# Reduction of emissions at Scania Engine Assembly

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The project was carried out in cooperation with Scania CV AB.

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# Abstract

This master thesis is carried out in collaboration with the company Scania which is a provider of transport solutions. The thesis is carried out at Scania's production unit Engine Assembly where engines are assembled, tested and painted. All engines proceed through a standard test procedure while some of the engines also proceed through special test procedures carried out in the "Audit Area". The special test procedures are the focus of this report. The special test procedures are called Conformity of Production-tests (COP) and Quality Assurance-tests (QA). COP-tests are needed to show that the products are in conformance with relevant administrative provisions and technical requirements that are regulated by law. QA-tests are needed in order for Scania to know that their products have the right quality and characteristics. These tests are currently carried out with mainly fossil diesel. The possibility to use alternative fuel during the tests and thus reduce the emissions from the Audit Area is analyzed in the report.

The thesis project is divided into four parts. The first part includes investigation regarding what alternative fuel that is technically possible to use. This is done by gaining information regarding engines and fuels and by performing three experiments on one engine type. The second part includes deriving the yearly emission reductions of tailpipe $CO_2$ and life cycle $CO_2$e related to changing the fuel-use. This is done by estimating the fuel consumption of the relevant tests over one year as well as finding the emission factors for the fuels that are currently used as well as for the alternative fuel. The third part includes evaluating the availability of the alternative fuel by performing a literature study. The last part includes finding the physical modifications needed to change the fuel-use, this is done by observations and communication with relevant Scania employee.

It is concluded that the fuel that is technically possible to use in as many engine as possible is the renewable diesel Hydrotreated Vegetable Oil, HVO. However, the COP- and QA-tests consist of different parts and not all of the parts are legally or technically possible to run with HVO. The experiments give varying results and show that it is important to further evaluate the technical possibility of running parts of the tests with HVO.

The results show that the yearly fossil tailpipe $CO_2$ -emission reductions could be almost 75 % when changing the fuel-use. The LCA $CO_2$e -emission could be reduced by 47-64 % when changing the fuel-use. However, these emission reductions are based on a best-case scenario which might be somewhat optimistic considering the number of parts of the test that can be run with HVO. For that scenario to be possible it might require changes to test-layouts, further experimenting and further studies. Regarding the availability of HVO the literature study shows that the future availability of HVO is somewhat unclear and needs to be further looked into if this change in fuel-use is implemented. Lastly, the modifications needed for changing the fuel-use are mainly related to fuel storage and fuel supply-system.

# Preface

This master thesis concludes the five year Environmental Engineering program with specialisation in Energy Systems at Lund University — Faculty of Engineering. I would like to take this opportunity to express my gratitude to my supervisor Martin Andersson, Associate Professor at the Department of Energy Sciences. I would also like to express my gratitude to Scania Engine Assmebly and especially to Anna Granqvist, Sonia Sivadasan, Anders Ingeström and Goce Peovski as well as to all employees in DETF and DEQA for their support and answers to my many questions.

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# Acronyms, Abbreviations and Nomenclature

## List of Acronyms and Abbreviations

**COP** = Conformity of production

**QA** = Quality Assurance

**ICE** = Internal combustion engine

**CI-engine** = Compression ignition engine

**DOC** = Diesel oxidation catalyst

**DPF** = Diesel particulate filter

**SCR** = Selective catalytic reduction

**BD1** = Baseline diesel 1

**BD2** = Baseline diesel 2

**WTW** = Well-to-wheel

**WTT** = Well-to-tank

**FIA** = Fuel injection adaptation

# Nomenclature list

**Energimyndigheten** = The Swedish Energy Agency in Swedish

**Transportstyrelsen** = The Swedish Transport Agency in Swedish

**Engine-out emissions** = Emissions upstream of aftertreatment system

**Tailpipe emissions** = Emissions downstream of aftertreatment system

**Reference case** = The case where only BD1 and BD2 are used

**HVO case** = The case were BD1, BD2 and HVO are used

**Baseline diesel** = The diesel currently used at the Audit Area

**”Kundkörningar”** = ”Customer runs”

**”Referensmotorer”** = ”Reference engines”

# Chapter 1

# Introduction

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*This first chapter gives the background and objective of this master thesis as well as an introduction to the company Scania.*

---

This degree project is carried out in collaboration with the company Scania CV AB (Scania). Scania was founded in Sweden 1891 and is a world-leading provider of transport solutions. Scania develops and delivers trucks and buses for heavy transport applications as well as marine and industrial engines. The company has 50 000 employees in about 100 countries. In 2014 Scania became wholly owned by Volkswagen Group. Scania's head office, parts of the company's production and the main part of the company's research and development activities are located in Södertälje, Sweden. (Scania CV AB n.d.[c])

The project is carried out at the production unit Engine Assembly in Södertälje, in a group called DETF. At Engine Assembly engines are assembled, tested and painted. DETF is responsible for the "final flows" at the Engine Assembly. These flows include testing procedures, repairing (if needed) and painting of the engines. All engines proceed through a standard test procedure while some of the engines also proceed through test procedures in the "Audit Area". The test procedures in the Audit Area will be the focus of this master thesis.

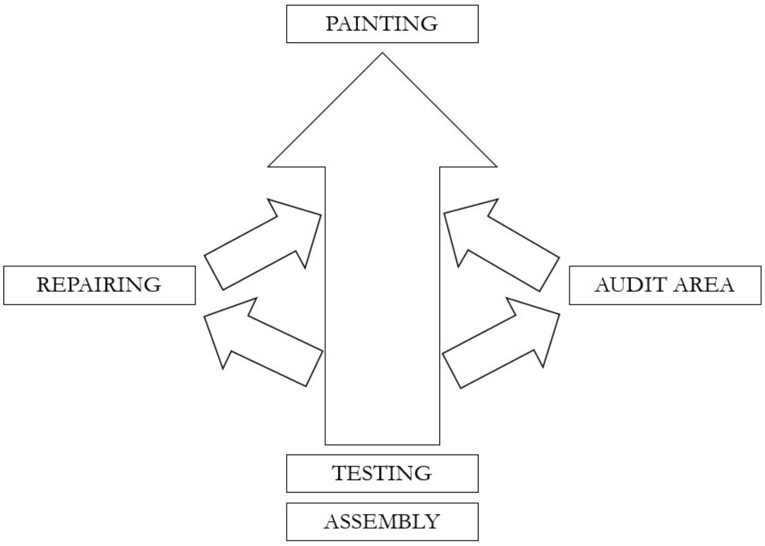

**Figure 1.1:** Schematic view over the flows at the Scania unit Engine Assembly.

Conformity of Production (COP)-tests and Scania internal Quality Assurance (QA)-tests are carried out on the engines in the Audit Area. COP-tests are required by law, and the number of COP-tests per engine type that a manufacturer has to do is regulated by law. The purpose of the COP-tests is to ensure that a vehicle or a component type meets the applicable EU-regulated technical requirements and thus can be granted with a type approval certificate. A type approval certificate is granted by an approval authority and shows that a type of vehicle, component, etcetera satisfies the relevant administrative provisions and technical requirements. (European Commission 2018) The approval authority in Sweden is the Swedish Transport Agency (in Swedish: Transportstyrelsen) (Transportstyrelsen 2021). The QA-test is carried out due to Scania internal quality standards. COP and QA are often performed at the same time and COP is a subset of QA. The test plans varies depending on engine.

What is equal for all engines is that when performing the tests the engines are running for hours in order to get into the correct conditions needed to perform the required measurements. A majority of the engines are currently running on fossil fuels. Engines consuming fuel for hours cause emissions. The possibilities to reduce these emissions will be the topic of this master thesis.

## 1.1 Aim

The main reason for the objective of this master thesis is Scania's work with sustainability:

> *"Scania's purpose is to drive the shift towards a sustainable transport system, creating a world of mobility that is better for business, society and the environment."* (Scania CV AB n.d.[a])

Scania has set three priorities in order for the company to be able to operate sustainable in the future: decarbonisation, circular business and people sustainability (Scania CV AB n.d.[d]). This master thesis is focused on Scania's work with reducing emissions from Scania's own operations.

The objective is to investigate the possibilities of reducing the environmental impact caused by emissions from the engines tested in Scania's Audit Area test cells by replacing parts of the consumption of fossil fuels with consumption of alternative fuels during the tests. The aim is to provide the Audit Area with a recommendation of what alternative fuel(s) to use as well as information regarding the emission savings when changing the fuel-use, the availability of the alternative fuel(s) and the physical modifications needed when changing the fuel-use. Within Scania this kind of project is a part of a "pre-study" being the first step in the procedure of implementing a change. The purpose of a pre-study is to give an indication of the advantages, disadvantages and meaningfulness of implementing the change.

### 1.1.1 Research questions

These questions will be the focus of this master thesis:

1. *What alternative fuel(s) are technically possible to use during running time?*
2. *What are the expected yearly emission savings when using alternative fuel(s)?*
3. *How is the future availability, and price development, of the alternative fuel(s)?*
4. *What are the modifications needed when changing the fuel use?*

## 1.2 Focus, delimitations and assumptions

- The main focus of environmental impact is that related to global warming. Thus principally only emissions of $CO_2$e will be considered, although some other emissions will be mentioned briefly. This means that environmental impact related to for example acidification, eutrophication, land use change or resource depletion will be excluded.
- The time for this project is limited to around 20 weeks.
- The focus is on Scania's operations in Södertälje, Sweden.
- The engine efficiency is assumed indifferent to the fuel that is used. This means the same energy amount of fuel is needed for the same engine work output for all fuels included in this project.
- For some of the LCA-values for FAME/RME the fuel is considered to have one fossil carbon atom for each 18C-carbon chain, for example for the LCA value taken from Hallberg et al. (2013). In the calculations for tailpipe $CO_2$ -emissions all carbon atoms in FAME/RME are considered biogenic. However this variation has negligible impact on the overall results of this project.
- Since the fuels that are currently used in the Audit Area are special certification fuels their prices are not published publicly. An analysis over the current and future price of those fuels is not included in this report.
- Regarding the tailpipe $CO_2$ -emission factors all carbon atoms are assumed to leave the engine as $CO_2$ .

## 1.3 Outline

The chapters in this report include the following:

- Chapter 2, *Background*: This chapter gives a background to the engines tested in the Audit Area and the emissions related to those engines. Also the COP and QA-tests are described.
- Chapter 3, *Methodology*: This chapter gives a description of the methods used in order to find the answers to the research questions.
- Chapter 4, *Findings from case study and literature study*: This chapter gives findings related to fuels, emission factors, availability and price as well as physical modifications needed when changing the fuel-use.
- Chapter 5, *Results*: This chapter gives the results from the three experiments as well as the results regarding fuel consumption and emissions for the reference case and the alternative fuel case.
- Chapter 6, *Discussion*: In this chapter the results presented in section 4 ”Findings from case study and literature study” and section 5 ”Results” are further analysed and discussed.
- Chapter 7, *Conclusions and recommendations*: In this chapter the main results are concluded and suggestions for improvements and future work are presented.

# Chapter 2

# Background

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*This chapter gives a background to the engines tested in the Audit Area and the emissions related to those engines. Also the COP and QA-tests are described.*

---

## 2.1 Engines in Audit Area

Scania's engines are produced with the configuration 5 or 6 cylinders in-line or V8, with displacement volumes ranging from 7 to 16 liters. Scania produces engines that can run on diesel, gas or ethanol. The engines are produced to be used in heavy duty vehicles (buses and trucks), in industrial applications, in power applications or in marine applications. (Scania CV AB n.d.[b]) This project includes engines that run on diesel. The engines also differs depending on the rated power. Two engines with the same displacement volume can have different power ratings. The engines are divided into engine families and within each engine family there are engine types. One engine family can for example be a 7 liter in-line diesel engine, called DC 07. One engine type within that engine family could be a DC 07 with a specific rated power.

### 2.1.1 Compression ignition engine

The diesel engine is an internal combustion engine (ICE) and more specifically a compression ignition engine. The diesel engine is often referred to as CI-engine or diesel-engine. In ICEs chemically bound energy in a fuel is used to generate mechanical work. The fuel is combusted in the engine cylinders and the energy within the fuel is converted into heat which causes the expansion that is needed in order for the ICE to function. (EERE 2007) In the CI-engine the fuel is combusted through the following process: air is compressed to high pressure and high temperature, small amounts of fuel is injected into the air and the fuel in the air reaches its auto-ignition temperature and auto-ignites. (Jääskeläinen and M. K. Khair 2021)

### 2.1.2 Emissions from CI-engines

Most fuels used in ICEs are forms of hydrocarbons (sometimes also containing some oxygen), with one exception being hydrogen, $H_2$. When hydrocarbon fuels is combusted with pure oxygen ( $O_2$ ) the fuel is converted into carbon dioxide ( $CO_2$ ) and water ( $H_2O$ ). However the fuel is most often combusted with air instead of oxygen and the combustion process is never perfect and complete. Consequently the combustion process will result in more products than $CO_2$ and $H_2O$ . In the following the products formed in the combustion process of an ICE are presented, with special focus on the CI engine. Also the methods that can be used in order to reduce how much of these products that leave the engine as tailpipe exhaust emissions are presented. Below the combustion reaction (2.1) when hydrocarbon fuel is combusted in air is shown, where $\mathrm{n_p}$ is number of product moles. Particle matter is excluded in the reaction. (Majewski and Jääskeläinen 2012)

$$\begin{gathered}\mathrm{C}_a\mathrm{H}_b\mathrm{O}_c + \lambda \mathrm{n}_{\mathrm{O_2},\gamma}(\mathrm{O_2} + 3.773\,\mathrm{N_2}) \\ \longrightarrow \\ \mathrm{n}_p(\mathrm{x}_{\mathrm{C_aH_bO_c}}\mathrm{C}_a\mathrm{H}_b\mathrm{O}_c + \mathrm{x_{CO_2}CO_2} + \mathrm{x_{H2O}H_2O} + \mathrm{x_{CO}CO} + \mathrm{x_{H2}H_2} + \mathrm{X_{O2}O_2} + \mathrm{x_{N2}N_2} + \mathrm{x_{NO_x}NO_x}^{+}\, \mathrm{x_{N_2O}N_2O})\end{gathered} \tag{2.1}$$

### $CO_2$

$CO_2$ is formed after a chemical reaction between carbon and oxygen. $CO_2$ is a greenhouse gas. The presence of $CO_2$ in the atmosphere will trap heat in the atmosphere and contribute to global warming. There is a factor called global warming potential (GWP) that was developed in order to enable comparison of the global warming impact of different gases. GWP is a relative value and gives information of the global warming impact of a gas relative to the global warming impact of the same amount of $CO_2$ , most commonly over a time period of 100 years. (United States Environmental Protection Agency 2021) The GWP of $CO_2$ is 1 (Greenhouse Gas Protocol n.d.).

Basically, the three ways in which $CO_2$ -emissions can be reduced are the following:

1. Decreasing the fuel consumption for the same work output by increasing the engine efficiency. Since the amount of $CO_2$ -emissions are proportional to the amount of fuel used less $CO_2$ will be formed. (Majewski and Jääskeläinen 2012)
2. The more hydrogen per carbon in a hydrocarbon fuel the more energy release on combustion. Thus, by using fuels with a high hydrogen to carbon ratio less $CO_2$ per fuel energy will be released. (Gopalakrishnan et al. 2019)
3. By using fuels based on bio-components. The amount of $CO_2$ emitted from the engine might be just the same as when using fuels based on fossil components. But since the carbon cycle time is shorter for carbon origin from bio-components, the emissions of biogenic $CO_2$ are considered carbon neutral and the emissions of $CO_2$ are reported as zero. (Energimyndigheten 2021d, p. 17)

### $NO_x$

$NO_x$ is short for nitric oxide ( NO ) and nitrogen dioxide ( $NO_2$ ). $NO_x$ is mainly formed from the reaction of $O_2$ and nitrogen ( $N_2$ ) from air under high temperatures. Thus fuelling an engine with only oxygen would eliminate the emissions of $NO_x$ , although it is hardly possible due to high economical costs of pure oxygen. $NO_x$ contributes to acidification of lakes leading to environmental issues. $NO_x$ also contributes to tropospherical ozone and smog causing damage to human health. Often exhaust after-treatment technology is necessary in order to keep $NO_x$ -emissions down. One common technology, also being the one that is used at Scania's Audit Area, is the selective catalytic reduction (SCR). The SCR reduces $NO_x$ into $N_2$ and $H_2O$ by the use of a catalytic surface as well as a reductant that is added upstream of the catalyst. Often the reductant is urea. (DieselNet 2020) (Majewski and Jääskeläinen 2021)

### HC and CO

Unburned hydrocarbons ( HC ) and carbon monoxide ( CO ) result from incomplete oxidation of fuel. HC includes also methane ($CH_4$ ) which is a green house gas. (DieselNet 2020) GWP for $CH_4$ is 28 (Greenhouse Gas Protocol n.d.). The exhaust gases from diesel engines exhaust contains very low levels of HC and CO and almost all of the HC and CO are then oxidized over the diesel oxidation catalyst (DOC) and leave the engine as $CO_2$ and $H_2O$ . (Majewski and Jääskeläinen 2021) HC can also be referred to as NMHC, non-methane hydrocarbons.

$N_2O$

Nitrous oxide $N_2O$ is a green house gas that can be produced from the combustion of fuel. $N_2O$ is not included in the definition for $NO_x$ and is an unregulated emission. $N_2O$ -emissions in CI-engines are typically very low (around 0.03 g/kWh when tested on "ETC", for information about ETC see section 2.2 about emission standards). (DieselNet 2020) GWP for $N_2O$ is 265 (Greenhouse Gas Protocol n.d.).

PM and PN

Particulate matter (PM) and particle number (PN) are complex mixtures of non-gaseous emissions. PM is often measured by filtering the exhaust gas and thereafter weigh or analyze the degree of blackening of the filter before and after the exhaust gas has been filtered. Thus PM is any solid or liquid emission that is caught by the filter. The solid part consists of soot and ash compounds from lubrication oil additives, engine wear and material formed during the combustion process. The liquid part consists of soluble organic material and in some cases sulphuric acid. PM, PN and soot can cause damage to human health and black soot particles are light absorbers impacting the climate. PM- and PN-emissions are reduced by using a filter, Diesel Particulate Filter (DPF). (DieselNet 2020) DPF traps and oxidizes PM and PN. (Majewski and Jääskeläinen 2021)

Smoke

Smoke may be in the form of particles, either solid or liquid suspended in the exhaust gases. (Jääskeläinen and M K Khair 2015)

## 2.2 The Audit Area tests

As stated in the Introduction, chapter 1, the purpose of the Conformity of Production-test (COP) is to assure that the produced vehicles and components, such as the engine, fulfil the same legal requirements as the type approved vehicles and components (European Commission 2018). The tests that run in the Audit Area test cells are a mix of a number of tests that fulfil a number of legislative COP-requirements considering power levels and emission levels specified in directives and regulations. This mix of tests as a whole constitutes the COP-test.[1] Specific and unique COP-tests are established for each engine type. The samples taken out for testing should for example represent the product and component types as well as it should reflect the production volume. (UN/ECE 2010)

Besides running COP-tests in the Audit Area test cells the Scania internal Quality Assurance (QA)-tests, also mentioned in the introduction, are carried out for some of the engines. The limits within which the results should be are stricter for the QA-tests compared to the limits in the COP-tests. In

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[1] Martin Jonsson, Head of Requirements, Scania CV AB - NME. Communication per e-mail February 28th 2022-

addition to the COP and QA-tests, tests that are based on external specific requirements from purchasers from foreign countries are performed in Audit Area. These are called ”Kundkörningar”. Also some tests required from different parts of Scania, called ”Referensmotorer”, as well as some tests on older engines, called ”COP NGS”, are performed in Audit Area. The tests for ”Kundkörningar”, ”Referensmotorer” and ”NGS” are, for the moment, not possible to even consider running on alternative fuel and thus these tests are not dealt with in this project.

The COP and QA-tests are configured to comply with the test procedure requirements for emission standards Euro III, Euro IV, Euro V or Euro VI. Thus the tests look different both depending on engine type but also depending on what emission standard the engine is tested for. The COP-tests are also configured to comply with a specific power test. The emission standards and the power test are described below.

**Power test:**

The net power test is run according to Regulation nr 85 of the Economic Commission for Europe of the United Nations (UN/ECE) (2014) and EC No. 582/2011 (European Parliament and the Council of the European Union 2011). The net power test consists of a run at full load. Power measurements are taken at the number of engine speeds that is sufficient in order to define the power curve between the minimum and maximum engine speeds. The range of speeds also include the speeds where the maximum engine power and torque is produced. (UN/ECE 2014, section 5.2). The power output should be within certain limits at each engine speed. Other parameters are measured during the test as well. These parameters and the applicable limits are explained in the Methodology-chapter, section 3.2.1.

**Emission standards:**

European emission standards are vehicle exhaust emission standards that apply to the tailpipe emissions of new-produced vehicles (European Parliament and the Council of the European Union 2011). Emission standards for new heavy duty engines are usually referred to as Euro I - VI. Euro I was introduced in 1992 while the latest emission standard, Euro VI, was introduced in 2009 and the emission limits became effective in 2013/2014 (DieselNet 2021). The emission standards that are relevant for this project are the emission standards Euro III, IV, V and VI for CI engines. In table 2.1 the testing requirements, included emission species and emission limits for the relevant standards are given followed by an explanation of the different types of tests needed in order to measure the emissions. The tests are performed by the manufacturer of the engine, in this case by Scania.

