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Period studied	**From:** 2021	**To:** 2025
Qualification to be gained: BEng (Hons) Automotive Engineering (Off-Highway)		
Project Title: The Impact of Exhaust Gas Emissions Legislation in Relation to Exhaust Temperatures		
Details of material submitted with nomination: (Project/Exec Summary/videos etc) Dissertation project report.		
SIGNED BY PROPOSER: Graham Higginson		**DATE SUBMITTED:** 30th September 2025

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The Impact of Exhaust Gas Emissions Legislation in Relation to Exhaust Temperatures

by

Edward Matthew Esden

Being an Honours Engineering Project submitted in partial fulfilment of the requirements for the BEng Honours Degree in Automotive Engineering Off-Highway

2025

HONOURS ENGINEERING PROJECT ASSESSMENT FORM

Student Declaration Form for Submission with Major Projects

Section 1

This form must be completed by the student and included at the beginning of the Honours Engineering Project.

Candidate's Name	Edward Esden
Candidate's Number	21132600
Degree Programme	BEng (hons) Automotive Engineering Off-Highway
Supervisor	Graham Higginson
Major Project Title	The Impact of Exhaust Gas Emissions Legislation in Relation to Exhaust Temperatures
Word Count	9976
Confidential?	No

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(Electronic) Signature of student: Edward Esden

Date: 18/04/2025

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Abbreviations

AOC – Ammonia Oxidation Catalyst

CARB – California Air Resources Board

CO – Carbon Monoxide

CO_2 – Carbon Dioxide

DEF – Diesel Exhaust Fluid

DOC – Diesel Oxidation Catalyst

DPF – Diesel Particulate Filter

ECU – Engine Control Unit or Electronic Control Unit

EPA – Environmental Protection Agency

g/kWh – Grams Per Kilowatt Hour

H_2O – Water

NOx – Nitrogen Oxide

O_2 – Oxygen

PEMS – Portable Emissions Measuring Equipment

ppm – Parts Per Million

RPM – Revolutions Per Minute

SCR – Selective Catalyst Reduction

SO_2 – Sulphur Dioxide

SOx – Sulphur Oxides

WHTC – Harmonized Transient Cycle

Glossary

Aftertreatment - Process of treating engine exhaust gases using exhaust technology to reduce harmful emissions before they are released into the atmosphere.

Cooling Medium – The substance (air, water, or other fluids) used to maintain the engine at an optimal temperature during operation.

Charge Air Cooler – A component that cools the compressed intake air, increasing its density for better combustion efficiency.

Dynamometer – A device used to measure the power output, torque, or rotational speed of an engine under different conditions.

Emission Standards – Regulatory limits set for the amount of pollutants an engine can emit during operation, specified for various categories of engines.

Exhaust Back Pressure – The resistance encountered by exhaust gases as they pass through the exhaust system and exit into the atmosphere.

Flywheel – A rotating mechanical device used to store kinetic energy on an engine.

Fuel Gas Probe – A device used to measure the concentration of gases in the exhaust, such as CO, CO_2, NOx, etc.

Load Bank – A device used to apply a controlled electrical load to an engine or alternator during testing

Regeneration – The process of cleaning and reactivating emissions control systems, such as diesel particulate filters, by raising exhaust temperatures to burn off accumulated soot.

Thermography – The use of infrared imaging to measure the temperature of the exhaust manifold and turbocharger.

Torque & Speed Points – Specific operating conditions of an engine, including its speed (RPM) and torque, used for emissions and performance testing.

Glycol – Represents sea water used as the cooling medium on the 4045HFC09.

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I would like to thank everyone who was involved with helping me to complete this project throughout this last year, in particular:

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ML Power Systems, in particular Barry, Bernadette and Pierre for access to the 4045HFC09 and 4045HF158 engines and engine test cell.

- Thank you Barry for checking over my written work and phone calls to answer questions.

- Thank you Pierre for your support and help with setting up the test cell, running the tests and recording the engine data.

Thank you to my family and friends for their support throughout the year and reading though my HEP.

Summary

The project aim was to investigate the impact of emissions legislation on diesel engine exhaust temperatures and their influence on pollutant formation and control. Two John Deere engines were selected for analysis: the 4.5L 4045HFC09, compliant with EU Stage V standards and the 4.5L 4045HF158 which meets Tier 1 requirements. The 4045HFC09 features a complex aftertreatment system, including twin turbochargers (fixed and wastegate), cooled EGR, DOC, DPF, SCR, and AOC while the 4045HF158 has no engine aftertreatment and operates with a single fixed turbo.

An information search and review were conducted to examine the formation of key diesel exhaust pollutants, notably oxides of Nitrogen (NOx) and Particulate Matter (PM), and how these are affected by combustion temperature and emission control technologies. The study follows the evolution of emissions regulations from Tier 1 to Stage V, highlighting how stricter standards have driven innovation in thermal management and aftertreatment strategies and their roles in meeting stringent emission standards.

Experimental testing conducted at fixed engine speeds and variable loads confirmed a strong correlation between exhaust temperature and emission reduction efficiency. Maintaining optimal thermal conditions proved essential for effective aftertreatment function and pollutant conversion. The 4045HFC09, equipped with electronic fuel control and a full aftertreatment system, consistently achieved lower NOx and CO emissions and higher CO_2 levels, indicating more complete combustion and better emissions control. In contrast, the 4045HF158 with a mechanical fuel system and no aftertreatment emitted significantly more NOx and CO, particularly at lower loads where thermal energy was reduced. ECU data reinforced the role of thermal management in sustaining DOC and SCR efficiency, especially under dynamic conditions. These findings underscore the critical relationship between exhaust temperature, engine efficiency, and compliance with modern emissions regulations.

Overall, the research improves understanding of how thermal management strategies impact emissions and highlights the technical challenges manufacturers face when designing efficient and regulation-compliant diesel engines.

Chapter 1. Introduction

With increasingly stringent emission regulations and future emission targets, improving diesel engine efficiency and reducing exhaust emissions have become fundamental to modern engine development (Diesel Net, 2021a). The aim of the project is to investigate the role of exhaust gas temperatures in pollutant formation and emission control, with reference to the impact of emissions regulations. The by-products of diesel engine combustion should be carbon dioxide (CO_2), water vapour (H_2O), nitrogen (N_2), and oxygen (O_2). However, due to combustion inefficiencies and impurities in the fuel and air, additional harmful pollutants are produced. According to Reşitoğlu, Altinişik and Keskin (2015), the primary emissions of concern include oxides of nitrogen (NO_x) which occurs when nitrogen is combined with oxygen and particulate matter (PM) made from unburned diesel and a combination of solid particles and gases, along with carbon monoxide (CO), unburned hydrocarbons (HC), and sulphur dioxide (SO_2).

To explore these issues, two John Deere 4.5L diesel engines were selected for comparison including the 4045HFC09 and the 4045HF158. The 4045HFC09, part of the PowerTech PSS series, complies with Environmental Protection Agency (EPA) Tier 4 and EU Stage V regulations. It incorporates a comprehensive aftertreatment system comprising of fixed and wastegate turbochargers, cooled exhaust gas recirculation (EGR), a diesel oxidation catalyst (DOC), diesel particulate filter (DPF), selective catalytic reduction (SCR) and an ammonia oxidation catalyst (AOC) for a rated output of 129 kW at 2200 RPM (Deere, 2014). The aftertreatment components are Size 4, appropriate for the engine's size power class.

In contrast, the 4045HF158 is an EPA California Air Resources Board (CARB) Tier 1-certified engine with a rated output of 88 kW at 1500 RPM, featuring a single fixed turbocharger and no exhaust aftertreatment system. It uses a 2-valve cylinder head, compared to the 4-valve configuration of the 4045HFC09 (Bundu Power, 2025).

This dissertation aims to assess the relationship between exhaust temperature, engine emissions and aftertreatment effectiveness through a series of fixed-speed, variable-load engine tests. In doing so, it explores how Stage V requirements have driven technological advancements in thermal management and emissions reduction strategies.

Chapter 2. Information Search and Review

2.1 US Environmental Protection Agency and European nonroad emissions regulations and Emission Reduction Technologies: 37 – 560 kW (Tier 1/Stage 1 through to Stage V)

2.1.1 Tier 1 Stage 1 (1996 – 1999)

US EPA Diesel Net (2023) and EU emission regulations Diesel Net (2021a) have become increasingly stringent and technological developments have made it possible to meet the emissions standards. Tier 1 and Stage 1 was first announced in 1994 and introduced between 1996 and 2000 by the US EPA and implemented by the EU in 1999, setting out the baseline levels allowed for NOx and PM production. Deere (2025a), achieved this through engine calibration with higher pressure fuel systems, engine cylinder heads which used 2-valves per cylinder (improved engine breathing) and 4-valves per cylinder (improved airflow), increased displacements for reducing NOx through lower combustion temperatures, and different aspirations options and advancements in increasing inlet air to reduce emissions. Particulate matter was reduced by improving oil control through directed top liner cooling.

2.1.2 Tier 2 Stage 2 (2001 – 2004)

From 2001 to 2004, EPA Tier 2 and EU Stage 2 regulations were in place which stated a 50% reduction of PM and a 20% reduction of NOx from Tier 1 and Stage 1 regulations. This was achieved through using full authority electronic controls for improved engine calibration which lowered exhaust emissions according to Deere (2025a). Other technological improvements included increasing fuel system pressure using electronically controlled mechanical rotary pumps and introducing common rail systems contributing to lowering PM. Air-to-air cooling was also implemented to lower inlet air temperatures to reduce emissions.

2.1.3 Tier 3 Stage 3 A (2006 – 2008)

Tier 3 and Stage 3 A began in 2006 and extended through to 2008 and focussed primarily on reducing NOx by a further 40%. This was achieved by increasing displacements to reduce combustion temperatures, cooled engine gas recirculation (EGR) which mixes exhaust gases and inlet air to reduce combustion temperatures, variable geometry turbos (VGT) and improving engine calibration using more engine electronics and a greater use of air-to-air aftercooling to reduce the temperature of the air exiting the intercooler or charge air cooler Deere (2025a). EPA and EU as stated by Diesel Net (2023) and Diesel Net (2021a) also enforced the use of low sulphur diesel fuels to help reduce particulate matter.

2.1.4 Tier 4 Stage III B (2008 – 2013)

In 2008, Interim Tier 4 and Stage III B was introduced and continued through to 2013 and targeted reducing PM by 90% and NOx by 50% (Deere 2025a). This involved increased use of electronic fuel pumps, common-rail and electronic unit injectors to reduce PM, enhancements in EGR systems with venturi flow measurement for better air-exhaust mixing and lowering NOx, series turbochargers for higher intake pressure, smart exhaust filters (DOC and DPF), and exhaust temperature management (ETM) to reduce PM. Ultra-low sulfur diesel fuel mandates also remained in effect.

2.1.5 Final Tier 4 Stage IV (2012 – 2015)

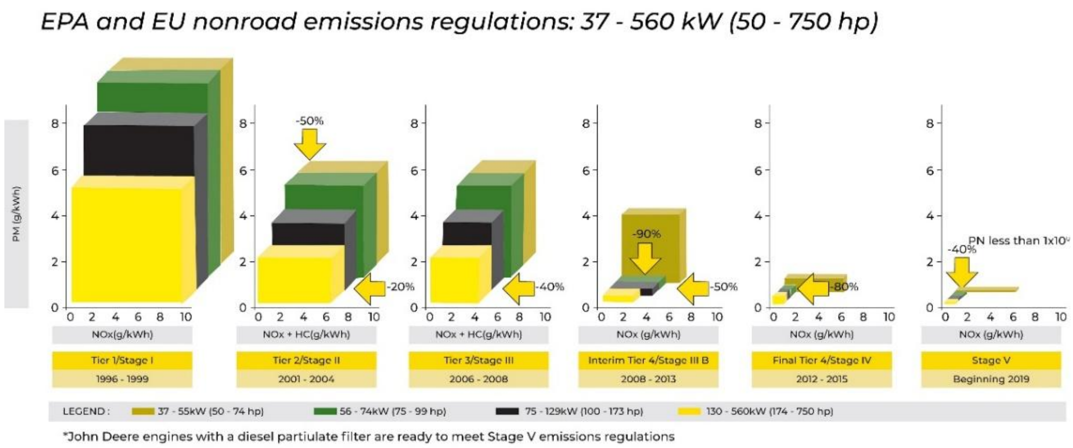
Final Tier 4 and Stage IV began in 2012 and continued through to 2015 and focussed on reducing NOx by a further 80% through the introduction of selective catalyst reduction (SCR) Deere (2025a). Further advancements in cooled EGR and turbocharging were also being used.

2.1.6 Stage V (2019 – Present)

Stage V is the most recent and up to date emissions regulation and began in 2019 and enforced a further 40% reduction of PM through John Deeres use of integrated emissions control system or IECS (Deere, no date). The purpose of IECS is to monitor and regulate PM and NOx levels exiting the engine for highest engine and fluid usage efficiency. Overall, the progression of diesel engine technology has resulted in cleaner and more efficient engines, contributing to improved air quality and less impact on the environment.

2.1.7 EPA and EU Nonroad Emission Regulations 37 – 570 kW Timeline

Figure 1 illustrates the EPA and EU nonroad emissions regulations for engines within the 37 to 560 kW power range. The John Deere emissions compliance timeline from Deere (2023) highlights the progressive reductions in allowable emissions mandated by these regulations and the impact on the different engine sizes.

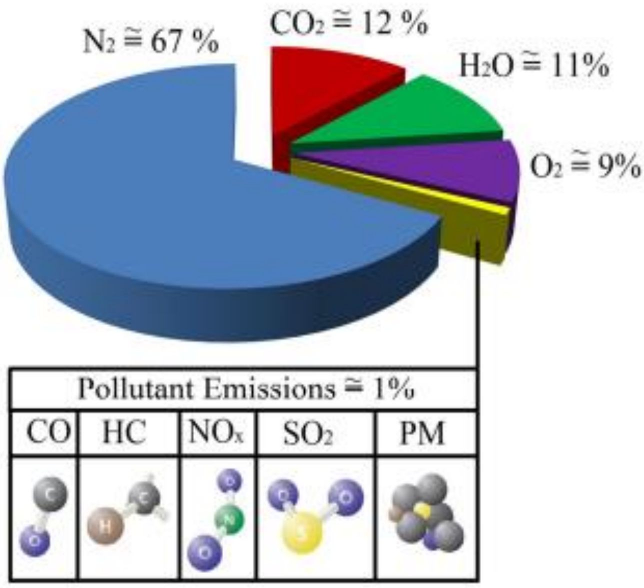


(source: Deere 2023)

Figure 1 John Deere EPA and EU nonroad emissions regulations: 37 - 560 kW

2.2 Compositions of Diesel Exhaust Gas

Figure 2 shows the approximate composition of polluting and non-polluting diesel exhaust emissions from Reşitoğlu, Altinişik and Keskin (2015). It can be determined that less than 1% of the emissions are polluting and of that percentage, NOx is the greatest contributor at 50% followed by PM. These two harmful by-products of diesel combustion are therefore the primary targets for reduction under the Stage V emissions regulations.



