# A Real-Time Platform for Closed-Loop Control and Crank Angle based Measurement

**Master's thesis**
performed in **Vehicular Systems**

by
**Klas Telborn**

Reg nr: LiTH-ISY-EX-3304-2002

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**Sammanfattning**
Abstract

A real time platform is designed, implemented and validated. The platform is going to work as an aid in the development work of new engines. Data can be acquired under a crank angle interval of an engine cycle and thereafter treated. This is going to be helpful when new technologies will be validated or a non directly measurable variable is will be controlled in a closed loop. The platform consists of a PC with three devices, an A/D device, a counter device and a CAN device. The counter device controls the A/D device with help of treated crank shaft information. The CAN device can send a calculated value every cycle. The platform is adapted to detect SOC on an HCCI engine. With help of the SOC history the combustion phase is going to be controlled in a closed loop. An SOC detecting algorithm developed of Rassweiler and Withrow is implemented. The algorithm is based on crank angle synchronic sampled pressure data.

**Nyckelord**
Keywords

Homogeneous charge compression ignition, Rassweiler Withrow, cylinder pressure

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# Contents

# Chapter 1

# Introduction

Engine manufactures have demands from two sides, the government sets thresholds for emissions and the customers have claims for high fuel efficiency. The hardest emission demand for heavy duty diesel (HDD) is to fulfil the thresholds for nitrogen oxides (NOx). Unfortunately is the fuel efficiency inversely proportional to the NOx emission. The only way for the manufactures to meet the claims, and thereby survival, is to develop more efficient engines. When new engines are developed new technologies are often tried. There is of course of importance to validate the technic under the development work. An example of new technic is to control the ignition timing in a closed loop.

This thesis introduces a data acquisition system that is going to be helpful when new technologies are going to be examined. The platform can work as a data acquisitions system which can save samples from one or two signals under a set crank angle interval for a predefined amount of cycles. This functionality makes it possible to record phenomenons and validate algorithms. The platform has also a real time functionality and works in this mode as a smart sensor. The expression smart sensor means in this case that the platform collects data, treats the collected data with an implemented algorithm and finally sends the result from the algorithm on a CAN bus every cycle. This is useful when a non direct measurable parameter is wanted to be controlled in a closed loop, for instance the ignition timing. Depending on what kind of signal which is going to be measured the sample interval can either be based on time or crank angles.

The first task for the platform is to work in a closed loop that controls the combustion phase in a homogeneous charge compression ignition (HCCI) engine. The HCCI process can be seen as a hybrid between the compression ignition (CI) and spark ignition (SI) process in that a homogenous charge, as in a SI process, is compressed until it auto ignites from the compression heat as in the CI process. The process is still under development and there are several problems which have to be solved before the HCCI engine can be used in a vehicle application. The main problem is to find a way to control the combustion timing. This is difficult since the process is unstable and there are no natural parameters that trig the onset in the same manner as the spark in a SI engine and the injection in a CI engine. One possible way to get around the problem is to control the system in an closed loop. The idea is to let the platform deliver the input signal to the closed loop algorithm as the combustion phase of the last cycle. The combustion phase is detected out of samples of a cylinder pressure signal and an algorithm. A lot of work of the thesis is spent on the algorithm because it affects not only the accuracy of the detected phase but also affects the calculation time which is very important in a real time system. An algorithm developed of Rassweiler and Withrow is chosen.

## 1.1 Outline

An introductory background of the HCCI concept is given in chapter 2. The HCCI process is compared with the CI and SI process and a motivation and an understanding for the problems of the research of the HCCI engine is given. Further the advantage of a closed loop controlled ignition timing is discussed and the conception SOC is defined.

Chapter 3 describes the Scania HCCI test engine and the sensors that has been used in the project.

Chapter 4 describes the hardware and software platform that has been developed. The aim is to show the architecture of the acquisition system and how the different devices communicate with each other. The presentation of the software algorithm shows the necessary steps to get to the final result.

The chosen SOC detecting algorithms are introduced in Chapter 5.

In chapter 6 the result from the algorithm is validated. It is examined how the result behaves with different inputs and how it behaves compared to results from other algorithms. It is also shown how the cut-off frequency for the filter was chosen.

# Chapter 2

# The Process

In this chapter a background to the problem is given. To motivate and understand what HCCI is a comparison to the common SI and CI engine is done. There are though many problems with HCCI and one of the biggest is to control the combustion phase. Further on the combustion phase is defined and it is discussed how it can be detected and used to control the combustion phase.

## 2.1 The HCCI Process

In the vehicle history mainly two types of combustion engines have dominated the market, the Otto engine (SI) and the diesel engine (CI). Both got there pros and cons and there is no natural choice between the two types, the application often decides which type is chosen. Generally the SI engine got the advantage of god emissions but a low part load efficiency. For the CI engine it is almost the opposite with the advantage of a god efficiency but high NOx emissions. With harder emission legislation and competition between the manufactures the engines are improved in small steps. To make a big step in the evolution maybe a new concept is needed.

A process that got potential for the future is the HCCI process. The HCCI process got similarities both to the SI and CI process. The hardware of the engine is build in the same way with a piston, connected to crank shaft, ruing in a cylinder. The gas exchange is controlled with an inlet and an exhaust valve. The engine works in four strokes with an inlet-, a compression-, an expansion and final a blow out stroke. Under the intake stroke the cylinder is filled with a homogeneous mixture of fuel and air just like an SI engine. The engine has no throttle and depending on the load an amount of fuel is added to the air in the inlet manifold. This will make the lambda vary with the load.

Under the compression the temperature of the homogeneous charge rises. When it has reached the auto ignition temperature the mixture ignites. Due to the homogenous mixture and the almost uniform heat in the bulk a multiple point ignition appears [1]. The multiple point ignition causes the whole mixture to burn homogeneously and very fast without flame propagation. The energy in the fuel is released in a few crank angles. At what time under the compression stroke the mixture reach the auto ignition temperature depends on the state at inlet valve closure(IVC) and the heat transfer.

What motivates and is the important thing with HCCI combustion is that the burn temperature can be kept under 1800K with a good efficiency. Under 1800 very low NOx emissions are created [2]. This is possible due to the multiple point ignition with a homogeneous combustion. This is not possible in the same way in a CI or SI engine because in the fuel spray or in the flame propagation the local temperature is clearly higher than 1800K. The global, or mean temperature in the combustion chamber is under 1800K though.