**Table 2.1:** Information regarding European emission standards for diesel engines (DieselNet 2021). Emissions in gram per energy delivered from the engine (Hallberg et al. 2013).

| **Emission standard** | **Test** | **CO [g/kWh]** | **HC [g/kWh]** | **$NO_x$ [g/kWh]** | **PM [g/kWh]** | **PN [#/kWh]** | **Smoke [1/m]** |
|---|---|---|---|---|---|---|---|
| **Euro III** | ESC& ELR | 2.1 | 0.66 | 5.0 | 0.10 | | 0.8 |
| **Euro IV** | ESC& ELR | 1.5 | 0.46 | 3.5 | 0.02 | | 0.5 |
| **Euro V** | ESC& ELR | 1.5 | 0.46 | 2.0 | 0.04 | | 0.5 |
| **Euro VI** | WHSC | 1.5 | 0.13 | 0.40 | 0.01 | $8.0 \text{x} 10^{11}$ | |

ESC is short for European Stationary Cycle where the engine is tested over a sequence of steady-state modes over a fixed period of time for each mode. One mode can for example be 75 % load, 10 % weight and duration of two minutes at a specific engine speed. ESC test has high load factors and high exhaust temperatures. (DieselNet 2000b)

ELR is short for European Load Response and consists of three load steps at three specific engine speeds and a fourth load step within specific load and speed-limits. Smoke measurement values are sampled during the ELR with a minimum frequency of 20 Hz. (DieselNet 2000a)

WHSC is short for World Harmonized Stationary Cycle and consists of a ramped steady state cycle. The cycle has a sequence of steady state engine modes and a defined ramp in between these modes. The speed and torque criteria are defined at each mode. The WHSC is run from a hot start. The WHSC is developed to cover typical driving conditions in the EU, USA, Japan and Australia. (DieselNet 2008)

There are transient variants of the ESC and WHSC called ETC, European Transient Cycle, and WHTC, World Harmonized Transient Cycle. The emission limits are different for the transient cycles compared to the stationary cycles due to the difference in test-designs. In ETC three different driving conditions are represented, urban, rural and motorway driving. Normalized speed and torque criteria vary with time. The entire cycle is 1800s. (DieselNet 2000c) WHTC is performed during 1800s, with normalized speed and torque criteria varying quickly with time. The WHTC has both hot and cold start requirements. The WHTC is developed as to cover typical driving conditions in the EU, USA, Japan and Australia. (DieselNet 2000d) The emission limits for the transient testing are shown in table 2.2 below.

**Table 2.2:** Information regarding transient European emission standards for diesel engines (DieselNet 2021). Emissions in gram per energy delivered from the engine (Hallberg et al. 2013).

| **Emission standard** | **Test** | **CO [g/kWh]** | **HC [g/kWh]** | **$NO_x$ [g/kWh]** | **PM [g/kWh]** | **PN [#/kWh]** |
|---|---|---|---|---|---|---|
| **Euro III** | ETC | 5.45 | 0.78 | 5.0 | 0.16 | |
| **Euro IV** | ETC | 4.0 | 0.55 | 3.5 | 0.03 | |
| **Euro V** | ETC | 4.0 | 0.55 | 2.0 | 0.03 | |
| **Euro VI** | WHTC | 4.0 | 0.16 | 0.46 | 0.01 | $6.0x10^{11}$ |

The emission limits displayed in table 2.1 and 2.2 must be followed including a multiplicative deterioration factor. The deterioration factor represents the emissions change over the durability years of the engine and thus making sure that the emission limits are kept throughout the durability years of the engine. Thus the actual emission limits when measuring the emissions during the cycles are lower than the ones presented in the above tables.

### 2.2.1 Test layouts

As already mentioned the tests are configured differently depending on engine type. Scania's Research and Development (R&D)-department creates the test design and set the limits and the precise test layouts based on tests that they perform. Hundreds of tests are performed per year in the Audit Area and the test layout is somewhat different for all tests. Consequently, it is not possible to describe the specific test for each engine type within the scope of this project. Thus a brief presentation of a "typical" test for emission standard VI is given in table 2.3 below. This is also the type of test that will be performed during the "experimental testing" of alternative fuel, see section 3.2.1. As stated all engine types have individual test plans. For example for Euro VI-engines WHSC and WHTC are performed whereas for Euro III-V engines ESC, ELR and ETC are performed and for some engines a "free acceleration smoke test" is also performed. Step 5, 7 and 10 are not carried out for all engines since those steps are dependent on for example whether or not the equipment is new. Even though the exact details for all kinds of tests are not considered relevant to present and analyse within the scope of this master thesis it is important to at least know that the variation in test layouts exist. This is necessary in order to understand the method used for estimating the yearly fuel consumption and the amount of current use of fuel that can be exchanged with alternative fuel. That method is further described in the "Methodology"-chapter, see section 3.2.2.

The requirement at Scania is to run the COP- and QA-tests on specific certification/reference fuels since that is the fuel used at the department where the type approval tests are performed. Thus the results from the tests are comparable and the risk for deviations in results related to differences in the fuel characteristics is lower.[2] Overall it can be stated that the steps that include measuring power and measuring emissions are not possible testing to run with alternative fuels, since the power and the emissions measurements should be within specific limits and be measured and reported for the specific certification fuel used during the type approval. However, at least for Euro VI-engines, the power- and emissions-tests that are parts of COP are *legally* allowed to be carried out either with the certification fuel or with the diesel available on the market (UN/ECE 2014) (European Parliament and the Council of the European

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[2] Martin Jonsson, Head of Requirements, Scania CV AB - NME. Communication per e-mail May 4th 2022

Union 2011). The diesel available on the market complies with diesel standard EN590[3].

Euro III-V vehicles have one certification fuel and Euro VI vehicles another. The certification fuels are hereafter called baseline diesels and are the diesel fuels that are currently used in the Audit Area, this is further explained in section 4. At Scania WHSC is the emission testing cycle that is part of COP and thus the results are reported to authorities whereas WHTC is part of the internal Quality Assurance-test and thus the results are not reported to any authority.

The green-marked rows in table 2.3 below are the parts of the test that will be tested to run with alternative fuel.

**Table 2.3:** Overview of the parts in a COP and QA test for a Euro VI-engine.

| **Part** | **Description** | **Possibility to run with alternative fuel** |
|---|---|---|
| 1. Engine installations, auxiliary adjustments and engine adaptations | This part of the test is done in order to evaluate the power used by auxiliary units and thus evaluate how much power that must be subtracted from the measured power demands in order to report correctly during later parts of the test. Also auxiliary units are adjusted in order to function correctly and the engine has to undergo engine adaptations in order for its relevant systems to be calibrated and adjusted for best engine performance in the test cells. | The results for this part are not reported to any authority thus this part might be possible to run with alternative fuel, as long as it does not have a negative impact on the results for later parts of the tests. |
| 2. Nulled power | This part is used for measuring the power output before the engine adaptation (part 3 below) has been performed. By doing the nulled power test the power output before and after the fuel injection adaptation can be compared. | The results for this part are not reported to any authority thus this part might be possible to run with alternative fuel, as long as it does not have a negative impact on the results for later parts of the tests. |

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[3] Martin Jonsson, Head of Requirements, Scania CV AB - NME. Communication via Teams May 9th 2022.

Table 2.3 – continued from previous page

| **Part** | **Description** | **Possibility to run with alternative fuel** |
|---|---|---|
| 3. Fuel injection adaptation | In order to ensure correct injected fuel quantities an injector adaption is needed, this is called fuel injection adaptation (hereinafter referred to as FIA). The FIA performed in the Audit Area are forced adaptations since unforced adaptations usually take up to a hundred hours. Adaptations that long are not possible to carry out in the Audit Area. | This part might be possible to run with alternative fuel. Since the fuel used during the FIA has an impact on the outcome of the adaptation it is important to extra carefully evaluate if the use of alternative fuels at this stage impact the engine performance during the power test and emission testing cycles (WHSC and WHTC). |
| 4. Power test | The results from the power test shall be within certain limits. Thus, the result from the power test will be of importance when evaluating whether or not it is possible to run the previous parts with alternative fuels. If the results are within the limits it can be seen as an indication of that it is possible to run the previous parts with alternative fuel, and vice versa. | The power test is required by law and the results are reported to the type approval authority. This part is not allowed to run with alternative fuel. |
| 5. Degreening of DOC and SCR catalyst | This part involves preconditioning of the diesel oxidation catalyst and selective catalytic reduction when these devices are used for the first time. | The results for this part are not reported to any authority thus this part might be possible to run with alternative fuel, as long as it does not have negative impact on the results for later parts of the tests. |
| 6. After treatment adaptation | This part covers controlling of the $NO_x$ -sensor and controlling of the ratio of ammonia to $NO_x$ flow into the catalyst. | The results for this part are not reported to any authority thus this part might be possible to run with alternative fuel, as long as it does not have a negative impact on the results for later parts of the tests. |

Table 2.3 – continued from previous page

| **Part** | **Description** | **Possibility to run with alternative fuel** |
|---|---|---|
| 7. Running-in test DPF | This part is only performed when there is a new DPF in the Audit Area test cell. It is performed in order to get the right amount of soot in the DPF. | The results for this part are not reported to any authority thus this step might be possible to run with alternative fuel, as long as it does not have a negative impact on the results for later parts of the tests. |
| 8. WHSC | In this part the emissions of $NO_x$ , HC, CO, PM (in mg/kWh) and PN (particle number, in T/kWh) are measured. | This emission cycle is required by law and the results are reported to the type approval authority. This part is not allowed to run with alternative fuel. |
| 9. WHTC | In this part the emissions of $NO_x$ , HC, CO, PM (in mg/kWh) and PN (particle number, in T/kWh) are measured. | This emission cycle is a part of the Scania internal Quality Assurance-test (the QA-test) and should not be run with alternative fuel. |
| 10. Urea test | Urea test is only carried out for some engine types. It evaluates the ability of the SCR system to reduce $NO_x$ as a function of certain parameters. | The results for this part are not reported to any authority thus this part might be possible to run with alternative fuel. |

# Chapter 3

# Methodology

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*This chapter gives a description of the methods used in order to find the answers to the research questions.*

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## 3.1 Research approach

The first phase of this project includes planning and evaluation of what methods that are necessary, and possible, to use in order to answer the four research questions. What is clear already from the beginning is that the four questions require somewhat individual method approaches. Figure 3.1 below shows an overall schematic view of the research approach.

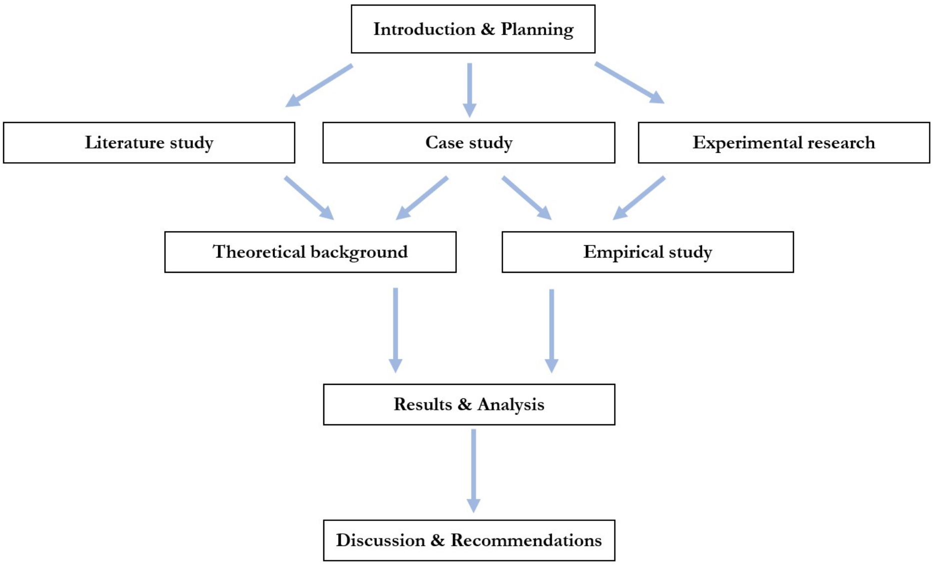

**Figure 3.1:** Schematic view over the research approach.

### 3.1.1 Literature study

The literature studies are used for answering parts of research questions number 2, 3 and 4.

### 3.1.2 Case study

The case study covers observations of the current situation. Information is collected through direct contact with relevant Scania employees in order to get relevant information regarding the tests, the engines and the fuels. Also participation during tests is carried out in order to understand how the tests are performed. Case study is used throughout the whole thesis and is in one way or another a relevant method for approaching parts of all research questions.

### 3.1.3 Experimental research

Experimental research or experimental testing is performed for answering parts of research question number 1.

## 3.2 Research design

In the following sections the research design for each research question will be explained.

### 3.2.1 Research design: What alternative fuel(s) are technically possible to use during running time?

Figuring out what alternative fuels that are technically possible to use in the engines that are tested in Audit Area's test cells requires two steps.

**Step one**

Knowledge is obtained regarding what alternative fuels that are technically compatible to run the engines with and possible to use without requiring any physical changes in the hardware or software of the engines and without damaging the engines. This is done firstly by figuring out what kind of engine models that are relevant to take into consideration in this project, and secondly by taking part of information regarding the relevant engine models. The knowledge is provided from communication with Scania employees as well as from information on Scania's web-page.

- The findings regarding what alternative fuel to consider is given in section 4.1.

**Step two**

This step consists of performing experimental tests in order to see if the alternative fuel that has been chosen in step one is possible to use when performing the tests in the Audit Area.

Even if the chosen alternative fuel is technically compatible to be used in the specific engine model, the fuel is not necessarily impacting the engine in the exact same way as the baseline diesel during the tests. Accordingly it is necessary to perform experimental testing to analyse how the alternative fuel effects the performance characteristics of the engine during the tests. Also the plan is to change fuel during the tests, something that has not been done before during the tests in the Audit Area.

The fact that the engine adaptations, including the fuel injection adaptation, will be carried out with alternative fuel while the power and emission tests will be carried out with baseline diesel require some extra focus and evaluation. Due to time limitations only three experiments will be carried out. The experiments and the evaluations will not focus on the engine performance when running the engine on alternative fuel, but will instead focus on the engine and emission performance from the power- and emission-tests that are carried out with baseline diesel when parts of the adaptations and running in procedures are carried out with alternative fuel. The main focus will be to examine whether or not the measurements from the power and emission tests are within the required COP- and QA-limits even though parts of the running in procedure is performed with alternative fuel. If the results are within the limits it can be seen as an indication of that it might be possible to perform parts of the tests with alternative fuel. The experimental setup including information regarding the test-engine and the fuel system, the applicable COP- and QA-limits for the test-engine as well as the test matrices for the three experiments will be explained in the following.

- The results from the experimental testing are given in section 5.1.

### Experimental setup

The engine used during the experiments is the engine type DC13 165, in this report hereafter called the Case Engine. The Case Engine is a 6-cylinders in-line diesel engine with the displacement volume of 12.7 liters, the rated power output of 500 hp and the rated speed 1800 rpm. The Case Engine is an engine complying with the emission standard Euro VI. Thus the test matrices for the experiments are based on the test layout presented in table 2.3.

The same engine type is used during the three experiments. Although different engine individuals are used for each experiment due to the fact that the experiments are carried at a production unit with a constant flow where one engine can not be ”stuck” at the Audit Area for a too long time. However, performing experiments on three different engine individuals is deemed advantageous since it lowers the dependence on the characteristics of one engine individual. There can be small variations between engine individuals.

The baseline diesel is transferred to the engine and injected into the engine through the ordinary fuel system in the test cell, whereas the alternative fuel is pumped into the engine from a fuel barrel. Each fuel barrel contains around 208 liter fuel so the fuel barrel needs to be changed during the test since more than 208 liter fuel is needed for the test. A three-way coupling is installed where the switch between baseline diesel and alternative fuel is done manually throughout the test.

Since the alternative fuel is ordered in fuel barrels it is necessary to know approximately how much alternative fuel that is needed. This is done by measuring the fuel consumption of baseline diesel for the same engine-type and test but on another engine individual. The fuel measurement is done for the different parts of the tests and from that an estimation is done of the amount of alternative fuel needed to perform the experiments and also when during the experiments the fuel barrels need to be changed.

### Applicable limits

The applicable limits for each engine type are derived at Scania and are specific for each engine type. The following limits are specific for the Case Engine and are the limits that the results from the experiments will be compared to.

For engines complying with Euro VI emission standard the emission limits for WHSC and WHTC in regards to the deterioration factor are the ones presented in table 3.1 below. These are the limits that the actual measured results are compared to when testing the engine. There is also a limit for bsfc (see explanation of bsfc after table 3.1). For WHTC, which is not part of COP but part of QA, there is a limit also for ammonia ($NH_3$). Due to that the exact limits are deemed company confidential the exact limits will not be given in the tables. What will be given is if there are min/max-limits or only max-limits.

**Table 3.1:** Emission limits without deterioration factors for the Case Engine.

| | **CO [g/kWh]** | **HC [g/kWh]** | **$NO_x$ [g/kWh]** | **PM [g/kWh]** | **PN [#/kWh]** | **$NH_3$ [ppm]** | **bsfc [g/kWh]** |
|---|---|---|---|---|---|---|---|
| WHSC | max | max | max | max | max | - | max |
| WHTC | max | max | max | max | max | max | max |

For the Case Engine the parameters with required COP-limits during the power test are the ones presented in table 3.2 below. The parameters with required QA-limits during the power test are the ones presented in table 3.3 and 3.4 below. Due to that the exact limits are deemed company confidential the exact limits will not be given in the tables. What will be given is if there are min/max-limits or only max-limits.

The measurements are made at full load at five engine speeds. For intake depression, exhaust back pressure and delta there are only COP-limits at 1800 rpm. Some of the parameters have both COP- and QA-limits, some have only COP- or only QA-limits. Note that for all parameters that have both COP and QA-limits, the QA-limits are stricter. The parameters that are measured during WHSC, WHTC and power test are briefly explained in the following:

- Speed [rpm] = Measure of how many times the crankshaft in the engine rotates during one minute. Expressed in revolutions per minute [rpm].
- Intake depression [mbar] = Pressure drop over intake.
- Exhaust back pressure [mbar] = The exhaust gas pressure produced by the engine to overcome hydraulic resistance in order to discharge exhaust gases into the atmosphere. (Jääskeläinen 2007)
- Net power [kW] = The power output of the engine. Defined as torque multiplied with speed. (Jääskeläinen and M K Khair 2020b)
- Delta [mg/str] = Amount of fuel delivered to the engine cylinder per power stroke. (Jääskeläinen and M K Khair 2020a)
- $NO_x$ = See section 2.1.2.
- Smoke [$mg/m^3$] = See section 2.1.2.
- bsfc [g/kWh] = Brake specific fuel consumption (bsfc) is the ratio of engine fuel consumption and hourly engine power output. Accordingly, it is a measure of engine efficiency (DieselNet n.d.).
- CO [ppm] = See section 2.1.2.
- HC [ppm] = See section 2.1.2.
- Temp after comp. [°C] = Comp is short for compressor.
- Temp inlet manifold [°C] = The inlet manifold supplies the fuel and air mixture to the cylinders.

- Boost pressure after int. cooler [bar] = Int. cooler is short for intercooler. The intercooler is a heat exchanger cooling down the gas after compression.
- Temp after turbine [°C] = No explanation needed.
- SCR-temp [K] = No explanation needed.
- Lambda [-] = The air to fuel ratio.

**Table 3.2:** COP-limits (min/max) for power test on the Case Engine.

| **Speed** | **Intake depression [mbar]** | **Exhaust back-pressure [mbar]** | **Net power [kW]** | **Delta [g/kWh]** |
|---|---|---|---|---|
| **1800** | min/max | min/max | min/max | min/max |
| **1640** | - | - | min/max | - |
| **1340** | - | - | min/max | - |
| **1100** | - | - | min/max | - |
| **925** | - | - | min/max | - |

**Table 3.3:** QA-limits (min/max) for power test on the Case Engine.

| **Speed** | **Net power [kW]** | **$NO_x$ [g/kWh]** | **Smoke [mg/$m^3$]** | **Delta [mg/str]** | **bsfc [g/kWh]** | **CO, max (pre cat.) [ppm]** | **HC, max (pre cat.) [ppm]** |
|---|---|---|---|---|---|---|---|
| **1800** | min | min/max | max | min/max | min/max | max | max |
| **1640** | min | min/max | max | min/max | min/max | max | max |
| **1340** | min | min/max | max | min/max | min/max | max | max |
| **1100** | min | min/max | max | min/max | min/max | max | max |
| **925** | min | min/max | max | min/max | min/max | max | max |

**Table 3.4:** QA-limits (min/max) for power test on the Case Engine.

| **Speed** | **Temp after comp.** [$\circ$ **C**] | **Temp inlet manifold.** [$\circ$ **C**] | **Boost pressure after int. cooler** [**bar**] | **Temp after turbine.** [$\circ$ **C**] | **SCR temp** [**K**] | **Lambda** [**-**] |
|---|---|---|---|---|---|---|
| **1800** | min/max | min/max | min/max | min/max | min/max | min/max |
| **1640** | min/max | min/max | min/max | min/max | min/max | min/max |
| **1340** | min/max | min/max | min/max | min/max | min/max | min/max |
| **1100** | min/max | min/max | min/max | min/max | min/max | min/max |
| **925** | min/max | min/max | min/max | min/max | min/max | min/max |

### The experiments

The results from the experiments will be compared against the COP- and QA-limits presented in the tables above. In addition to that the exact limits are company confidentials, so are also the exact test results. Although, what will be analysed in the results is whether or not the results are within the applicable limits. That can be perfectly done without presenting the exact test results.

