure at that temperature, ethanol lessens the amount of NOx emitted into the atmosphere, showing its greenness to be an eco-friendly fuel.

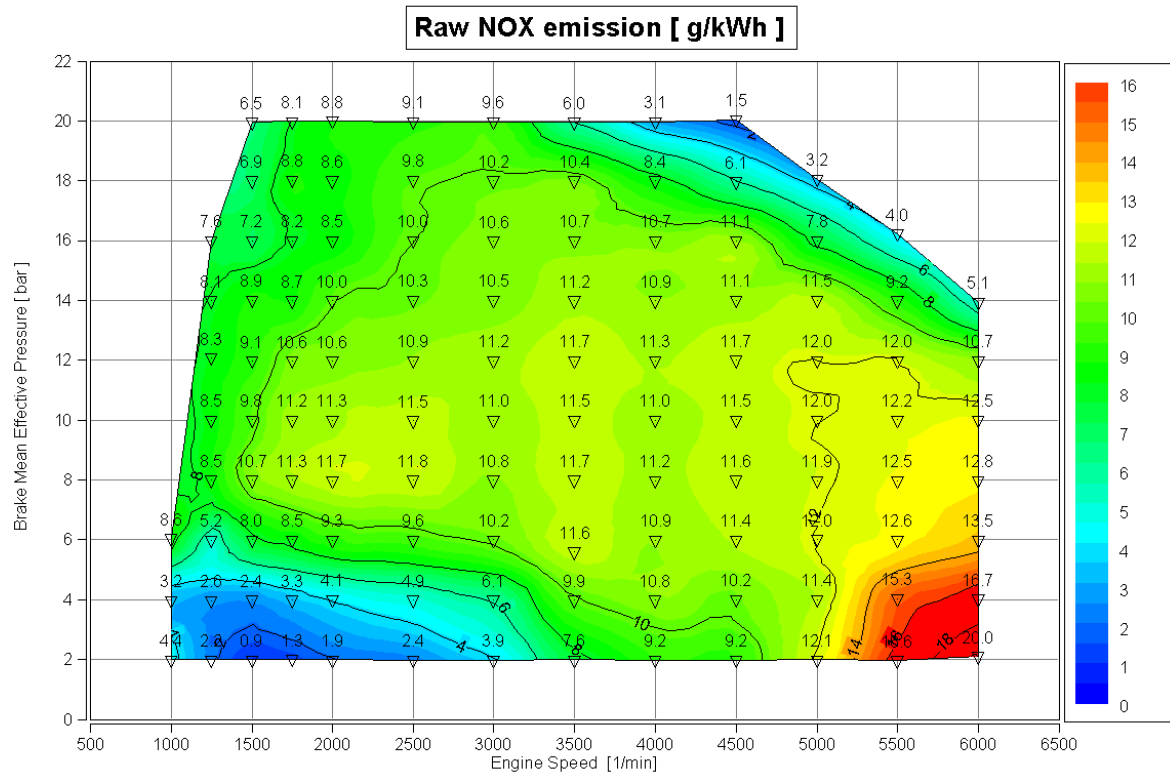


Figure 21 E10 NOx emissions

As illustrated in Table 19 E34 managed to reduce NOx emissions by 5.8% even at 14 bar and 6000 RPM, though this is less than it would have been at lower speeds and loads. At the same time, it goes on to show that E34 works consistently in different settings of an engine, which is again an important fact because of the emission reduction that it provides also while going fast. In the end, E34 was able to reduce NOx emissions within a range of 5.8% down to 26.66%, hence proving effective in this area, particularly when the engine load is heavier and/or speedier. This inference shows that ethanol-blended fuels, like E34, are environmentally friendly because they reduce NOx emissions and ease the path towards cleaner and greener fuel practices.