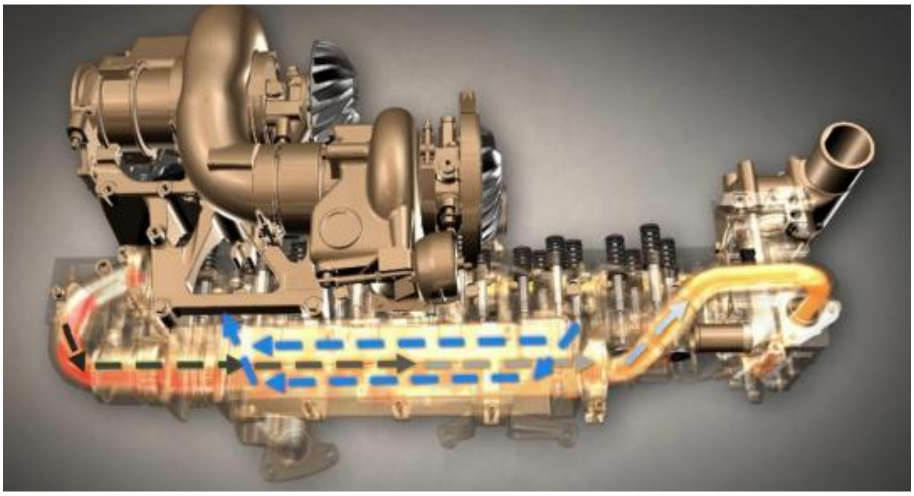
(source: Reşitoğlu, Altinişik and Keskin, 2015)

Figure 2 Compositions of Diesel Exhaust Gas

2.3 Emission Reduction Exhaust Technology

2.3.1 Exhaust Gas Recirculation (EGR)

Exhaust gas recirculation (EGR) as reported by Latarche (2021) is a method of reducing NOx by recycling a percentage of cooled exhaust gases back into the combustion chamber. The John Deere EGR system in Figure 3 works by recycling some of the exhaust gases back through the EGR according to (Deere, 2025b). The exhaust gases leave the exhaust manifold and are routed and travel to the EGR cooler. The cooler uses fins and engine coolant traveling in the opposite direction of the flow of exhaust gases to reduce the temperature of the exhaust gases. The opposite flow directions of the coolant and gases ensure that the coldest gases encounter the coldest coolant, maximising heat transfer efficiency and improving overall heat rejection. The EGR system features an EGR valve which is adjusted by the engine ECU using pulse width modulation (PWM) to increase or decrease EGR flow. When the EGR opens and allows exhaust gases to flow through, the temperature sensor takes readings of the gases.



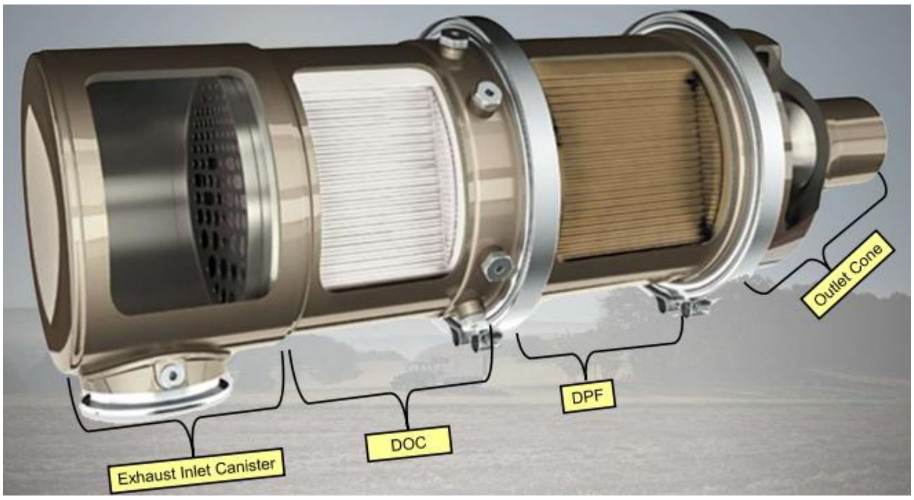
(source: Deere, 2024)

Figure 3 Exhaust Gas Recirculation (EGR)

John Deere's EGR system as stated by Deere (2024) also uses a cooled venturi situated after the EGR valve and features a restriction in the centre of the venturi which changes the velocity of the exhaust gases as they flow through. The venturi has a pressure and temperature sensor which the ECU takes readings from to determine the position of the EGR valve. The gases which flow through the venturi are directed into EGR mixer, where cooled exhaust gases are mixed with fresh air, before being fed into the inlet manifold. By recycling and cooling the exhaust gases, the temperature of the combustion chamber is reduced which decreases the NOx being produced.

2.3.2 Diesel Oxidation Catalyst Diesel Particulate Filter

The exhaust filter system from Deere (2022) consists of the DOC and DPF which is a canister made up of four main parts including the exhaust inlet, DOC, DPF and outlet cone which can be seen in Figure 4.



(source: Deere, 2022)

Figure 4 Exhaust Filter Components

2.3.3 Diesel Oxidation Catalyst (DOC)

The DOC is a catalyst with a precious metal coating inside, often made from platinum (Deere, 2022). The coating reduces harmful exhaust gas by reacting with carbon monoxide (CO) caused by incomplete combustion and carbon content in the fuel as reported by Ramalingam and Rajendran (2019), hydrocarbons (HC) from unburned fuel and nitric oxide (NO) to form carbon dioxide (CO_2), water (H_2O) and nitrogen dioxide (NO_2). York and Tsolakis (2010) states that CO and HC are removed with the help of excess oxygen in the exhaust, which as previously mentioned, makes up approximately 9% of the diesel exhaust gases. The performance of the DOC is reliant on excess oxygen remaining in the exhaust gas. The DOC is also responsible for reducing some PM. The catalyst reaction produces heat which is essential for the DPF to perform efficiently and effectively.

2.3.4 Diesel Particulate Filter (DPF)

The DPF functions by collecting particulate matter (PM) and soot produced during combustion. The DPF contains open and closed channels that collect PM and soot but allow exhaust gases to flow through the walls. When DPF soot levels become too high, a regeneration is carried out by the ECU. The different engine regenerations include passive and ECU (active). Passive occurs during normal engine running and utilises heat from the DOC for the DPF oxidation reaction to occur. With higher soot levels in the filter, (monitored and determined by the ECU) the ECU will carry out a more intense regeneration which requires adjusting the exhaust throttle actuator, and injecting fuel into the exhaust gases inside the cylinders which oxidises the PM and soot more effectively (Deere, 2022).

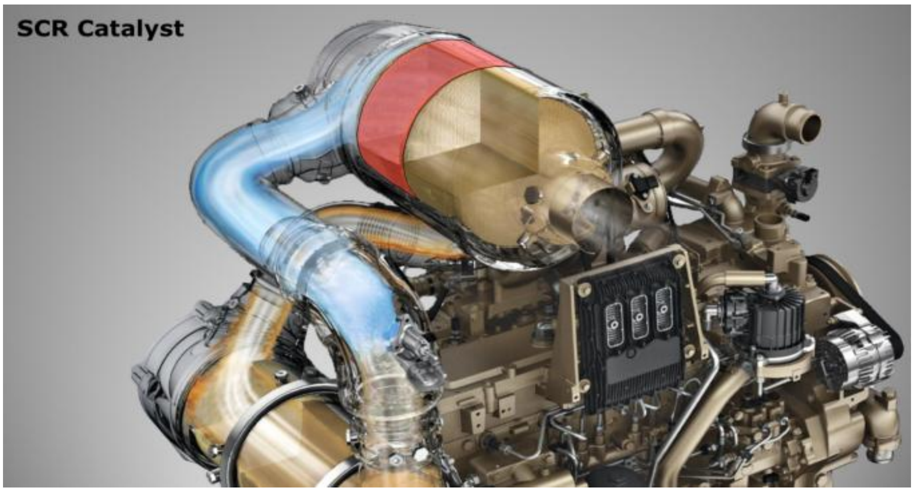
An active regeneration involves closing the exhaust throttle actuator valve to restrict the flow of exhaust gases. Deere (2013) suggests that changing the valve to a closed position will cause the exhaust gas temperature to increase and when an exhaust gas temperature of 300°C has been achieved, the regeneration will begin. To increase exhaust gas temperatures further, the ECU sends a command for fuel dosing into the exhaust gases inside the cylinder. The injected fuel increases the exhaust temperature needed for the oxidation of PM. When exhaust gas temperatures reach 500°C - 650°C, the ECU begins recording data provided from the sensors in the exhaust filter.

The ECU uses sensors including DOC inlet and outlet temperature and DPF differential pressure (measures pressure changes across the DPF) to monitor the engine and aftertreatment performance (Deere, 2022). The temperature and pressure data are used to adjust engine performance and determine when a regeneration needs to be carried out and when the regeneration can be finished.

Ash is created along with PM and soot during combustion and is one of the main limitations affecting the filter's service life according to research from Sappok (2013). Ash is the by-product of engine oils and fuel and air impurities and additives which collect in the exhaust filter and are monitored by the ECU. Ash cannot be cleaned through regeneration and needs to be manually removed from the exhaust filter when the ECU determines the ash loading levels are too high.

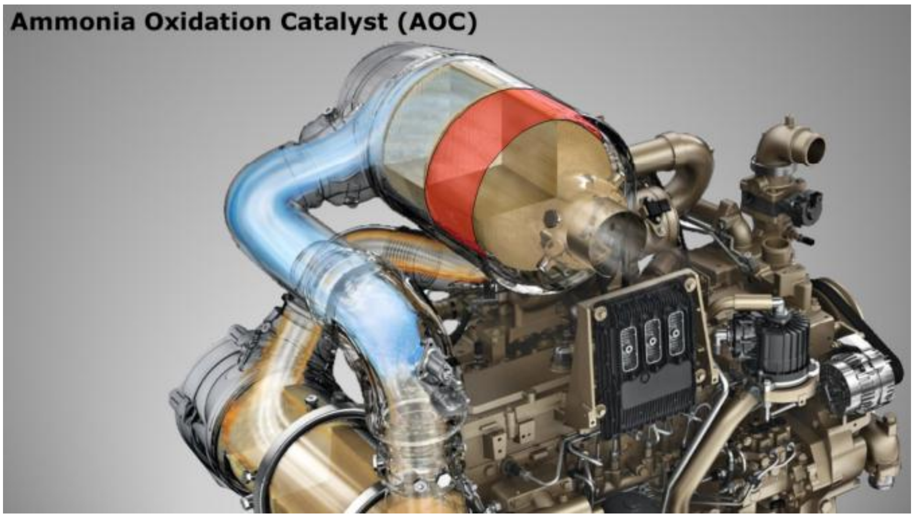
2.3.5 Selective Catalyst Reduction (SCR) and Ammonia Oxidation Catalyst (AOC)

The SCR system is responsible for NOx which is a gas produced during combustion when nitrogen is combined with oxygen. Diesel exhaust fluid (DEF) commonly referred to as AdBlue is made up of 32.5% urea and 67.5% water as reported by Deere (2016) and is injected through a DEF injector into the exhaust system mixer before the exhaust gases enter the SCR and AOC shown in Figures 5 and 6. When the DEF contacts the hot exhaust system and gases, the water evaporates leaving ammonia (NH3) which chemically reacts with the NOx in the SCR and AOC cannister, producing nitrogen gas (N_2) and water vapor H_2O. Research from Sadeghbeigi (2012) suggests that NOx can be reduced by more than 20 ppm through the SCR AOC system.



(source: Deere, 2016)

Figure 5 Selective Catalyst Reduction (SCR)



(source: Deere, 2016)

Figure 6 Ammonia Oxidation Catalyst (AOC)

The system from Deere (2016) consists of a DEF dosing injector, decomposition tube, SCR cannister containing the SCR and AOC catalysts and SCR diffuser. The DEF injector is positioned before the decomposition tube and is ECU-controlled to inject exact quantities of DEF at the correct times. The DEF injector is cooled or warmed by the engine coolant depending on whether the injector is too hot from exhaust temperatures or needs warming due to cold external temperatures called defrosting. The decomposition tube contains a mixer which can be in a compound or mesh form. It is located between the DOC DPF and

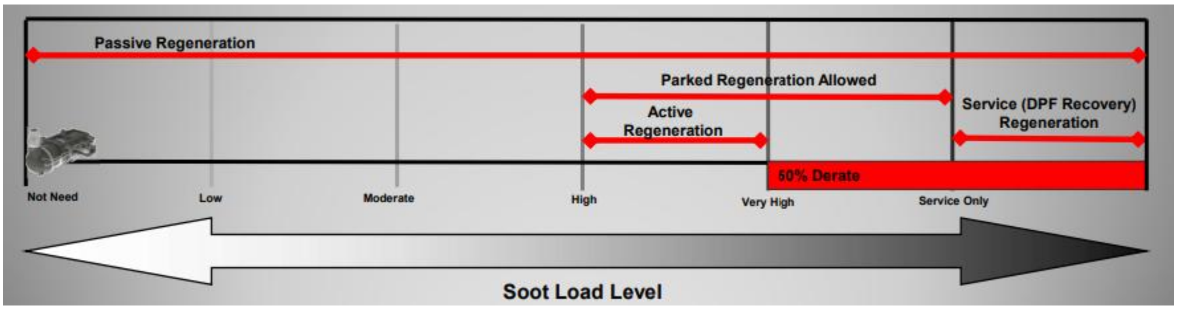
SCR and can be in either a straight or elbow form. The decomposition tube is situated after the DEF injector so the exhaust gases and DEF can effectively mix for optimum conversion of DEF into Ammonia.