**Summary**

**The Otto process**

| | |
|---|---|
| Fuel supply: | Fuel and air premixed or direct injection of fuel with in-cylinder mixing |
| Air/fuel-ratio: | Almost constant, independent of load lambda=0.8-1.8 |
| Ignition: | Spark ignition |
| Ignition timing: | Spark timing |
| Combustion: | Turbulent flame development |
| Fuel requirement: | Large resistance to auto-ignition |
| Emission: | Very low with 3-way catalyst |
| Efficiency: | Overall Low and very low at part load |

**The Diesel process)**

| | |
|---|---|
| Fuel supply: | Pure air entering the cylinder. Fuel directly injected to start combustion. |
| Air/fuel-ratio: | Very lean, depending on load lambda=2.2-14 |
| Ignition: | Compression ignition |
| Ignition timing: | Injection timing |
| Combustion: | Diffusion flame |
| Fuel requirement: | Low resistance to auto-ignition |
| Emission: | NOx and soot are high |
| Efficiency: | High |

**The HCCI process**

| | |
|---|---|
| Fuel supply: | Fuel and air pre mixed or direct injection of fuel with in-cylinder mixing |
| Air/fuel-ratio: | Depends linearly on engine load lambda=1.4-20 |
| Ignition: | Compression ignition |
| Ignition timing: | Pressure and temperature history |
| Combustion: | Homogeneous slow oxidation |
| Fuel requirement: | Matched with the compression ratio |
| Emission: | Extremely low NOx, more HC and CO |
| Efficiency: | High |

## 2.2 Closed Loop Control

The HCCI engine is in the beginning of its development. There are many problems to solve before the engine is usable. One of the biggest problem is to control the ignition timing. In an HCCI engine there are no natural things that control the ignition timing, like the spark timing in a SI engine or the injection timing in a CI engine. Too early timing will result in too high pressure rise and knock and too late timing will result in misfire. Today it is only possible to run the engine in a steady state condition. This is done by setting the boundary conditions in a way that makes the mixture auto-ignite in a drivable crank angle range. The system is not stable which means that a change in one of the boundary conditions will make the ignition angle run out of the drivable crank angle range after a couple of cycles.

To continue the development the ignition angle must be controlled, a parameter that effect the charge temperature or the auto-ignition temperature must be found. The parameter must influence the system fast, preferably on a cycle to cycle basis, and it must be easy to change.

A couple of methods have been suggested under the history, often mentioned are variable compression ratio, variable octane number and variable valve timing. Scania has chosen to try to control the combustion with variable valve timing (VVT). The technique is to keep an amount of residual gases for the next cycle with help of different valve timing. In this way the mixture temperature can be influenced over a wide range and thereby the combustion timing.

The VVT system should be controlled in a closed loop control. The platform calculates the last combustion phase and sends it to the controller. In the controller the calculated combustion phase value is compared with a set combustion phase and a new valve timing is calculated. In the next cycle the new valve timing is used and the combustion is hopefully displaced in a desirable way.

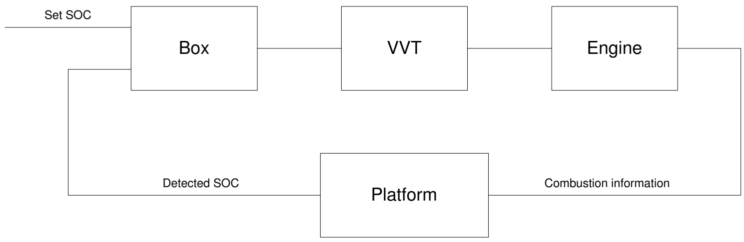


Figure 2.1: The figure shows the closed control loop.

## 2.3 Ignition Timing and Definition of SOC

In an HCCI engine the feedback of the combustion phase is used to keep the engine alive. This is maybe an extreme case but for that reason it is not unwanted in a SI or CI engine. A proper combustion phase is important but is sometimes difficult to realize. One of the reasons is the non constant delay between the ignition timing and the combustion. The delay is influenced of many parameters that are hard to measure or take affect off. If the combustion phase was controlled in a closed loop the delay would not be an argue and the combustion phase could be better optimized for every driving condition.

As a quantity for the combustion phase a measure called start of combustion (SOC) is introduced. There are many algorithms based on different methods that are used to define SOC. Every algorithm gives an answer which in some kind of way tells were the combustion occurs. The answer is not an absolute value in the meaning that different algorithms give different answers for the same combustion. Most common when detecting SOC is to use the pressure trace. This is widely used and has been investigated for over hundred years.

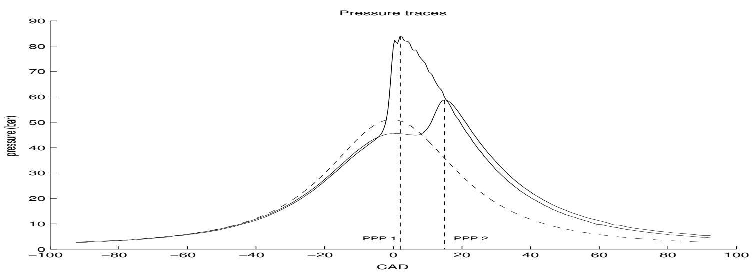


Figure 2.2: The figure shows how the pressure peak position, ppp, changes with the ignition timing. Two pressure traces, one with early and one with late ignition timing, are displayed. The dashed trace is the pressure from a motored cycle.

An easy way to examine the combustion phase is to look at the pressure peak position (PPP). Depending on the ignition timing the PPP will occur at different angles, se figure 2.2.

Another possibility to describe the position of the combustion is to check when the energy in the fuel is released. This is done with help of the mass fraction burned profile. SOC is said to occur when a pre decided percentage fuel is burned, se figure 2.3. Different thresholds can be used. 45-50% is suggested by Lars Eriksson [3]

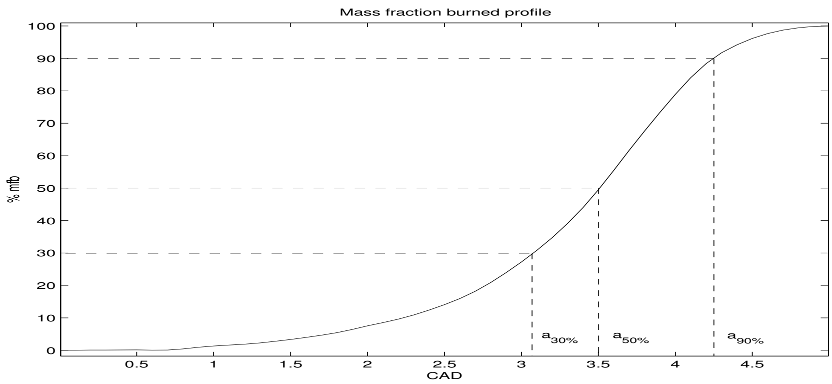


Figure 2.3: The figure shows how the detected angle varies with different thresholds for the mfb. The angle for 30%, 50% and 90% mfb are marked in the figure.