(Note: In the first two experiments power tests were carried out with alternative fuel, these are written in pink in the tables with the test plans. The results from those power tests are not analysed since those are considered not relevant within the scope of this experiment and since the power test is supposed to be carried out with baseline diesel.)

#### Experiment 1

The test plan displayed in table 3.5 is in accordance with the test layout presented in table 2.3, section 2.2.

The results from the power test, WHSC and WHTC are analysed in order to see if the results are within the limits laid out in the COP and QA-instructions, even though the running-in parts and adaptations are carried out with alternative fuel. All the parameters that have applicable COP- or QA-limits will be evaluated.

**Table 3.5:** Test plan experiment 1.

| **Test-part** | **Fuel** |
|---|---|
| Engine installations and auxiliary adjustments | alternative fuel |
| Nulled power | alternative fuel |
| FIA | alternative fuel |
| Power test | alternative fuel |
| Power test | baseline diesel |
| Degreening of DOC and SCR catalyst | alternative fuel |
| After-treatment adaptation | alternative fuel |
| Running in test DPF | alternative fuel |
| WHSC | baseline diesel |
| WHTC | baseline diesel |
| Urea test | alternative fuel |

Experiment 2

The aim of this experiment is exclusively to examine the consequences on the power test when performing the first three parts of the test with alternative fuel. Not all parts of a typical test are carried out. The test plan is displayed in table 3.6. Why the power tests are carried out more than once is in order to get more test results.

The difference between the power tests A.1-A.3 and B.1-B.2 is that before A.1-A.3 FIA is carried out with alternative fuel whereas before B.1-B.2 FIA is carried out with baseline diesel. The results from A.1-A.3 and B.1-B.2 are analysed and compared. The parameters that will be analyzed from A.1-A.3 and B.1-B.2 are the net power output, delta and bsfc. Whether or not those measurements are within the limits laid out in the COP and QA-instructions will be examined. Additionally, the amount of fuel that is demanded by the control unit ($\text{delta}_{\text{demanded}}$) will be compared to the amount of fuel that is actually injected (delta), since those two amounts should be approximately the same when FIA is working correctly.

**Table 3.6:** Test plan experiment 2.

| **Test-part** | **Fuel** |
|---|---|
| Engine installations and auxiliary adjustments | alternative fuel |
| Nulled power | alternative fuel |
| FIA | alternative fuel |
| Power test | alternative fuel |
| A.1 Power test | baseline diesel |
| A.2 Power test | baseline diesel |
| A.3 Power test | baseline diesel |
| FIA | baseline diesel |
| B.1 Power test | baseline diesel |
| B.2 Power test | baseline diesel |
| Power test | alternative fuel |
| Power test | alternative fuel |

Experiment 3

The aim of this experiment is exclusively to examine the consequences on the power test when performing FIA with alternative fuel, thus not all parts of a typical test are carried out. The test plan is displayed in table 3.7. Why the power test are carried out more than once is in order to get more test results.

The main difference between the test plan for experiment 2 and 3 is that in experiment 3 the first two parts are not carried out with alternative fuel. Experiment 3 is carried out in order to further analyse the consequences of using alternative fuel when performing FIA.

The results from the power tests performed after FIA with alternative fuel (C.1-C.2) as well as the results from the power tests performed after FIA with baseline diesel (D.1-D.2) are analysed and compared. The same parameters will be analysed as in experiment 2.

**Table 3.7:** Test plan experiment 3.

| Test-part | Fuel |
|---|---|
| Engine installations and auxiliary adjustments | baseline diesel |
| Nulled power | baseline diesel |
| FIA | alternative fuel |
| C.1 Power test | baseline diesel |
| C.2 Power test | baseline diesel |
| FIA | baseline diesel |
| D.1 Power test | baseline diesel |
| D.2 Power test | baseline diesel |

### 3.2.2 Research design: What are the expected yearly emission saving(s) when using alternative fuels?

The emissions origin from the use of the fuels will be presented both as tailpipe $CO_2$ -emissions and as life cycle $CO_2e$ -emissions. The information needed is emission factors for the tailpipe (expressed as $gCO_2/MJ_{fuel}$ ) and life cycle emissions (expressed as $gCO_2e/MJ_{fuel}$ ) as well as the yearly fuel consumption for the current consumption of fuel as well as for the possible consumption of alternative fuel.

#### Tailpipe emissions

The tailpipe $CO_2e$ -emission factors are derived for the relevant fuels. All carbon atoms that enters the engine are assumed to exit the engine as $CO_2$ . Biogenic and fossil $CO_2$ -emissions are accounted for in different ways. The emission factors are calculated by using fuel-specific information and the following equations:

$$\frac{m_{\mathrm{C}}}{m_{\mathrm{fuel}}} + \frac{m_{\mathrm{C}}}{m_{\mathrm{fuel}}} \cdot \frac{M_{\mathrm{O_2}}}{M_{\mathrm{C}}} = \frac{m_{\mathrm{CO_2}}}{m_{\mathrm{fuel}}} \tag{3.1}$$

with the emission factor being either:

$$\frac{m_{\mathrm{CO_2}}}{m_{\mathrm{fuel}}} \cdot \rho = \frac{m_{\mathrm{CO_2}}}{V_{\mathrm{fuel}}} \tag{3.2}$$

or:

$$\frac{m_{\mathrm{CO_2}}}{m_{\mathrm{fuel}}} \cdot \frac{1}{LHV} = \frac{m_{\mathrm{CO_2}}}{E_{\mathrm{fuel}}} \tag{3.3}$$

where:

$m_{\mathrm{C}}$ = mass of carbon [kg]

$m_{\mathrm{fuel}}$ = mass of fuel [kg]

$\frac{m_{\mathrm{C}}}{m_{\mathrm{fuel}}}$ = carbon content [mass%]

$M_{O_2}$ = molar mass of oxygen [kg/kmol]

$M_C$= molar mass of carbon [kg/kmol]

$\rho$ = fuel density [$kg_{fuel}/l_{fuel}$]

LHV = lower heating value [$MJ_{fuel}/kg_{fuel}$]

$V_{fuel}$ = volume of fuel [MJ]

$E_{fuel}$ = energy content of fuel [MJ]

Also the tailpipe emissions of other species resulting from combustion of the fuels are presented as well as a brief analysis of how they might vary depending on fuel.

- All tailpipe emission species are explained and presented in section 2.1.2.
- Tailpipe $CO_2$ -emission factors are presented in section 4.1.

**Life cycle emissions**

About LCA

The life cycle environmental impact considered in this project is only focused on the global warming impact of the life cycle of the fuel and expressed as $gCO_2e/MJ_{fuel}$ . $CO_2e$ is a collective concept for green house gases and is calculated by using the global warming values for greenhouse gases presented in section 2.1.2, although the values have been changed over time and thus earlier sources might use somewhat different values (Greenhouse Gas Protocol n.d.). The value for the life cycle greenhouse gas emissions is in this report referred to as LCA-value. The life cycle emissions of a fuel includes emissions during the phases well-to-tank (WTT) and tank-to-wheel (TTW). WTT includes the production process of the fuel as well as the transportation and distribution of the fuel. TTW includes the combustion of the fuel in the engine.

Life cycle analyses can be based on different methods and one must distinguish, or at least reflect upon the difference, between LCA:s based on attributional approach and LCA:s based on consequential approach. A LCA based on the attributional approach estimates what global environmental impacts that belongs to the specific product. The counterpart, the consequential approach, estimates how the global environmental impacts are affected by the production-chain and use of the product, for example by comparing the emissions of a fuel production chain compared to if the fuel was not produced at all. The consequential approach is based on market driven scenarios and market projections and mainly considers marginal data, whereas the attributional approach is more retrospective and considers average data. An attributional approach is often based on *allocation* where the environmental impacts from the fuel production chain are divided between each unit of fuel product. If more product types than the fuel product are produced during the production the environmental impacts are distributed between the different products based on the energy or mass content or economical value of the products. A consequential approach is often based on *system expansion* where the evaluated environmental impacts during life cycle of a product includes not only the product itself but also the life cycle of relevant co-products. (Klöpffer and Grahl 2014)

LCA in this report

There has not been any life cycle analysis-modelling in this project, instead LCA-values has been obtained from literature and fuel supplier. The LCA-values that are used are, as far as possible, taken from references using the attributional approach including allocation of the environmental impact. However, the focus has not exclusively been on attributional approach. Whether the LCA-value is based on an attributional/allocation approach or on a consequential/system expansion approach is, when known, stated for each value. LCA:s can be conducted in numerous ways with numerous varying results, thus it is necessary to have information regarding the methods used (Källmén et al. 2019).

Since this project is focused on the operations at Scania's production unit located in Sweden it is of importance to find LCA-values based specifically on fuels that are available on the Swedish market. Additionally, the Swedish Knowledge Center for Renewable Transportation Fuels (f3) recommend in their publication (ibid.) that in order to get detailed information on LCA-values for fuels supplied to a specific user in a specific time frame data should be requested by the supplier. Since October 2021 Swedish fuel suppliers are required by law to account for and present easy-access ”environmental information” regarding their fuels (Energimyndigheten 2021b). Thus information from the suppliers is easily available. But after direct contact[4] with a fuel supplier that is relevant for this project, Preem, it is clear that no details regarding the methods they use when conducting the LCA are given to external stakeholders. With a lack of transparency regarding how the LCA is conducted, it is difficult to validate, or disclaim, the accuracy of the LCA-values. Also the possibility of comparing the value to other values is lowered since the method is unknown.

However, the ”environmental information” that the fuel supplier is required to account for is managed by the Swedish Energy Agency (in Swedish: Energimyndigheten). After direct contact with the Swedish Energy Agency[5] it is clear that the Agency does not verify the calculations yearly, but the companies must have control systems over the sustainability reporting of at least the biofuels. Within the scope of the control system the companies calculate LCA-values according to formulas in ”Statens energimyndighets föreskrifter om hållbarhetskriterier för biodrivmedel och biobränslen” (in English: The Swedish Energy Agency's regulations on sustainability criteria for biofuels) (Energimyndigheten 2021d). These calculations are reviewed by an independent party and the Swedish Energy Agency conducts supervision over the control system. Consequently Preem's (and other fuel suppliers in Sweden) LCA-values for at least biofuels are probably somewhat accurate despite the lack of transparency. Consequently, LCA-values from fuel suppliers will be used in this report.

Furthermore, in order to increase the accuracy of the results LCA-values that are derived by a variety of stakeholders or LCA-values taken from literature are presented in addition to the fuel supplier specific LCA-values. For the baseline diesels that are currently used in Audit Area only one LCA-value is chosen when doing the final emissions-calculations since that will be the reference LCA-emissions that the LCA-emissions relating to the alternative fuel are compared to. For the alternative fuel two LCA-values are chosen in order to show the sensitivity of the results depending on the choice of LCA-value, the calculated emissions when using the different values are referred to in the results as sensitivity 1 and sensitivity 2. When the LCA-values are presented for each fuel there is a reasoning around what sources and LCA-values that has been used and why.

The sources used for LCA-values are the following:

- Fuel suppliers Preem (Preem 2020), OKQ8 (OKQ8 2020), Circle K (Circle K 2020), Shell (Shell 2020). These fuel suppliers provide WTW LCA-values complying with the Swedish Energy Agency's ”environmental information”.
- The reports *Well-to-wheel LCI data for HVO fuels on the Swedish market* (Källmén et al. 2019) and *Well-to-wheel LCI data for fossil and renewable fuels on the Swedish market* (Hallberg et al.

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[4] Product specialist, Preem. Communication per e-mail March 8th 2022.

[5] The Swedish Energy Agency. Communication per e-mail March 10th 2022.

2013). Both reports are written as parts of a project within the Swedish Knowledge Centre for Renewable Transportation Fuels (f3). The reports aim at reflecting fuels on the Swedish market specifically. The values from the sources are not derived from LCA-modelling performed by f3, but derived by f3 by comparison and collection of analyses from different available LCA sources. The LCA-methods used in the reports vary depending on fuel.

- Scania internal values[6]: Scania considers these WTW LCA-values as typical values for the specific feedstocks for the alternative fuels. The values are based on attributional approach.
- European Parliament (European Parliament 2009): Default LCA-values for cultivation, processing, transport and distribution (WTT) of the fuels. Whether the values are based on the attributional or the consequential approach is unclear.
- European Commission's Research Centre JEC (Prussi et al. 2020): These WTT LCA-values are based on analysis in a European context and based on the consequential method.
- Council Directive (EU) 2015/652 (Council Of The European Union 2015). This source gives default weighted WTW LCA-value for fossil diesel. Whether the attributional or the consequential approach is used is unclear.

The LCA-values in this report are representing both WTT and TTW emissions and it is important to keep in mind that since the TTW-emissions are dependent on for example the engine and the aftertreatment devices the amount of TTW emissions are not reflecting Scania's engines specifically. The LCA-values and the LCA-analysis made in this report should be seen as an overview of the overall difference in life cycle emissions depending on fuel. However, in the sources Prussi et al. (2020) and European Parliament (2009) only LCA-values for WTT has been found. For these cases default TTW LCA-values for the different fuels have been added, in order for the different LCA-values to be comparable. These TTW LCA-values are calculated with data from Hallberg et al. (2013) and is an average of the TTW LCA-values for Euro V and Euro VI heavy duty vehicles for the different fuels. Since the data only include two emission standards and since the aftertreatment systems and thus cleanliness of the exhaust gases most likely have improved since the date of publication of the data for TTW LCA-values (2013) these default values should not be seen as exact numbers. But, as already mentioned, all LCA-values have uncertainties and assumptions and these default TTW-values are evaluated as not considerably impacting the (already uncertain) accuracy. Those calculations are presented in Appendix A.2.3.

- The LCA-values are presented in section 4.3.

### Fuel consumption and calculation of change in tailpipe and LCA emissions

As stated earlier the yearly fuel consumption expressed in $MJ_{\text{fuel}}$ for the current consumption of baseline diesel as well as for the possible consumption of alternative fuel is needed in order to calculate the related emissions. The current fuel consumption is needed for the relevant tests (relevant tests=all tests on engines running on diesel excluding "Kundkörningar", "Referensmotorer" and "NGS"), and the parts of the tests that can be run on alternative fuel instead of baseline diesel has to be estimated. These are the two cases for fuel consumption used as a basis for calculating the emissions relating to the different cases:

Reference case: The yearly consumption of baseline diesel.

Alternative fuel case: The yearly consumption of alternative fuel and baseline diesel. Alternative fuel is assumed to be used in the parts of the tests where it is considered possible to use alternative

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[6] Magnus Fröberg, Technical Manager Fuels, Scania CV AB - NMER. Communication per e-mail February 2d 2022.

fuel according to table 2.3 in section 2.2. The other parts of the tests are run with baseline diesel. For the tests complying with emission standards other than Euro VI, and thus having a somewhat different test layout, the same kind of reasoning is done regarding what parts of the tests that might be possible to run with alternative fuel.

There has not been enough time to measure the baseline diesel consumption for all tests that are carried out over a year, and no previous data of fuel measurements per test has been found. What is needed is an estimation of the yearly fuel consumption in Audit Area that is related to the relevant tests as well as an estimation of what share of the fuel consumption per test that can be exchanged with alternative fuel (based on the test-parts in table 2.3 assumed to be possible to run with alternative fuel). Note that the engine efficiency is assumed to be independent of fuel. The principals for the fuel consumption of one test for reference case vs alternative case is the following:

Reference case:
Baseline diesel consumption = 7000 MJ

(Estimated share of baseline diesel consumption that can be changed to alternative fuel consumption: 75 %)

Alternative fuel case:
Alternative fuel consumption = 5250 MJ
Baseline diesel consumption = 1750 MJ

This kind of estimation have to be done for all the different types of (relevant) tests that are carried out in the Audit Area during one year so that the outcome is:

Case 1:
Yearly baseline diesel consumption = x MJ

(Estimated share of yearly baseline diesel consumption that can be changed to alternative fuel consumption: y)

Case 2:
Yearly alternative fuel consumption = $y \cdot x$ MJ
Yearly baseline diesel consumption = $(1\text{-}y)\cdot$ x MJ

However, since the tests vary quite heavily depending on engine type and emission standard, detailed information regarding current baseline diesel consumption for each unique test is needed. Due to the limited time available for this project the fuel consumption for all tests carried out during one year can not be measured. Instead 13 numbers of measurements of fuel consumption of tests is done. From these measurements the fuel consumption for each unique test carried out over one year is estimated. The measurements are made for each part of the test, so that the exact fuel consumption of baseline diesel for the parts of the test that can be changed to alternative fuel is known. The share of fuel consumption for each unique test that can be run on alternative fuel is then estimated. The fuel consumption is measured in liters and then calculated to MJ by using the lower heating values (MJ/l).

Data is taken from year 2021 regarding how many of each unique test that is carried out over one year. From the estimations of fuel consumption per unique test and the data from 2021 the baseline diesel consumed during one year (for the relevant tests) in the Audit Area is estimated as well as the total share of yearly baseline diesel consumption than can be changed to alternative fuel consumption.

The estimations are performed in an Excel-sheet including the data over exact number of unique test per year. However this information is confidential and thus the Excel-sheet is not included in this report. The information that is given regarding the fuel consumption in this report is the overall consumption of baseline diesel and the share of baseline diesel assumed possible to exchange with alternative fuel.

Knowing the yearly fuel consumption for the different fuels in reference case and alternative fuel case the tailpipe as well as LCA-emissions related to the different cases is calculated using the emission factors for the different fuels. The emissions related to the different cases are compared and the change in emissions when using alternative fuel is shown. This comparison is made both in absolute tonne of $CO_2$ -emissions and in relative term expressed in percentage. The change in tailpipe $CO_2$ -emissions is also put in relation to the total direct $CO_2$ -emission from the production unit Engine Assembly and Scania's global operations in total for the year 2021. This comparison is made in order to provide a picture of the size and scope of the change in emissions compared to current emissions. The $CO_2$ -emissions from Engine Assembly and Scania's operations globally are given below. Scania has a target of reducing $CO_2e$ -emissions by 50 % 2015-2025 (Scania CV AB 2022).

**Table 3.8:** Total tonnes of $CO_2$ -emissions from Engine Assembly and Scania's operations globally in 2021.

| **Engine Assembly [t$CO_2$]** | **Scania's operations [t$CO_2$e]** |
|---|---|
| 1 988[7] | 105 800 (Scania CV AB 2022) |

- Results from measurement of fuel consumption and calculations of yearly emissions for the different cases are presented in section 5.2.

### 3.2.3 Research design: How is the future availability, and price development, of the alternative fuel(s)?

In a previous project at another area at the Engine Assembly unit the possibility of using alternative fuel was evaluated. One conclusion was drawn that it was difficult to secure a sufficient supply over time. Thus, since the possibility of using alternative fuel is dependent on the availability as well as on the price an analysis regarding these factors is made. The analysis is mainly based on literature studies.

- Findings regarding future availability, and price development, of alternative fuel is given in section 4.4.

### 3.2.4 Research design: What are the modifications needed when changing the fuel use?

In order to partly change the fuels used in the Audit Area there are needs for modifications of the fuel system in the test cells as well as modifications in the storage of fuels. Knowledge regarding what modifications that are necessary is contained by observations of the current storage and fuel system at the Engine Assembly.

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[7] Per Möller, Environmental Coordinator, Scania CV AB - DES. Communication March 21st 2022.

- Results from investigation of physical modifications needed to change the fuel system are given in section 4.5.

# Chapter 4

# Findings from case study and literature study

*This chapter gives findings related to fuels, emission factors, availability and price as well as physical modifications needed when changing the fuel-use.*

## 4.1 Findings regarding fuels

The alternative fuel that will be of main focus in this project is Hydrotreated Vegetable Oil, HVO. This fuel will be further described in the following sections. All of Scania's diesel vehicles that are produced from November 2012 are technically compatible to run on HVO and thus all diesel engines that are considered in this project are technically compatible to run on HVO. The engines that are compatible to run on HVO do not need modifications when HVO is used instead of baseline diesel. All Euro VI-engines are emission certified to run on HVO and no emission certification is needed when running Euro III-V-engines on alternative fuels [8].

Worth mentioning is that a number of Scania's diesel engines are possible to run on FAME (this fuel will also be further described in the following sections). Although for an engine to be technically compatible to run on diesel with a FAME-content exceeding 10 % slight modifications on hardware and change of settings are needed. Additionally, if using FAME in the Audit Area it is important to make sure no FAME is left in the engines when the tests are done since FAME easily oxidizes.[9]

Since HVO is the alternative fuel possible to use in all engines relevant for this project that are tested in the Audit Area, *HVO is the alternative fuel that will be considered during this project.* In the following sections (section 4.1, 4.2 and 4.3) the baseline diesel used today and the alternative fuel, HVO, are presented. The tailpipe emissions and LCA-emissions per energy content for the specific fuels are also presented.

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[8] Magnus Fröberg, Technical Manager Fuels, Scania CV AB - NMER. Communication per e-mail February 10th and April 25th 2022.

[9] ibid.