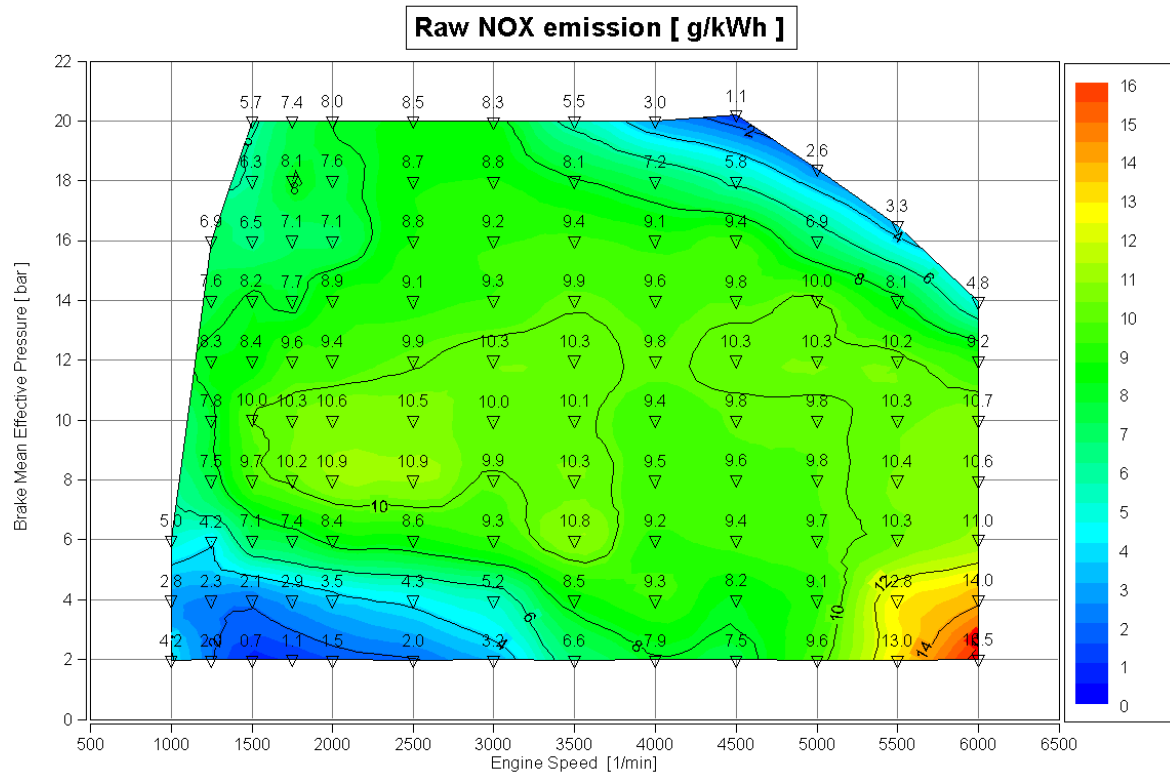


Figure 22 E34 NOx emissions

Table 19 E10 & E34 NOx operating points

Operating Point	E10 NOx Emission (g/kWh)	E34 NOx Emission (g/kWh)	Improvement by using E34
1500 rpm, 6 bar	8	7.1	-11.25%
2500 rpm, 10 bar	11.5	10.5	-8.6%
3500 rpm, 10 bar	11.5	10.1	-12.17%
4500 rpm, 20 bar	1.5	1.1	-26.66%
6000 rpm, 14 bar	5.1	4.8	-5.8%
Average			-12.9%

4.1.11. Total Hydrocarbons (THC)

Examining Total Hydrocarbon (THC) emissions from E10 and E34. The tests were conducted at engine speeds between 1000 and 6000 RPM with weights ranging between 2 and 20 bar, therefore ensuring a comprehensive evaluation of several driving circumstances. Under the same running conditions, the fuel mixes E10 (10% ethanol, 90% petrol) and E34 (34% ethanol, 66% petrol) were evaluated to determine how ethanol concentration affects emissions. Using an AVL SESAM i60 FT SII exhaust gas analyzer, accurate THC levels were measured, therefore allowing a precise comparison of emissions under various speed and load situations.