Today it is not possible to detect SOC in production vehicles with pressure transducers because they are to expensive and not reliable. The benefits with closed loop controlled ignition timing is still wanted to be used so alternative methods, that are not based on the pressure trace, like ionizations current, are investigated.

## 2.4 The Mission

The task for this thesis is to create a real time platform. It can be said this is done for two reasons, one specific and one general reason. The specific one is to make it possible to control the combustion phase in a HCCI engine. With the known SOC it is thought to control the VVT in a closed loop. The general reason is to create a flexible platform. With help of the platform it should be possible to examine and validate new techniques and methods. It should also be possible to connect a system in a closed loop.

To fulfil the specific missions a realtime platform must be created that collects data, calculates SOC and finally delivers the result on a

CAN bus every cycle. For the second task it must also be possible to save data from two signals simultaneously. Depending on what is going to be examined it is important that the sample interval and rate are variable. It is also desirable to be able to chose whether the sample rate should be based on time or crank angle degrees. The requirements for the platform are:

- Acquire data in a variable crank angle interval of +-60 CAD around TDC
- Time or crank angle based sample rate, changeable up to 200kHz respective changeable between 0.4-1.2 CAD/sample
- Save two signals simultaneously
- Connected to a CAN bus

# Chapter 3

# Hardware

This chapter describes the HCCI engine and the signal that is going to be used in the data acquisition system.

## 3.1 The engine and the cell

The Scania HCCI test engine is made for experimental work and is placed in a test cell with its outgoing shaft connected to a dynamometer. The engine is a four stroke one cylinder engine. Basically it is a modified Scania production engine with parts from the Scania module system. The engine has been custom-made for the HCCI process with a hydraulic variable valve system and an inlet manifold with injectors. A number of extra sensors has been installed on the engine to be able to closely monitor the behavior of certain parameters.

Scania makes a lot of testing on the engine to investigate the HCCI process. To be able to do repeatable attempts things like exhaust back pressure, inlet temperature, inlet pressure, oil temperature, cooling water temperature are externally controlled and can also be set to a desirable value. An acquisition system from AVL is recording drift parameters, like different flows, temperatures, pressures etc. The data can afterwards be treated and analyzed in a software program from AVL.

## 3.2 Signals and sensors

A SOC detecting algorithm is based on one signal that gives information about what happens with the heat release in the combustion camber. In this case the cylinder pressure signal is used. To be able to reference the measured signal to the movement of the piston two signals that give information of the position of the crank shaft are used. A short description of the sensor and the signals are introduced below.

**Cylinder pressure transducer** The cylinder pressure is measured with a Kistler 7061 piezoelectric transducer. This sensor can record very rapid changes of the cylinder pressure. When a pressure change occur an electric charge is developed in the sensor. To get the charge over to a more useful quantity a charge amplifier transduces the charge to a voltage. The transformation from voltage to pressure is assumed to be linear. The cylinder pressure transducer is connected to the combustion chamber trough a drilled hole in the cylinder head.

**Crank angle signal** The crank angle signal, or CDM signal, gives information of the rotation of the crank shaft and is a pulse train. The signal is created of an optical encoder mounted on one of the crank shafts ends. The encoder contains a stroboscopic disc with 720 slots and is lighted from one side. On the other side the light pulses are received with a optical receiver and transformed to an electrical pulse. The signal is tidy up and up scaled to 1800 pulses per revolution, 0.2 CAD per pulse. The encoder is made by AVL.

**Revolution signal** The revolution signal refer to a fix position of the crank shaft. The signal is created in the same way as the crank angle signal, besides that only one pulse per revolution is created, the optical disc got only one slot. The optical disc is manually corrected and gives a pulse that goes low at TDC.

# Chapter 4

# The Data Acquisition Platform

The system is based on 1 GHz PC with 256 Mbyte RAM. To handle the data collection and to be able to send and receive CAN messages three plug-in devices are mounted in the PC. The devices are:

- A/D device PCI-MIO-16E-1
- Counter device PCI-6602
- CAN device PCI-CAN

All the devices are from the manufacturer National Instruments. The A/D- and the counter device are connected together with an data bus called RTSI. By using the RTSI bus the communication between the devices are not disturbed by interrupts on the PC. The CAN device can send and receive CAN messages of different standards. Everything is controlled by a C-program programmed in the software program LabWindows/CVI, also from National Instruments. This configuration makes the platform flexible as different tasks can be programmed and the PC can be exchanged if more calculation performance is needed.

Figure 4.1 shows how the hardware are put together. The function of the devices and how the software program works are described in the following sections.

## 4.1 A/D

The A/D device is 12-bits device with possibility to connect up to eight input signals in differential mode. The device converts continuously

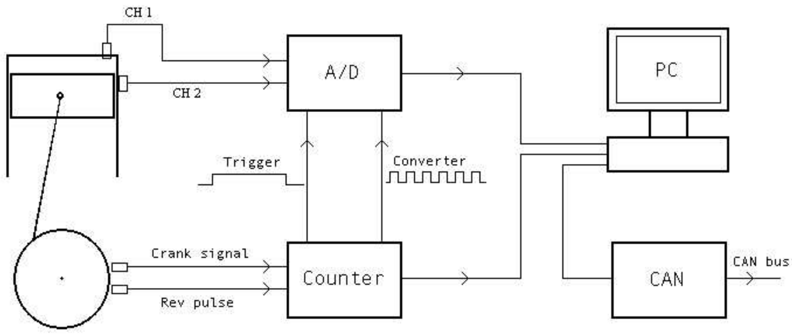


Figure 4.1: A view over the systems architectures

analog signals to discrete digital signals up to a rate at 1.25 mega samples per second.

The device is controlled by two external signals, the converter and the trigger signal. The trigger signal controls when, in a crank angle range, the A/D device is active and by that acquire data. The device starts to acquire data when the trigger signal goes high and it stops when the signal goes low. The converter signal controls the rate that the data is acquired with. The device takes a sample on every rising edge of the converter signal.