### 4.1.1 Baseline Diesel 1: Euro III-V Certification Fuel

Baseline Diesel 1: Euro III-V Certification Fuel is the diesel used during COP and QA-tests that comply with the emission standards Euro III-V. Euro III-V Certification fuel, also called S10, will hereon be referred to as Baseline Diesel 1 (BD1). BD1 consists of 100 % fossil diesel. In table 4.1 the characteristics of BD1 are given.

### 4.1.2 Baseline Diesel 2: Euro VI Certification Fuel

Baseline Diesel 2: Euro VI Certification Fuel is the diesel used during COP and QA-tests that comply with the emission standard Euro VI. Euro VI Certification Fuel will hereon be referred to as Baseline Diesel 2 (BD2). This fuel is the one that is currently used during the tests performed on the Case Engine. BD2 has an added content of biodiesel of between 6 and 7 volume per volume percent (%v/v). The added biodiesel is Fatty Acid Methyl Esthers (FAME). (European Parliament and the Council of the European Union 2011). In table 4.1 the characteristics of BD2 are given. Due to the Swedish legislation called ”Lag (2017:1201) om reduktion av växthusgasutsläpp från vissa fossila drivmedel” (Reduktionsplikten) the Swedish market diesel fuel, besides having the added content of 6-7 %v/v of FAME, must also have an additional content of other biofuels in order to reduce the greenhouse gas emissions from usage of the diesel (Energimyndigheten 2021c). This is not the case for BD2 and besides the 6-7 %v/v of FAME the diesel is exclusively of fossil origin[10]. FAME, commonly referred to as biodiesel, is a leading renewable liquid fuel globally. FAME is produced through transesterification of fatty acids and methanol (f3 - Swedish Knowledge Centre for Renewable Transportation Fuels 2017).

### 4.1.3 Alternative fuel: Hydrotreated Vegetable oil

Hydrotreated Vegetable oil (HVO) is a non-fossil hydrocarbon liquid fuel with the same chemical structure as conventional diesel fuel (Suarez-Bertoa et al. 2019). It consists of straight-chain paraffinic hydrocarbons that are free from aromatics, sulphur and oxygen (Bortel et al. 2019). As the name implies the fuel is produced by hydrotreatment. Hydrogen is used in the hydrotreating process to remove oxygen and double-bonds from the structure of triglycerides. HVO can be produced not only from vegetable oil but from a variety of triglyceride-based biomass such as waste cooking oil and animal fats. (Suarez-Bertoa et al. 2019) The different feedstocks are presented in section 4.3.3.

HVO can be blended with fossil diesel and the use of HVO in a diesel engine does not require changes in the fuel supply infrastructure or adaptations of the vehicle powertrain (ibid.). However, the effects of using HVO in an engine might impact the engine performance and sometimes even improve the performance. The following information can give an indication of what results can be expected when using HVO for parts of the tests in the Audit Area test cells. The use of HVO may impact the engine performance in the ways presented below:

> Combustion Behavior
>
> The high cetane number of HVO can shorten ignition delay and accelerate start of combustion, especially on low and medium loads. On high loads the effect of high cetane number on start of combustion is less dominant. (Hunicz et al. 2020, p. 2)
>
> Injection Systems and Power Output
>
> When the fuel injection system is adapted to fossil diesel a sudden change from fossil diesel to HVO results in a decrease in maximum power. On the other hand, if the injection system is allowed to

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[10] Pelle Janson, Key Account Manager - Special Fuels, Preem. Communication per e-mail March 10th.

adapt to HVO and HVO is used the maximum power may be slightly increased compared to if the injection system is adapted to fossil diesel and fossil diesel is used. Furthermore, when the injection system is adapted to HVO a sudden change from using HVO to using fossil diesel results in an increase in maximum power.[11]

Engine Oil

Compared to fossil diesel HVO does not cause increased oil dilution, aging or thickening. (Neste 2020, p. 45)

Fuel Consumption and Engine Efficiency

The volumetric fuel consumption of HVO is slightly higher than of fossil diesel, and there is possibly a small improvement of engine efficiency when using HVO. (ibid., p. 47)

In table 4.1 the specification for the HVO used in this project is given. Because of a higher hydrogen content HVO has a slightly higher mass based heating value (MJ/kg) compared to Baseline Diesel (Hartikka et al. 2012) and thus, if engine efficiency remains constant, a slightly lower gravimetric fuel consumption can be expected for HVO compared to the Baseline Diesels. HVO has a lower volumetric heating value (MJ/l) compared to the Baseline Diesels and thus, if engine efficiency remains constant, a slightly higher volumetric fuel consumption can be expected for HVO compared to the Baseline Diesels. Theoretically for HVO, based on the values in table 4.1, per energy input the increase in volumetric fuel consumption would be around 5 % compared to BD1 and around 4 % compared to BD2 and the decrease in mass based fuel consumption would be around 2 % compared to BD1 and around 3 % compared to BD2.

### 4.1.4 Fuel Specifications

In table 4.1 characteristics for the fuels that are relevant in this project are given. The values are taken from specifications delivered with the fuel by the supplier Preem. The physical properties of different batches of the fuels can show variances. However these variances are assumed to have minimal impact on the results of the project and are not adjusted for in e.g. calculations. Characteristics of FAME are included since BD2 contains FAME. The characteristics for FAME are taken from Prussi et al. (2020, p. 41) and are not specifically given by the fuel supplier.

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[11] Magnus Fröberg, Technical Manager Fuels, Scania CV AB - NMER. Communication over Teams February 1st and May 9th 2022.

**Table 4.1:** Fuel specifications

| Parameter | BD1 | BD2 | HVO | FAME |
|---|---|---|---|---|
| **Volumetric heating value [MJ/l]** | 35.90 | 35.61 | 34.20 | 33.10 |
| **Gravimetric heating value [MJ/kg]** | 42.94 | 42.64 | 43.80 | 37.20 |
| **C/H-ratio [%m/m]** | 6.320 | 6.320 | 5.560 | |
| **Carbon content calc. [%m/m]** | 86.60 | 86.00 | 85.00 | 77.30 |
| **Hydrogen content calc. [%m/m]** | 13.70 | 13.60 | 15.30 | |
| **Density @ 15°C [kg/m$^3$]** | 835.0 | 835.1 | 780.1 | 890.0 |
| **Cetane number** | 53.00 | 53.50 | 71.70 | 56.00 |
| **FAME content [%V/V]** | <0.100 | 6.000 | <0.100 | 100.0 |
| **Sulphur content [mg/kg]** | <3.000 | 6.500 | <3.000 | |
| **Aromatic contents [%V/V]** | 15.10 | 13.40 | <1.000 | |

## 4.2 Findings regarding tailpipe emissions

The combustion emissions from running the engine on BD1, BD2 or HVO are the ones that are explained in section 2.1.2. According to a report by SAE International (Hartikka et al. 2012) based on a compilation of 40 scientific publications regarding the performance of using HVO in diesel engines, the use of HVO has beneficial impacts on the aftertreatment system and can decrease regulated and unregulated emissions as well as green house gas emissions. According to the report the use of HVO will impact emission characteristics in the ways presented below:

> Fuel Properties on Emissions
>
> The combustion emissions from combustion of HVO are lower compared to fossil diesel since HVO only consists of paraffinic hydrocarbons. Fossil diesel consists of aromatics, napthenes and paraffins. Engine out (before aftertreatment system) $NO_x$ and PM emissions are reduced due to absence of aromatics, higher H/C ratio and lower final boiling point. Engine out CO and HC are reduced due to high cetane number and absence of aromatics. Important to notice is that speed and load conditions impact the magnitude of emission reductions and the actual tailpipe emissions depend on the EGR rate and characteristics of the aftertreatment system. (Hartikka et al. 2012)
>
> Regulated Emissions
>
> Engines that comply with the Euro I, II and III standards have the highest yield of emissions reductions when running on HVO due to absence of complex aftertreatment systems and control strategies. For Euro IV, V and VI engines with more emission reduction devices show a low absolute change in tailpipe emissions when running on HVO. The effect of HVO on tailpipe emissions for Euro IV, V and VI engines varies from test to test. There are indications of that heavy-duty engines show a decrease in all emission species when using HVO instead of fossil market diesel. (ibid.)

$CO_2$ Emissions

The actual tailpipe $CO_2$ emissions (including biogenic $CO_2$ emissions) are shown to be slightly lower when running the engine on HVO compared to fossil diesel. This is due to the high H/C ratio of HVO. (Hartikka et al. 2012)

Table 4.2 displays the results from seven different studies regarding the change in emissions when using HVO compared to using conventional/market diesel. These are given in order to provide a picture of how HVO impacts emissions as well as the variation in results depending on study. Information regarding if the results are for engine out emissions (upstream of aftertreatment systems) or tailpipe emissions (downstream of aftertreatment systems) and for heavy-duty or light-duty engine is given in the table where $CO_2$ includes both biogenic and fossil, D = decrease and I = increase.

**Table 4.2:** Results from different studies of the change in emissions when using HVO compared to using conventional/market diesel.

| **Study** | **$NO_x$** | **HC** | **CO** | **$CO_2$** | **PM/PN** | **Comment** |
|---|---|---|---|---|---|---|
| (Suarez-Bertoa et al. 2019) | Same | Same | Same | D | Same | Tailpipe.<br>Light-duty. |
| (Bortel et al. 2019) | D | D | D | D | D | Engine out.<br>Light-duty. |
| (Athanasios et al. 2019) | Mixed trends | - | - | D | D | -<br>Light-duty. |
| (Wu et al. 2017) | Same | D | - | - | Same | Tailpipe.<br>Light-duty. |
| (Murtonen et al. 2010) | Mixed trends | Mixed trends | Mixed trends | D | D | Tailpipe.<br>Heavy-duty. |
| (Karavalakis et al. 2016) | Mixed trends | D | - | D | Mixed trends | Tailpipe.<br>Heavy-duty. |
| (Neste n.d.[a]) | D | D | D | - | D | Tailpipe.<br>- |

Considering the fact that biogenic $CO_2$ is reported as zero, the tailpipe $CO_2$ -emissions from HVO and from the 6 vol% of FAME in BD2 can be disregarded and assumed to equal zero. The amount of tailpipe $CO_2$ per fuel energy, the emission factor, for each fuel is given in table 4.3. Emission factors including biogenic *and* fossil $CO_2$ and emission factors including exclusively fossil $CO_2$ are given.

**Table 4.3:** Tailpipe $CO_2$ emission factors (rounded).

| | **Biogenic+fossil $CO_2$** [$gCO_2/MJ_{fuel}$] | **Fossil $CO_2$** [$gCO_2/MJ_{fuel}$] |
|---|---|---|
| **BD1** | 73.95 | 73.95 |
| **BD2** | 73.95 | 69.99 |
| **HVO** | 71.16 | 0 |

## 4.3 Findings regarding LCA emissions

### 4.3.1 Baseline Diesel 1

According to Council Directive (EU) 2015/652 (Council Of The European Union 2015) the LCA-value for fossil diesel is 95.1 $gCO_2e/MJ_{fuel}$ . This is also the value recommended to use by The Swedish Energy Agency (Energimyndigheten 2021c). Accordingly, in this report the LCA-value for BD1 is assumed to be 95.1 $gCO_2e/MJ_{fuel}$ .

### 4.3.2 Baseline Diesel 2

Since BD2 consists of both fossil diesel and FAME LCA-values must be found for both fuels in order to calculate the LCA-value for BD2.

FAME
On the Swedish market the most commonly used feedstock for production of FAME is rapeseed. In 2020 90 % of the feedstock for FAME on the Swedish market was rapeseed. Other feedstocks are used cooking oil and other residues. (Energimyndigheten 2021a, p. 29) In Europe also sunflower oil is a common feedstock. Methanol that is used in the production of FAME can be of either fossil or renewable origin. (f3 - Swedish Knowledge Centre for Renewable Transportation Fuels 2017) According to the supplier of BD2 the FAME in BD2 is made from rapeseed oil, called RME (Rapeseed Methyl Ester). The information obtained from the supplier combined with the fact that RME by far is the dominant FAME on the Swedish market and has been so for at least the last ten years (Energimyndigheten 2021a, p. 28), the focus of FAME in this report will exclusively be on RME.

Due to the uncertainties related to life cycle analyses a number of alternative LCA-values for RME are given in table 4.4.

**Table 4.4:** Alternative LCA-values for RME.

| **LCA-value** [$gCO_2e/MJ_{fuel}$ ] | **LCA-method and source** |
|---|---|
| 29.92 | Allocation/Attributional (Hallberg et al. 2013) |
| 28.97 | Unknown (Shell 2020) |
| 32.10 | Unknown (Circle K 2020) |
| 33.22 | System expansion/Consequential (Hallberg et al. 2013) |
| 34.00 | Attributional[12] |
| 55.22 | Consequential (Prussi et al. 2020) |
| 58.82 | Unknown (European Parliament 2009) |

BD2

Knowing the LCA-value for fossil diesel (see section 4.3) and RME an estimation of the LCA-value for BD2 is derived (see Appendix A.2.1 for calculations). From table 4.4 it is clear that the LCA-values for RME differ depending on source. In order to show the sensitivity depending on source, the LCA-value for BD2 when using the highest and lowest LCA-value for RME is given in table 4.5. However the value for BD2 that will be used as a basis for calculations in this report is the "reference" value, based on the LCA-value for RME from the fuel supplier Shell of 28.97 $gCO_2e/MJ_{fuel}$ . Preferably a value from Preem should be used since that is the relevant supplier for this project. However, no LCA-value for RME from Preem has been found.

**Table 4.5:** LCA-values for BD2.

| | **LCA-value** [$gCO_2e/MJ_{fuel}$ ] |
|---|---|
| **Highest** | 93.08 |
| **Lowest** | 91.40 |
| **Reference** | 91.40 |

### 4.3.3 Hydrotreated Vegetable Oil

The HVO used in this project is purchased from the Swedish petroleum and biofuel company Preem. Preem claims that the average LCA-based $CO_2e$ -emissions for their HVO is 13,7 $gCO_2e/MJ_{fuel}$ (Preem 2020).

In table 4.6 below LCA-values from the four largest diesel fuel suppliers on the Swedish market (Drivkraft Sverige 2020), including Preem, are given. The values are taken from the suppliers' "environmental information" 2020.

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[12] Magnus Fröberg, Technical Manager Fuels, Scania CV AB - NMER. Communication per e-mail February 2d 2022.

**Table 4.6:** LCA-values for HVO from different fuel suppliers.

| **Fuel supplier** | **LCA-value** [$gCO_2e/MJ_{fuel}$ ] |
|---|---|
| Shell | 11.26 (Shell 2020) |
| Preem | 13.70 (Preem 2020) |
| OKQ8/st1 | 22.25 (OKQ8 2020) |
| Circle K | 23.10 (Circle K 2020) |

The share of different feedstocks in the production of HVO are constantly changing and developing and so are the life cycle emissions relating to the feedstocks and production processes (Energimyndigheten 2021a, p. 27). In order to evaluate the emissions savings when exchanging BD1 or BD2 with HVO, it is necessary to perform an analysis over the different feedstocks and the related LCA-values. According to the Swedish Energy Agency (ibid.) the dominating feedstock used for the production of the HVO on the Swedish market in 2020 was slaughterhouse waste. See table 4.7 below for a list of the feedstocks for HVO on the Swedish market 2020 (ibid., p. 28).

**Table 4.7:** HVO feedstocks 2020 (Energimyndigheten 2021a, p. 28)

| **Feedstock** | **Share (of energy content)** |
|---|---|
| Slaughterhouse waste | 72 % |
| Crude tall oil | 12 % |
| Palm oil | 6 % |
| Rapeseed | 6 % |
| PFAD | 4 % |

The feedstocks presented in table 4.7 are further described below. Specific LCA-values are presented for each feedstock. In order to reflect the the HVO on the Swedish market specifically the values are all taken from the report *Well-to-wheel LCI data for HVO fuels on the Swedish market* (Källmén et al. 2019), except for the value for palm oil that is taken from the report *Well-to-wheel LCI data for fossil and renewable fuels on the Swedish market* (Hallberg et al. 2013). The value for palm oil is based on the method system expansion whereas the values for the other feedstocks are based on the method allocation or cut-off (cut-off if the feedstock is considered a residue). Animal residue are mentioned under varying names in literature. Here animal residue such as beef tallow, animal fat and slaughterhouse waste are all referred to as slaughterhouse waste.

**Table 4.8:** WTW LCA-values for the feedstocks for HVO on the Swedish market 2020.

| **Feedstocks** |
|---|
| **Slaughterhouse waste**<br>Slaughterhouse waste is considered a residue feedstock. This means none of the emissions associated with the production of the slaughterhouse waste is allocated to the feedstock (Källmén et al. 2019). According to Källmén et al. (2019), the well to wheel LCA-value for HVO produced from slaughterhouse waste is 33.44 $gCO_2e/MJ_{fuel}$ . |
| **Crude tall oil**<br>Crude tall oil is a viscous and sulfur-containing fluid that is a bi-product mainly from the pulp and paper industry (Preem n.d.). It is considered a residue feedstock. According to Källmén et al. (2019), the well to wheel LCA-value for HVO produced from crude tall oil is 7.091 $gCO_2e/MJ_{fuel}$ . |
| **Palm oil**<br>Palm oil is an edible vegetable oil origin from oil in palm fruits from palm trees. Palm oil is not considered a residue feedstock. Palm oil is widely used in food, animal feed and biofuels. The use of it has been criticised since it is a driver for deforestation of biodiverse forests. This deforestation causes destruction of the habitats of already endangered species as well as contributes to carbon leakage and greenhouse gas emissions (WWF n.d.) According to Hallberg et al. (2013), the well to wheel LCA-value for HVO produced from palm oil is 78.49 $gCO_2e/MJ_{fuel}$ . |
| **Rapeseed**<br>The oil from the oil-rich rapeseed crop is used in production of HVO. Rapeseed is not considered a residue feedstock. According to Källmén et al. (2019), the well to wheel LCA-value for HVO produced from rapeseed is 60.32 $gCO_2e/MJ_{fuel}$ . |
| **PFAD**<br>PFAD is short for Palm Fatty Acid Distillate. PFAD is derived from the refining process of palm oil. Parts of the fats in the palm fruit is degrading during transportation and processing of the fruit. In order to keep a certain quality standard of the palm oil, these degraded fats are removed from the palm oil and ending up as PFAD. (Neste n.d.[b]) Consequently, PFAD is considered a residue feedstock. According to Källmén et al. (2019), the well to wheel LCA-value for HVO produced from PFAD is 16.13 $gCO_2e/MJ_{fuel}$ . |

Using the LCA-value presented in table 4.8 for each feedstock a LCA-value for the average feedstock mix on the Swedish market (from table 4.7) is calculated and presented in table 4.10. Due to the risks for uncertainties related to values derived from life cycle analyses a number of LCA-values for the different feedstocks are given in table 4.9. The LCA methods the values are based on are given as well as the sources for the values. The highest and lowest LCA-values for the average feedstock mix on the Swedish market are also given in table 4.10 in order to show the sensitivity of the LCA-value when using different sources and values. Calculations are given in Appendix A.2.

**Table 4.9:** Alternative WTW LCA-values for the feedstocks for HVO on the Swedish market 2020.

| **Feedstock** | **LCA-value** [$gCO_2e/MJ_{fuel}$ ] | **LCA-method and source** |
|---|---|---|
| Slaughterhouse waste | 16.00 | Attributional[13] |
| | 33.44 | Cut-off/Attributional (Källmén et al. 2019) |
| Crude tall oil | 7.091 | Cut-off/Attributional (Källmén et al. 2019) |
| | 35.00 | Allocation/Attributional (Källmén et al. 2019) |
| Palm oil | 30.74 | Unknown (European Parliament 2009) |
| | 63.74 | Unknown (European Parliament 2009) |
| | 64.14 | Consequential (Prussi et al. 2020) |
| | 78.49 | System expansion/Consequential (Hallberg et al. 2013) |
| Rape seed | 53.64 | Consequential (Prussi et al. 2020) |
| | 60.32 | Allocation/Attributional (Källmén et al. 2019) |
| | 44.00 | Unknown (European Parliament 2009) |
| PFAD | 16.13 | Cut-off/Attributional (Källmén et al. 2019) |

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[13] Magnus Fröberg, Technical Manager Fuels, Scania CV AB - NMER. Communication per e-mail February 2d 2022.

**Table 4.10:** LCA-values for average HVO feedstock mix on the Swedish market.

| | **LCA-value** [$gCO_2e/MJ_{fuel}$ ] |
|---|---|
| **Highest** | 37.25 |
| **Lowest** | 17.60 |
| **Swedish mix** | 33.90 |

When calculating the overall life cycle $CO_2e$ -emissions reductions when using HVO in parts of the tests, two LCA-values will be considered. Firstly, the fuel supplier specific value from Preem (table 4.6) will be used. Preem is chosen because that is the fuel supplier from where the HVO in this project was purchased. Secondly, the "Swedish mix" value (table 4.10) for the average feedstock mix on the Swedish market will be used as an alternative that reflects the overall Swedish market and not represents a specific fuel supplier.