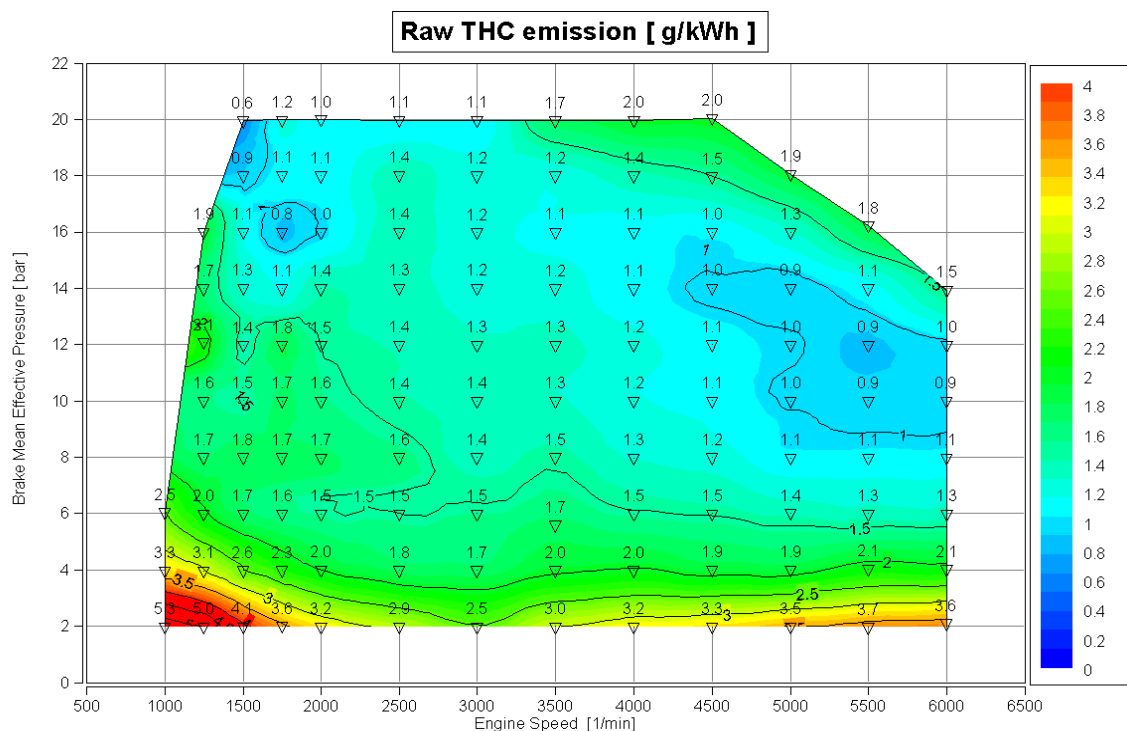


Figure 23 E10 THC emissions

Indicating a more complete combustion process, E34 under all conditions considerably reduced THC emissions relative to E10. Apart from the oxygen content of ethanol, its combustion properties also help to improve faster flame propagation and effective mixing guaranteed by higher flame speed and volatility providing a complete burn with less residual hydrocarbons.

E34 reduced THC by 29.4% at low speeds (1500 RPM, 6 bar) and by 35.7% at intermediate conditions (2500 RPM, 10 bar). Under high load (4500 RPM, 20 pressure), E34 dropped by 60%; under even high-speed conditions (6000 RPM, 14 bar), E34 maintained a 53.3% decrease. This spectrum of 29.4% to 60% as mentioned in Table 20 THC decline emphasizes E34's role as a cleaner fuel blend that lowers hydrocarbon emissions, therefore promoting ecologically friendly burning over a spectrum of engine loads and speeds.