Attached to the inlet side of the SCR canister is an SCR diffuser which spreads the exhaust gases as they enter the SCR in Figure 5 and AOC in Figure 6. The SCR and AOC both perform as catalysts and are constructed from a high-temperature resistant ceramic honeycomb and contain precious metals required for the reactions. The SCR unlike the DPF does not filter exhaust gases but collects and holds onto ammonia which is then used for the conversion of NOx into water vapor and nitrogen (Zhao *et al.*, 2023). Heat is required for desulfurisation (DeSOx) to occur or the removal of sulfur deposits inside the canister. The time the canister can store ammonia for is determined by the amount of NOx being produced from combustion and the temperatures that are occurring inside the exhaust system.

The AOC is the second section of the canister and consists of a different selection of precious metals to convert any remaining ammonia into nitrogen through a second catalyst reaction. The combination of the SCR and AOC increases NOx conversion efficiency, greater ammonia storage and increased DEF dosing for overall improved engine efficiency (Deere, 2016). Before and after the SCR canister is a NOx and temperature sensor which are used to monitor NOx conversion efficiency and the exhaust gas temperatures. The NOx sensor begins taking readings once the SCR is at the optimum temperature and is used to calculate whether the engine is within specification for emissions compliance.

2.4 Regenerations

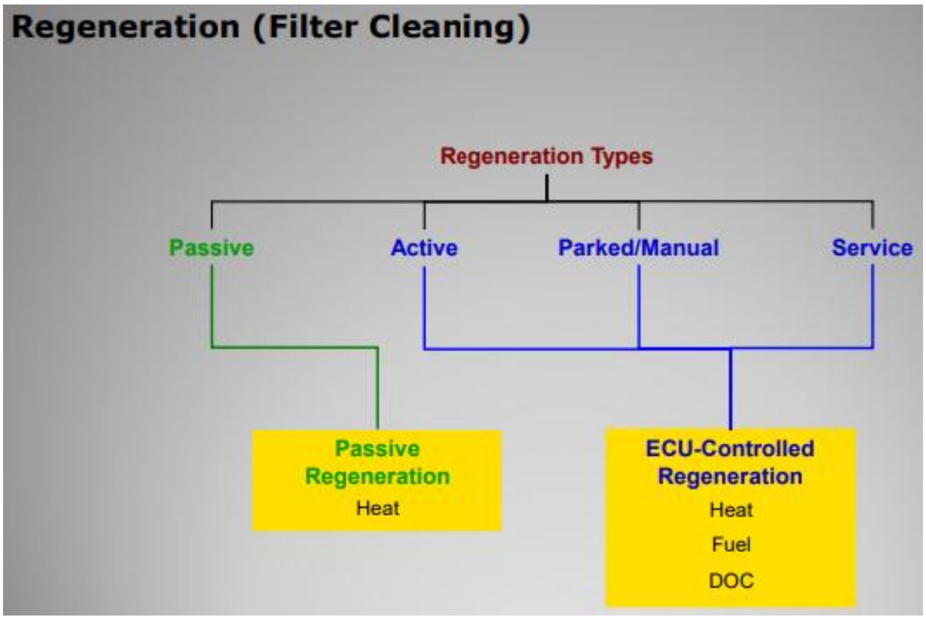
The four different John Deere regenerations can be seen in Figure 7 and include passive, active, parked and service with the soot level and a breakdown of what is involved at each stage of the regeneration (Deere, 2022).



(source: Deere, 2022)

Figure 7 Regeneration Soot Load Level

Figure 8 shows the required temperature parameters for each of the four regeneration types which are explained in further detail in Table 1.



(source: Deere, 2022)

Figure 8 Regeneration Filter Cleaning

Table 1 Regeneration Parameters

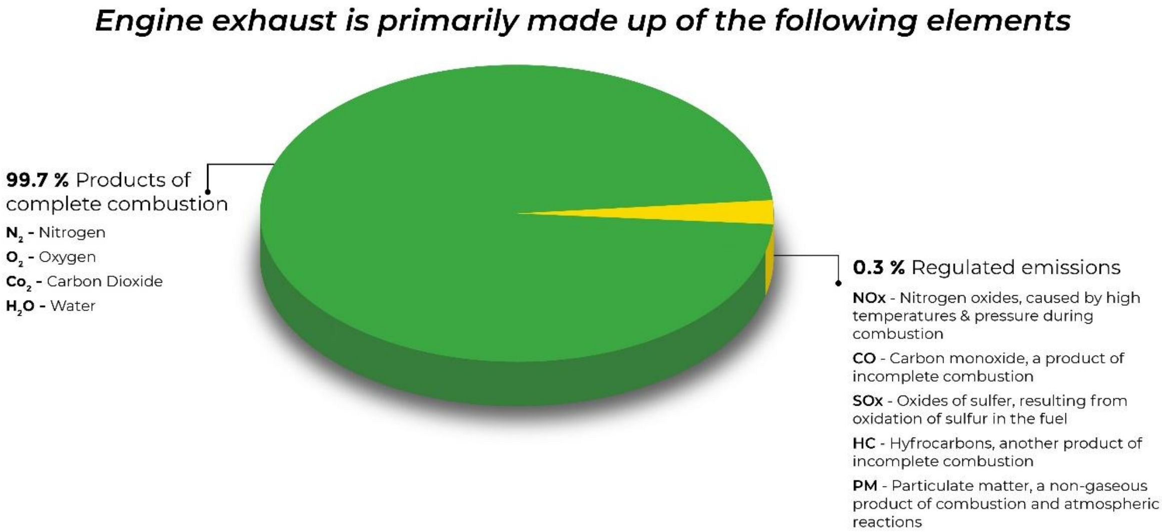
Passive
No ECU command.
Most fuel-efficient regeneration method.
DOC inlet temperatures are required to be 250 ˚C with best conversion rates between 300 and 350 ˚C.
Soot is oxidised by a catalytic or chemical reaction through oxidation from the nitrogen oxide NO_2 in the exhaust gases.
Passive regeneration requires the engine to operate at a stable rated load and RPM for a sustained period. If conditions such as load, temperature, or humidity are unsuitable (during light loading or idling), the ECU initiates active regeneration instead.
Active
Started from an ECU command.
Exhaust temperature is increased by injecting excess fuel via the main fuel injectors into the cylinders.
Exhaust temperatures must be 300 ˚C for cylinder dosing to begin.
Efficient method to increase exhaust temperature with minimal impact on fuel usage.
Once 300 ˚C has been reached, the ECU will send a command and fuel dosing will begin.
When the desired temperature has been met, the precious metal or catalyst coating on the walls of the DPF allow for oxidation to occur.
The ECU controls the DOC temperature by performing an elevated idle, which requires the engine to be running above 1200 RPM.
Parked/manual
Same ECU commands as active regeneration but now with the ECU controlling the speed of the engine.
Service DPF recovery
A more intense cleaning procedure taking up to 3.5 hours to complete depending on exhaust filter soot levels.

(source: adapted from Deere, 2022)

Engine regenerations play a significant role in understanding the impact of exhaust temperature on engine and aftertreatment performance. As shown in Figure 8, exhaust temperature increases as the soot load rises. There is a clear correlation between high exhaust temperatures and reducing aftertreatment soot loads suggesting lower exhaust temperatures (with the aims of reducing NOx) are potentially contributing to exhaust blockages from soot and PM.

2.5 The Development of EPA And EU Emission Regulations

Figure 9 shows the primary elements which make up exhaust gases from Deere (2023). Analysing the graph shows that 99.7 % of elements which are produced during complete combustion are harmless and consist of N_2, O_2, CO_2 and H_2O. This is slightly higher than what is suggested by Reşitoğlu, Altinişik and Keskin (2015) in section 2.2 which is a more generic diesel exhaust gas composition graph and not specific to John Deere engines. 0.3% of elements produced are however regulated emissions and consist of NOx, CO, SOx and PM. The percentages of these gases are fundamental when analysing the performance of the John Deere engines.



(source: Deere, 2023)

Figure 9 Engine Exhaust Combustion Gases

2.6 Exhaust Temperatures

Managing diesel engine exhaust gas temperature is essential for protecting engine and exhaust components, ensuring safe operation, and maximising performance. Jääskeläinen (2024) argues that maintaining optimal temperatures is crucial for effective aftertreatment and low emissions. However, the research is largely conceptual without experimental data or consideration of variable engine loads and real-world duty cycles. This limits its applicability and leaves a gap in understanding of exhaust temperature behaviour under different operating conditions and loads.

To achieve maximum catalytic activity, the exhaust and aftertreatment should reach optimum operating temperatures as quickly and efficiently as possible and maintain this temperature throughout the duty cycle. The importance of exhaust temperature will be determined by the engine Tier or Stage, engine application and aftertreatment technology being used. For engines with an SCR catalyst, Jääskeläinen (2024) suggest an exhaust temperature between 185-200°C or higher is needed before DEF dosing can start as can be seen in Table 2 (HC desorption). If DEF is injected into the exhaust system and the adequate temperature isn't achieved, DEF crystallisation on the injector and deposits in the exhaust canister can occur, impacting engine reliability and component service life. In relation to the John Deere 4045HFC09 which uses a DOC, DPF, SCR and AOC and utilises the DOC to generate heat for the SCR, Fayad *et al*. (2015) suggest that the DOC temperature should be at least 220°C before the DOC will oxidise hydrocarbons and create sufficient heat.

Table 2 Different Catalyst Regeneration Functions and the Required Exhaust Temperatures

Function	Target Exhaust Temperature, ˚C
HC desorption	> 200
Desulfation	>400 to >650
Urea deposit (ammonium sulfate) removal	>280
Hard urea deposit removal	>400 to >500
Soot oxidation in DPF	250-350 with NO_2 >550 with O_2

(source: adapted from Jääskeläinen, 2024)

Research by Woodyard (2009) highlights the critical role of exhaust temperature in influencing both emission levels and the behaviour of exhaust gases, a view supported by more recent findings from Jääskeläinen (2024). Excessive exhaust temperatures can restrict an engine's maximum power output. This relationship is evident when examining how mean indicated pressure corresponds with exhaust temperature. As the engine reaches its economical combustion limit (optimal balance between power output and fuel efficiency) the exhaust temperature typically increases in a near-linear trend. Shortly after this point, the temperature may rise sharply, signalling that the engine is approaching its safe operating threshold. This threshold reflects the thermal and mechanical stress tolerances the engine is designed to withstand. Woodyard (2009) also observed that exhaust temperature tends to have a greater influence on torque than on power output and that exhaust system design plays a critical role in temperature regulation. Systems that allow exhaust gases to flow freely help reduce temperatures, whereas restrictive systems can elevate them. For the John Deere 4045HFC09 and 4045HF158 engines, the OEM-supplied exhaust systems are specifically designed to meet the required back pressure, thermal and flow characteristics for their intended applications.

Combustion temperature and NOx production can be reduced by delaying fuel injection causing the combustion to occur later. The result of this is increased fuel consumption referred to as the diesel dilemma (Woodyard, 2009). Research from Tan *et al*. (2012) suggests Common rail fuel injection systems such as on the 4045HFC09 compared to traditional mechanical diesel pumps on the 4045HF158 increase the precision of the fuel injection and can be electronically controlled to change the pressure the fuel is injected at, the spray timing and time the fuel is injected for which improves engine efficiency and performance. Mechanical fuel pumps require manual calibration which can lead to inefficiencies. In contrast, common rail fuel systems offer improved control across all engine loads and speeds, contributing to reduced NOx and better fuel efficiency.

A test from Sun *et al*. (2023) investigated NOx emissions and exhaust and aftertreatment performance during cold-start and medium to low engine loads using a World Harmonized Transient Cycle (WHTC). The experiment looked at reducing NOx emissions when the exhaust temperatures were lower (engine start up). The results showed that when electrical heating is applied to the exhaust system at the previously stated operating conditions, NOx was lower. The test showed that the NOx conversion rate (when ammonia reacted with NOx in the SCR system), was significantly lower at reduced exhaust gas temperatures. This reduced efficiency at low temperatures was further supported by findings from Mera *et al*. (2021), who confirmed that SCR-equipped vehicles outperformed non-SCR vehicles at elevated temperatures but exhibited similar NOx levels during cold starts. Their study also showed improved NOx reduction during motorway driving, attributed to the more stable exhaust temperatures at higher speeds.

Sun *et al*. (2023) stated a conversion rate of 87.07% was achieved, increasing to 97.81% at 260 °C. With a 7.2 kW heater activated between 200–500 seconds, NOx was reduced by 45% at the SCR outlet. Additionally, a DOC placed before the SCR further reduced NOx by 63%, though it increased N_2O during cold start. The study's reliance on added thermal management technologies (electric heaters) which are not used on engines like the John Deere 4045HFC09 or 4045HF158 limits its direct applicability. While the results demonstrate the potential of active thermal control, they may overemphasise effectiveness under typical, unmodified engine conditions, highlighting a gap this project addresses through testing in standard configurations.

In the maritime industry, wet exhaust systems are commonly used with companies such as Vetus (2025) manufacturing them. The Vetus wet marine exhaust system differs significantly from the emissions control strategies studied by Sun *et al*. (2023) and Mera *et al*. (2021). The Vetus system focuses on cooling and reducing exhaust gases by injecting seawater into the gas stream, lowering gas temperatures by approximately 40–50°C from 400°C. In contrast, the previous research emphasises maintaining higher exhaust temperatures to enable effective SCR performance and NOx reduction which relies on sustained and stable heat for the chemical reaction with AdBlue.

2.7 Research Gap

While extensive research exists on the evolution from Tier 1 to Stage V regulations and the development of emissions control technologies such as EGR, DOC, DPF, SCR, and AOC, there remains a gap in understanding how exhaust temperature, particularly under varying engine loads in standard engine configuration influences emissions performance across different regulatory stages. This is particularly evident when comparing engines used in different applications, such as maritime and non-road sectors, which differ in duty cycles and operational environments. The aim of this study is to experimentally investigate how temperature influences emission outputs, with a specific focus on the impact of engine load on exhaust temperature and the emissions found in exhaust gases when exiting the exhaust. By comparing Tier 1 and Stage V-compliant engines, the research offers new insights into how thermal management contributes to emissions control.

Chapter 3. Methodology

3.1 Study Aim

The aim of this study is to investigate how exhaust gas temperature influences emissions from diesel engines, focusing on different engine loads at fixed RPM's. It compares two John Deere engines including a 4045HF158 (Tier 1 compliant) and 4045HFC09 (Stage V compliant) under a range of operational loads. The research aims to address the gap in knowledge regarding the importance and impact of exhaust temperature on emissions control technologies and provide insight into performance differences across emissions standards.