### 4.3.4 Conclusion LCA-values

**Table 4.11:** LCA-values for BD1, BD2 and HVO.

| | | **LCA-value** [$gCO_2e/MJ_{fuel}$ ] |
|---|---|---|
| **BD1** | | 95.10 |
| **BD2** | | 91.40 |
| **HVO** | Preem | 13.70 |
| | Swedish mix | 33.90 |

## 4.4 Findings regarding future availability and price development of HVO

### 4.4.1 Demand

The Swedish legislation "Reduktionsplikten", mentioned in section 4.1.2, is designed so that the fuel suppliers must reduce greenhouse gas emissions per energy content from all fuels used as engine fuels containing maximum 98 % biofuel by a certain percentage each year until 2030 (Energimyndigheten 2021c). The percentage is in relation to a default emissions value for the 100 % fossil equivalent fuel. The greenhouse gas emissions reduction percentage will increase for the upcoming years as in table 4.12. "Reduktionsplikten" was introduced in 2018 and the purpose of the legislation is to decrease the greenhouse gas emissions from domestic transportation. How "Reduktionsplikten" impacts the use, supply and price of biofuels, including HVO, will be explained in the following.

**Table 4.12:** Greenhouse gas emissions reduction percentage 2020-2030 for diesel, according to Law (2017:1201) (Sveriges Riksdag 2017).

| **Year** | **Reduction percentage** [%] |
|---|---|
| 2020 | 21.0 |
| 2021 | 26.0 |
| 2022 | 30.5 |
| 2023 | 35.0 |
| 2024 | 40.0 |
| 2025 | 45.0 |
| 2026 | 50.0 |
| 2027 | 54.0 |
| 2028 | 58.0 |
| 2029 | 62.0 |
| 2030 | 66.0 |

The maximum amount of FAME allowed to add in market diesel is 7 vol% (European Parliament and the Council of the European Union 1998). A 7 % addition of FAME is not enough to reach the reduction percentages established in ”Reduktionsplikten”. FAME and HVO are the only two biofuels that are added to diesel in a large scale and consequently the by far most added biofuel in 2018, 2019 and 2020 was HVO (Energimyndigheten 2021a, p. 38).

The Swedish Energy Agency has made estimations over the development of the Swedish energy system up to and including 2050 (Energimyndigheten 2020). The estimations were compiled in 2020 (with base year being 2018) and aim at analysing the development of the energy system according to six different scenarios. The scenarios are the following:

- *Reference EU*: Prerequisites for price development of emission allowances and fossil fuels taken from the EU Commission.
- *Lower BNP*: Prerequisites are the same as in *Reference EU*, besides that a lower economic development is assumed.
- *Lower energy prices*: Prerequisites are the same as in *Reference EU*, besides that lower prices on emission allowances and fossil fuels are assumed.
- *Additional measures*: Based on the emission reduction percentage levels with regards to ”Reduktionsplikten” laid out in the Budget Bill 2021 (the same values for 2030 as the current ones, see table 4.12 above), a ”Reduktionsplikten” for renewable fuel for aviation and continued tax reductions for pure and high share biofuels.

- *Electrification*: Higher speed of electrification in different sectors. The measures in scenario *Additional measures* are included.
- *Sensitivity case with higher or lower traffic work, respectively*: Two sensitivity cases are established, with 10 % increase and decrease in traffic work, respectively.

The first three scenarios are based on policies implemented before, up to and including $1^{st}$ of July 2020. The estimations over the development of the energy system for those three scenarios is based on the assumption that no additional policies are implemented.

Only in the scenarios *Additional measures* and *Electrification* the emission reduction percentages in "Reduktionsplikten" are assumed to be the same as the actual levels today (Energimyndigheten 2020, p. 69). In the other scenarios the emission reduction percentages are assumed the same as it was in 2020 for the whole period (ibid., p. 140). Thus it is likely that the most representative scenarios to consider regarding the future consumption of HVO are *Additional measures* and *Electrification.* Although, in the two scenarios the current tax reductions for high share and pure biofuels are assumed to stay in force until 2050 (ibid., p. 139). It is however not certain whether or not these tax reductions will continue after 2022 (instead HVO might be included in "Reduktionsplikten") (Finansdepartementet 2022). This might imply that the biofuel consumption is overestimated in the two scenarios. Nevertheless, the tax reduction is estimated to have a much smaller effect on the biofuel consumption than "Reduktionspliken" so the overestimation is moderate. (Energimyndigheten 2020, p. 7) The two scenarios are based on the assumption that the availability of biofuels as well as charging infrastructure is unlimited or sufficient to cover the needs. (ibid., p. 28)

In figure 4.1 the estimations of HVO consumption in TWh from 2025-2050 for the two scenarios are given. The HVO consumption increases in both scenarios until 2030 whereafter it decreases due to an increased electrification that lowers the demand for biofuels such as HVO. Additionally, no increase in emissions reduction percentage in "Reduktionsplikten" is included after 2030. (ibid., p. 7) The HVO consumption is estimated to be lower at all times in *Electrification* compared to *Additional Measures* due to the higher share of electrification of the vehicle fleet in *Electrification* (ibid., p. 22, 102). In absolute numbers the HVO consumption in 2050 compared to 2020 (Energimyndigheten 2021a, p. 26) is slightly higher for *Additional measures* and about the same for *Electrification.* (Energimyndigheten 2020, p. 97, 102)

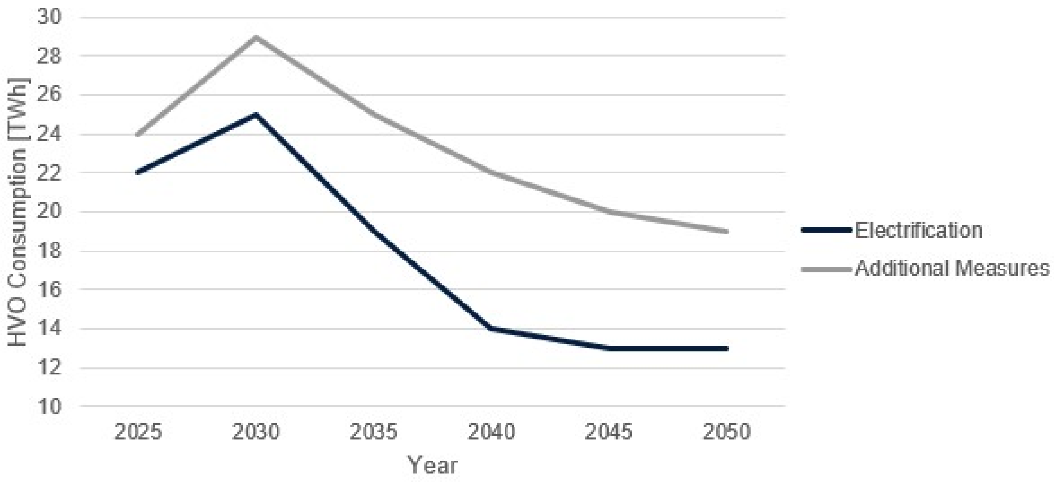

**Figure 4.1:** Prognosis of HVO consumption 2025-2050 according to the scenarios *Additional Measures* and *Electrification* (Energimyndigheten 2020, p. 97, 102).

Stated in a more recent report composed by The Swedish Energy Agency is that an absence of increase in emissions reduction percentage after 2030 is unrealistic considering the Swedish goal of zero net emissions 2045. (Energimyndigheten 2021e)

Since Sweden alone uses around 30 % of the global supply of HVO and 55 % of the supply in EU (ibid., p. 17-18), and only around 5 % of the HVO used in Sweden is produced in Sweden (Sydost 2021), it is important to consider also international patterns in the demand, availability and price for biofuels. A report from OECD/FAO (Organisation for Economic CO-operation and Development, Food and Agriculture Organization of the United Nations 2021, p. 208) states that the global as well as the European demand for biodiesel, including FAME and HVO, will stay the same or increase only slightly until 2026 and thereafter decrease slightly until 2030. The reason for the decrease is claimed to mainly relate to that EU classifies palm-oil based diesel under the high risk category Indirect Land Use Change (ILUC). On the other hand a report written by the International Energy Agency (IEA) states that the global demand for HVO might nearly triple between 2020 and 2026, where the majority of the increase in HVO demand derives from Europe and the United States (IEA 2021, p. 91). A report written by the management consultant firm Material Economics states that if current trends of increasing demand continue the global demand for biofuels and biomass might exceed the global supply by 40-100 %. The report states that a major course correction is needed from EU policymakers and business leaders in order to change the current trends (Material Economics 2021).

### 4.4.2 Supply and price development

The Swedish as well as the overall global production capacity of biofuels, including HVO, is expected to increase over the upcoming years (IEA 2021, p. 95). Although the possibility of producing enough HVO to meet the demands is not limited foremost by the amount of installed production capacity but by the availability of raw materials and the competition of the raw material between different fuel types. The Swedish or European situations for the most common feedstocks for production of HVO are the following (Energimyndigheten 2021e, p. 24):

- *Slaughterhouse waste:* Sweden is dependent on import. Due to climate action the consumption of meat is estimated to decrease in the future and thus also the slaughterhouse waste.

- *Crude tall oil:* Dependent on the development of the forest industry. As for now the Swedish supply is deemed mortgaged.
- *Palm oil:* Can not be cultivated in Sweden and from 2022 is not allowed to be included in ”Reduktionsplikten”.
- *Rape seed:* The use in biofuel production is limited in the EU Taxonomy and in the EU Renewable Energy Directive.
- *Used cooking oil:* The use is problematic since it is massively globally imported from Asia where domestic use of used cooking oil has been replaced with increased use of palm oil, other virgin oils or fossil fuels.

There are a few additional raw materials, such as branches and wood waste, that may have potential to contribute at least to the Swedish production of biofuels. Although not enough to meet the estimated demands up to 2030 (Energimyndigheten 2021e, p. 25).

According to estimations over the price development of HVO laid out in the scenarios by the Swedish Energy Agency the price of HVO will stay the same until 2050. However, that price estimation is based on the assumption that the availability of HVO is not a limiting factor and thus that the availability is not affecting the price. (Energimyndigheten 2020, p. 141) The Agency states in the report that there is great uncertainty regarding the price development of biofuels (ibid., p. 119). The Agency also states that there is a risk that the price and competition of biofuels increase as a consequence of rising demands for biofuels in the rest of the world. (ibid., p. 28)

Furthermore The Swedish Energy Agency publishes a monthly report over the situation on the energy markets with a special focus on biofuels and biomass. The Agency states that the price of average European market HVO has increased from around 10 SEK/l in November 2020 to almost 23 SEK/l in March 2022. Historical prices for HVO from 2016 until March 2022 for companies purchasing HVO from the fuel companies OKQ8 and Preem are given in figure 4.2 below. The figure shows an overall increase in HVO prices since 2016 and a remarkably steep increase during 2022. 2016 is chosen since that is the first year with complete and available data from the fuel companies. There is a lack of data for April-October 2020 for the prices from Preem.

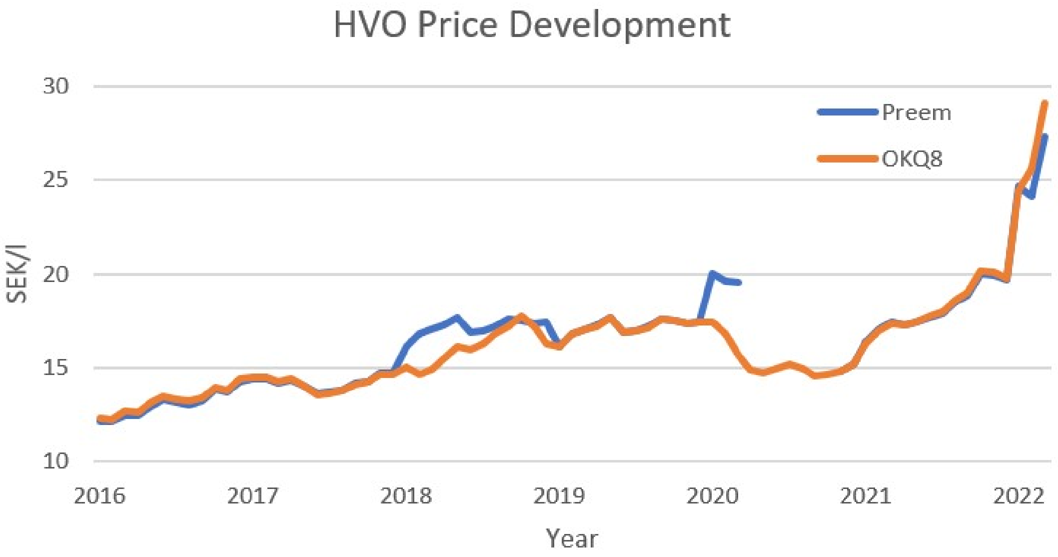

**Figure 4.2:** Development of HVO-prices for companies buying from OKQ8 and Preem. (OKQ8 2022) (Preem 2022)

The Swedish Energy Agency explains the price increase during 2022 by high prices on raw material as a consequence of the demand for HVO and that the producers of renewable aviation fuel demand the same type of raw material (Energimyndigheten 2022c). Also an increased demand of HVO in Europe in combination with limited increases in production capacity during 2022 affects the price (Energimyndigheten 2022b) as well as high prices of the natural gas used in the production processes of HVO (Energimyndigheten 2022d). The prices of natural gas might increase even more since the Russian invasion of Ukraine and its consequences on the geopolitical situation can lead to either that Russia decreases its export of gas to EU or that EU decides to stop or decrease the import of Russian gas (Energimyndigheten 2022a). Around 40 % of the gas import in EU originate from Russia (Infrastrukturdepartementet 2022).

According to the report by OECD/FAO (Organisation for Economic CO-operation and Development, Food and Agriculture Organization of the United Nations 2021, p. 208) the international biodiesel prices are expected to increase expressed in nominal terms and decrease expressed in real terms until 2030. Furthermore the report states that domestic and international prices often diverge due to national policies. (ibid., p. 205) Biofuel prices are, beside being related to feedstock prices, crude oil price and distributions costs, strongly affected by national policies (ibid.).

## 4.5 Findings regarding modifications

### 4.5.1 Storage

The way HVO was supplied into the engine in this project (by placing fuel barrels in the Audit Area test cells) is not a long-term solution. Depending on the amount of HVO that will be used in the Audit Area in the future different kind of solutions are needed. Using more than one cubic meter of HVO per week probably requires a cistern or a container solution. The cistern solution requires soil preparation whereas the container solution is somewhat simpler and does not require soil preparation. For both the cistern and the container solutions electrical wiring, pump systems and piping is needed. No fuel storage should be inside the building and thus the cistern or container is placed outside of the building and the piping goes through a pipe bridge into the building and down to the basement. Pipes for refueling the container or cistern must also be installed. The time needed for implementation is dependent on how much additional time that is needed for performing pre-studies. Also, if the project is decided to be put into reality the installation of the storage solution as well as the electrical wiring, pump system and piping require some time. Furthermore, environmental permits and risk assessments have to be carried out.[14]

### 4.5.2 Fuel system

From the basement in the building the fuel is supplied to the Audit Area test cells through pipes. There are two test cells in the Audit Area and when adding the use of HVO two new pipes have to be installed from the basement into the cells.[15]

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[14] Björn Davidsson, Process Engineer, Scania CV AB - DETF. Communication April 11th 2022.

[15] ibid.

# Chapter 5

# Results

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*This chapter gives the results from the three experiments as well as the results regarding fuel consumption and emissions for the reference case and the alternative fuel case.*

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## 5.1 Results regarding experimental testing

For the results from the experimental testing green-marked means that the result is within the applicable limits. Yellow-marked means the result is outside the QA-limits (but within the COP-limits, if COP-limits apply). Red-marked means the result is outside the COP-limits. If the result is above the applicable limit it is marked as ”above”. If the result is below the applicable limit it is marked as ”below”. Note that not all measurements have both COP- and QA-limits, see the Methodology-section (section 3).

### 5.1.1 Experiment 1

Power test, WHSC and WHTC run with BD2. All other parts run with HVO. The results from power test, WHSC and WHTC are presented below.

**Power test**

Results from the measurements required by COP are displayed in table 5.1.

**Table 5.1:** Results for power test-measurements required by COP.

| **Speed** | **Intake depression** [mbar] | **Exhaust back-pressure** [mbar] | **Net power** [kW] | **Delta** [mg/str] |
|---|---|---|---|---|
| **1800** | 🟩 | 🟩 | 🟩 | 🟩 |
| **1640** | - | - | 🟩 | - |
| **1340** | - | - | 🟩 | - |
| **1100** | - | - | 🟩 | - |
| **925** | - | - | 🟩 | - |

Results from the measurements required by QA are displayed in table 5.2 and table 5.3.

**Table 5.2:** Results for power test-measurements required by QA.

| **Speed** | **Net power** [g/kWh] | **NO$_x$** [g/kWh] | **Smoke** [mg/m$^3$] | **Delta** [mg/str] | **bsfc** [g/kWh] | **CO (pre cat.)** [ppm] | **HC (pre cat.)** [ppm] |
|---|---|---|---|---|---|---|---|
| **1800** | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| **1640** | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| **1340** | 🟩 | 🟩 | 🟩 | above | 🟩 | 🟩 | 🟩 |
| **1100** | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| **925** | 🟩 | 🟩 | 🟩 | above | above | 🟩 | 🟩 |

**Table 5.3:** Results for power test-measurements required by QA.

| **Speed** | **Temp after comp.** [◦ C] | **Temp inlet manifold.** [◦ C] | **Boost pressure after int. cooler** [bar] | **Temp after turbine.** [◦ C] | **SCR temp** [K] | **Lambda** [-] |
|---|---|---|---|---|---|---|
| **1800** | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| **1640** | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| **1340** | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| **1100** | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| **925** | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |

### WHSC

Results from the measurements required by COP are displayed in figure 5.4.

**Table 5.4:** Results from WHSC.

| **CO** [g/kWh] | **HC** [g/kWh] | **NO$_x$** [g/kWh] | **PM** [g/kWh] | **PN** [#/kWh] | **bsfc** [g/kWh] |
|---|---|---|---|---|---|
| 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |

### WHTC

Results from the measurements required by QA are displayed in table 5.5.

**Table 5.5:** Results from WHTC.

| **CO** [g/kWh] | **HC** [g/kWh] | **NO$_x$** [g/kWh] | **PM** [g/kWh] | **PN** [#/kWh] | **NH$_3$** [ppm] | **bsfc** [g/kWh] |
|---|---|---|---|---|---|---|
| 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |

## 5.1.2 Experiment 2

All the results are for power tests that are run with BD2.

A.1 Power test after FIA with HVO

A.2 Power test after FIA with HVO

A.3 Power test after FIA with HVO

B.1 Power test after FIA with BD2

B.2 Power test after FIA with BD2

### Measured power output

Table 5.6 shows the net power measurements for A.1-A.3 and B.1-B.2 at the five different speeds. Figure 5.1 graphically displays the net power measurements for A.1-A.3 and B.1-B.2 at the five different speeds.

**Table 5.6:** The net power measurements for A.1-A.3 and B.1-B.2.

| **Speed** | **A.1** [kW] | **A.2** [kW] | **A.3** [kW] | **B.1** [kW] | **B.2** [kW] |
|---|---|---|---|---|---|
| **1800** | above | above | above | 🟩 | 🟩 |
| **1640** | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| **1340** | above | above | above | 🟩 | 🟩 |
| **1100** | above | above | above | 🟩 | 🟩 |
| **925** | above | above | above | 🟩 | 🟩 |

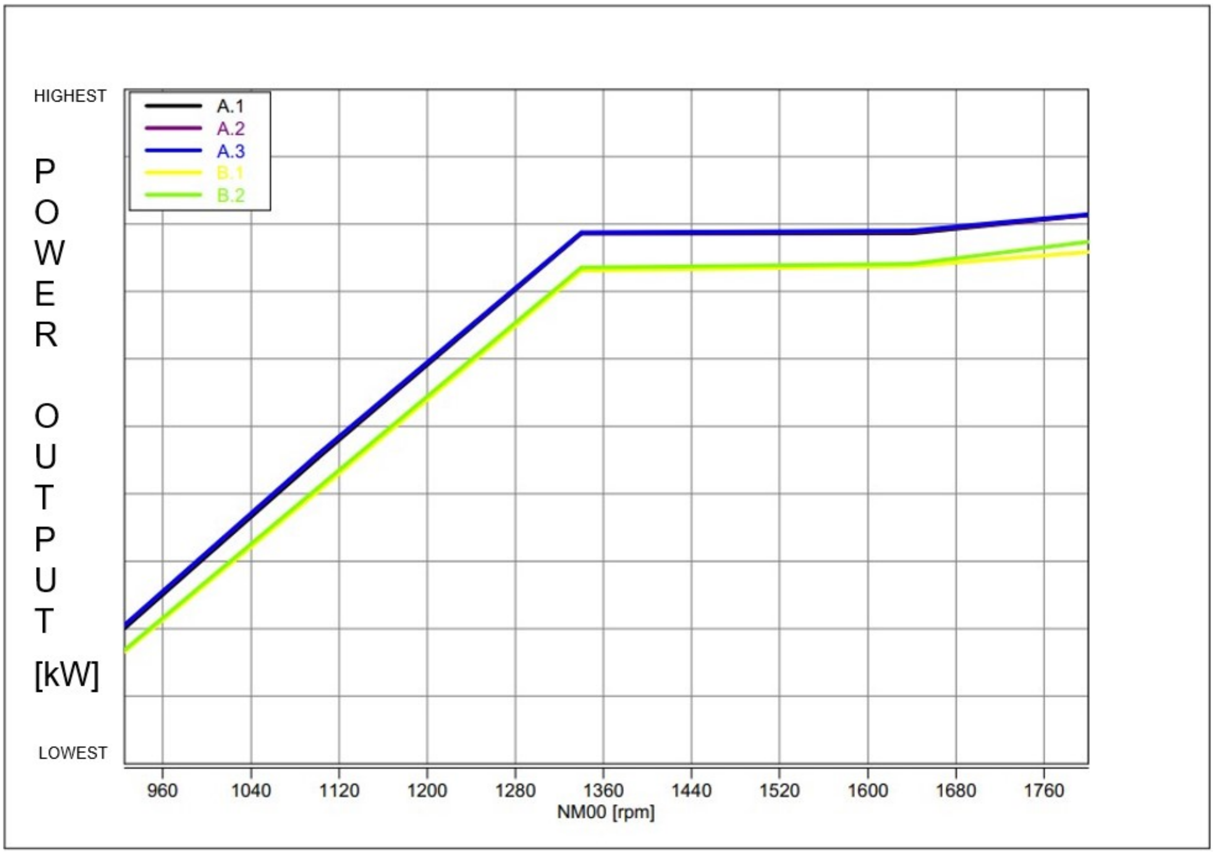

**Figure 5.1:** Results of measured power output in experiment 2.

### Measured delta

Table 5.7 shows the delta measurements for A.1-A.3 and B.1-B.2 at the five different speeds. Figure 5.2 graphically displays the delta measurements for A.1-A.3 and B.1-B.2 at the five different speeds.