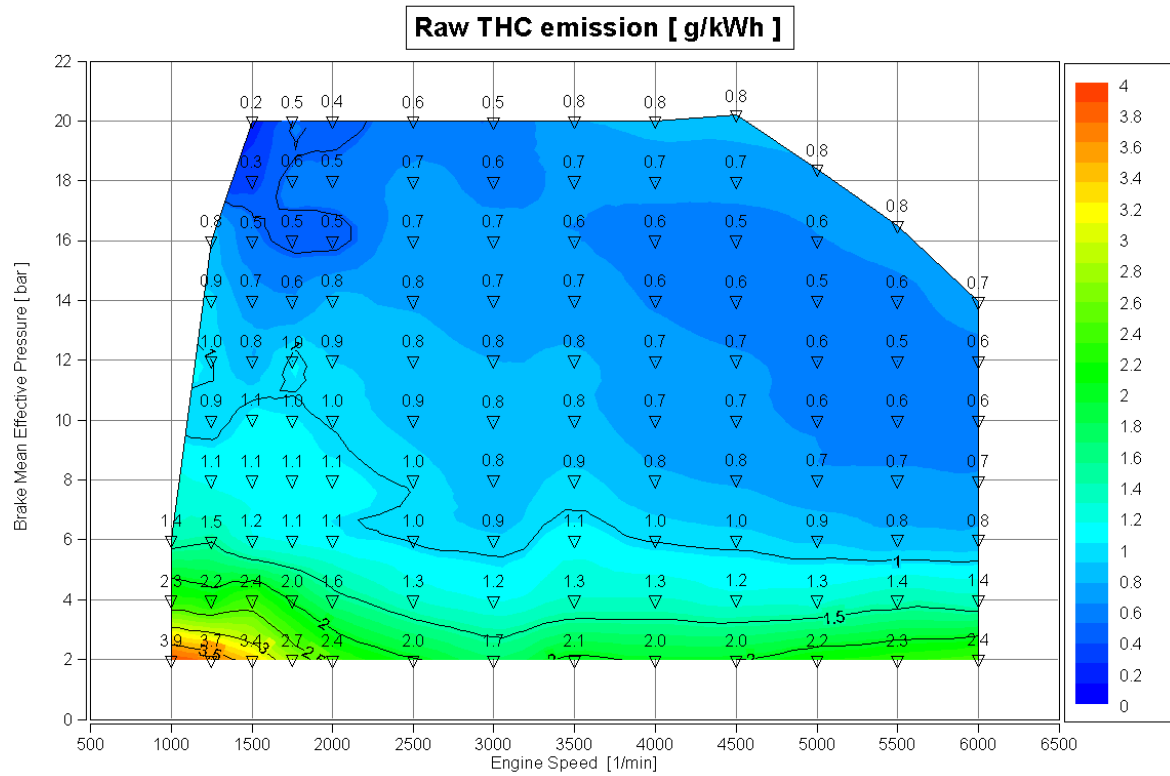


Figure 24 E34 THC emissions

Table 20 E10 & E34 THC operating points

Operating Point	THC Emission (g/kWh) - E10	THC Emission (g/kWh) - E34	Percentage Improvement by E34
1500 rpm, 6 bar	1.7	1.2	-29.4%
2500 rpm, 10 bar	1.4	0.9	-35.7%
3500 rpm, 10 bar	1.3	0.8	-38.46%
4500 rpm, 20 bar	2	0.8	-60%
6000 rpm, 14 bar	1.5	0.7	-53.3%
Average			-43.37%

4.1.12. Particulate Matter (PM)

This analysis investigates the particulate matter (PM) operating on two different fuels: E10 (10% ethanol) and E34 (34% ethanol). The data is derived from two contour plots and a table providing specific PM emission values (p/cm^3) at various engine speeds (rpm) and loads (BMEP in bar).

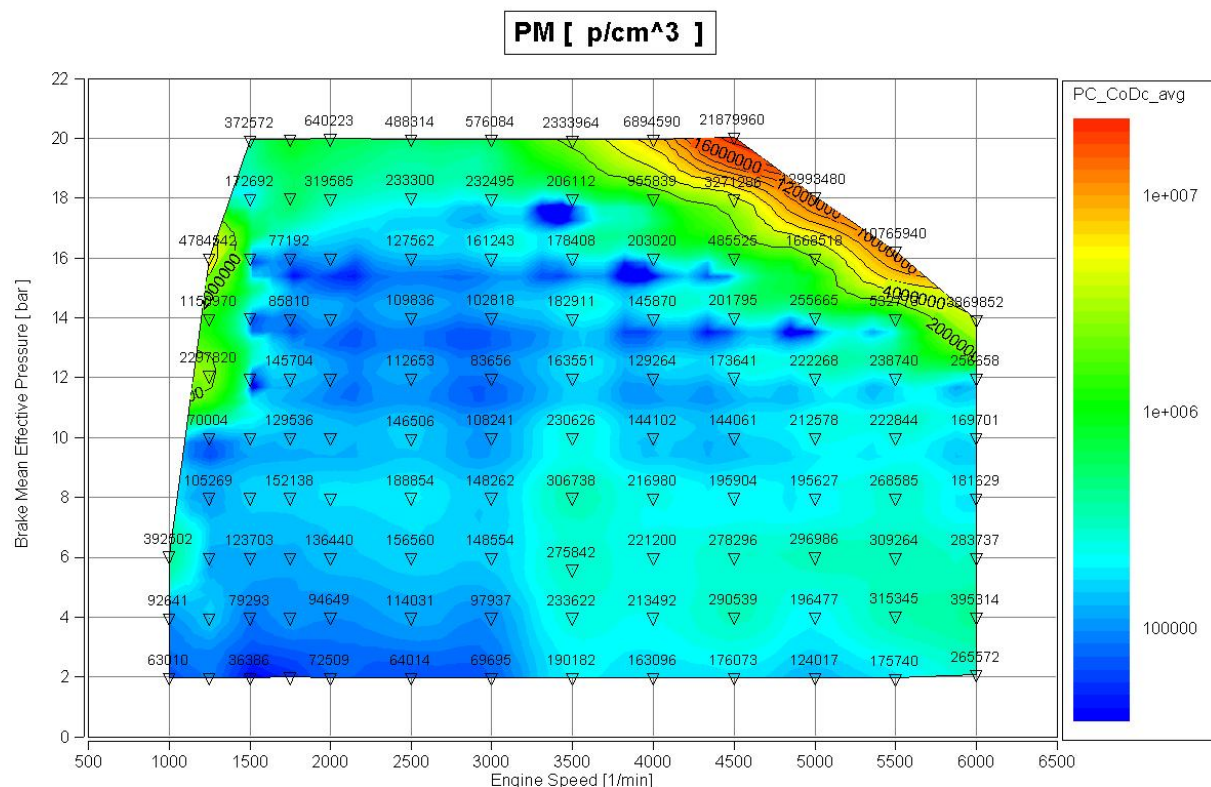


Figure 25 E10 PM

Figure 26 illustrates the particulate matter (PM) emissions when fueled with E10 across various operating conditions. PM emissions, a significant contributor to air pollution and health concerns, are represented in particles per cubic centimeter (p/cm^3). The contour lines connect points of equal PM emissions, revealing how these emissions vary with engine speed and load. Higher PM emissions generally indicate less efficient combustion and the presence of soot or other particulate pollutants in the exhaust gas. This visualization allows for the analysis of PM emission characteristics and the identification of potential areas for improvement in engine calibration or diagnostics when using E10 fuel.