The acquired data is temporary stored before it is transferred to the PC. The data is first buffered in an intern buffer which can contain 512 samples. The data is then transferred to the PC in so called double buffer mode which works almost as two buffers. When the first buffer is completely filled the collected data in the first buffer is available to be saved in the RAM meanwhile the second buffer is filled with new data. The two buffers alternate either being the reading or the writing buffer.

The A/D device is programmed to be able to sample one channel or two channels simultaneously. The one channel mode is mainly aimed for real time calculations and the two channel mode is for the off line validations.

## 4.2 Counter

The counter device can create different types of pulse trains based on the signals connected to the device. The period of a connected signal can also simultaneously be measured.

The main purpose of the counter is to control the A/D device. The counter device sends two signals, the trigger- and converter signal, on the RTSI bus to the A/D device. Another task for the counter device is to measure the period time of the CDM signal. The tasks are described more thoroughly below.

**The Trigger Signal** The trigger signal activates the A/D device. The signal is high during the crank angle range when data should be acquired. The counter device creates the trigger signal with help of the rev signal and the CDM signal. The rev signal is used as a reference point and the CDM signal gives information of small crank angle changes. By knowing this a trigger signal can be created to go high x crank angles after the rev pulse and stay high for y crank angles. Figure 4.2 shows an example.

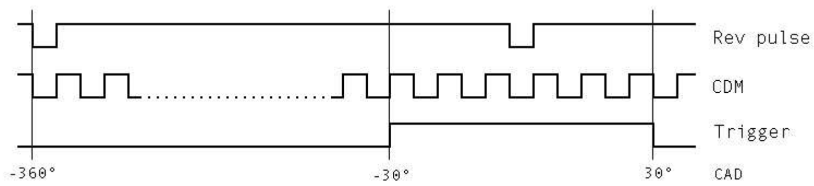


Figure 4.2: A trigger pulse that is high from -30 to 30 CAD

**The Converter Signal** The converter signal decides the acquisition rate. The signal differs if crank angle- or time-synchronous sample rate is chosen. In the crank angled based case the converter signal is a down scaled CDM signal. It is possible to scale down the signal two to six times which gives a sample rate of 0.4 to 1.2 degrees per sample. In figure 4.3 a three times down scaled CDM signal is shown. In the time based case the converter signal is created by an internal clock in the counter device. The clock is set so the frequency of the pulse train becomes 200kHz. It is possible to change the sample rates in the both cases.

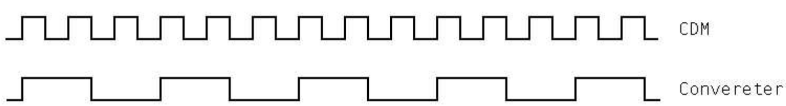


Figure 4.3: The converter signal is a three times down scaled CDM signal

**Period Time Measurement** When combustion engines are investigated phenomenons often want to be referred to a crank angle. If a signal is acquired with a sample rate based on time, the samples must be converted to a crank angle base. To make the conversion possible the period time of the CDM signal is measured. With this information and by knowing the current sample rate the corresponding crank angle for every sample can be calculated.

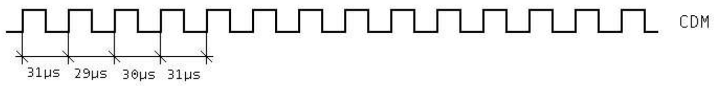


Figure 4.4: Period time measurement on the CDM signal.

## 4.3 Software

The acquisition is controlled from a graphical interface. Acquisition rate and range and save mode can be set and controlled from the window. In this case when the platform works as an SOC detecting sensor the pressure trace and the burn profile are displayed and the SOC value is recorded in the graphical interface. The way the smart sensor works consist of three steps. First the pressure signal is sampled during the combustion and the acquired data is stored in a PC. Then an algorithm in the PC takes care of the collected data and calculate the SOC angle and finally the SOC angle is sent on a CAN bus. The main steps in the SOC detecting method are shown in figure 4.5.

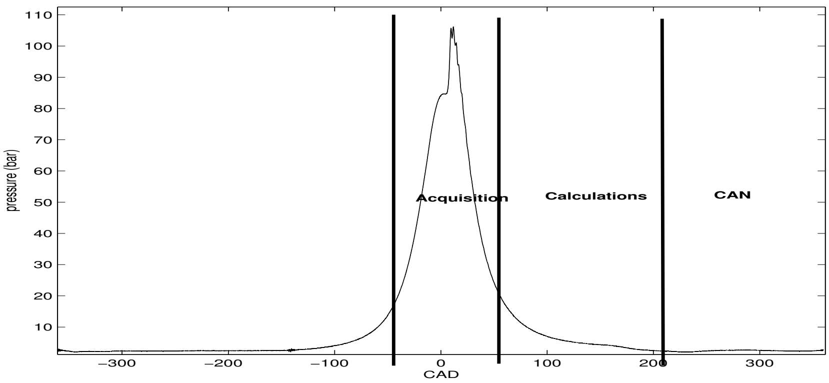


Figure 4.5: The main steps in the SOC detecting system.

A cutting from the C-cod shows how the platform works. Every function represents a necessary step in the algorithm and can contain several sub functions. The cutting is listed and deeper described below.

```
GetDAQVariabler();
DAQConfig();
CANConfig();
CounterConfig();
GenerateVolumVektor();
while ( quit == No )
{
   DAQStart();
   LoadBuffer();
   FilterData();
   ParameterEstimation();
   Bits2Pressure();
   CalculateSOCangle();
   SendSOConCAN();
   Plot();
   Save2File();
   if ( first run == yes )
   {
      inSync();
   }
}
```

Before the loop starts the program gets acquisition parameters from the graphical interface and the devices are configured for the wished acquisition. Also a vector containing $(\mathrm{Vo}/\mathrm{Vi})^n$, se ekv 5.3, is pre made. The functions in the loop are passed once for every specific SOC detection, which means that for every engine cycle the program does one loop.

First in the loop DAQStart() is called. The function makes the A/D device active and ready to sample data. When the acquisition is ready the A/D devise turns in to an inactive state and waits for a new DAQStart() call the next cycle. The LoadBuffer() function controls that the data is properly transmitted to the PC with the double buffer mode.

When the data is acquired some after treatments are made. First the signal is filtered with a non casual low pass Butterworth filter. The filter gives a flat frequency response and zero phasing. The filter parameters are calculated in Matlab. On the filtered data set Po and C are estimated as described in chapter 5.