**Table 5.7:** The delta measurements for A.1-A.3 and B.1-B.2.

| **Speed** | **A.1** [mg/str] | **A.2** [mg/str] | **A.3** [mg/str] | **B.1** [mg/str] | **B.2** [mg/str] |
|---|---|---|---|---|---|
| **1800** | above | above | above | 🟩 | 🟩 |
| **1640** | above | 🟩 | 🟩 | 🟩 | 🟩 |
| **1340** | above | above | above | 🟩 | 🟩 |
| **1100** | above | above | above | 🟩 | 🟩 |
| **925** | above | above | above | 🟩 | 🟩 |

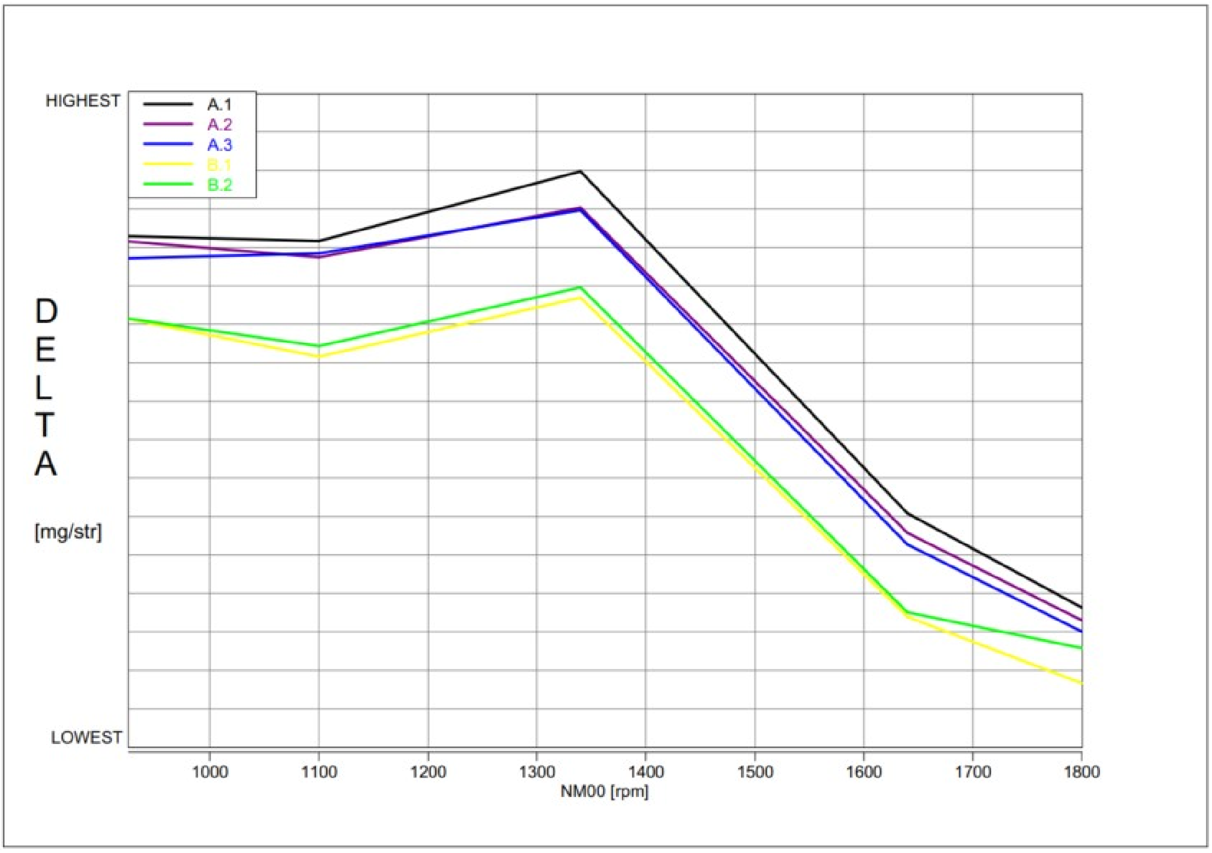

**Figure 5.2:** Results of measured delta in experiment 2.

### Measured bsfc

Table 5.8 shows the bsfc measurements for A.1-A.3 and B.1-B.2 at the five different speeds. Figure 5.3 graphically displays the bsfc measurements for A.1-A.3 and B.1-B.2 at the five different speeds.

**Table 5.8:** The bsfc measurements for A.1-A.3 and B.1-B.2.

| Speed | A.1 [g/kWh] | A.2 [g/kWh] | A.3 [g/kWh] | B.1 [g/kWh] | B.2 [g/kWh] |
|---|---|---|---|---|---|
| **1800** | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] |
| **1640** | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] |
| **1340** | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] |
| **1100** | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] |
| **925** | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] |

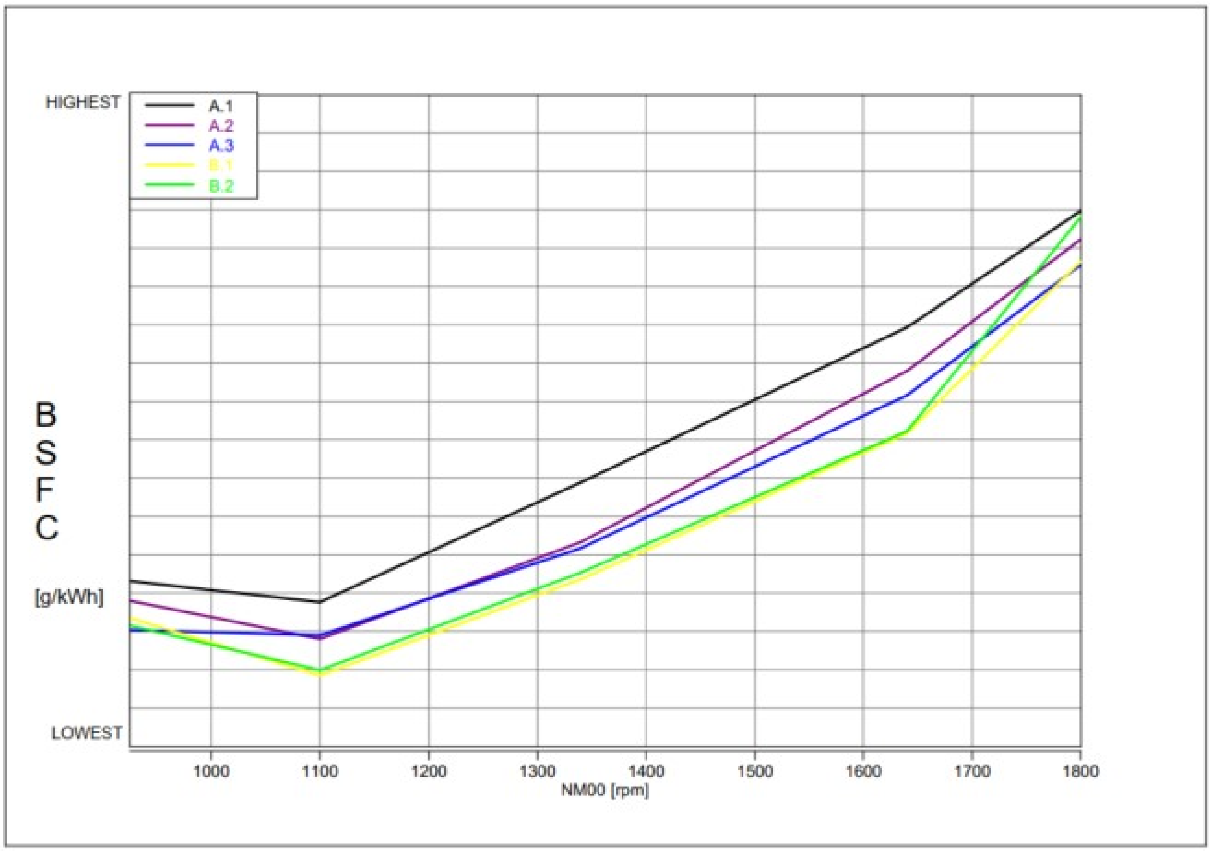

**Figure 5.3:** Results of measured bsfc in experiment 2.

### Delta vs $\text{delta}_{\text{demanded}}$

Table 5.9 shows a comparison between delta and $\text{delta}_{\text{demanded}}$ for A.1-A.3 and B.1-B.2 at the five different speeds. The comparison is expressed in the percentage of increase/decrease of delta compared to $\text{delta}_{\text{demanded}}$.

**Table 5.9:** Comparison between delta and $\text{delta}_{\text{demanded}}$ for A.1-A.3 and B.1-B.2.

| **Speed** | **A.1** [%] | **A.2** [%] | **A.3** [%] | **B.1** [%] | **B.2** [%] |
|---|---|---|---|---|---|
| **1800** | 2.168 | 3.696 | 3.088 | 0.184 | 0.441 |
| **1640** | -1.310 | 2.847 | 2.240 | -1.260 | -1.085 |
| **1340** | 0.807 | 4.499 | 4.367 | 0.281 | 0.557 |
| **1100** | -0.031 | 4.069 | 4.247 | -0.165 | 0.318 |
| **925** | 0.303 | 3.880 | 3.096 | 0.218 | 0.233 |

## 5.1.3 Experiment 3

All the results are for power tests that are run with BD2.

C.1 Power test after FIA with HVO

C.2 Power test after FIA with HVO

D.1 Power test after FIA with BD2

D.2 Power test after FIA with BD2

### Measured power output

Table 5.10 shows the net power measurements for C.1-C.2 and D.1-D.2 at the five different speeds. Figure 5.4 graphically displays the net power measurements for C.1-C.2 and D.1-D.2 at the five different speeds.

**Table 5.10:** The net power measurements for C.1-C.2 and D.1-D.2.

| **Speed** | **C.1** [kW] | **C.2** [kW] | **D.1** [kW] | **D.2** [kW] |
|---|---|---|---|---|
| **1800** | above | above | 🟩 | 🟩 |
| **1640** | 🟩 | 🟩 | 🟩 | 🟩 |
| **1340** | above | above | 🟩 | 🟩 |
| **1100** | above | above | 🟩 | 🟩 |
| **925** | above | above | 🟩 | 🟩 |

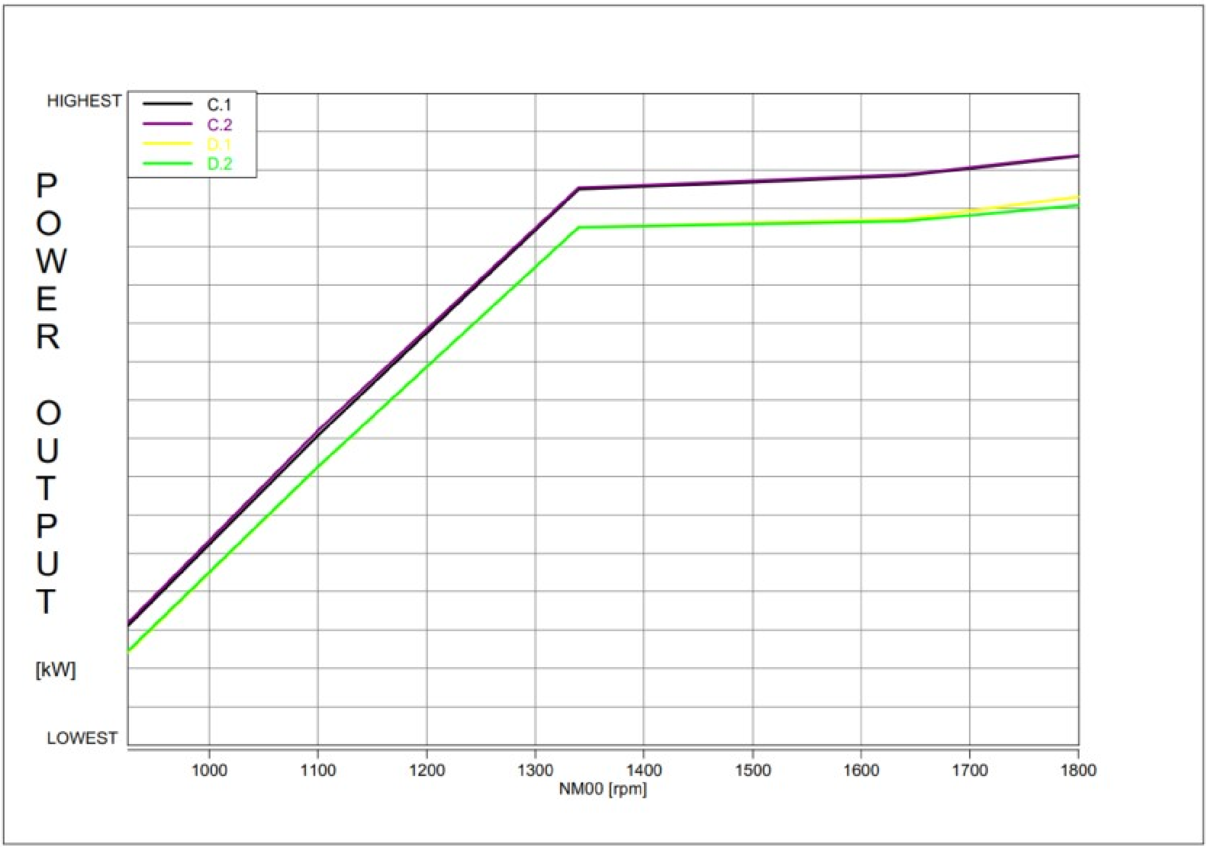

**Figure 5.4:** Results of measured power output in experiment 3.

### Measured delta

Table 5.11 shows the delta measurements for C.1-C.2 and D.1-D.2 at the five different speeds. Figure 5.5 graphically displays the delta measurements for C.1-C.2 and D.1-D.2 at the five different speeds.

**Table 5.11:** The delta measurements for C.1-C.2 and D.1-D.2.

| Speed | C.1 [mg/str] | C.2 [mg/str] | D.1 [mg/str] | D.2 [mg/str] |
|---|---|---|---|---|
| **1800** | above | above | 🟩 | 🟩 |
| **1640** | 🟩 | 🟩 | 🟩 | 🟩 |
| **1340** | above | above | 🟩 | 🟩 |
| **1100** | above | above | 🟩 | 🟩 |
| **925** | above | above | 🟩 | 🟩 |

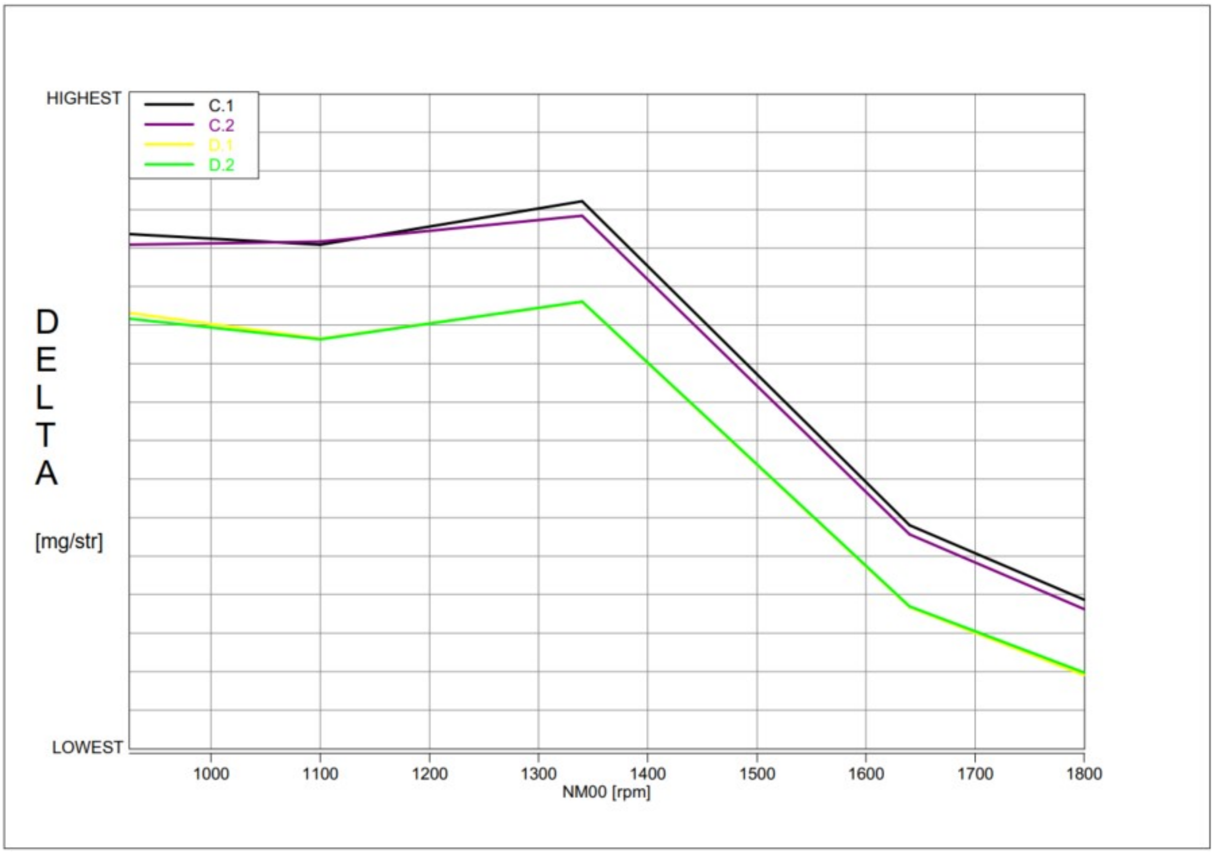

**Figure 5.5:** Results of measured delta in experiment 3.

### Measured bsfc

Table 5.12 shows the bsfc measurements for C.1-C.2 and D.1-D.2 at the five different speeds. Figure 5.6 graphically displays the bsfc measurements for C.1-C.2 and D.1-D.2 at the five different speeds.

**Table 5.12:** The bsfc measurements for C.1-C.2 and D.1-D.2.

| **Speed** | **C.1** [g/kWh] | **C.2** [g/kWh] | **D.1** [g/kWh] | **D.2** [g/kWh] |
|---|---|---|---|---|
| **1800** | [redacted] | [redacted] | [redacted] | [redacted] |
| **1640** | [redacted] | [redacted] | [redacted] | [redacted] |
| **1340** | [redacted] | [redacted] | [redacted] | [redacted] |
| **1100** | [redacted] | [redacted] | [redacted] | [redacted] |
| **925** | [redacted] | [redacted] | [redacted] | [redacted] |

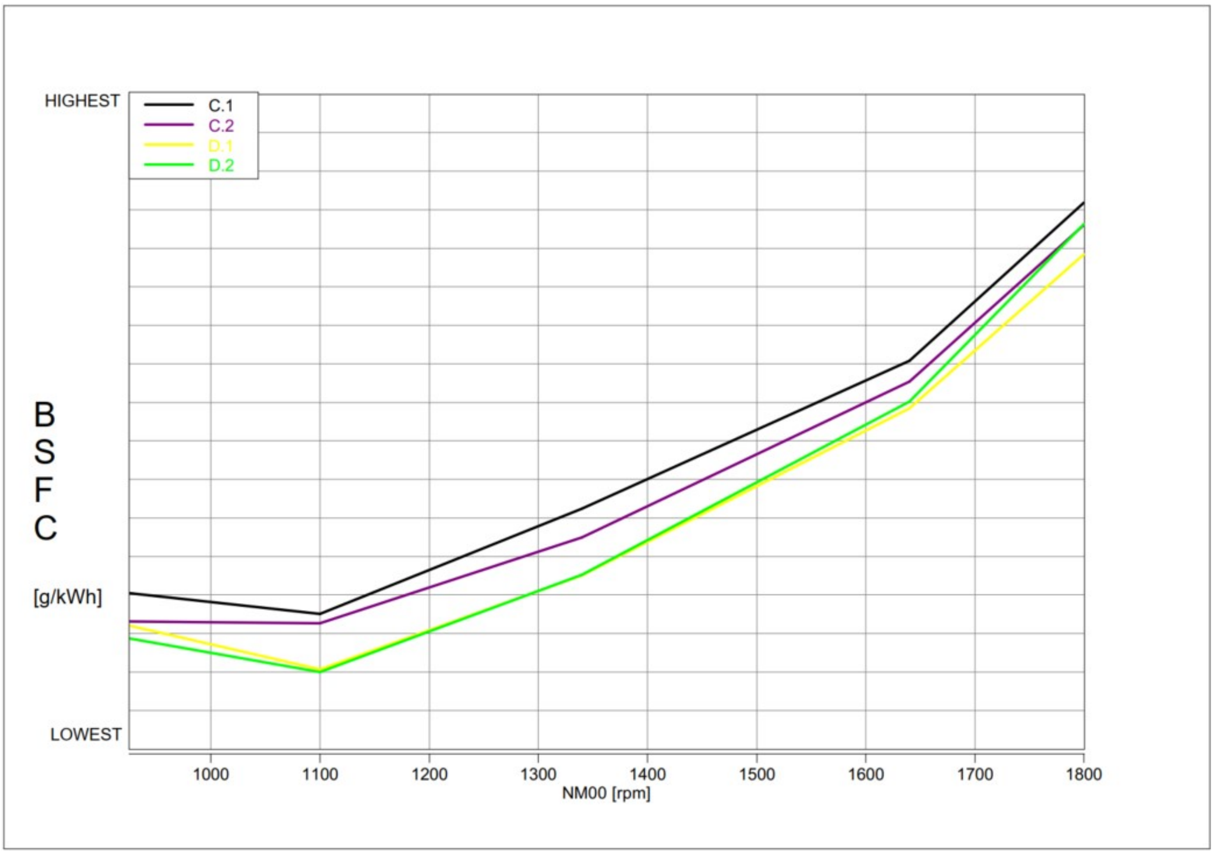

**Figure 5.6:** Results of measured bsfc in experiment 3.

### Delta vs delta$_{\text{demanded}}$

Table 5.13 shows a comparison between delta and delta$_{\text{demanded}}$ for C.1-C.2 and D.1-D.2 at the five different speeds. The comparison is expressed in the percentage of increase/decrease of delta compared to delta$_{\text{demanded}}$.