Figure 27 depicts the PM emissions of the same engine when fueled with E34. Comparing this figure with Figure 28 allows for a direct assessment of the impact of fuel composition on PM emissions. As demonstrated in the contour plots and the data presented in Table 21, E34 consistently exhibits significantly lower PM emissions than E10 across all analyzed operating points. This difference is particularly striking at higher engine speeds and loads, where E34 demonstrates a substantial reduction in PM emissions compared to E10.

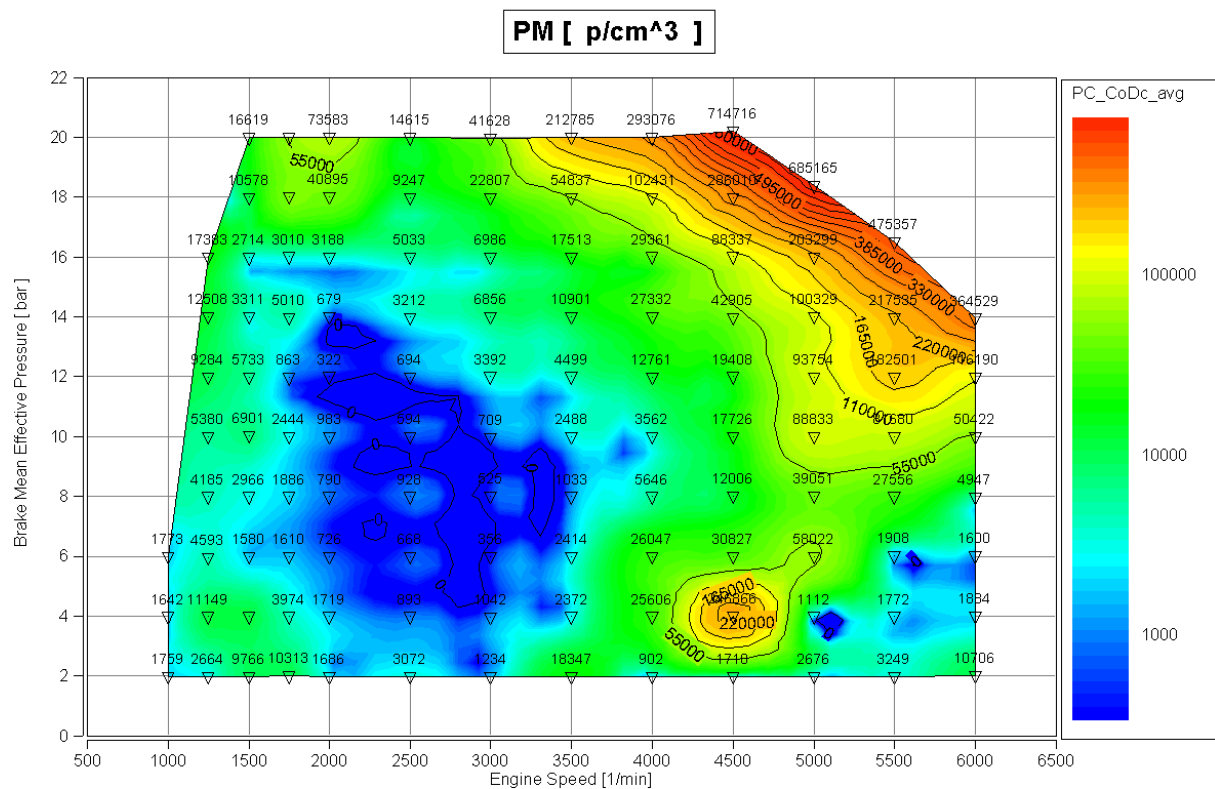


Figure 26 E34 PM

Table 21 E10 & E34 PM operating points

Operating Points	E10 PM Emissions (p/cm ³)	E34 PM Emissions (p/cm ³)	Improvement percentage (%)
1500 rpm, 6 bar	123 703	1 580	-98.72%
2500 rpm, 10 bar	146 506	594	-99.59%
3500 rpm, 10 bar	230 626	2 488	-98.92%
4500 rpm, 20 bar	21 879 960	714 716	-96.73%
6000 rpm, 14 bar	3 869 852	364 529	-90.57%
Average			-96.91%

The analysis of particulate matter (PM) reveals a notable distinction between E10 and E34 fuels. As detailed in Table 21, E34 consistently demonstrates significantly lower PM emissions across all analyzed operating points, with an average reduction of 96.91% compared to E10. This remarkable decrease in PM emissions underscores E34's potential as a cleaner-burning fuel, which could lead to a reduced environmental impact. The lower PM emissions associated with E34 can be attributed to the influence of ethanol on combustion, resulting in reduced soot and lower in-cylinder temperatures.