3.2 Study Design

Data collection was conducted on ML Power Systems premises during March 2025. All test procedures were carried out to BS ISO 8178-2:2021 which is recognised as the international standard for measuring gaseous and particle exhaust emissions on non-road application engines (British Standards Institution, 2021). Ethical approval was granted by Harper Adams University before engine testing was carried out, shown in Appendix 1, and permission from ML Power Systems to use their facilities was obtained shown in Appendix 2.

3.3 John Deere 4045HFC09 Specifications

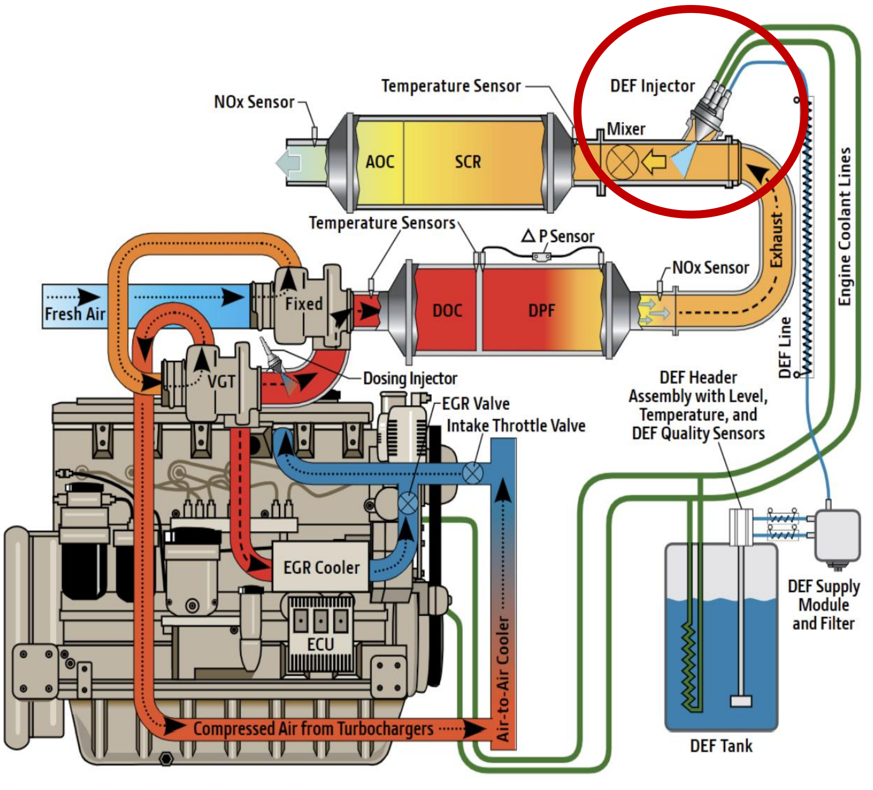
Figure 10 shows the 4045HFC09 situated in the test cell with the aftertreatment, dynamometer and hoses attached.

(source: author's own)

Figure 10 John Deere 4045HFC09

The 4045HFC09 generator designed for marine application used heat exchangers which relied on seawater (glycol) to cool the coolant and charge air (Alde, 2025) rather than a traditional radiator which uses air to cool the coolant. This setup was consistent with the engine's intended marine configuration and correctly specified for the 4045HFC09.

The 4045HFC09 features an ECU which allowed John Deere Service Advisor to be connected to take recordings of engine performance and emissions data. This was used alongside the Testo 885 and 350 portable measuring equipment. The specifications for the 4045HFC09 can be seen in Figure 11 with the power rating and exhaust system setup.



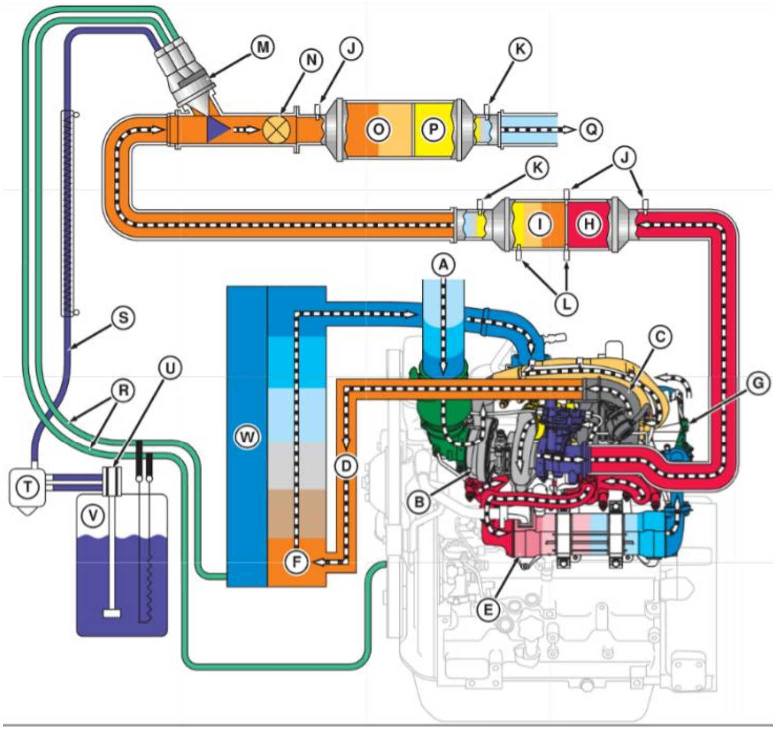
Engine	Power ratings	Valves per cylinder	Turbo
PowerTech PSS 4.5L	116–129 kW (155–173 hp)	4-valve	Series

Cooled EGR	Aftertreatment	Exhaust filter size	Exhaust filter dosing	SCR size
Yes	DOC/DPF/SCR	4	Internal	4

(source: Deere, no date c)

Figure 11 Engine Specification 4045HFC09

The engine componentry and technology on the 4045HFC09 was almost identical to Figure 10. However, the 4045HFC09 did not use a diesel dosing injector in the exhaust but utilised the 4 main cylinder injectors to inject fuel into the combustion chamber to increase the temperature of the exhaust gases for regenerations. The layout and details of the exhaust system and labelled parts are further explained in Figure 12 and Table 3.



(source: Deere John, 2025)

Figure 12 Aftertreatment and Exhaust Components

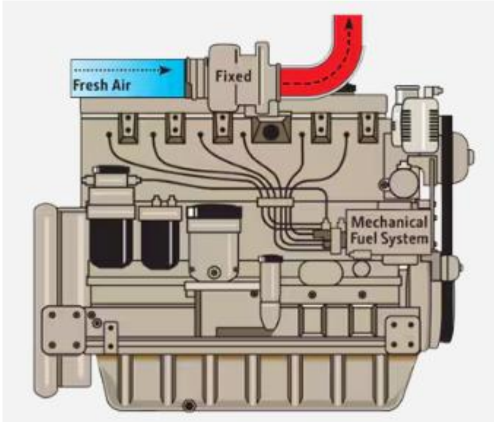
Table 3 Labelled Aftertreatment and Exhaust Components

A – Inlet Air
B – Fixed Turbocharger
C – Wastegate Turbocharger
D – Compressed Air from Wastegate Turbocharger
E – EGR Cooler
F – Charge Air Cooler
G – EGR Valve
H – DOC
I – DPF
J – Temperature Sensors in Aftertreatment
K – A NOx Sensor Before and After SCR and AOC.
L – DPF Differential Pressure Sensors
M – DEF Injector
N – Decomposition Tube Mixer
O – SCR
P – AOC
Q – Exhaust Gas Outlet
R – DEF Injector and DEF Tank Coolant Lines
S – DEF Injector Pressure Line
T – DEF Dosing Unit
U – DEF Tank Header
V – DEF Tank
W – Radiator

(source: adapted from Deere, 2025)

3.4 John Deere 4045HF158 Specifications

The 4045HF158 is shown in Figure 13. The engine is fully mechanical and does not use an ECU.



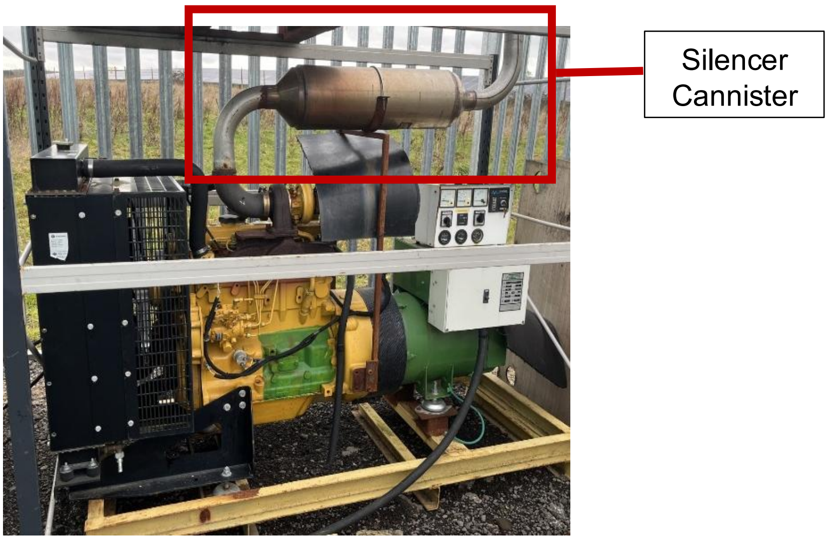
(source: Deere, 2025 a)

Figure 13 John Deere 4045HF158 Exhaust System Components

The exhaust consisted of a straight pipe from the outlet of the turbo into a single silencer cannister, seen in a Figure 14. The silencer was installed primarily for environmental noise reduction and introduced minimal back pressure, defined as the resistance encountered by exhaust gases as they pass through the exhaust system and exit into the atmosphere (Jääskeläinen, 2007). The engine featured a mechanical fuel pump, fixed turbo and no emissions aftertreatment.

Although both engines are John Deere 4045's, some componentry was different between the engines due to technological advancements. The result of this was different methods of loading the engines.

The 4045HF158 was paired with the Antler Power alternator in Figure 14. The alternator was connected to a load bank which is shown in Figure 18 to apply an electrical load during testing. The alternator was specified to the power rating of the engine (88 kW).



(source: author's own)

Figure 14 4045HF158 Alternator and Radiator and Intercooler Package

The 4045HF158 specifications are shown in Figure 15. The engine was set to reach a maximum speed of 1500 RPM. The specifications stated that the exhaust system should not exceed 545˚C for prime usage (the power the engine can generate consistently over an extended period) and 565˚C for standby usage (the power the engine can generate for a limited time) according to FW Power (2024).

Exhaust System	**1500 rpm**	**1800 rpm**
Exhaust Flow		
Prime = PRP – m^3/min (ft^3/min)	17.0 (600)	24.0 (847)
Standby = LTP – m^3/min (ft^3/min)	18.7 (660)	26.4 (932)
Exhaust Temperature		
Prime = PRP – °C (°F)	545 (1013)	490 (914)
Standby = LTP – °C (°F)	565 (1049)	475 (887))
Max. Allow. Back Pressure – kPa (in.H_2O)	7.5 (30)	7.5 (30)
Recommended Exhaust Pipe Dia – mm (in.)	101.6 (4)	101.6 (4)
Cooling System	**1500 rpm**	**1800 rpm**
Thermostat Start to open – °C (°F)	82 (180)	82 (180)
Power Unit Coolant Capacity – L (qt)	25.0 (26.5)	25.0 (26.5)
Minimum Air to Boil temperature – °C (°F)	47 (117)	47 (117)

(source: Bundu Power, 2025)

Figure 15 John Deere 4045HF158 Exhaust System Specification

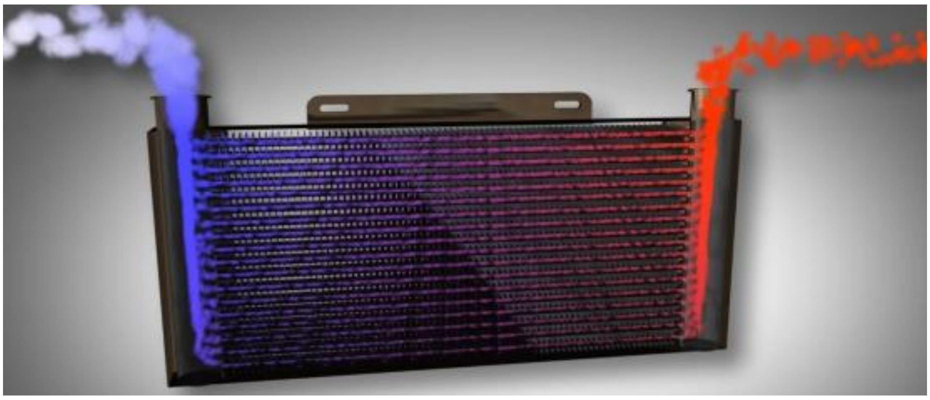
The 4045HF158 used a radiator and charge air cooler package seen in Figure 16. This was correctly specified for a John Deere 4045HF158 to ensure the engine received adequate cooling as determined by Deere (no date c).

(source: Deere, no date c)

Figure 16 RE545484 Radiator Charge Air Cooler Package

3.5 Charge Air Cooler

Charge air cooling shown in Figure 17 reduces the temperature of the intake air which gets warmer when compressed by the turbo. Cooler air is denser and carries a greater charge, increasing the efficiency of the combustion as reported by Jääskeläinen and Khair (2017). The charge air coolers were part of the experimental control to ensure both engines were receiving equal cooling to the charge air. The 4045HFC09 used air to water cooling whereas the 4045HF158 used air to air cooling and no adjustments or restrictions to the charge air coolers were made.



(source: Deere, 2024)

Figure 17 Charge Air Cooler

3.6 Engine Loading

3.6.1 CRESTCHIC 610 kW Load Bank

Figure 18 shows the CRESTCHIC 610kW electrical load bank which was used to load the 4045HF158. The controller located to the right in Figure 18 was used to adjust the load applied to the alternator and engine.

(source: author's own)

Figure 18 CRESTCHIC 610kW Resistive Lond bank

3.6.2 Go Power Systems DT20000 Engine Dynamometer

The 4045HFC09 was paired with the calibrated Go Power Systems DT20000 dynamometer shown in Figure 19 to apply load to the engine. Although a different method of loading the engine to the 4045HF158, (water driven instead of electrical loading) the load being applied remained consistent and was adjusted accordingly in line with the test procedure. The 4045HFC09 used a different flywheel which resulted in incompatibility between the alternator and load bank. The purpose of the flywheel is to store the kinetic energy as stated by Martyr and Rogers (2021) and is mounted from the crankshaft onto the dynamometer or alternator.