**Table 5.13:** Comparison between delta and $\text{delta}_{\text{demanded}}$ for C.1-C.2 and D.1-D.2.

| **Speed** | **C.1** [%] | **C.2** [%] | **D.1** [%] | **D.2** [%] |
|---|---|---|---|---|
| **1800** | 5.002 | 4.039 | 0.401 | 0.358 |
| **1640** | 3.325 | 2.708 | -1.266 | -1.231 |
| **1340** | 5.179 | 4.437 | 0.272 | 0.304 |
| **1100** | 4.440 | 4.453 | 0.374 | 0.362 |
| **925** | 4.492 | 3.809 | 0.562 | 0.351 |

## 5.2 Results regarding emissions

The emission-calculations are given in Appendix B.

### 5.2.1 Fuel consumption

Estimated yearly fuel consumption based on fuel consumption of the, for this project relevant, number of tests performed during 2021 in the Audit Area is presented in table 5.14 below.

**Table 5.14:** Estimated yearly fuel consumption based on fuel consumption of the, for this project relevant, tests performed during 2021 in the Audit Area.

| | **BD1** [MJ], [l] | **BD2** [MJ], [l] | **HVO** [MJ], [l] |
|---|---|---|---|
| **Reference case** | 280 200, 7 816 | 1 357 000, 38 115 | 0, 0 |
| **HVO case** | 99 410, 2 773 | 313 700, 8 808 | 1 224 000, 35 830 |

### 5.2.2 Tailpipe emissions

Table 5.15 presents the yearly tailpipe $CO_2$ -emissions based on the fuel consumption presented in table 5.14 and the emission factors presented in table 4.3 in section 4.2. The emissions are presented in tonnes $CO_2$ .

**Table 5.15:** Yearly tailpipe $CO_2$ emissions for the two cases.

| | **Biogenic + fossil** [t$CO_2$ ] | **Fossil** [t$CO_2$ ] |
|---|---|---|
| **Reference case** | 121.1 | 115.7 |
| **HVO case** | 117.7 | 29.30 |

Table 5.16 presents the decrease in tailpipe $CO_2$ -emissions for HVO case compared to reference case. The decrease is also presented relative to emissions from Engine Assembly and Scania's operations.

**Table 5.16:** Decrease in tailpipe $CO_2$ -emissions for HVO case compared to reference case.

| | **Biogenic + fossil** | **Fossil** |
|---|---|---|
| **Absolute numbers** [t$CO_2$ ] | 3.422 | 86.41 |
| **Relative to reference case** [%] | 2.826 | 74.68 |
| **Relative to Engine Assembly** [%] | - | 4.347 |
| **Relative to Scania's operations** [%] | - | 0.082 |

### 5.2.3 LCA emissions

Table 5.17 presents the yearly LCA-emissions based on the fuel consumption presented in table 5.14 and the emission factors presented in table 4.11 in section 4.3.4. The emissions are presented in tonnes $CO_2$e . ”Sensitivity 1” is based on the LCA-value for HVO from Preem and ”Sensitivity 2” is based on the ”Swedish mix” LCA-value for HVO (see table 4.11).

**Table 5.17:** Yearly LCA emissions for the two cases.

| | **Sensitivity 1** [t$CO_2$e ] | **Sensitivity 2** [t$CO_2$e ] |
|---|---|---|
| **Reference case** | 150.7 | 150.7 |
| **HVO case** | 54.90 | 79.63 |

Table 5.18 presents the decrease in LCA $CO_2$e -emissions for HVO case compared to reference case.

**Table 5.18:** Decrease in LCA $CO_2$e -emissions for HVO case compared to reference case.

| | **Sensitivity 1** | **Sensitivity 2** |
|---|---|---|
| **Absolute numbers** [t$CO_2$e ] | 95.81 | 71.07 |
| **Relative to reference case** [%] | 63.57 | 47.16 |

# Chapter 6

# Discussion

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*In this chapter the results presented in section 4 ”Findings from case study and literature study” and section 5 ”Results” are further analysed and discussed.*

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## 6.1 What alternative fuel(s) are technically possible to use during running time?

In Appendix C a technical interpretation of the results from the three experiment is given. This section is focused on the overall results from the experiments.

### Experiment 1

Since the difference between experiment 1 and an ”ordinary” test procedure was that all test-parts except power test, WHSC and WHTC was run with HVO it is likely that the deviation from QA-limits in the power test is related to the use of HVO. However, since the results are within all COP-limits this engine is ”legally” approved and overall the results from experiment 1 indicate that it is be possible to run all parts except power test, WHSC and WHTC with HVO.

### Experiment 2

Both for A.1-A.3 and B.1-B.2 the first two parts of the test ”engine installations, auxiliary adjustments and engine adaptations” and ”nulled power” were carried out with HVO. Moreover only for A.1-A.3 also the third part, the fuel injection adaptation FIA, was carried out with HVO. The results for B.1-B.2 are within the applicable limits even though the first two parts where performed with HVO. Thus there are indications of that running those two first parts with HVO and the subsequent FIA and power test with baseline diesel is not causing the results from the power test to be outside the limits. Although, running also the FIA wih HVO causes some of the results from the power test to be outside limits. Not only outside QA-limits but also, for the net power output, outside the legislative COP-limits. The engine would thus not be ”legally” approved.

**Experiment 3**

The results from experiment 3 basically indicate the same as the results from experiment 2. The first two parts of the test "engine installations, auxiliary adjustments and engine adaptations" and "nulled power" were carried out with baseline diesel in this experiment. The results thus indicate that specifically running FIA with HVO is the reason why some of the results from the power test are outside QA-limits, and for some parameters at some speeds also outside COP-limits. Neither this engine would be "legally" approved.

### 6.1.1 Overall discussion technical possibility

It is clear that in experiment 1 all measurements were within the applicable COP-limits and almost all measurements were within the applicable QA-limits. However, this was not the case in experiment 2 and 3. There are clear indications of that running FIA with HVO causes problems. The increase in power output when performing power test with baseline diesel directly after FIA was performed with HVO is in accordance with theory, see section 4.1.3. The power output and some of the other analyzed measurements of the power test are increased to the extent that the engines in experiment 2 and 3 are not within limits at all speeds and thus the engines would not be approved. This implies that it is not possible to perform FIA with HVO if the limits or the test layout is not changed. Suggested solutions to the problem of running FIA with HVO are the following:

- Assuming that the fuel properties of HVO and the fuel properties of the baseline diesel are perfectly constant, a factor can be derived that is "translating" the results from the power test after FIA with HVO to the corresponding results if FIA was performed with baseline diesel. However there might be a source of error and a risk related to this due to that the assumption of completely constant fuel properties has to be made. Additionally, this will probably require quite a lot of testing to make sure the factor is applied correctly for all engine types. The factor will most likely vary depending on engine type. Furthermore, whether this solution is legislatively acceptable must be looked into.

- Perform the tests at the R&D-department, where the test layouts are designed and the limits established, with HVO during FIA and then set the limits in regard to that. However, this will probably also require a lot of testing to make sure the new limits are applied correctly for all engine types.

- Continue to perform FIA with baseline diesel. Although it would mean less emission reductions for HVO case compared to reference case.

- Exclude FIA completely. Then the results from the nulled power (which is run with baseline diesel) could be used instead of the results from the power test and thus only one power test would have to be carried out. The possibility of doing that could be evaluated by analysing results from earlier nulled power tests and, if they are within the limits, use the results from the nulled power test or, if they are outside the limits, consider to change the limits or find factors between nulled power results and power test results. Since the difference between the results from the nulled power test and the power test might vary between engine types this probably requires a thorough investigation of results for different engine types. Although, up to more than a hundred liters of fuel per test could be saved if the FIA were excluded and only one power test were performed. This would mean saved fuel and saved emissions. However, there could be a risk that results from other parts of the test, such as the emission tests, are affected by not doing FIA. Thus a thorough investigation of potential consequences should be carried out.

Regarding the results of WHTC and WHSC from experiment 1 no exceeding of limits is observed when fuel injection adaptations and running in procedures were performed with HVO. Although, the procedure of for example running in the diesel particulate filter (DPF) (see section 2.2) might be negatively impacted by using HVO. The DPF needs to be conditioned/run-in to reach a representative and repeatable state before emission testing. Operating on HVO will affect (lower) the engine-out soot emissions and thus the running-in procedure for the DPF must be adapted. Not performing a correct running-in procedure may give an unrepresentative DPF efficiency which could increase PN emissions.[16] Suggested solutions to the unrepresentative DPF efficiency:

- A new layout of the DPF running-in procedure could be designed with regards to the characteristics of HVO. Although, the current procedure has been developed to work for all engine types thus it will require extensive work to adapt to HVO. The emission benefits of only operating the running-in procedure of the DPF on HVO might not exceed the drawbacks in terms of extra work and risk of errors.[17]
- Continue to perform the DPF running-in procedure with baseline diesel. Although it would mean less emission reductions for HVO case compared to reference case.

Important to note is that the experiments were only performed on one engine-type. Only the test layout that is specific for a Euro VI-engine has been considered, meaning for example that the baseline diesel used during the test has been BD2 and not BD1 and that the emission cycles have not been ESC or ETC. However, the running in procedure until and including the power test is somewhat alike for all test layouts and thus the results from at least experiment 2 and 3 could to some extent be applied on other engine-types complying with other emission standards. However the subsequent parts of the test varies more dependent on emission standard and more experiments should be carried out for those emission standards in order to investigate potential consequences when using HVO.

The complete test layout (as in table 2.3 in section 2.2) was only carried through in experiment 1. Experiment 1 showed remarkably good results, in terms of being within the limits, in comparison to the results from experiment 2 and experiment 3 when running FIA with HVO. This might indicate that the results for WHSC and WHTC also could have been worse, being outside limits, in experiment 2 and 3 compared to experiment 1 if the the complete test layout would have been performed in experiment 2 and 3. More experiments are needed considering the impacts of using HVO on the results from emission tests, since only one experiment regarding that was carried out.

From the three experiments the conclusion can be drawn that performing FIA with HVO causes problems. However, whether or not the other parts that are run with HVO do not cause problems can not be concluded from from the experiments, even though there are indications from experiment 2 of that running the first two parts (”engine installations, auxiliary adjustments and engine adaptations” and nulled power test) with HVO do not have negative consequences. It is clear that further testing is needed.

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[16] Martin Jonsson, Head of Requirements, Scania CV AB - NME. Communication via e-mail May 23d 2022.

[17] ibid.

## 6.2 What are the expected emission savings when using alternative fuel(s)?

### 6.2.1 Fuel consumption

The estimation over the yearly total fuel consumption for the relevant tests were performed in accordance with the method laid out in 3.2.2. Since the estimation is based on assumptions it is important to note that the fuel consumption, which the emission calculations are based upon, undeniably has margins of error. However, the fuel consumption estimation can be used to provide a picture of the scope of emission reductions for HVO case compared to reference case. The results from the experiments show that some parts of the tests might be problematic to run with HVO. Nevertheless the fuel consumption estimation is based on that HVO is used in all parts of the test that were initially considered possible to run with HVO in table 2.3 in section 2.2, or the corresponding parts in the tests for other engine types complying with emission standards other than Euro VI. Consequently the emission reduction estimation is kind of a "best-case-scenario", showing an optimistic potential without excluding any possibilities. The fuel consumption and emission reduction if some additional parts are deemed not possible to run with HVO is easily calculated. Furthermore, in order to get a more accurate fuel consumption estimation, the Audit Area could continue the fuel consumption measurements per test.

### 6.2.2 Tailpipe emissions

From table 5.16 it is clear that tailpipe $CO_2$ -emissions decrease with nearly 75 % for HVO-case compared to reference case. This is a significant decrease. Also the total (biogenic+fossil) tailpipe $CO_2$ -emissions show a minor decrease, which is in accordance with theory. In relation to the total fossil $CO_2$ -emissions from the production unit Engine Assembly the decrease is approximately 4.3 %, which can be considered quite significant. Compared to Scania's operations in total the decrease is only around 0.08 %. In relation to Scania's goal of reducing $CO_2$e -emissions by 50 % in 2015-2025 the reduction of 0.08 % might seem quite insignificant.

In section 4.2 and table 4.2 it is shown that using HVO has a positive, or at least neutral, impact also on the emissions of $NO_X$, HC, CO and PM/PN. This is an additional argument for using HVO during the tests.

### 6.2.3 LCA

From table 5.18 it is clear that the decrease in LCA $CO_2$e -emission for HVO case compared to reference case is significant. It is also clear from the results from "Sensitivity 1" and "Sensitivity 2" that the choice of LCA-value and source has great impacts on the results. Nevertheless, independent on LCA-value and source the results imply that changing the fuel use partly to HVO is advantageous in regards to LCA-emissions.

Considering the sensitivity case and the varying LCA-value for HVO depending on origin and feedstock, there are arguments for that obtaining information from sources other than a specific fuel supplier might be favorable. This is since the supplier-specific LCA gives information of the HVO from one specific supplier during one specific period. The production methods and feedstocks of the supplier's HVO as well as Scania's choice of HVO-supplier can change over time. Therefor adding a more objective approach, such as for the "Swedish-mix"-value derived in this report, and thus avoiding considering only one supplier's specific LCA-value might give more accurate and reliable results. Furthermore, LCA-value for HVO from Preem (that sensitivity 1 is based upon) is considerably lower compared to all the other LCA-values presented for HVO and thus using the LCA-value from Preem might include a risk of underestimating the global warming impact of HVO.

### 6.2.4 Overall discussion emissions

The emission reductions are significant in comparison to reference case as well as, for direct tailpipe $CO_2$, relative to the emissions from Engine Assembly. Regarding the emission reductions of direct tailpipe $CO_2$ in relation to emissions from Scania's operations the reduction is less significant. It is important to further evaluate the costs for implementing this change against the benefits in terms of emission reductions.

Furthermore, since it is not certain that all the parts of the test that the fuel consumption estimation is based upon actually will be possible to run with HVO (FIA and running in DPF for example) the emission benefits for HVO case might be somewhat smaller than those presented in the results.

## 6.3 How is the future availability, and price development, of the alternative fuel(s)?

The information presented in section 4.4 raises the following questions: Will the future availability of raw material and production capacity of HVO satisfy the possibly increasing future demand for the fuel? How will the market price of HVO develop? Since the price for HVO in Sweden is strongly related to national policies, but also affected by international price development due to a high share of international imports, it is necessary to consider the global and European situations as well as to consider and follow the development of Swedish policies affecting the use of biofuels.

It can be concluded that there is a risk for variations and scarceness in supply of HVO over the upcoming years. If HVO is to be used in the Audit Area there is a need to communicate with the fuel suppliers regarding whether or not supply can be ensured, and possibly also reflect upon the possible price increases related to factors such as shortage of raw material. Although, whether the possibility of using HVO in the Audit Area is dependent on assurance of supply at all times is questionable. If the supply of HVO would be occasionally scarce it might not be devastating since BD1 or BD2 could be used during periods of scarceness. However, it might not be useful to implement this project if the supply of HVO can not be guaranteed at all or if the price of HVO increases to too high levels, stressing the importance to further investigate the risk for and consequences of limited supply of HVO and increased prices.

## 6.4 What are the modifications needed when changing the fuel use?

From section 4.5 it is clear that some physical installations and modifications are needed in order for HVO to be used in the Audit Area test cells. What could be further investigated is the possibility of making changes to the current use of cisterns. If HVO is replacing large parts of the use of BD1 and BD2 in the Audit Area there might be possibilities of storing HVO where BD1 or BD2 is now stored and use smaller scale solutions for BD1 and BD2. This could lower the costs and optimize the storage. From table 5.14 in section 5.2 it is clear that the consumption of HVO in HVO case is almost the size of the consumption of BD2 in reference case. However, BD2 is also used in other tests at Audit Area that are outside the scope of this project, and thus the consumption of BD2 might still be too big for having a ”smaller” storage solution.

As of today there is no routine of how to burn of the amount of fuel from the previous test when another fuel is to be used in the next test. However, today the delay in injection of the right fuel and mixing of fuels is not impacting any important test results since the change of fuel is done only when the test is starting, and the test almost always starts with parts such as auxiliary adjustments. When using HVO in some parts and BD1 or BD2 in other parts within the same test the consequence of using the wrong fuel in a specific part is more severe. Accordingly a routine for burning of the fuel left in the system might be needed. A measurement of the amount of fuel left in the system could be performed with a flow meter and an estimation of how much fuel that has to be burned of after a switch of fuel can be done. Also an approximation of the amount of time needed to burn of the fuel can be done. For the parts of the tests where it is essential to use the right fuel, such as the power test and the emission cycles, the shift from HVO to BD1 or BD2 could be done so that a certain amount of BD1 or BD2 has flowed before e.g. WHSC starts. Alternatively the shift from HVO to BD1 or BD2 could be done a number of minutes before e.g. WHSC starts.

Furthermore, considering the fact that the results show that in order to use HVO for as many parts of the test as possible there is a need for evaluating or implementing the ”solutions” presented in section 6.1.1. Some of these solutions requires further experiments and changes in test layouts. That may also be sorted under modifications and may require time and working hours and thus also further costs.

## 6.5 Extra: What about changing the legislative requirements?

An even better scenario in terms of emission reductions would be if all parts of the tests could be carried out with HVO. The test-parts with measurement-limits that are included in the QA-requirements but not required by law (such as WHTC) are dependent upon Scania’s own regulations whereas for those parts included in COP and required by law the possibility of using HVO is dependent upon the legal requirements. As far as understood from the regulations read within the scope of this project, and as stated in section 2.2, for Euro VI-engines it is legally possible to perform power- and emission-tests that are part of COP with the diesel that is available on the market or with the specific certification fuel (BD1 or BD2). Since HVO is not included in that definition, lobbying with the aim of changing legislation would be required in order to use HVO for those test-parts. However, considering the fuel that should be used for Euro III-V the exact definition of what fuel that is legally possible has not been found.

Accordingly, the legal possibilities to use HVO also in the test-parts required by law could be further investigated.

# Chapter 7

# Conclusions and recommendations

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*In this chapter the main results are concluded and suggestions for improvements and future work are presented.*

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The fuel that seems technically best suited to use during parts of the running time is HVO. Conclusions regarding the exact parts of the tests that can be run with HVO can not be drawn after performing only three experiments and on only one engine type. However, the results indicate that performing FIA with HVO causes problems. It is also suspected that running in DPF with HVO might cause problems. It is clear that the technical possibility of running all the steps with HVO that was initially suggested is complex. Further experiments and evaluations are needed.

The expected yearly emission savings were calculated for all parts initially suggested as possible to run with HVO (the green marked parts in section 2.2, table 2.3). These emission savings might be somewhat optimistic since it has not been proven that all those parts actually can be run with HVO. Also the fuel consumption that the emission calculations are based upon is roughly estimated. However, the yearly fossil $CO_2$ -emission reductions where significant for HVO case compared to reference case and somewhat significant compared to the yearly $CO_2$ -emissions from Engine Assembly and Scania's operations globally. There were also significant benefits regarding LCA-emissions for HVO case compared to reference case.

There are uncertainties regarding the future development of availability and price of HVO. Thus this has to be further investigated if this change is implemented. Nevertheless, availability should not be a limiting factor for implementing the change since there are solutions where the Audit Area could switch to baseline diesel in times of scarceness of HVO. Furthermore the physical modifications needed when changing the fuel use are mainly related to storage and fuel supply-system.

Conclusively whether the emission benefits of operating parts of the tests with HVO exceeds the drawbacks in terms of the costs and extra work needed for making the change technically possible to implement needs to be further evaluated.