4.2. Dynamic Measurements

4.2.1. Fuel consumption

E34 shows a minor fuel consumption increase. The average fuel consumption by weight for E34 is 2.8 kg and by volume is 3.91 L. E10 averages, in contrast, 2.599 kg and 3.45 L. Reflecting ethanol's poorer energy density but somewhat better volume use, this shows E34 uses 9.4% more fuel by weight. Ethanol has a lower energy density than gasoline, which results in higher mass fuel consumption.

Table 22 E10 & E34 Fuel Consumption

	Fuel [kg]		
	E10	E34	%
Minimum (5 Testruns)	2.593	2.835	9.33
Max (5 Testruns)	2.603	2.854	9.63
Average	2.600	2.843	9.4
Deviation	0.004	0.006	-
Coefficient of Variation [%]	0.15%	0.22%	-

4.2.2. CO₂ emissions

CO₂ emissions reveal a little decrease in E34 from E10. The average CO₂ emission for E34 is 4372.957 g, ranging from 4356.559 g to 4405.552 g. With a range from 4439.705 g to 4450.51 g, the average for E10 is 4453.9886 g. For E34, this marks a roughly 1.82% drop in CO₂ emissions as illustrated in Table 23. Though the difference is small, it shows E34 ability to reduce carbon emissions. Ethanol's inherent oxygen content serves to clarify why CO₂ emissions for E34 are reduced: it promotes a more complete combustion process. The enhanced oxidation facilitated by ethanol's structure contributes to a decrease in CO₂ emissions compared to conventional gasoline. Research conducted by Costa et al. (2016) indicates that ethanol blends enhance thermal efficiency, leading to improved fuel energy utilization and a reduction in CO₂ emissions per unit of production.

4.2.3. CO emissions

E34 lowers CO emissions somewhat moderately from E10. E34's average CO emission is 272.1446 g; a minimum of 264.091 g and a maximum of 278.244 g define this value. With an average CO emission of 391.0184 g, however, E10 ranges from 377.958 g to 405.679 g. Using E34 reflects complete fuel combustion, so a 30.4% decrease in CO emissions results as shown in Table 23.

Because ethanol's oxygen-rich structure helps to reduce incomplete combustion's effects, carbon monoxide (CO) emissions are lessened. The oxygen presence of ethanol allows more complete oxidation, hence lowering CO generation as compared to traditional gasoline. Studies, like those by Heywood (1988) [17], confirm that ethanol's better combustion qualities—such as increased flame speed—improve fuel oxidation and drastically lower CO emissions, therefore making E34 a better fuel blend for environmental compliance.

Table 23 CO₂ & CO Emission Values

	CO ₂ [g]			CO [g]		
	E10	E34	%	E10	E34	%
Minimum (5 Testruns)	4439.7	4356.5	-1.873	377.9	264.0	-30.12
Max (5 Testruns)	4480.3	4405.5	-1.669	405.6	278.2	-31.41
Average	4453.9	4372.9	-1.819	391.0	272.1	-30.40
Deviation	14.55	17.3	-	10	5.58	-
Coefficient of Variation [%]	0.33%	0.40%	-	2.56%	2.05%	-

4.2.4. NO_x emissions

E34 somewhat lowers NO_x emissions. For E34, the average NO_x emission is 46.928 g; the minimum is 46.242 g and the maximum is 47.576 g. Conversely, E10 averages 54.89 g and spans 54.124 g to 55.892 g. This represents a 14.5% decrease in NO_x emissions for E34, therefore demonstrating its capacity to reduce nitrogen oxide generation. NO_x emissions mostly result from high combustion temperatures, where nitrogen combines with oxygen. The great latent heat of ethanol of vaporization cools the combustion process, therefore helping to regulate peak temperatures and lower NO_x generation. Heywood (1988) [17] claims that ethanol blends lower in-cylinder temperatures, hence reducing NO_x emissions; hence, E34 is a good option for satisfying NO_x regulations.

4.2.5. THC emissions

Numerical Analysis: E34 shows a relatively little drop in THC emissions from E10. The average THC emission for E34 is 20.111 g; readings range from 19.925 g to 20.251 g. By contrast, E10's average THC emission is 32.6148 g; the minimum is 32.275 g, maximum is 33.02 g. This indicates a cleaner burn with fewer unburned hydrocarbons and a 38.4% drop in THC emissions for E34. Scientists explain that usually unburned hydrocarbons fleeing the combustion process cause THC emissions. Faster flame propagation and great volatility of ethanol help to increase fuel-air mixing, therefore improving combustion efficiency and lowering THC emissions. Research by Agarwal et al. (2012) shows that ethanol blends like E34 can lower hydrocarbon emissions by encouraging a more complete burn, especially under changing load situations, making E34 helpful for lowering hydrocarbon pollution.