(source: Go Power Systems, 2020)

Figure 19 Go Power Systems DT20000 Engine Dynamometer

3.7 Fuel EN 590

Both engines were run on EN 590 ultra-low sulphur diesel which is the current standard for diesel sold in the European Union members states and a selection of other European countries (Diesel Net, 2024). The diesel as stated by Crown Oil (2025) in Table 4 contains a mandatory 7% biodiesel or Fatty Acid Methyl Ester (FAME). In the case of the engine tests which were carried out, EN 590 Gas oil was used. Gas oil is referred to as red diesel and can be used for stationary diesel engines. The 7% biodiesel content in gas oil is optional; these tests used EN 590 diesel without biodiesel content. The engines were both provided fuel from the same fuel tank. As the tests proceeded, the volume of fuel in the tank reduced and therefore the back pressure on the engine lift pump also reduced. This had a very minimal effect on the performance of each engine as the capacity of the tank was 4000L and the engines were only run for short periods of time, reducing the volume insignificantly.

Table 4 EN 590 Gas Oil

Parameter	Unit	Minimum	Maximum	Typical
Appearance	–	Clear & bright, Cherry Red, Free from visible sediment.	–	Pass
Density at 15°C	kg/l	0.820	0.845	0.830
Kinematic viscosity at 40°C	cSt	2.0	4.5	2.90
Carbon residue (Ramsbottom on 10% residue)	% (m/m)	–	0.30	<0.10
Distillation recovery at 250°C	% (v/v)	–	65	37
Distillation recovery at 350C	% (v/v)	85	–	93
Flash point (PMCC)	°C	<55	–	64
Water content	mg/kg	–	200	70
Particulate content	mg/kg	–	24	<12
Ash content	% (m/m)	–	0.01	<0.001
Sulphur content	mg/kg	–	10	9
Copper corrosion(3 hrs at 50°C)	Class	–	1	1
Cold filter plugging point(1) Summer	°C	–	-5	-8
Cold filter plugging point(1) Winter	°C	–	-15	-20
Cetane number	–	51	–	53
Cetane index	–	46	–	55
Fatty acid methyl ester (FAME)	% (v/v)	–	7.0	6.5
Carbon	% (m/m)	–	–	87
Cloud point Summer	°C	–	+3	-2
Cloud point Winter	°C	–	-5	-10
Hydrogen	% (m/m)	–	–	12.75
Nitrogen	% (m/m)	–	–	0.01 – 0.05
Gross specific energy (MJ/kg)	MJ/kg	–	–	45.4
Gross specific energy (MJ/litre)	MJ/litre	–	–	37.7
Mean specific heat capacity over 0 – 100°C	KJ/kg °C	–	–	2.05
Strong acid number	mg KOH/g	–	nil	nil
Lubricity (HFRR)	µm	–	460	390
Oxidation stability 0.0 – 7.0% FAME	g/m^3	–	25	5

(source: Crown Oil, 2025)

3.8 Test Equipment

The Testo 885 was used throughout the two engine tests to record thermal concentrations on the exhaust manifold and turbo on both engines (Testo, 2025) . Thermography was an appropriate method to measure temperature on the two engines and determine any variations.

The Testo 350 Maritime exhaust gas analyser was used during both tests and measured emissions in compliance with MARPOL Annex VI and NOx Technical Code 2008 (Testo, 2025). The Testo 350 precisely measured gases including NOx, CO_2, O_2, CO and SO_2. However, measurements of HC and PM could not be carried out using the equipment available. The Testo 350 used a fuel gas probe which was attached to the end of the outlet of the exhaust, recording the gases leaving the engine.

The Testo 610 thermohygrometer from Testo (2025) was used to measure the air humidity and temperature which were input into the Testo 350 before exhaust emission measurements were performed.

3.9 Engine Testing ISO 8178

ISO 8178 as stated by British Standards Institution (2021) is the international standard for measuring both gaseous and particle exhaust emissions on engines of non-road applications including machinery, generator sets, marine installations and industrial equipment to mention a few. The test is used for engine certification and approval in the United States, European Union, and Japan and outlines different dynamometer test and loading cycles for the different types of engines and their application (Diesel Net, 2021b).

A similar test from Kamińska *et al.* (2022) looking at the measurement of rail vehicle exhaust emissions used ISO 8178 and portable emissions measuring systems (PEMS) to compare engine performance data in real operating conditions against the relevant standards. The test is also commonly used in the maritime industry as reported by Sustainable Ships (2025) suiting engines like the John Deere 4045HFC09 which is designed as a marine application generator.

ISO 8178 was chosen due to its wide industry adoption and its ability to generate replicable results in both field and test settings.

3.10 Stage V Emission Standards

Table 5 shows the emission standard for the Stage V non road 4045HFC09 which is positioned in the 56 ≤ P ≤ 130 Net Power kW category as the rated engine power or peak power is 129KW for an intermittent application (Deere, 2014).

Table 5 Stage V Emission Standards for Nonroad Engines

Category	Ign.	Net Power	Date	CO	HC	NOx	PM	PN
		kW	2020	*g/kWh*				*1/kWh*
NRE-v/c-5	All	56 ≤ P ≤ 130		5.00	0.19[c]	0.40	0.015	$1x10^{12}$

(source: adapted from Diesel Net, 2021a)

3.11 Tier 1 Emission Standards

Table 6 shows the emission standards for Tier 1 non road 4045HF158 which is positioned in the 37 ≤ kW < 75 Net Power category as the rated engine power or peak power is 88 kW at 1500 RPM (Bundu Power, 2025).

Table 6 EPA Tier 1 nonroad diesel engine emission standards, g/kWh

Engine Power	Tier	Year	CO	HC	NMHC+NOx	NOx	PM
			g/kWh				
37 ≤ kW < 75	Tier 1	1998	-	-	`-	9.2(6.9)	-

(source: adapted from Diesel Net, 2023)

3.12 Pre In-Service Test Parameters and Procedures ISO 8178

An important consideration during the engine testing was the distinction between controllable and uncontrollable variables. One key uncontrollable variable was the weather. As the tests were performed outside, the engines were exposed to varying temperatures, humidity levels and wind speeds. To reduce the influence of these environmental factors, the engines were placed in a test cell. The cell had a roof to protect against precipitation, while the open sides allowed for adequate airflow and cooling. Ideally, the tests would have been conducted consecutively to maintain consistent conditions as changes in wind speed and ambient temperature could affect the engine's operating conditions. Using the same fluids, operating under similar ambient environments and ensuring the test equipment remained properly calibrated helped minimise the impact of external variables and improve the result accuracy.

Although the tests were carried out on different days to reduce environmental noise interference, the variation in ambient conditions was minimal. The relative humidity differed by 4.2%, and ambient temperature varied by 4.0°C. While such changes were unavoidable, they are recognised as uncontrollable variables and should be considered in the analysis and interpretation of the results.

Table 7 shows the pre in service test parameters and procedures adapted from the British Standards Institution (2021).

Table 7 Pre in Service Test Parameters and Procedures ISO 8178

Parameter	Procedure / Requirement
Ambient Conditions	The intake air temperature (°C) and humidity (%) of the intake air were recorded before testing commenced.
Engine Fluids and Filters	The engine oil, fuel, and reagent (AdBlue) conformed to the manufacturer's specifications. – The 4045HFC09 and 4045HF158 were 4-cylinder 4.5 L engines. – John Deere PLUS-50 II SAE 15W-40 oil and Cool-Gard II coolant were used. – Oil and coolant were changed prior to each test. – Oil filters were replaced, and new identical air filters were installed to ensure uniform intake conditions.
Emission Measurement Equipment	Emission measurement equipment was brought to operating exhaust temperature, pressure and flow as specified by the manufacturer. – Equipment used included Testo 350 Maritime and Testo 885, both calibrated to ISO/IEC 17025. – Readings were cross-referenced with Service Advisor data on the 4045HFC09 to confirm accuracy.
Exhaust System	Originally specified exhaust systems were fitted that complied with the manufacturer's specified back pressure limits.
Cooling System	A cooling system was installed to maintain the engine at normal operating temperatures as specified by the manufacturer.
Diesel Fuel Specification	The diesel fuel used was verified, recorded, and declared. – EN 590 fuel was used to replicate field application conditions. – Fuel temperature was recorded and confirmed to be within specification.
Exhaust Configuration	The engine exhaust was routed using short, flexible connectors, where possible, positioned at the end of the exhaust pipe or after the aftertreatment system, if applicable.

Engine Maintenance Records	A complete service and maintenance record was provided for the engines.
Engine Eligibility	Both engines showed no signs of misuse, overloading, or misfuelling, and no unauthorised adjustments were made that could affect emissions performance. – The 4045HFC09 ECU was functional and included complete communication data for identification and validation.
Assembly and Installation	The engines were assembled and installed in full accordance with the manufacturer's guidelines.

(source: adapted from British Standards Institution, 2021)

3.13 Test Conditions

Table 8 ISO 8178 Test Conditions

Condition	Procedure / Requirement
Test Duty Cycle	A representative test duty cycle was developed through agreement between the relevant parties to replicate real-world engine operation as closely as possible. The cycle reflected the type of work both engines would encounter in field applications, minimised idle operation and had a variety of loads. (Type D1).
Torque & Speed Point Selection	All torque and speed points conformed to what was specified in Type D1 of ISO 8178-2:2021 and agreed between parties. Therefore, no weighting factors were adjusted.
Test Sequence Agreement	For torque or speed-specific tests, the sequence of measurement points conformed to ISO 8178-2:2020. The selected points accurately represented the intended test cycle and followed a decreasing order of power or torque, as specified by the standard.
Load Limitation	100% engine load was achievable on both engines and the maximum power output measurements were not limited to the maximum allowed speed and torque.
Drift Correction	Data drift within ±2% was accepted with or without correction. Drift did not exceed ±2%, therefore corrections were not applied.
Data Completeness	Data completeness reached 98%. No more than 2% of data from any operating sequence was excluded due to no signal loss.
Coolant Conditions	Engine coolant reached 70°C (from cold start) or stabilised within ±2°C for 5 minutes prior to emission measurement. Testing began 20 minutes after the engines were started.
Cooling Medium Monitoring	The cooling medium (seawater or air-based) was monitored and recorded during the test period.
Idle Time & Load Activity	The representative test cycle excluded idle periods and included sufficient loaded operation to meet test duration requirements.
Ambient Test Conditions	Tests were conducted under ambient conditions: ambient temperature equal to or greater than - 7 ˚C
Pollutants Measured	Gaseous emissions measured during the tests in accordance with ISO 8178-2:2021 included CO_2, O_2, NOx, CO and SO_2.
Exhaust Configuration	A single exhaust stack was used on both engines to simplify emissions recording and eliminate the need to average data across multiple stacks.

(source: adapted from British Standards Institution, 2021)

3.14 Test Sequence

The John Deere 4045HFC09 and 4045HF158 were positioned in the constant speed class of engines. Under the constant speed category specified by British Standards Institution (2021) is Type D1 and Type D2 shown in Table 9. ISO 8178 states the different engine application types and correlating engine test sequences shown in the table from Diesel Net (2021b). Type D1 focussed on higher loads and Type D2 is for constant speed engines designed to run across a greater range of loads. The Table also displayed the weighting factors for each mode as a percentage of the overall test.

- Type D1, the engine test should be divided as follows: 30% duration at 100% of the available torque at the rated speed, 50% duration at 75% and 20% duration at 50%.
- Type D2, the engine test should be divided as follows: 5% at 100% of the available torque at the rated speed, 25% at 75%, 30% at 50%, 30% at 25% and 10% at 10%.

Type D1 was selected as the more representative duty cycle for the 4045HFC09 and 4045HF158 engines. As generator sets, both engines are typically required to operate at medium to high loads for extended periods. Due to the shorter test duration, chosen for feasibility and to limit environmental impacts from noise and emissions, Type D1 was preferred as it more accurately reflected real-world usage. Sustained operation at higher loads also increased exhaust temperatures, allowing more effective emissions analysis compared to the Type D2 cycle, which focused on lower load conditions.

Table 9 ISO 8178 Weighting Factors of B-Type

Mode number	1	2	3	4	5	6	7	8	9	10	11
Torque, %	100	75	50	25	10	100	75	50	25	10	0
Speed	Rated speed					Intermediate speed					Low idle
Off-road vehicles											
Type C1	0.15	0.15	0.15	-	0.10	0.10	0.10	0.10	-	-	0.15
Type C2	-	-	-	0.06	-	0.02	0.05	0.32	0.30	0.10	0.15
Constant speed											
Type D1	0.30	0.50	0.20	-	-	-	-	-	-	-	-
Type D2	0.05	0.25	0.30	0.30	0.10	-	-	-	-	-	-
Locomotives											
Type F	0.25	-	-	-	-	-	-	0.15	-	-	0.60
Utility, lawn and garden											
Type G1	-	-	-	-	-	0.09	0.20	0.29	0.30	0.07	0.05
Type G2	0.09	0.20	0.29	0.30	0.07	-	-	-	-	-	0.05
Type G3	0.90	-	-	-	-	-	-	-	-	-	0.10
Marine application											
Type E1	0.08	0.11	-	-	-	-	0.19	0.32	-	-	0.30
Type E2	0.20	0.50	0.15	0.15	-	-	-	-	-	-	-
Marine application propeller law											
Type E3, Mode #	1		2		3		4				
Power, %	100		75		50		25				
Speed, %	100		91		80		63				
Weighting factor	0.2		0.5		0.15		0.15				
Type E4, Mode #	1		2		3		4		5		
Power, %	100		80		60		40		0		
Speed, %	100		71.6		46.5		25.3		Idle		
Weighting factor	0.06		0.14		0.15		0.25		0.4		
Type E5, Mode #	1		2		3		4		5		
Power, %	100		75		50		25		0		
Speed, %	100		91		80		63		Idle		
Weighting factor	0.08		0.13		0.17		0.32		0.3		

Notes:
- Engine torque is expressed in percent of the maximum available torque at a given engine speed
- Rated speed is the speed at which the manufacturer specifies the rated engine power
- Intermediate speed is the speed corresponding to the peak engine torque.

(source: Diesel Net, 2021b)

The ISO 8178 Type D1 testing procedure from British Standards Institution (2021) specified the engine speed, load and corresponding weighting factor. For the Type D1, the cumulative weighted times across all modes determined the total test duration.