To be able to get the measured voltage to a pressure value a manual calibration must be done. The calibration is made before the engine is turned on and done so the expected pressure range gives a voltage that match the voltage range of the A/D device input channel.

When all after treatment is done the SOC angle is determined in the SOC algorithm. Directly after the SOC angle is known a CAN message is send on the CAN bus. Now the time critical work is over and the graphical interface can be updated. To be able to do off line analysis the acquired data can be saved. To get on each other following cycles the data first is saved in the RAM. When the desired number of cycles are received the data is transferred to hard disc. Data from one or two channels can be saved.

In a four stroke engine the crank shaft rotates two turns every cycle. That means that the piston is located at TDC two times during a cycle, one time during the combustion process and the other time during the gas exchange. To detect SOC it is only necessary to sample data around TDC under the combustion turn, every second turn is uninteresting. Therefor the cylinder pressure are sampled during both the combustion and exchange stroke the first cycle. The pressure traces are then compared and the trigger signal is set so the combustion stroke will be sampled in the future. The inSync() function takes care of this.

# Chapter 5

# The SOC Detecting Algorithm

Detecting SOC from the pressure trace is widely spread in both SI and CI engines. There are many different methods at disposal which are well investigated. No method is specially investigated for the HCCI process but with thought of the homogenous charge and the multiple ignition a single zone model for an SI engine is suitable. In this application a method developed of Rassweiler and Withrow is used.

## 5.1 Based on Pressure Trace

Rassweiler and Withrow developed a method for investigation of the energy(chemical) release [4] in 1938. It is well known and used. The method do not consider effects of heat transfer, crevices and leakage but it is possible with smaller changes to take affect of the phenomenons. The basic method is suitable for real time calculation because of its simplicity and its insensibility to errors [5]. The cylinder pressure is the only thing that is needed to be measured.

The method attempt to find out when the energy in the fuel is released. Between two samples, a crank angle interval, there is a pressure change $\triangle$p. The pressure change originates in either volume changes, $\triangle p_v$, or energy release from the fuel, $\triangle p_c$.

$$\triangle p = \triangle p_c + \triangle p_v \tag{5.1}$$

The pressure changes due to volume changes can be thought being the pressure trace if the engine was drawn around without combustion. This theoretical pressure trace can be calculated if the volume changes, polytropic exponent, n, and the inlet pressure, $p_0$, are known. The volume can be described as a function of crank angle, if the engine geometry is known, and thereby the theoretical pressure corresponding to every sample can be calculated.

$$p_0 V_0^n = p_i V_i^n \tag{5.2}$$

which gives the corresponding pressure change, due to volume change, between two samples, i and j

$$\triangle\, p_v = p_j - p_i = p_0[(\frac{V_0}{V_j})^n - (\frac{V_0}{V_i})^n] \tag{5.3}$$

The mass fraction burned(mfb) tells when the SOC occurs, in this case 50% mfb is chosen as threshold.

$$mfb = \frac{m_{b(i)}}{m_{b(total)}} = \frac{\sum_0^i \triangle\, p_c}{\sum_0^N \triangle\, p_c} \tag{5.4}$$

If the mfb is saved for every $i$ in a vector it can later be plotted. The curve that appears is called the burn profile curve but it is often mentioned as the integrated heat release curve.

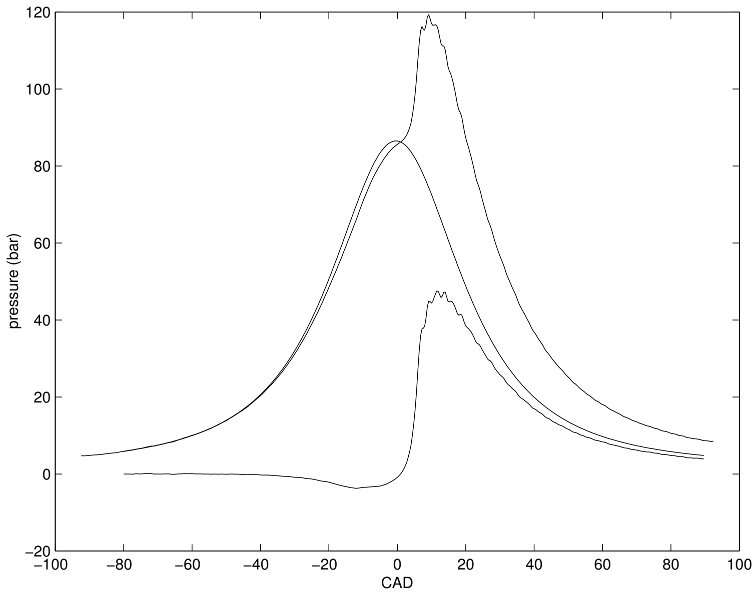


Figure 5.1: A pressure trace, theoretical pressure and a burn profile are shown.

To speed up the calculations a vector containing $(\frac{V_0}{V_i})^n$ that matches all samples is precalculated.

The measured pressure will not be correct because of the charge leakage in the charge amplifier. If the pressure transducer is loaded with a constant load the output voltage from the charge amplifier will sink exponential with a time constant [6]. Although the time constant is enormously lager than the cycle period time the voltage will sink because the pressure variate around the mean effective pressure, mep, an almost constant pressure load. This will have the affect that the measured pressure, $p_m$, will differ from the real pressure, $p_r$, with approximately a constant C, se equation 5.5 .

$$p_r = p_m + C \tag{5.5}$$

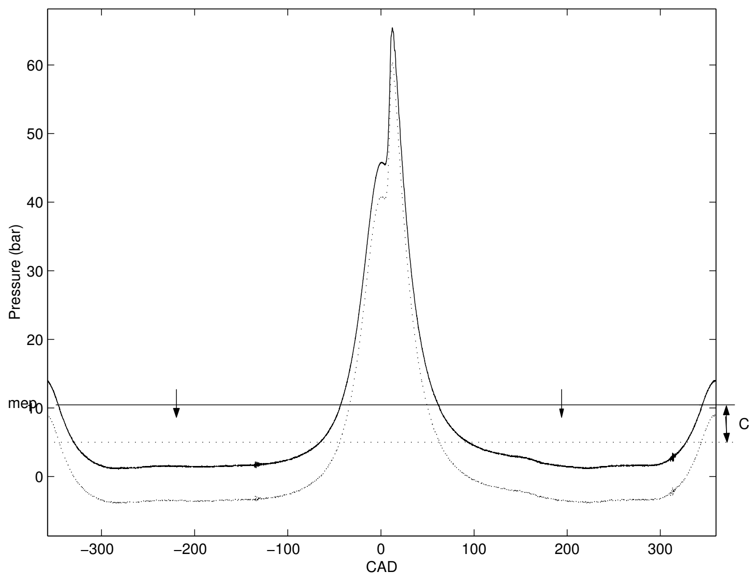


Figure 5.2: The figure shows how the mean effective pressure sinks with the time, dotted pressure trace.