## 7.1 Improvements and future work

- What should be seriously considered is the possibility of using HVO in the Testing Area at Engine Assembly instead of, or in addition to, in the Audit Area. The arguments for doing so are: firstly that all engines pass through the Testing Area and the fuel consumption and emissions related to that area are higher compared to the Audit Area, and secondly the tests performed at the Testing Area are less complex and the possible complications of using HVO fewer. The emission reductions from using HVO in the Testing Area can be calculated and compared to the emission reductions from using HVO in the Audit Area.[18]

- Another area where the use of HVO has emerged as being possible is at the ”factory fill” where the vehicles are filled with fuel before they leave the factory. In this area the consequences of scarce availability of HVO is not as problematic since the vehicles easily can be filled with market diesel if HVO is not available.[19]

- Further studies are needed regarding the overall costs of implementing this change. The costs depend for example on whether more tests and experiments are needed, the difference in price between HVO and BD1 and BD2 as well as the investments needed to change the fuel storage and fuel system. No exact costs have been derived in this report, but it might be valuable to put the emission reductions in relation to costs ($CO_2$ -reduction/SEK) in order to make the costs for this change comparable to costs for emission reductions at other parts of Scania.

- Related to the costs of implementing the change a comparison between estimated future price for HVO and estimated future price for BD1 and BD2 could be performed. Reference case and HVO case could then be compared with regards to overall fuel costs. However, since BD1 and BD2 are ”special fuels” their prices do not follow the general market price for diesel. Thus that issue needs to be approached in order to perform a price comparison between the different fuels.

- Further look into the solutions laid out in section 6.1.1 regarding the FIA and the DPF running in procedure.

- Since the experiments were only carried out on one engine type complying with one emission standard, additional experiments should be performed on other engine types, complying with other emission standards.

- More parameters from the experiments can be analysed. This could easily be done in the future since the data from the experiments is saved in the measuring program at Scania.

- Contact the owner of the fueling system equipment in the test cells to get more details about the costs for modifications when changing fuel use.

- Further evaluate the possibility of running also the tests excluded from this project with HVO; ”Kundkörningar”, ”Referensmotorer” and ”NGS”.

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[18] Martin Jonsson, Head of Requirements, Scania CV AB - NME. Magnus Fröberg, Technical Manager Fuels, Scania CV AB - NMER. Communication via Teams May 9th 2022.

[19] Magnus Fröberg, Technical Manager Fuels, Scania CV AB - NMER. Communication via Teams May 9th 2022.

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# Appendix A

# Emission factors

## A.1 Tailpipe $CO_2$

Using equations 3.1, 3.2 and 3.3 from section 3.2.2 and the specifications for the fuels from table 4.1 the tailpipe $CO_2$ -emission factors are calculated for BD1, BD2 and HVO.

$M_{O_2} = 32$ g/mol

$M_C = 12$ g/mol

### A.1.1 Baseline Diesel 1

$$0.866 + 0.866 \cdot \frac{32}{12} = 3.175 g_{\mathrm{CO_2}} / g_{\mathrm{BD1}} \tag{A.1}$$

$$3.175 \cdot 835.0 = 2651 g_{\mathrm{CO_2}} / l_{\mathrm{BD1}} \tag{A.2}$$

$$3.175 \cdot \frac{1}{42.94} = 73.95 g_{\mathrm{CO_2}} / MJ_{\mathrm{BD1}} \tag{A.3}$$

### A.1.2 Baseline Diesel 2

Biogenic + fossil $CO_2$

$$0.860 + 0.860 \cdot \frac{32}{12} = 3.153 g_{\mathrm{CO_2}} / g_{\mathrm{BD2}} \tag{A.4}$$

$$3.153 \cdot 835.1 = 2633 g_{\mathrm{CO_2}} / l_{\mathrm{BD2}} \tag{A.5}$$

$$3.153 \cdot \frac{1}{42.64} = 73.95 g_{\mathrm{CO_2}} / MJ_{\mathrm{BD2}} \tag{A.6}$$

Fossil $CO_2$

The $CO_2$ origin from the 6 %V/V FAME in BD2 has to be subtracted since the $CO_2$ from FAME is assumed completely biogenic. It is here assumed that amount of $CO_2$ per liter of fuel for the fossil part of BD2 is the same as for BD1. The volume percentage of BD1 in BD2 is used to calculate the amount of fossil $CO_2$ per liter and per MJ from BD2. Then the amount of $CO_2$ per MJ is calculated by using the volumetric lower heating value for BD2.

Volume of BD1 per volume of BD2:

$$\frac{V_{\mathrm{BD1}}}{V_{\mathrm{BD2}}} = 1 - \frac{V_{\mathrm{FAME}}}{V_{\mathrm{BD2}}} = 1 - 0.06 = 0.94 l_{\mathrm{BD1}} / l_{\mathrm{BD2}} \tag{A.7}$$

Amount of $CO_2$ per liter of BD2.

$$2651 \cdot 0.94 = 2492.32 g_{\mathrm{CO_2}}\ / l_{\mathrm{BD2}} \tag{A.8}$$

Amount of $CO_2$ per MJ of BD2.

$$2492.32 g_{\mathrm{CO_2}}\ / l_{\mathrm{BD2}} \cdot 35.61 = 69.99 g_{\mathrm{CO_2}}\ / MJ_{\mathrm{BD2}} \tag{A.9}$$

### A.1.3 Hydrotreated Vegetable Oil

$$0.850 + 0.850 \cdot \frac{32}{12} = 3.117 g_{\mathrm{CO_2}}\ / g_{\mathrm{HVO}} \tag{A.10}$$

$$3.117 \cdot 780.1 = 2431 g_{\mathrm{CO_2}}\ / l_{\mathrm{HVO}} \tag{A.11}$$

$$3.117 \cdot \frac{1}{43.80} = 71.16 g_{\mathrm{CO_2}}\ / MJ_{\mathrm{HVO}} \tag{A.12}$$

## A.2 LCA-value

### A.2.1 Baseline Diesel 2

Amount of FAME in BD2 expressed as $\mathrm{MJ_{FAME}/MJ_{BD2}}$ (LHV for the fossil part of BD2 is assumed to be the same as LHV for BD1):

$$1 - \frac{E_{\mathrm{BD1}}}{E_{\mathrm{BD2}}} \approx 0.05566 MJ_{\mathrm{FAME}}/MJ_{\mathrm{BD2}} \tag{A.13}$$

Highest:

$$0.056 \cdot 58.82\ \mathrm{gCO_2e/MJ_{fuel}}\ + (1 - 0.056) \cdot 95.10\ \mathrm{gCO_2e/MJ_{fuel}}\ \approx 93.08\ \mathrm{gCO_2e/MJ_{fuel}} \tag{A.14}$$

Lowest:

$$0.056 \cdot 28.97\ \mathrm{gCO_2e/MJ_{fuel}}\ + (1 - 0.056) \cdot 95.10\ \mathrm{gCO_2e/MJ_{fuel}}\ \approx 91.40\ \mathrm{gCO_2e/MJ_{fuel}} \tag{A.15}$$

Reference:

$$0.056 \cdot 28.97\ \mathrm{gCO_2e/MJ_{fuel}}\ + (1 - 0.056) \cdot 95.10\ \mathrm{gCO_2e/MJ_{fuel}}\ \approx 91.40\ \mathrm{gCO_2e/MJ_{fuel}} \tag{A.16}$$

### A.2.2 Hydrotreated Vegetable Oil

The global warming values for average feedstock mix on the Swedish market in table 4.10 are calculated by using the share (of energy content) for each feedstock from table 4.7 and the highest and lowest global warming values for each feedstock respectively, as well as the values presented in table 4.8.

Highest:

$$(0.72 \cdot 33.44 + 0.12 \cdot 35.00 + 0.06 \cdot 78.49 + 0.06 \cdot 60.32 + 0.04 \cdot 16.13)\ \mathrm{gCO_2e/MJ_{fuel}}\ = 37.25\ \mathrm{gCO_2e/MJ_{fuel}} \tag{A.17}$$

Lowest:

$$(0.72 \cdot 16.00 + 0.12 \cdot 7.091 + 0.06 \cdot 30.74 + 0.06 \cdot 45.74 + 0.04 \cdot 16.13) \text{ gCO}_2\text{e/MJ}_{\text{fuel}} = 17.60 \text{ gCO}_2\text{e/MJ}_{\text{fuel}} \tag{A.18}$$

Reference:

$$(0.72 \cdot 33.44 + 0.12 \cdot 7.091 + 0.06 \cdot 78.49 + 0.06 \cdot 60.32 + 0.04 \cdot 16.13) \text{ gCO}_2\text{e/MJ}_{\text{fuel}} = 33.90 \text{ gCO}_2\text{e/MJ}_{\text{fuel}} \tag{A.19}$$

### A.2.3 Default tank-to-wheel-values

The LCA-values that was only including WTT were the ones from the following sources: Prussi et al. (2020) and European Parliament (2009). Thus TTW-values are added. The TTW-values are calculated in the following way for FAME and for HVO. GWP values for $CO_2$ , $CH_4$ and $N_2O$ are the ones given in section 2.1.2. The data for amount of emissions per Euro V or Euro VI are taken from (Hallberg et al. 2013).

TTW FAME

**Euro V:**

$$m_{\text{CO}_2} = 5.08 \tag{A.20}$$

$$m_{\text{CH}_4} = 6.72 \cdot 10^{-3} g/MJ_{\text{fuel}} \tag{A.21}$$

$$m_{\text{N}_2\text{O}} = 6.11 \cdot 10^{-3} g/MJ_{\text{fuel}} \tag{A.22}$$

$$m_{\text{CO}_2\text{e}} = 5.08 + (6.72 \cdot 28 + 6.11 \cdot 265) \cdot 10^{-3} g/MJ_{\text{fuel}} = 6.887 g/MJ_{\text{fuel}} \tag{A.23}$$

**Euro VI:**

$$m_{\text{CO}_2} = 5.08 \tag{A.24}$$

$$m_{\text{CH}_4} = 1.96 \cdot 10^{-3} g/MJ_{\text{fuel}} \tag{A.25}$$

$$m_{\text{N}_2\text{O}} = 6.11 \cdot 10^{-3} g/MJ_{\text{fuel}} \tag{A.26}$$

$$m_{\text{CO}_2\text{e}} = 5.08 + (1.96 \cdot 28 + 6.11 \cdot 265) \cdot 10^{-3} g/MJ_{\text{fuel}} = 6.754 g/MJ_{\text{fuel}} \tag{A.27}$$

**Average:**

$$m_{\text{CO}_2\text{e}} = \frac{6.887 + 6.754}{2} = 6.821 g/MJ_{\text{fuel}} \tag{A.28}$$

TTW HVO

**Euro V:**

$$m_{\text{CO}_2} = 0 \tag{A.29}$$

$$m_{\text{CH}_4} = 6.72 \cdot 10^{-3} g/MJ_{\text{fuel}} \tag{A.30}$$

$$m_{\text{N}_2\text{O}} = 6.11 \cdot 10^{-3} g/MJ_{\text{fuel}} \tag{A.31}$$

$$m_{\mathrm{CO_2e}} = (6.72 \cdot 28 + 6.11 \cdot 265) \cdot 10^{-3} g/MJ_{\mathrm{fuel}} = 1.807 g/MJ_{\mathrm{fuel}} \tag{A.32}$$

**Euro VI:**

$$m_{\mathrm{CO_2}} = 0 \tag{A.33}$$

$$m_{\mathrm{CH_4}} = 1.96 \cdot 10^{-3} g/MJ_{\mathrm{fuel}} \tag{A.34}$$

$$m_{\mathrm{N_2O}} = 6.11 \cdot 10^{-3} g/MJ_{\mathrm{fuel}} \tag{A.35}$$

$$m_{\mathrm{CO_2e}} = (1.96 \cdot 28 + 6.11 \cdot 265) \cdot 10^{-3} g/MJ_{\mathrm{fuel}} = 1.674 g/MJ_{\mathrm{fuel}} \tag{A.36}$$

**Average:**

$$m_{\mathrm{CO_2e}} = \frac{1.807 + 1.674}{2} = 1.740 g/MJ_{\mathrm{fuel}} \tag{A.37}$$

# Appendix B

# Emission results

Calculations of LCA and tailpipe emissions for HVO case and reference case from estimated fuel consumption where:

TEF = tailpipe emission factor from table 4.3.
LCAEF = life cycle emission factor factor from table 4.11.

## B.1 Tailpipe emissions

### Reference case

Biogenic + fossil:

$$FC_{\mathrm{BD1}} \cdot TEF_{\mathrm{BD1}} + FC_{\mathrm{BD2}} \cdot TEF_{\mathrm{BD2}} + FC_{\mathrm{HVO}} \cdot TEF_{\mathrm{HVO}}$$

$$=$$

$$(280242 \cdot 73.95 + 1357240 \cdot 73.95 + 0 \cdot 71.16)t\mathrm{CO}_2 = 121.1t\mathrm{CO}_2 \tag{B.1}$$

Fossil:

$$FC_{\mathrm{BD1}} \cdot TEF_{\mathrm{BD1}} + FC_{\mathrm{BD2}} \cdot TEF_{\mathrm{BD2}} + FC_{\mathrm{HVO}} \cdot TEF_{\mathrm{HVO}}$$

$$=$$

$$(280242 \cdot 73.95 + 1357240 \cdot 69.99 + 0 \cdot 0)t\mathrm{CO}_2 = 115.7t\mathrm{CO}_2 \tag{B.2}$$

### HVO case

Biogenic + fossil:

$$FC_{\mathrm{BD1}} \cdot TEF_{\mathrm{BD1}} + FC_{\mathrm{BD2}} \cdot TEF_{\mathrm{BD2}} + FC_{\mathrm{HVO}} \cdot TEF_{\mathrm{HVO}}$$

$$=$$

$$(99411 \cdot 73.95 + 313656 \cdot 73.95 + 1224414 \cdot 71.16)t\mathrm{CO}_2 = 117.7t\mathrm{CO}_2 \tag{B.3}$$

Fossil:

$$FC_{\mathrm{BD1}} \cdot TEF_{\mathrm{BD1}} + FC_{\mathrm{BD2}} \cdot TEF_{\mathrm{BD2}} + FC_{\mathrm{HVO}} \cdot TEF_{\mathrm{HVO}}$$

$$=$$

$$(99411 \cdot 73.95 + 313656 \cdot 69.99 + 1224414 \cdot 0)t\mathrm{CO}_2 = 29.30t\mathrm{CO}_2 \tag{B.4}$$

## B.2 LCA emissions

### Reference case

Sensitivity 1:

$$FC_{\mathrm{BD1}} \cdot LCAEF_{\mathrm{BD1}} + FC_{\mathrm{BD2}} \cdot LCAEF_{\mathrm{BD2}} + FC_{\mathrm{HVO}} \cdot LCAEF_{\mathrm{HVO}}$$

$$=$$

$$(280241 \cdot 95.10 + 1357240 \cdot 91.40 + 0 \cdot 13.70)t\mathrm{CO_2e} = 150.7t\mathrm{CO_2e} \tag{B.5}$$

Sensitivity 2:

$$FC_{\mathrm{BD1}} \cdot LCAEF_{\mathrm{BD1}} + FC_{\mathrm{BD2}} \cdot LCAEF_{\mathrm{BD2}} + FC_{\mathrm{HVO}} \cdot LCAEF_{\mathrm{HVO}}$$

$$=$$

$$(280241 \cdot 95.10 + 1357240 \cdot 91.40 + 0 \cdot 33.90)t\mathrm{CO_2e} = 150.7t\mathrm{CO_2e} \tag{B.6}$$

### HVO case

Sensitivity 1:

$$FC_{\mathrm{BD1}} \cdot LCAEF_{\mathrm{BD1}} + FC_{\mathrm{BD2}} \cdot LCAEF_{\mathrm{BD2}} + FC_{\mathrm{HVO}} \cdot LCAEF_{\mathrm{HVO}}$$

$$=$$

$$(99411 \cdot 95.10 + 313656 \cdot 91.40 + 1224414 \cdot 13.70)t\mathrm{CO_2e} = 54.90t\mathrm{CO_2e} \tag{B.7}$$

Sensitivity 2:

$$FC_{\mathrm{BD1}} \cdot LCAEF_{\mathrm{BD1}} + FC_{\mathrm{BD2}} \cdot LCAEF_{\mathrm{BD2}} + FC_{\mathrm{HVO}} \cdot lCAEF_{\mathrm{HVO}}$$

$$=$$

$$(99411 \cdot 95.10 + 313656 \cdot 91.40 + 1224414 \cdot 33.90)t\mathrm{CO_2e} = 79.63t\mathrm{CO_2e} \tag{B.8}$$

# Appendix C

# Technical interpretation of the results from the experiments

## C.1 Experiment 1

### Power test

At engine speeds 925 and 1340 rpm the results for delta are above the QA-limit. This indicates that too much fuel was injected per stroke at those speeds. At engine speed 925 rpm the results for bsfc are above the QA-limit. This indicates that the fuel efficiency is too low at those speeds. All the other results are within applicable limits.

#### WHSC

Test results within all applicable limits.

#### WHTC

Test results within all applicable limits.

## C.2 Experiment 2

### Measured power output

From figure 5.1 it is clear that the net power is higher for A.1-A.3 compared to B.1-B.2 at all speeds. For A.1-A.3 all net power measurements are above COP-limits for 1340 rpm, 1100 rpm and 925 rpm and above QA-limits for 1800 rpm. This is a clear difference from the net power measurement for B.1-B.2 which are all within the applicable limits.

### Measured delta

From figure 5.2 it is clear that the amount of fuel injected per stroke (delta) is higher for A.1-A.3 compared to B.1-B.2 at all speeds. Delta for A.1-A.3 is above the QA-limits at all speeds, except for A.2 and A.3 at 1640 rpm. This is a clear difference from the delta measurement for B.1-B.2 which are all within the applicable limits.

### Measured bsfc

Table 5.7 gives that the bsfc is highest for A.1 at all speeds and lowest for B.1 at 1100, 1340 and 1640 rpm. The bsfc is higher for A.1-A.3 than for B.1-B.2, at the speeds 1100, 1340 and 1640 rpm. The bsfc is within applicable limits for all cases at all speeds.

Since the bsfc has the same variation between A.1 and A.2/A.3 as between A.2/A.3 and B.1/B.2 it is difficult to draw any conclusions regarding how using HVO in previous steps impacts bsfc. Bsfc is a measure of the engine efficiency and it can be seen that the engine efficiency is higher for B.1-B.2 than for A.1-A.3 at a majority of the speeds.

### Delta vs delta$_{\text{demanded}}$

For A.2 and A.3 it is clear that the deviation between demanded fuel and injected fuel is higher than for B.1 and B.2, indicating that performing the fuel injection adaptation with HVO and then running the power test with BD2 results in inaccurate quantities of injected fuel. For A.2 and A.3 the injected fuel quantity is around 2-3 % higher than the demanded fuel quantity. This could further explain why the power output is above the limits at some speeds. Why the difference between demanded fuel and injected fuel is smaller for A.1 compared to A.2 and A.3 might be because the part that was run before A.1 (a power test with HVO, see table 3.6 in section 3.2.1) was done with HVO and thus there might have been some HVO left in the fuel system. Since the fuel injection adaptation was performed with HVO the fuel injection probably was performing better with HVO left in the fuel system.

## C.3 Experiment 3

### Measured power output

From figure 5.4 it is clear that the power output is higher for C.1-C.2 compared to D.1-D.2 at all speeds. For C.1-C.2 net power measurements are above COP-limits for 1100 rpm and 925 rpm (for C.2 also at 1340 rpm) and above QA-limits for 1800 rpm (for C.1 also at 1340 rpm). This is a clear difference from the net power measurement for D.1-D.2 which are all within the applicable limits.

### Measured delta

From figure 5.5 it is clear that the amount of fuel injected per stroke (delta) is higher for C.1-C.2 compared to D.1-D.2 at all speeds. Delta for C.1-C.2 is above the acceptable QA-limits at all speeds (and for C.1 above COP-limit at 1800 rpm), except at 1640 rpm. This is a clear difference from the delta measurement for C.1-C.2 which are all within the applicable limits.

### Measured bsfc

Table 5.7 gives that the bsfc is highest for C.1-C.2 at all speeds except at 1800 rpm where C.2 and D.2 is the same. The bsfc is within applicable limits for all cases at all speeds.

Since bsfc is a measure of the engine efficiency it can be seen that the engine efficiency is higher for D.1-D.2 than for C.1-C.2 at a majority of the speeds.

### Delta vs delta$_{\text{demanded}}$

For C.1-C.2 it is clear that the deviation between demanded fuel and injected fuel is higher than for D.1-D.2, indicating that performing the fuel injection adaptation with HVO and then running the power test with BD2 results in inaccurate fuel injection quantities. For C.1-C.2 the injected fuel quantity is around 3-5 % higher than the demanded fuel quantity. This further explains why the power output is above the limits at some speeds for C.1-C.2. The difference between A.1 and A.2-A.3 for this measurement in experiment 2 is not seen in experiment 3 between C.1 and C.2. This reduces the liability of the possible explanation regarding this for experiment 2 since, as in experiment 2, the part that was run before C.1 (FIA with HVO, see table 3.7 in section 3.2.1) was done with HVO and thus there might have been some HVO left in the fuel system also for C.1 in experiment 3. However, a difference in this part of the experiments is that in experiment 2 the previous part run with HVO was a power test whereas in experiment 3 the previous part run with HVO was the FIA.