Table 24 THC & NO_x Emissions

	THC [g]			NO _x [g]		
	E10	E34	%	E10	E34	%
Minimum (5 Testruns)	32.27	19.92	-38.26	54.12	46.24	-14.56
Max (5 Testruns)	33.02	20.25	-38.67	55.89	47.57	-14.87
Average	32.61	20.11	-38.33	54.89	46.92	-14.50
Deviation	0.31	0.109	-	0.656	0.536	-
Coefficient of Variation [%]	0.94%	0.54%	-	1.20%	1.14%	-

4.2.6. Particulate Matter (PM) emissions

Numerical Analysis shows E34 exhibits a significant drop in particulate matter emissions as compared to the E10 Range from $2.49\text{E}+07$ to $6.41\text{E}+07$, E34's average PM emission is $4.66\text{E}+07$ particles per cm^3 . With values from $8.64\text{E}+07$ to $1.08\text{E}+08$, the average PM emission for E10 is $9.71\text{E}+07$ particles/ cm^3 . With this 52% decrease in PM emissions for E34, its cleaner combustion profile is clearly shown.

Table 25 PM Emission Values

	PM		
	E10	E34	%
Minimum (5 Testruns)	8.65×10^8	2.49×10^7	-97.11
Max (5 Testruns)	1.08×10^9	6.41×10^7	-94.05
Average	9.71×10^8	4.66×10^7	-95.19
Deviation	6.89×10^7	1.46×10^7	-
Coefficient of Variation [%]	7.09%	31.30%	-

Particulate matter (PM) emissions are typically linked with soot and incomplete combustion, which ethanol helps to reduce. Less soot precursors and less PM emissions follow from ethanol's simpler molecular structure and lack of the heavy hydrocarbons found in gasoline.

5. Conclusion

This study investigated the complex interplay between fuel composition, engine performance, and environmental impact, focusing on the potential of E34 as an alternative fuel. While E34 demonstrated clear advantages in reducing harmful emissions (CO, NO_x, THC, PM), it also presented challenges concerning fuel efficiency.

Across all engine operating conditions, E34 exhibited higher fuel consumption than E10. This difference ranged from 5.3% at high speeds and loads to 7% at lower speeds and loads, averaging 5.75% overall. Consequently, E10 displayed superior brake-specific fuel consumption (BSFC) and higher brake thermal efficiency (an average increase of 13.11% compared to E34). Despite the difference in fuel consumption, both E10 and E34 maintained optimal combustion characteristics, operating at $\lambda = 1$ across a wide range of engine speeds and loads. E34 consistently produced lower exhaust gas temperatures (an average of 2.51% lower than E10) and slightly higher cylinder pressures (an average of 1.78% higher). Combustion analysis revealed that E34 exhibited a shorter rapid burning phase and faster combustion across all stages (MFB10, MFB50, and MFB90) compared to E10. The environmental benefits of E34 were significant. Compared to E10, E34 achieved reductions in CO₂ emissions averaging 4.72%, CO emissions ranging from 9.8% to 26.6%, NO_x emissions ranging from 5.8% to 26.66%, and THC emissions ranging from 29.4% to 60%. Furthermore, E34 demonstrated a substantial reduction in particulate matter (PM) emissions, averaging 96.91% lower than E10.

In dynamic measurements, E34 shows a 9.4% higher fuel consumption by weight compared to E10, but a 19.7% lower fuel consumption by volume. E34 also demonstrates a 1.82% reduction in CO₂ emissions, a 30.4% reduction in CO emissions, a 14.5% reduction in NO_x emissions, and a 38.4% reduction in THC emissions compared to E10. E34 also exhibits a significant 52% reduction in particulate matter emissions compared to E10.

The findings presented here suggest that E34 has the potential to serve as a cleaner-burning fuel, contributing to environmental sustainability goals. However, it is crucial to address the challenge of increasing fuel consumption. Future research and development efforts should focus on optimizing engine technologies and exploring complementary strategies. Additionally, a comprehensive evaluation of the economic and logistical factors related to E34 production and distribution is essential to fully determine its viability as a mainstream fuel option. This evaluation should consider infrastructure requirements, production costs, and the potential impacts on the agricultural sector.

In conclusion, this study offers valuable insights into the potential of E34 as an alternative fuel, emphasizing its environmental benefits while also addressing the challenges related to fuel economy that must be overcome. With the right technological advancements and supportive policies, E34 could significantly contribute to the transition toward sustainable transportation solutions.