C can be estimated by using equation 5.2 and least square [7]. This is done once every cycle. The method finds the best fit between the measured data and the theoretical pressure trace. To get a good fit it is important that the measured data is free from disturbances. Therefore the data is filtered before the estimation. It is also important in which crank angle range the estimation is done in. It has been found out that between -80 and -55 CAD is good. Before -80 CAD there is a strange disturbance which is not possible to filter all away and after -55 the energy losses starts to be to sufficient for a good fit.

# Chapter 6

# Analysis and Validation

This chapter describes how the cut off frequency for the filter is chosen and how the result from the SOC detecting algorithm behaves with different inputs and compared other algorithms.

## 6.1 Load Points for Statics

To do validation on the system and algorithms data is collected from three different load points. Two load points are taken at 1000 rpm, high and low charge, and one point at 2000 rpm, low charge, se figure 6.1. In every load point cycles with early and late combustion phase are taken. The collected data is supposed to represent the utilities of different amount and speed of heat release and heat transfer. The two different rpm's represent different rates of heat transfer. The biggest influence on the heat transfer is time though the heat transfer parameters does not change much with different load points. High and low charge represent the utilities of amount of heat release cause the amount of fuel that are added to the mixture are directly proportional to the charge or output torque. The combustion phase represent different speeds of heat release. An early combustion have a fast heat release because at TDC the pressure and temperature are highest in the cycle which makes the reaction time faster.

| load point | rpm | charge | combustion phase |
|---|---|---|---|
| 1 | 1000 | low | late |
| 2 | 1000 | low | early |
| 3 | 1000 | high | late |
| 4 | 1000 | high | early |
| 5 | 2000 | low | late |
| 6 | 2000 | low | early |

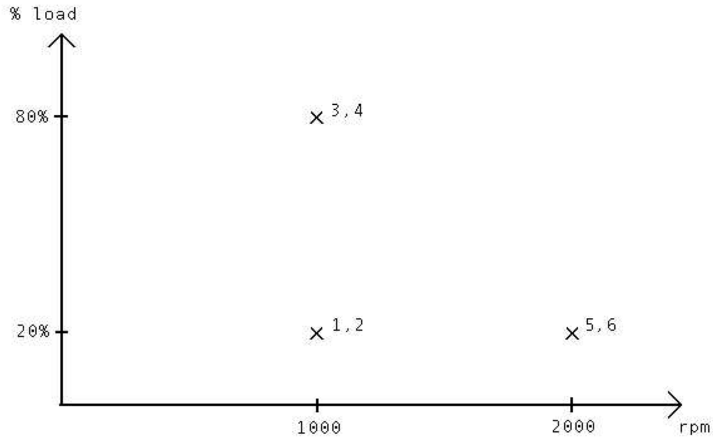


Figure 6.1: The figure shows at which rotation speeds and percent of maximum charge the load points are chosen.

## 6.2 Cut Off Frequencies

The pressure trace contains unwanted oscillations short after that the pressure start to rise due to the combustion, see figure 6.2. The measured pressure is just representative for the local volume around the pressure transducer and not for the hole volume of the combustion chamber. When the pressure trace with oscillations is used in the Rassweiler Whitrow algorithm the answer will not be reliable because the burn profile will be affected of the amplitude and phase of the oscillations. The 50% mfb will depend on the amplitude of the oscillation and not correspond to the real value which gives the consequence of a not reliable SOC angle.

To make the measured pressure representative for the whole mixture and get rid of the problems the mean value of the cylinder pressure must be taken, in other words the data must be low pass filtered. To find out which type of filter and cut off frequency are desirably spectral analysis for different load points are made. From the spectral analysis it is easy to see that oscillations mainly obtains two frequencies 2.7 kHz and 3.9 kHz, see figure 6.3. Those frequencies can be found in every pressure trace but the magnitude varies from load point and from cycle to cycle. With this information a low pass filter with a cutoff frequency of 1.5 kHz is chosen. A pressure trace filtered with the chosen filter is shown in figure 6.4.

Three different phenomenon, that can cause this phenomena, has

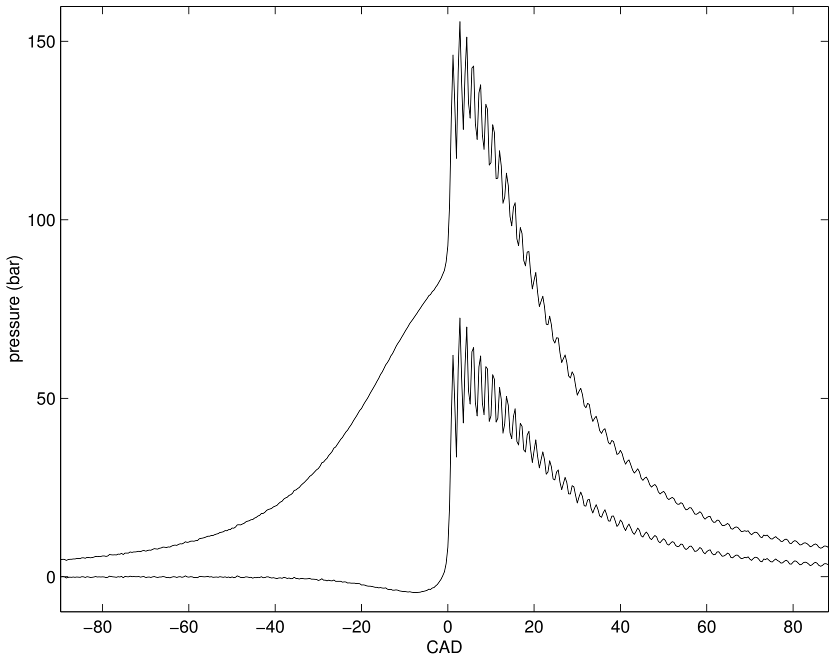


Figure 6.2: A pressure trace with oscillations with its burn profile are here shown.

their resonance frequencies in the above mentioned frequency range. The combustion has a similarity to the unwanted self ignition, knock, in an SI engine caused of a too high bulk temperature. The self ignition cause oscillations in the mixture. The resonances of the oscillations depends on the size of the combustion camber and the temperature. Another reason could be that the pressure transducer is connected to combustion camber trough a drilled channel in the cylinder head. In the channel a standing wave can occur, a quarter wave. The third phenomena that can cause the oscillations is the resonance frequency of the cylinder head.