A test duration of 30 minutes was chosen for each engine to ensure that sufficient data could be collected under each mode. This duration allowed for an adequate number of measurements within each mode (1 every minute) while maintaining compliance with the time allocation requirements shown in Table 10. Although ISO 8178 did not mandate a fixed total test time, the selected 30-minute period provided sufficient data readings and time for the engines to stabilise between each mode without excessive run time and fuel usage.

The test duration did not include pre-conditioning or engine warm-up time which was conducted beforehand to stabilise operating temperatures and ensure the engine was in a steady-state condition before recording to data.

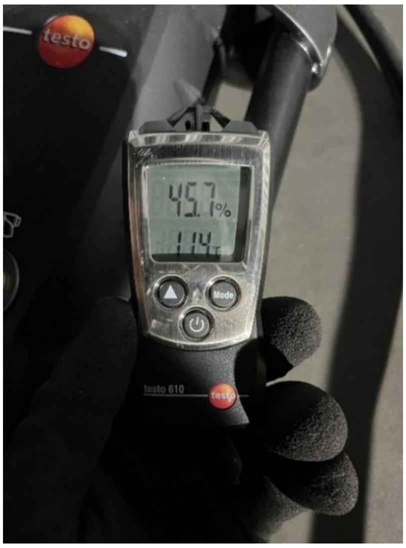
Table 10 Adapted Test Modes and Weighting Factors for 1500 RPM Operation for 30 Minutes Per Engine

Mode Number	Engine Speed (RPM)	Load (% of Max Power @ 1500 RPM)	4045HFC09 Load (DC 150 – S Dynamometer works in %)	4045HF150 Load (CRESTCHIC Load Bank Works in kW)	Weighting Factor (WF)	Time (30 Total Time)
1	1500	100%	100%	88 kW	0.30	9
2	1500	75%	75%	66 kW	0.50	15
3	1500	50%	50%	44 kW	0.20	6

(source: adapted from British Standards Institution, 2021)

3.15 Test Protocol John Deere 4045HF158

The 4045HF158 was the first engine which was tested. The air temperature and humidity were measured using the Testo 610 in Figure 20 and inputted into the Testo 350.



(source: author’s own)

Figure 20 Testo 610 Used to Measure Air Temperature and Humidity

The Testo 885 and Testo 350 were setup and the filters inside the Testo 350 were changed before any readings were taken shown in Figure 21.

(source: author’s own)

Figure 21 Testo 350 Filter Change

The Testo 885 was secured in position to provide consistent thermal imaging of the exhaust manifold and turbocharger. To maintain repeatability, images were captured from identical locations throughout the 30-minute test. The Testo 350 analyser was mounted on a stable surface with its flue gas probe aligned to intersect the exhaust flow, ensuring representative sampling. Both devices were powered on and allowed to complete their startup procedures. Figure 22 illustrates the Testo 350 configured in flue gas analysis mode.

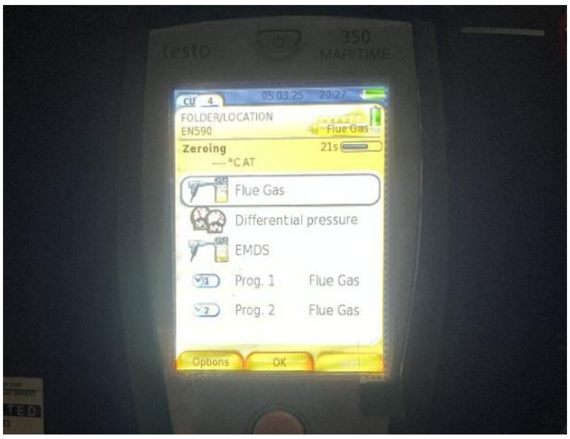


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Figure 22 Testo 350 Flue Gas Mode

Prior to testing, both the coolant and engine oil levels were inspected and confirmed to be within the recommended operating range. The engine was connected to the load bank and the fuel lines and battery terminals attached. The engine was started and brought up to speed at 1500 RPM which was maintained throughout the test.

In accordance with the British Standards Institution (2021), engine preconditioning was performed for 20 minutes under no-load conditions. During this period, the coolant temperature reached 78.4 °C and the oil temperature stabilised at 77.6 °C. Exhaust manifold and turbocharger temperatures were recorded at 267 °C and 274 °C respectively. These values were documented at the 0-minute interval to serve as baseline measurements.

Following preconditioning, the engine load was gradually increased to 100% (88 kW) using the load bank controller, and data collection commenced as illustrated in Figure 23. Exhaust emissions and temperature readings were recorded at one-minute intervals over a 30-minute duration. The engine was operated at 100% load (88 kW) for the first 9 minutes (30% of the test duration), followed by 75% load (66 kW) for 15 minutes (50%), and finally at 50% load (44 kW) for the remaining 6 minutes (20%).

(source: author's own)

Figure 23 John Deere 4045HF158 Testo 350 First Emissions Reading at 100% Load

3.16 Test Protocol John Deere 4045HFC09

The following test was conducted on the 4045HFC09 engine. The engine was attached to the Go Power Systems DT20000 engine dynamometer and placed into the test cell. The hoses were connected to the heat exchangers for cooling the coolant and charge air cooler and the DEF and fuel hoses were connected to the engine. The air temperature and humidity were again measured using the Testo 610 seen in Figure 24 and inputted into the Testo 350.

(source: author's own)

Figure 24 Testo 610 Used to Measure Air Temperature (˚C) and Humidity (%)

The same initial setup procedures for the Testo 885 and the Testo 350 on the 4045HF185 engine were replicated for the 4045HFC09. Prior to testing, the filters in the Testo 350 analyser were replaced to remove any contamination and improve accuracy in the measurements. The engine's coolant and oil levels were confirmed to be within the recommended operating range. Additionally, the seawater cooling pumps were activated, and the cooling circuit was purged of air via the manifold bleed point in the test cell to ensure consistent flow throughout the system. Once all preparatory steps were completed, the battery was connected to the engine and the engine was started. The engine speed was gradually increased to 1500 RPM using the John Deere engine controller in conjunction with the Go Power Systems DC 150-s electronic dynamometer interface shown in Figure 25.

(source: author’s own)

Figure 25 John Deere Controller and Go Power Systems DC 150-s Electronic Dynamometer Display

The engine was held at 1500 RPM under no-load for 20 minutes. This procedure resulted in a stabilised coolant temperature of 79 °C and an oil temperature of 90.6 °C. Exhaust temperature readings at the manifold and turbocharger were recorded as 235 °C and 206 °C respectively. These values were documented at the 0-minute interval to serve as baseline reference data prior to the commencement of the test.

Following pre-conditioning, the engine load was gradually increased to 100% of its rated capacity. Emissions and exhaust temperature data were subsequently recorded at one-minute intervals over a continuous 30-minute test duration. The first emissions reading under full-load conditions is presented in Figure 26. The engine was maintained at 100% load for 10 minutes, accounting for 30% of the total test period. The load was then reduced to 75% and held for 15 minutes (50% of the duration), followed by a final reduction to 50%, which was sustained for the remaining 6 minutes (20%) of the test.

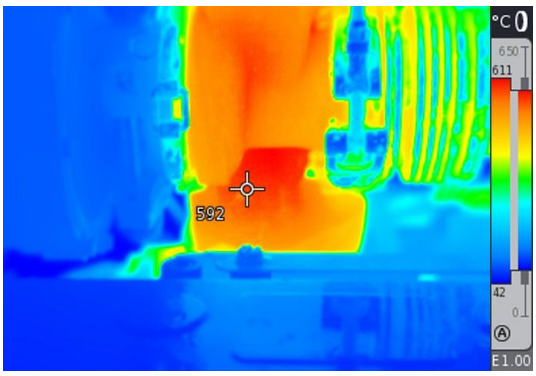
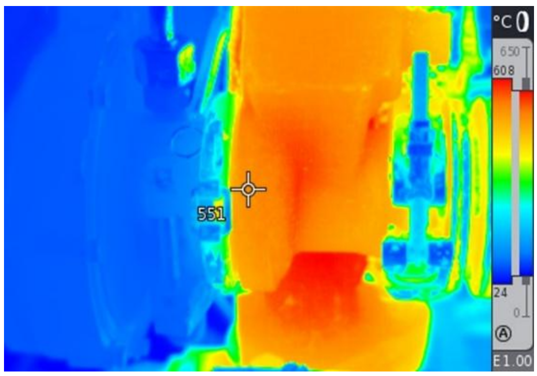
(source: author's own)

Figure 26 John Deere 4045HFC09 Testo 350 First Emissions Reading at 100% Load

3.17 Temperature Results

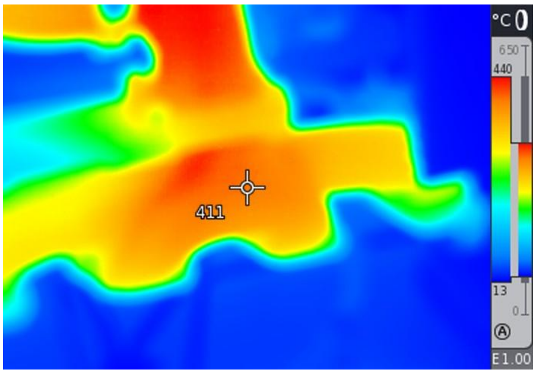
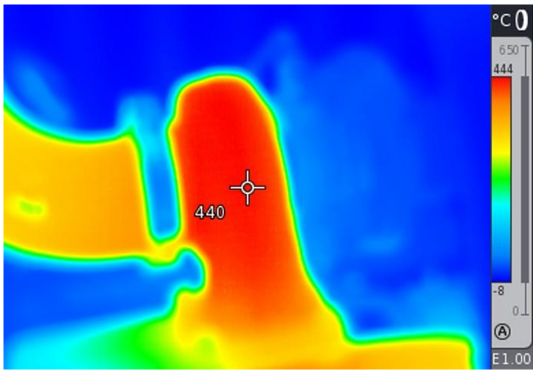
Table 11 and 12 shows the locations the temperature of the exhaust manifold and turbo were taken from throughout the 30-minute test on each engine. This location remained consistent to ensure repeatability in the measurements and eliminate any fluctuations in readings from hotter or colder points on the exhaust manifold or turbo.

Table 11 John Deere 4045HFC09 Exhaust Manifold and Turbo Temperature Reading Location

John Deere 4045HFC09	
Exhaust Manifold Temperature (˚C)	Turbo Temperature (˚C)
	

(source: author's own)

Table 12 John Deere 4045HF158 Exhaust Manifold and Turbo Temperature Reading Location

John Deere 4045HF158	
Exhaust Manifold Temperature (˚C)	Turbo Temperature (˚C)
	

(source: author's own)

For the 4045HFC09 and 4045HF158, the exhaust manifold and turbo heat were localised with a clear transition between the exhaust side and the intake side of the turbo, (identified by the transition in colour from red and orange to green and blue). From a performance perspective, this indicates correct thermal distribution as hot components reach target temperatures encouraging exhaust gas flow, while cooler areas (intake) remain cold. Cooler intake air increases density, improving cylinder charge according to research from Reif (2014).

3.18 Convert Emission Concentration Gas (ppm) to Specific Fuel Consumption (g/kWh)

Equations 1 to 3 show the formulas from Pilusa, Mollagee and Muzenda (2012) for converting emission gas concentrations from ppm and % to specific fuel consumption in g/kWh. These equations were used to calculate the average emission values in g/kWh over the 30-minute test period.

Equation 1 Conversion of CO in ppm to CO in g/kWh

$$CO(g/kWh) = 3.591 \times 10^{-3} \times CO(ppm)$$

Equation 2 Conversion of CO2 in vol % to CO2 in g/kWh

$$CO_2(g/kWh) = 63.470 \times CO_2(\text{vol }\%)$$

Equation 3 Conversion of NOx in ppm to NOx in g/kWh

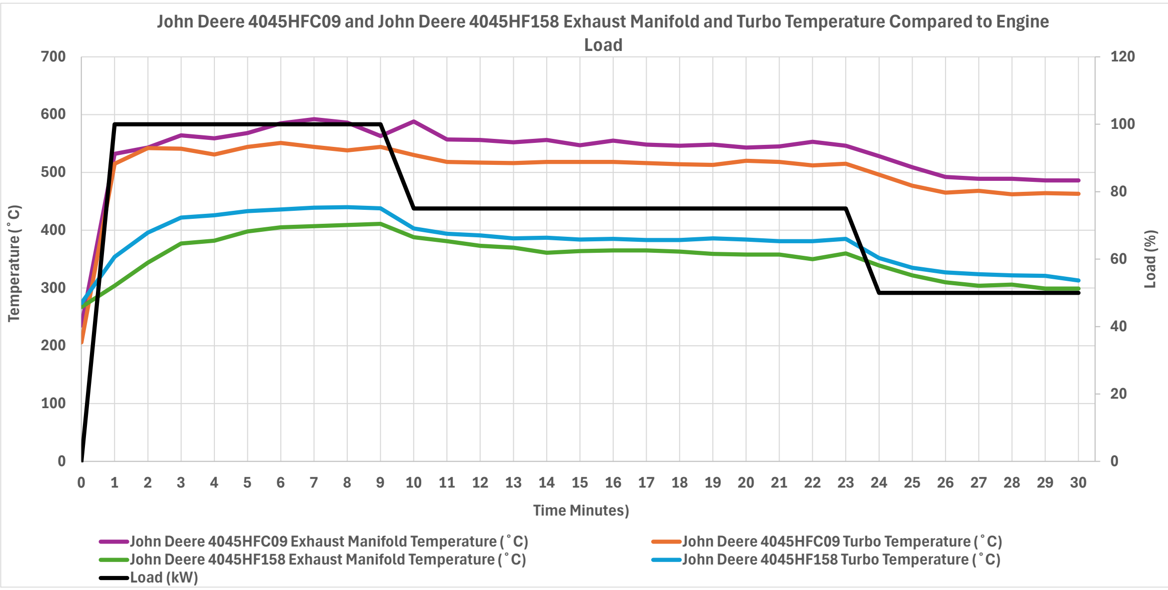
$$NO_x(g/kWh) = 6.636 \times 10^{-3} \times NO_x(ppm)$$

(source: Pilusa, Mollagee and Muzenda, 2012)

Chapter 4. Engine Test Results and Discussion

4.1 John Deere 4045HFC09 and 4045HF158 Exhaust Manifold and Turbo Temperature Compared to Engine Load

Figure 27 shows the exhaust manifold and turbo temperature compared to engine load for the 4045HFC09 and 4045HF158 across the 30-minute tests. Exhaust manifold and turbo temperatures were overall greater on the 4045HFC09 compared to the 4045HF158. The 4045HFC09 exhaust manifold temperature was greater than the turbo temperature across the duration of the duty cycle whereas on the 4045HF158, the turbo temperature remained greater than the exhaust manifold temperature. The results suggest the combustion temperatures on the 4045HFC09 was greater compared to the 4045HF158 (higher temperatures at the position closest to the combustion event). The reduction in temperature from the exhaust manifold to the turbo on the 4045HFC09 suggests greater heat dissipation through the twin turbo setup when compared to the temperature increase on the 4045HF158 with the single fixed turbo. Across the duration of the duty cycle for both engines, there was a correlation between increased loads resulting in increased exhaust and turbo temperatures.