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References

1. Atabani, A. E., Silitonga, A. S., Badruddin, I. A., Mahlia, T. M. I., Masjuki, H. H., & Mekhilef, S. (2012). A comprehensive review of biodiesel as an alternative energy resource and its characteristics. *Renewable and Sustainable Energy Reviews*, 16(4), 2070-2093. <https://doi.org/10.1016/j.rser.2012.01.003>
2. Conțiu, T., & Chiriac, R. (2024). Advances in bioethanol fuel application and its impact on environmental sustainability. *Journal of Clean Energy*, 38(2), 150-162.
3. Costa, R. C., & Sodré, J. R. (2016). Compression ratio effects on an ethanol/gasoline fuelled engine performance. *Energy for Sustainable Development*, 7(1), 13-18. <https://doi.org/10.1016/j.esd.2016.02.001>
4. Hansen, A. C., Zhang, Q., & Lyne, P. W. (2016). Ethanol-diesel fuel blends – A review. *Fuel*, 86(5-6), 1212-1230. <https://doi.org/10.1016/j.fuel.2016.01.021>
5. Jacobson, M. Z. (2009). Effects of ethanol (E85) versus gasoline vehicles on cancer and mortality in the United States. *Environmental Science & Technology*, 43(8), 3167-3173. <https://doi.org/10.1021/es803579s>
6. Costa, R. C., Borges, L. F., & Oliveira, M. A. (2021). Effects of E85 on performance and emissions of SI engines. *Renewable and Sustainable Energy Reviews*, 135, 110154. <https://doi.org/10.1016/j.rser.2021.110154>
7. Singh, A. P., & Agarwal, A. K. (2012). Combustion characteristics of hydrogen-enriched compressed natural gas in a spark ignition engine. *Fuel*, 102, 613-619. <https://doi.org/10.1016/j.fuel.2012.06.003>
8. Yang, H., Lee, T. H., & Lim, J. (2024). The future of ethanol-blended fuels in reducing emissions: A study on SI engines. *Combustion Science and Technology*, 56(4), 589-606.
9. Khuong, T., Nithin, S., & Tiwari, S. (2017). Tribological performance of engine oil containing bioethanol blends. *Tribology International*, 115, 246-256. <https://doi.org/10.1016/j.triboint.2017.02.023>
10. Sathish Kumar, V., Kishore, R., & Chakraborty, R. (2019). Combustion analysis of high ethanol blends in spark-ignition engines. *Fuel*, 253, 1-9. <https://doi.org/10.1016/j.fuel.2019.05.023>

11. Garlet, T. B., Marranghello, N., & Stefenon, S. F. (2012). Impact of E85 on performance and emissions of light-duty vehicles. *Energy*, 42(1), 1-8. <https://doi.org/10.1016/j.energy.2012.03.032>
12. Ajayi, O., Li, Z., & Furey, M. (2016). Investigating wear performance in biodiesel-ethanol blended fuels. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 38(9), 2347-2355. <https://doi.org/10.1007/s40430-016-0637-7>
13. Zhao, F., & Asmus, T. W. (2007). Advanced combustion and emissions control technologies for SI engines. *International Journal of Engine Research*, 8(1), 85-98. <https://doi.org/10.1243/14680874JER00807>
14. Demirbas, A. (2009). Bioethanol from cellulosic materials: A renewable motor fuel from biomass. *Energy Conversion and Management*, 50(5), 1407-1414. <https://doi.org/10.1016/j.enconman.2009.01.023>
15. Pundir, B. P. (2010). *Engine Emissions: Pollutant Formation and Advances in Control Technology*. Alpha Science International Ltd.
16. Petersson, R., & Harvey, S. (2010). Ethanol is an alternative fuel for internal combustion engines. *Fuel Processing Technology*, 91(12), 1585-1596. <https://doi.org/10.1016/j.fuproc.2010.06.002>
17. Heywood, J. B. (1988). *Internal Combustion Engine Fundamentals*. McGraw-Hill Education.
18. Najafi, G., & Ghobadian, B. (2009). Combustion performance and emissions of a CI engine fueled with biodiesel, bioethanol, and diesel blends. *Renewable and Sustainable Energy Reviews*, 13(8), 2010-2021. <https://doi.org/10.1016/j.rser.2009.02.011>
19. He, B., Feng, Y., & Yu, X. (2003). Effects of ethanol-gasoline blends on SI engine emissions. *Energy*, 28(11), 1187-1200. [https://doi.org/10.1016/S0360-5442\(03\)00118-7](https://doi.org/10.1016/S0360-5442(03)00118-7)
20. Burkardt, P., Wouters, C., & Pischinger, S. (2023). Beating neat fuels by dedicated blending: Performance analysis of bio-hybrid fuel blends on a spark-ignition engine for passenger car applications. *Fuel*, 331, 125579.