## 6.3 How Good are the SOC Detecting Algorithms?

The result from the SOC detecting algorithm should not be thought of as an absolute truth. Many parameters influence the result and different algorithms give different results. This section shows how the result is influenced of changes in inputs parameters and how the result

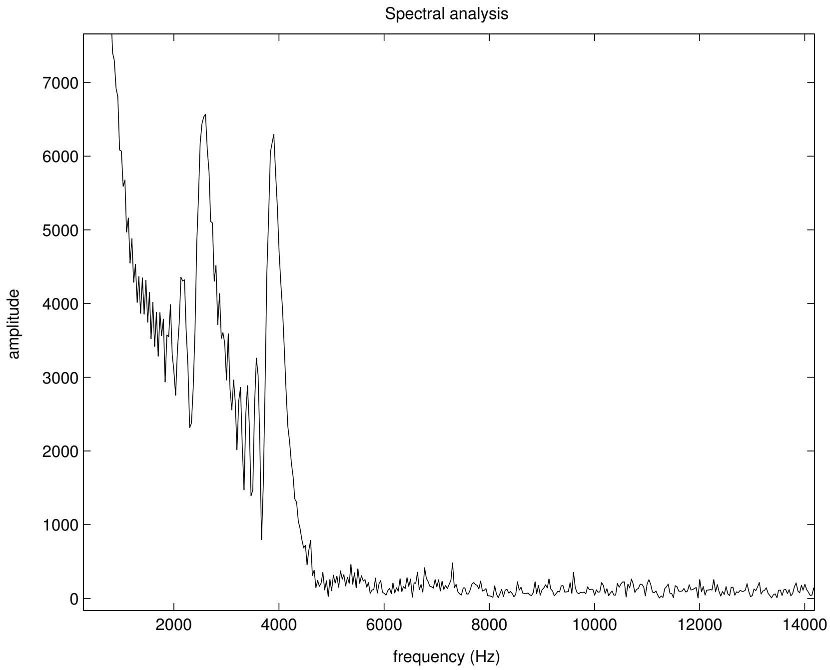


Figure 6.3: A spectral analysis over a pressure data with oscillations.

from the Rassweiler Withrow algorithm behaves compared to the result from other algorithms.

### 6.3.1 The Rassweiler Withrow Algorithm Compared to other Algorithms

There are many different algorithms to detect SOC with. Every algorithm has its own threshold and method to calculate SOC and gives consequently different values for the same data set. No method can be said to give the right answer and there is therefore of interest to se how different algorithms behaves compared to each other. To show how Rassweiler Withrow behaves it is compared with two other algorithms, Pressure peak position (PPP) and a heat release model. The PPP angle is the angle where the pressure is as highest. PPP is sometimes used when SOC is wanted fast and with no hard calculations. A heat release model is often used in off line calculations because of its well accepted result. More inputs parameters than the cylinder pressure are often necessary and the calculation time is often longer then more simple algorithms. This makes the algorithm not suitable for realtime systems. The chosen heat release is from AVL and to be able to use it

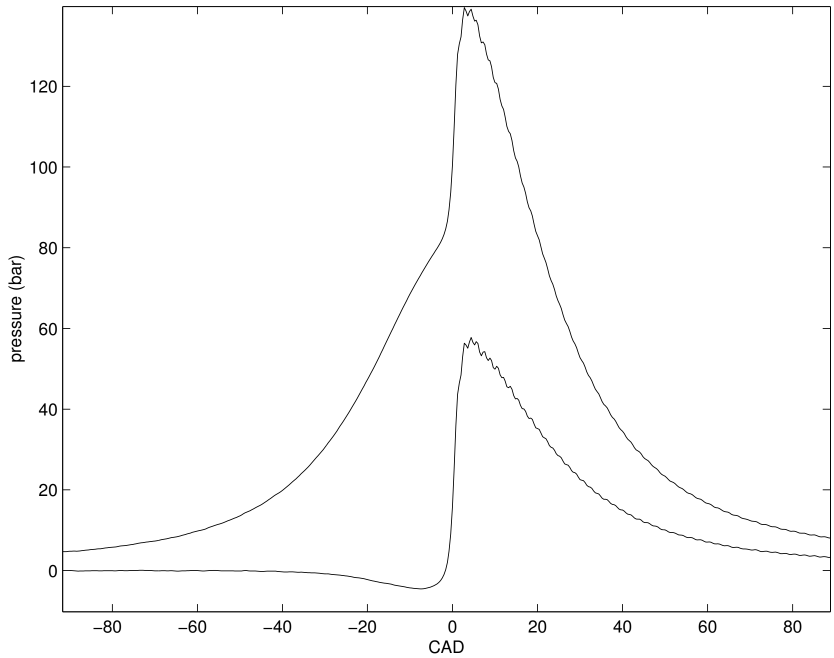


Figure 6.4: A filtered pressure trace with its burn profile are here shown.

data must be sampled with a data acquisition system from AVL. SOC angles for 32 cycles in load point 1 to 4 are calculated with each and every algorithm. Then the resulting SOC angles calculate with two different algorithms are compared. The difference in the resulting angle for every cycle is calculated and mean value and standard deviation for the 32 differences are taken. The result from the comparison are presented in the table below.

| load | SOC(RW-PPP) | | SOC(RW-HR) | | SOC(HR-PPP) | |
|---|---|---|---|---|---|---|
| point | mean | std | mean | std | mean | std |
| 1 | -2.89 | 0.18 | 0.57 | 0.04 | -3.46 | 0.20 |
| 2 | -2.90 | 0.15 | 0.05 | 0.08 | -2.95 | 0.15 |
| 3 | -2.50 | 0.51 | 0.51 | 0.03 | -3.01 | 0.51 |
| 4 | -3.25 | 0.13 | -0.20 | 0.04 | -3.05 | 0.14 |

The result shows that the Rassweiler Withrow and the heat release model almost gives the same answers, differ approximately up to 0.6 crank angle degrees. The small standard deviation tells that the difference is almost constant from cycle to cycle. The PPP algorithm gives an answer around 3 crank angles degrees more than the other two. No connection to charge or combustion phase can be found in the difference.