(source: author's own)

Figure 27 John Deere 4045HFC09 and John Deere 4045HF158 Exhaust Manifold and Turbo Temperature (˚C) Compared to Engine Load

Table 13 shows the max, min and elevated average temperatures across all load conditions for the 4045HFC09. The 4045HF158 operated below the predicted exhaust temperatures at 355˚C as stated by Bundu Power (2025) who specified an exhaust temperature of 545˚C to 565˚C at 1500 RPM. This could have been the result of different environmental conditions.

Table 13 John Deere 4045HFC09 Compared to 4045HF158 Exhaust Manifold and Turbo Average Temperature (˚C)

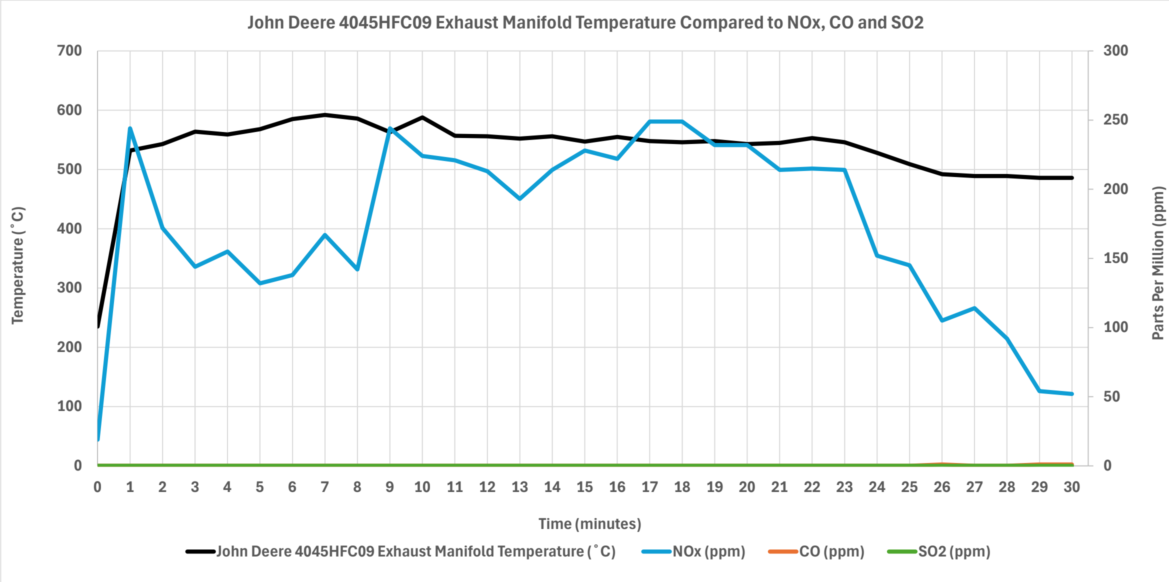
Load (%)	John Deere 4045HFC09			John Deere 4045HF158		
	Exhaust Manifold Temperature ˚C			Exhaust Manifold Temperature ˚C		
	Max	Min	Average	Max	Min	Average
100	**592**	**532**	566	**411**	**304**	382
75	**557**	**528**	553	**381**	**339**	365
50	**509**	**486**	497	**322**	**299**	311
Average Temperature ˚C (30 minutes)			534			355
Load (%)	**John Deere 4045HFC09**			**John Deere 4045HF158**		
	Turbo Manifold Temperature ˚C			**Turbo Manifold Temperature ˚C**		
	Max	**Min**	**Average**	**Max**	**Min**	**Average**
100	**551**	**515**	539	**440**	**354**	420
75	***520***	***496***	517	***394***	***352***	387
50	***477***	***462***	471	***335***	***313***	328
Average Temperature ˚C (30 minutes)			503			380

(source: author's own)

4.2 John Deere 4045HFC09 Exhaust Manifold Temperature, NOx, CO and SO_2

Figure 28 shows the relationship between exhaust manifold temperature, NOx, CO, and SO_2 for the 4045HFC09 during a 30-minute test cycle. The data indicates that NOx was the prominent exhaust emission throughout the duty cycle which agrees with findings from Reşitoğlu, Altinişik and Keskin (2015). An initial NOx peak of 244 ppm was observed at the 1-second interval, after which levels decreased up to the 8-second interval, coinciding with 100% load and rising exhaust temperatures. Between the 8 and 23 second intervals at 75% load, NOx levels increased and remained relatively high. This trend supports findings from Mera *et al*. (2021) who reported that SCR systems exhibit better NOx conversion efficiency at higher engine loads (100%) compared to lower loads (75%), shown through research into motorway versus urban driving conditions.

From the 23 to 30 second interval at 50% load, the exhaust manifold temperature decreased alongside a reduction in NOx levels. The average NOx concentration over the 30-minute test was 174 ppm. Throughout the entire duty cycle, CO and SO_2 concentrations remained extremely low with SO_2 consistently reading 0 ppm and CO registering 1 ppm at only three intervals (all at 50% engine load). A reasonable conclusion is that while trace amounts of SO_2 and CO may have been present, their concentrations were below the detection threshold of the Testo 350 analyser because of the DOC removing CO with the use of excess oxygen.

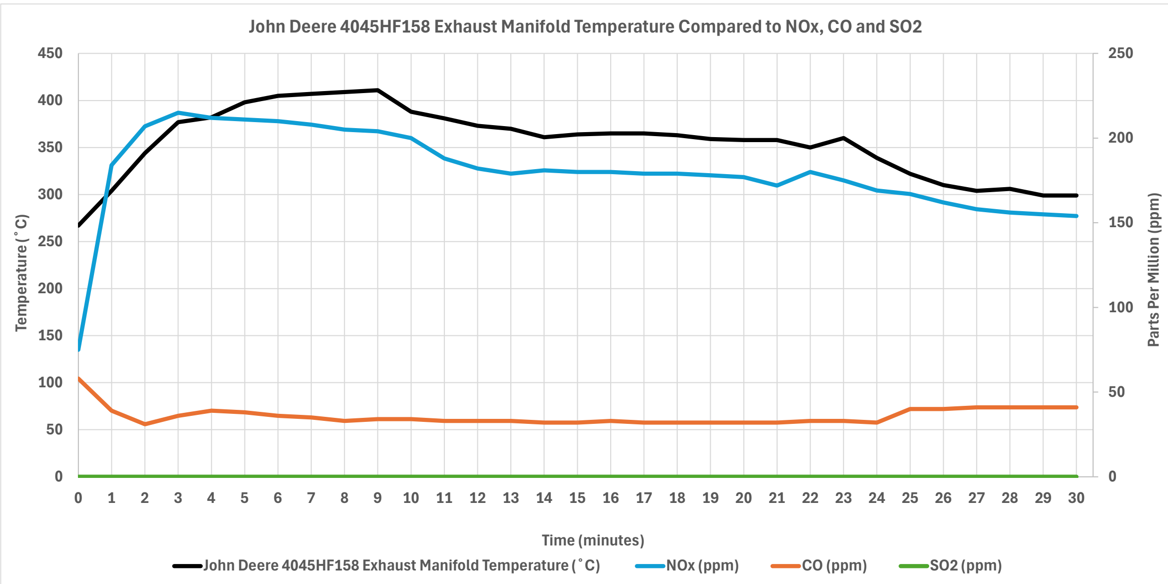


(source: author's own)

Figure 28 John Deere 4045HFC09 Exhaust Manifold Temperature (˚C) Compared to NOx, CO and SO2

4.3 John Deere 4045HF158 Exhaust Manifold Temperature, NOx, CO and SO_2

Figure 29 shows the relationship between exhaust manifold temperature on the 4045HF158 and NOx, CO and SO_2 outputs across the 30-minute test. As previously mentioned, the exhaust manifold temperature was lower across the duty cycle compared to the 4045HFC09. The relationship between the temperature and the NOx output remained more consistent and followed a steadier trend, (as exhaust manifold temperature increased or decreased, NOx levels changed accordingly). Although the NOx levels were overall more consistent, the NOx on average across the test was overall higher at 180 ppm. Regardless of engine load and fluctuating exhaust manifold temperatures, the CO ppm remained relatively consistent and higher than the 4045HFC09. SO_2 had a reading of 0 ppm.

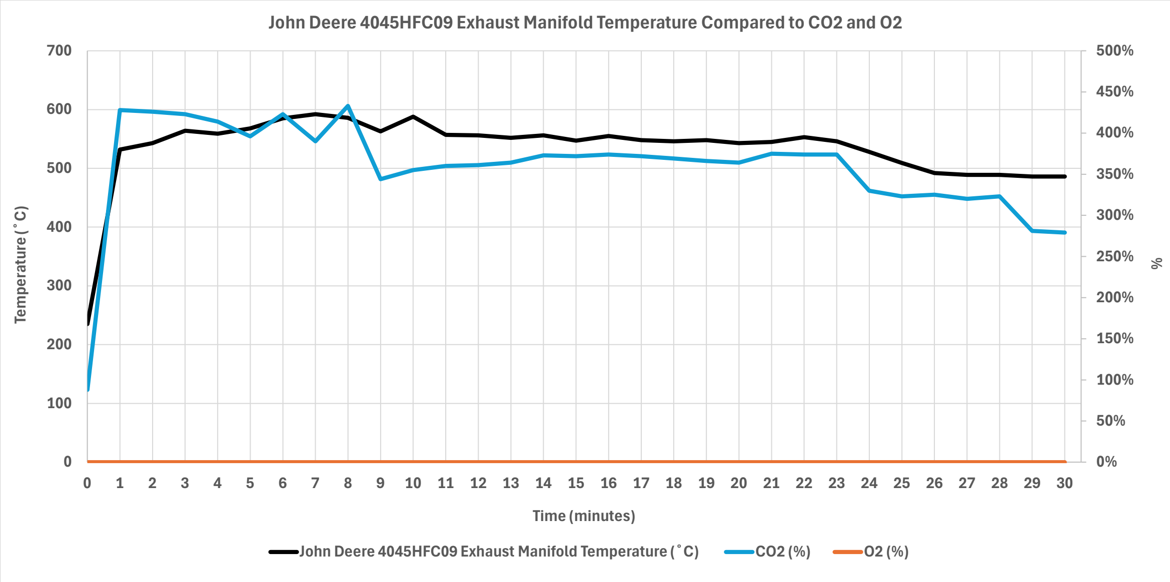


(source: author's own)

Figure 29 John Deere 4045HFC09 Exhaust Manifold Temperature (˚C) Compared to CO2 and O2.

4.4 John Deere 4045HFC09 Exhaust Manifold Temperature, CO_2 and O_2

Figure 30 shows the relationship between exhaust manifold temperature on the 4045HFC09 and CO_2 and O_2 output across the 30-minute test. Throughout the test there were no traces of any O_2 which could be result of levels being either at 0 or so low the Testo 350 couldn't not detect any O_2. A conclusion for this supported by York and Tsolakis (2010) is that the excess oxygen present in the exhaust stream is largely consumed by the SCR and DOC during the oxidation of CO and HC. This results in very low concentrations of O_2 at the tailpipe outlet likely due to complete oxidation within the aftertreatment system. Had measurements been taken upstream, traces of O_2 may have been detected. CO_2 was present throughout the 30-minute test, resulting from DOC-facilitated oxidation of CO, HC, and NO. The trend mirrored that of NO_x, rising with increased load and exhaust manifold temperature. Notably, CO_2 levels fluctuated during the first 9 seconds at 100% load, with an average concentration of 358% across the test duration (Table 14).

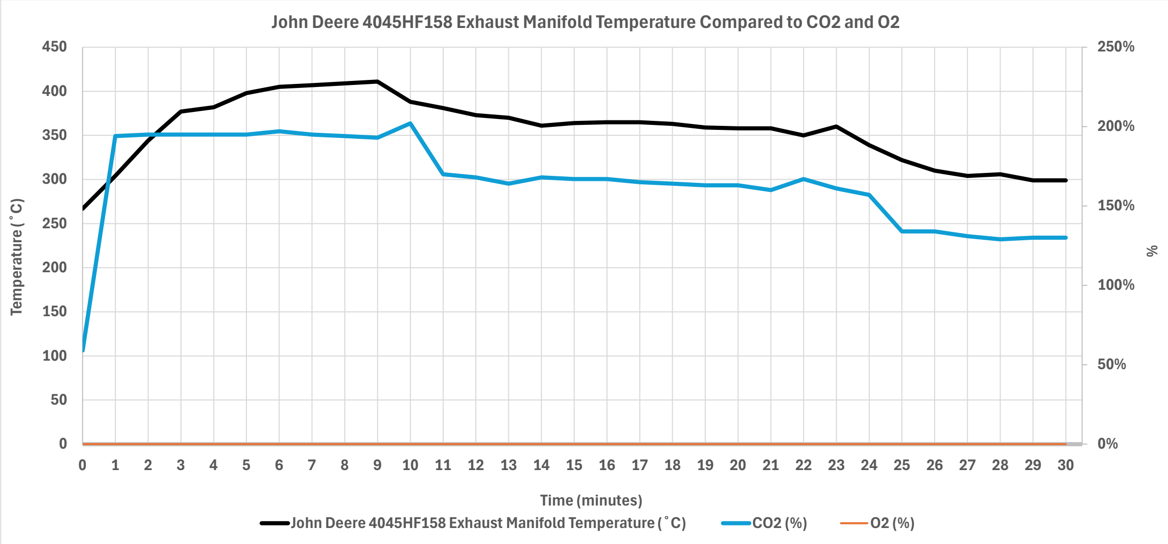


(source: author's own)

Figure 30 John Deere 4045HFC09 Exhaust Manifold Temperature (˚C) Compared to CO2 and O2.