### 6.3.2 Inputs to the Rassweiler Withrow Algorithm

In the Rassweiler Withrow algorithm the polytropic exponent is used. The polytropic exponent depends on temperature, lambda, and amount of residual gases [2]. This means that the value of the polytropic exponent will change under the compression and from cycle to cycle. As an approximation the polytropic exponent is set to a fixed value of 1.35 and called kappa. This is far from reality and it is of interest to prove how much the calculated SOC angle change with a different kappa. If there are big differences in the calculated values a model for kappa must be considered. To see how the result changes with different kappas SOC is calculated for 50 cycles whit the chosen kappa, 1.35, and two alternative kappas, 1.3 and 1.4. Then the result calculate with two different pairs of kappa are compared. The difference in the resulting angle for every cycle is calculated and mean value and standard deviation for the 50 differences are taken. The Result is shown in the table under.

| load point | SOC(1.35)-SOC(1.40) mean | std | SOC(1.35)-SOC(1.30) mean | std |
|---|---|---|---|---|
| 1 | 0.360 | 0.07 | -0.375 | 0.07 |
| 2 | 0.111 | 0.01 | -0.119 | 0.01 |
| 3 | 0.272 | 0.02 | -0.300 | 0.02 |
| 4 | 0.127 | 0.01 | -0.143 | 0.01 |
| 5 | 0.192 | 0.02 | -0.196 | 0.02 |
| 6 | 0.134 | 0.02 | -0.138 | 0.02 |

The experiment shows that there are small changes in the calculated SOC angle, approximate 0.1-0.4 CAD with a small variation from cycle to cycle. For this application the calculated SOC angle is accurate enough and no model for kappa is needed.

### 6.3.3 Time Requirement

In a real time system the time consumption is of importance. In this case it is interesting to know when the CAN message can be sent, the sooner the better for the closed loop controller. When it can be sent depends of when the data acquisition stops and how long the calculation time is. The end of the acquisition can manual be set depending on how late SOC is wanted to be registered. The calculation time is dependent of how many samples that are acquired, in other word which sample rate and sample interval data is acquired with. To get an idee how long the calculation time is the time between that the acquisition stops until the system is ready to send the CAN message is measured. This is done for two acquisition setups, one that acquire maximum of samples and one that acquire normal of samples. The maximum setup samples data from -60 CAD to 60 CAD with a rate of 0.4 CAD per sample and the normal setup samples data between -15 CAD and 30 CAD with a rate of 1.2 CAD per sample. The time is measured with the internal clock in the PC.

**Calculation time:**

Maximum setup= 2-3 ms,

Normal setup=1-2 ms

The time measurement shows that the worst case took 2-3 ms and the normal case took 1-2 ms to calculate. This correspond to 30-45 CAD and 15-30 CAD at 2400 rpm which is the rev limit.

It is also of interest to see if the calculated angle is sensitivity of the amount of samples. SOC angles for 50 cycles in the 6 load points are calculated with the two different acquisition setups. The difference in the resulting angle, calculated with the two setups, for every cycle is calculated and mean value and standard deviation for the 50 differences are taken.

| load point | SOC(Maximum)-SOC(Normal) mean | std |
|---|---|---|
| 1 | 0.02 | 0.15 |
| 2 | -0.07 | 0.14 |
| 3 | -0.01 | 0.10 |
| 4 | -0.03 | 0.14 |
| 5 | 0.00 | 0.11 |
| 6 | 0.07 | 0.07 |

In the table above the result from the SOC calculation comparison is presented. It shows clearly that the mean value hardly not differ but from cycle to cycle the standard deviation is 0.10-0.15 degrees.

# Chapter 7

# Conclusions

To fulfil the demands from the customers and the government the engine manufactures must develop more efficient engines. This is done whit new technic and methods. One example could be the closed loop control of the combustion phase. The benefits from using the combustion phase in a closed loop control are many. For the HCCI engine it is a necessity, otherwise the engine can only be performed in a static state point. In a CI or SI engine it is mostly the emission versus the fuel consumption optimization that looms. To be able to validate new technic and methods a real time platform is created.

This thesis presents the real time platform. The platform can work as a smart sensor that collects data, do calculations on the collected data and finally sends the calculated result on a CAN bus. This is useful when a not directly measurable variable is wanted to be controlled in a closed loop. The platform can collect data in a variable crank angle range with different sample rates. The sample rate can either be based on time or crank angles. The flexible sample performance makes it possible to implement different algorithms based on different types of signals. The platform can also save data from one channel or two channels simultaneous sampled. That makes the platform very useful when phenomenons is wanted to be recorded or validated. The performance demands is fulfilled in the choice of hardware.

The platform is adapted to detect SOC on an HCCI engine. An SOC detecting algorithm developed of Rassweiler and Withrow is implemented. The algorithm is based on crank angle synchronic sampled pressure data. The algorithm have shown result close to a heat release model and no sensitivity of amount of samples and variations in kappa. It takes approximately 2 ms, 30 CAD at 2400 rpm, for the algorithm to calculate SOC. The experiments are done on an HCCI engine and it is possible that the rapid heat release have influenced the result in a good way.

## 7.1 Future work

To improve the platform it should also be possible to receive CAN messages. From an engine control unit a lot of interesting CAN messages are send, like rpm, different temperatures and pressures, etc. This information can be used in an implemented algorithm. An other improvement is to implement an algorithm that detect the real TDC from a pressure trace without combustion. Although it was found out that no model for the polytropic exponent was needed it would anyway be interesting to implement a model and se how the calculated SOC behaves.

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# Notation

| | |
|---|---|
| **CAD** | Crank Angle Degrees |
| **CAN** | Control Area Network |
| **CI** | Compression Ignition |
| **CO** | Carbon Monoxide |
| **HC** | Hydrocarbons |
| **HCCI** | Homogeneous Charge Compression Ignition |
| **HDD** | Heavy duty diesel |
| **IVC** | Inlet Valves close |
| **mep** | Mean Effective Pressure |
| **mfb** | Mass Fraction Burned |
| **NOx** | Nitrogen oxides |
| **PPP** | Pressure Peak Position |
| **rpm** | Revolutions Per Minute |
| **SI** | Spark Ignition |
| **SOC** | Start Of Combustion |
| **TDC** | Top Dead Center |
| **VVT** | Variable Valve Timing |