4.5 John Deere 4045HF158 Exhaust Manifold Temperature, CO_2 and O_2

Figure 31 shows exhaust manifold temperature on the 4045HF158, CO_2 and O_2 output across the 30-minute test. The O_2 levels were at 0% across the 30-minute test. The levels were either at 0% or too low for the Testo 350 to detect suggesting the combustion event was relatively efficient, using most to all the oxygen in the combustion event, converting it into CO_2 and H_2O. Analysing the CO_2 levels shows an initial steep incline from 0% to 100% load, which then plateaus and remains consistent at approximately 200% until the load is decreased to 75% at the 9 to 10 second interval where there is a sudden peak due to the mechanical fuel pump injecting less fuel in response to less demand. This characteristic was less noticeable with the electronically controlled common rail 4045HFC09. From 11 seconds the CO_2 levels followed a similar trend to the exhaust manifold temperature, decreasing simultaneously with the load. Another peak in CO_2 occurred when the load was reduced from 75% to 50%. This peak could also be seen with temperature increasing. The average CO_2 output over the 30-minute test was 166%, notably lower than that of the 4045HFC09, primarily due to the absence of a DOC and the resulting lack of CO oxidation to CO_2 causing the higher CO and lower CO_2 levels observed in agreement with findings from York and Tsolakis, (2010).



(source: author's own)

Figure 31 John Deere 4045HF158 Exhaust Manifold Temperature (˚C) Compared to CO2 and O2

4.6 30 Minute Test Average Temperatures

Table 14 shows a comparison of the average CO_2, NOx and CO levels for the 4045HFC09 and 4045HF158 for each of the different engine loads and the overall 30-minute test. The results show an overall higher average CO_2 percentage and a lower overall average NOx level and a CO level on the 4045HFC09.

Table 14 John Deere 4045HFC09 and 4045HF158 Exhaust Gas Analysis

Load (%)	John Deere 4045HFC09	John Deere 4045HF158	John Deere 4045HFC09	John Deere 4045HF158	John Deere 4045HFC09	John Deere 4045HF158
	CO_2 (%)		NOx (ppm)		CO (ppm)	
	Average		Average		Average	
100	409%	195%	171	206	0	36
75	368%	168%	223	181	0	33
50	312%	135%	102	160	0.43	39
Average vol% / ppm (30 minutes)	358%	165%	174	180	0	36
Average g/kWh (30 minutes)	227	105	1.15	1.19	0	0.13

(source: author's own)

Table 15 and 16 display the average emissions for the 4045HFC09 and 4045HF158 for each of the rated loads during the 30-minute test compared to exhaust manifold and turbo temperatures. For both engines there is a correlation between high loads and high average exhaust temperatures and an increase in CO_2 production. For the 4045HFC09, the highest average NOx level was at 75% load when exhaust and turbo temperatures were at their mid-range temperature. NO_x levels were lowest at 100% load, when the exhaust manifold and turbocharger temperatures were at their highest, and highest at 50% load, when the exhaust and turbo temperatures were at their lowest.

Table 15 John Deere 4045HFC09 Average Exhaust Emissions Compared to the Average Exhaust Manifold Temperature and Turbo Temperature (˚C)

John Deere 4045HFC09							
Load (%)	Exhaust Manifold Temperature ˚C	Turbo Manifold Temperature ˚C	CO_2 (%)	O_2 (%)	NOx (ppm)	CO (ppm)	SO_2 (ppm)
	Average						
100	566	539	409%	0%	171	0	0
75	553	517	368%	0%	223	0	0
50	497	471	312%	0%	102	0.43	0
Average Temperature ˚C (30-minutes)	534	503					
Average vol% / ppm (30 minutes)			358%	0%	174	0	0
Average g/kWh (30 minutes)			227	0%	1.15	0	0
High							
Medium							
Low							

(source: author's own)

NO_x emissions were highest on the 4045HF158 at 100% load, corresponding with peak exhaust and turbocharger temperatures. As engine load and temperatures decreased, NOx levels also declined. In contrast, the 4045HFC09 equipped with EGR, SCR and AOC consistently demonstrated lower NO_x emissions while maintaining higher power and torque output, highlighting the effectiveness of its advanced aftertreatment system.

The most significant difference observed in the test results between the two engines was the concentration of CO in the exhaust gases. The CO levels remained consistently close to 0 ppm throughout the entire test cycle on the 4045HFC09 due to the presence of the DOC which facilitates the oxidation of CO into CO_2 via a catalytic reaction, using the DOC's platinum coating and the available O_2 in the exhaust stream.

In contrast, the 4045HF158 engine, which does not use a DOC, produced measurable CO levels, peaking at 39 ppm under 50% load, coinciding with the lowest recorded exhaust and turbocharger temperatures. As load increased, CO concentrations declined to 36 ppm at 100% load and 33 ppm at 75% load, reflecting more complete oxidation due to elevated combustion temperatures. These results emphasise the importance of thermal energy in enhancing combustion efficiency and minimising pollutant formation under variable loading conditions.

Table 16 John Deere 4045HFC158 Average Exhaust Emissions Compared to the Average Exhaust Manifold Temperature and Turbo Temperature (˚C)

John Deere 4045HF158							
Load (%)	Exhaust Manifold Temperature ˚C	Turbo Manifold Temperature ˚C	CO_2 (%)	O_2(%)	NOx (ppm)	CO (ppm)	SO_2 (ppm)
	Average						
100	382	420	195%	0%	206	36	0
75	365	387	168%	0%	181	33	0
50	311	328	135%	0%	160	39	0
Average Temperature ˚C (30-minutes)	355	380					
Average vol% / ppm (30 minutes)			165%	0%	180	36	0
Average g/kWh (30 minutes)			105	0%	1.19	0.13	0
High							
Medium							
Low							

(source: author's own)

The overall average NOx levels were lower on the 4045HFC09 compared to the 4045HF158. However, referring to previous research from Deere (2023) and Woodyard (2009) in the literature review, higher combustions temperatures resulted in higher NOx levels. Research from Sun *et al*. (2023) in contrast suggested NOx conversion rate when Ammonia (DEF) reacted with NOx was at a lower efficiency at lower exhaust temperatures. It is clear in the tests that exhaust temperature was sufficiently high for an efficient reaction to take place which was shown in Lower NOx levels on the 4045HFC09 with the use of the SCR cannister and DEF.

Figure 32 presents ECU data from the 4045HFC09, including temperatures at the DOC inlet and outlet, SCR inlet, and exhaust manifold over the 30-minute test. Compared to the temperature measurements from the Testo 885, the ECU was able to take readings from a variety of places on the exhaust system which would not be possible without having more Testo equipment. The exhaust manifold temperature recorded by the ECU was higher at 100% load than that recorded by the Testo. The DOC inlet temperature remained relatively stable, while the DOC outlet and SCR inlet temperatures steadily increased. Despite some variation in absolute values, both the Testo and ECU data exhibited similar trends. Up to 800 seconds at 100% load, the exhaust manifold remained the hottest section. From 1400 seconds (23 minutes) at 50% load, the DOC outlet and SCR inlet temperatures plateaued as the exhaust manifold temperature declined, suggesting the aftertreatment system retained sufficient thermal energy to sustain catalytic activity, consistent with findings by Jääskeläinen (2024).

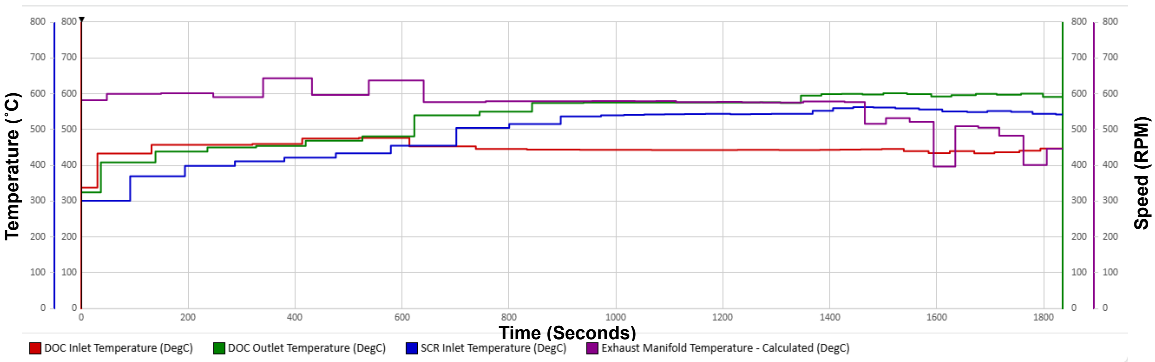


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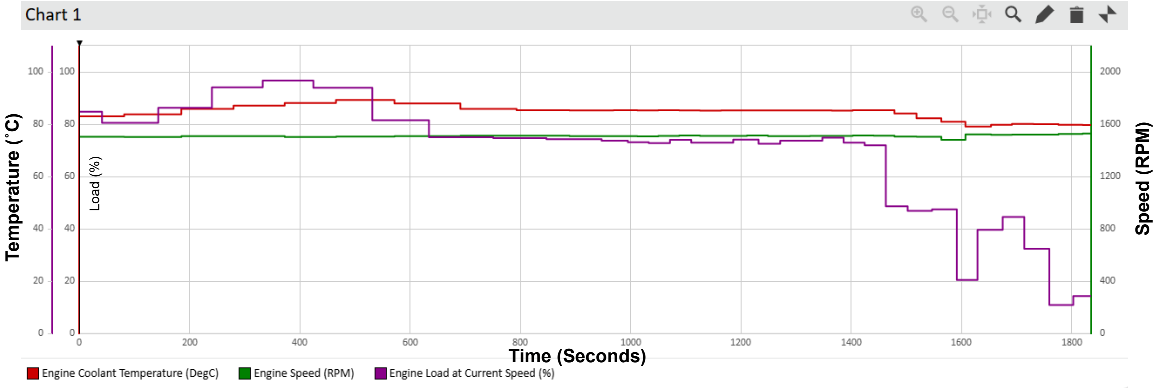
Figure 32 John Deere 4045HFC09 ECU Recorded Exhaust Temperature (˚C) Data

Figure 33 shows the ECU data for the coolant temperature, engine speed and Load on the 4045HFC09. The engine speed remained stable at 1500 RPM throughout the 30-minute duty-cycle. The coolant temperature also remained relatively stable, reducing slightly as expected with reducing load. The load did however slightly fluctuate throughout the test but remained close to the 100%, 75% and 50% as set. This fluctuation was unavoidable and was determined by the dynamometer.



(source: author's own)

Figure 33 John Deere 4045HFC09 ECU Recorded Coolant Temperature (˚C), Speed (RPM) and Load (%) Data.

Chapter 5. Conclusion

The study aimed to find the 'Impact of Exhaust Gas Emissions Legislation in Relation to Exhaust Temperatures' and demonstrated a comparative analysis of the thermal and emissions performance characteristics of the John Deere 4045HFC09 and 4045HF158 diesel engines under a controlled 30-minute duty cycle in line with BS ISO 8178-2:2021. The tests focused on exhaust manifold and turbo temperatures in relation to key regulated emissions including NOx, CO, SO_2, CO_2 and O_2.

The results indicate that the 4045HFC09, equipped with an ECU and common rail fuel injection system, twin turbochargers, and aftertreatment including DOC, DPF, SCR, AOC and DEF consistently operated at higher exhaust temperatures than the 4045HF158. This elevated thermal profile resulted in more complete combustion and improved emissions control performance, particularly in reducing NO_x and CO concentrations. The findings from a study by Zhao *et al*. (2023) agree with this and higher temperatures resulted in better SCR conversion efficiencies. In contrast, the 4045HF158 with a mechanical fuel system and single turbocharger demonstrated lower overall thermal efficiency and higher NO_x and CO outputs, particularly at intermediate to lower loads with lower thermal conditions.

A key finding is the effectiveness of the aftertreatment system in the 4045HFC09 in reducing NOx emissions, even at high combustion temperatures through effective thermal management and catalytic conversion. The DOC effectively oxidised CO into CO_2 as predicted by Ramalingam and Rajendran, (2019), evidenced by near-zero CO measurements across the test cycle. Furthermore, higher CO_2 concentrations on the 4045HFC09 align with what is expected with complete combustion. In contrast, the 4045HF158 with no aftertreatment resulted in significantly higher CO emissions, particularly at reduced loads and cooler combustion conditions.

Data collected via the ECU complemented the thermographic measurements, revealing insights into thermal storage and distribution throughout the exhaust and aftertreatment system. The thermal rise at the DOC outlet and SCR inlet, even as engine load decreased, confirms sustained catalytic activity highlighting the importance of thermal retention essential for efficient NO_x reduction.

In conclusion, the 4045HFC09 demonstrated improved emissions performance and thermal efficiency due to its advanced aftertreatment and electronic control systems. This underscores the significance of maintaining optimal heat distribution to maximise catalytic activity and reduce emissions across varying load conditions. The results contrast with those of Vetus, (2025) who use seawater injection to cool exhaust gases, potentially reducing aftertreatment efficiency. This highlights the critical role of integrated emission control strategies in meeting increasingly stringent global diesel emission standards, such as Stage V, while maintaining performance across different applications.

This study improves the understanding of the relationship between exhaust temperature, emissions control, and thermal management in modern diesel engines in the context of meeting evolving global emission standards. The findings show the need for the continued development of emission control technologies which has potential to significantly influence the design of future engine systems and ensure compliance with increasingly stringent regulations. Ultimately, this research addresses a gap in knowledge regarding the crucial role of thermal management, providing insights that can guide the next generation of diesel engine design and emissions strategies.

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Appendices

Appendices 1: Ethics Form

Project Summary

View Summary PDF

Version: 01
Last updated: 14:12 Wednesday, 29 January 2025
Status: Approved (Proportionate) *(Your research ethics form has been approved)*

- Section A
- Section B: Project Objectives
- Section C1: Data
- Section C2: Place of Research
- Section C3: Research Involving People
- Section C4: Research Involving Animals or Animal By-products
- Section C5: Impacts on the Environment
- Section D: Research Ethics and The Prevent Duty
- Section E: Supporting Documents
- Section F: Sponsors and Collaborating Organisations

Version history

V01 Proportionate Review

29/01/25 Approved (Proportionate)

10/12/24 Supervisor Review

Graham Higginson Approval of Proportionate Review.

05/12/24 New

Appendices 2: Company Consent Form

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10th December 2024

To whom it may concern,

We at McCooey Engineering t/a ML Power Systems give Edward Esden permission to use our test cell facilities for his dissertation research. If you have any questions, please feel free to contact me. My details are below.

Yours sincerely,

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