DIPLOMA THESIS

Optimization of the calibrations of the start for a mass production Flex-fuel direct-injection engine

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DIPLOMA THESIS ASSIGNMENT

Student:	**Bc. Valentin RAUTE**
Study program:	**N2307 Master of Automotive Engineering**
Field of study:	**2301T050 Advanced Powertrains**
School year:	2016/2017
Title:	**Optimization of the strategies and calibrations of the start for a production Flex-fuel direct-injection engine**

Assignment:

The thesis will address the optimization of the combustion control of a production turbocharged direct injection spark ignition Flex fuel engine during cranking and after-start phases for operation on neat ethanol (100%) and on ethanol-gasoline blends containing 22% or more of ethanol.

The focus of the thesis will be experimental work targeting the optimization of the engine control unit strategies and calibrations. The aim of the thesis is to highlight the impact of different parameters (including ignition timing and phasing, injection timing and phasing, throttle position) on several criteria imposed by the client (lambda overshoot, cranking duration). This study will be made at several fuel-ethanol composition and temperature.

Based on literature review and experimental findings, a preliminary investigation on the effects of ethanol on engine performance, fuel consumption and exhaust emissions will be conducted.

Thesis extent: minimally 55 pages

Graphical extent:

Specialized literature list:

Supervisor: doc. Michal Vojtíšek, M.S., Ph.D.

Specialist: Alexandre De Mascarel

Date of thesis assignment: 21 March 2017

Deadline of submission: 21 August 2017

The student acknowledges that he/she must elaborate the project by himself/herself, without any help except consultations with his/her supervisor. A list of used literature, other sources and names of consultants must be listed in the thesis.

I received the assignment on (date):

9 May 2017

Student's signature

Doc. Ing. Oldřich VÍTEK, Ph.D.
Head of Department

Prof. Ing. Michael VALÁŠEK, DrSc.
Dean

L.S.

Prague, 10 March 2017

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I would like to thank my supervisor Ing. Alexandre de Mascarel for his guidance, his patience but most of all his support during this six months internship. I would also like to thank each member of the DGS-EC/ECP-PS service for their support and integration as a part of the service. Lastly, I would like to thank M. Vojtisek and Julien Amiot for their help during this thesis redaction.

Title:

Optimization of the calibrations of the start for a mass production flex-fuel direct-injection engine

Author: Bc. Raute Valentin

Study program: Master of Automotive Engineering
Field of study: Advanced Powertrains
Assignment: Diploma Thesis

Supervisors: Alexandre De Mascarel (company supervisor)
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Keywords: Start, calibration, functions' strategies, flex-fuel engine, ethanol

Abstract:

This thesis describes the calibration process of the start for a mass production Flex-fuel direct-injection engine running on neat ethanol. This process is composed of several aspects from the software and calibration documentation to measurements on vehicle. First, a brief description of the different tools used is made to understand what is available to calibrate an engine. After choosing several parameters that impact the start of the engine, this study explains the different strategies to obtain the parameters previously selected in the documentation. Then, these parameters are modified and measured in order to list the impact of each parameter on the start of the engine. The results of the calibration measurements are analyzed in order to obtain an engine start which corresponds as much as possible to Bosch definition and criteria of an engine start.

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Nomenclature

ECU: Engine Control Unit

H: Hydrogen

CO: Carbon monoxide

C: Carbon

O: Oxygen

NOx: Nitrogen Oxides

% wt: percentage by weight

% dk: percentage of throttle opening (drosselklappe)

RON: Research Octane Number

MON: Motor Octane Number

HC: Hydrocarbon

CAN: Controller Area Network

CCP: CAN Calibration Protocol

ETK: Embedded ToolKit

TDC: Top Dead Center

BDC: Bottom Dead Center

ECT: Engine coolant temperature

NTC sensor: Negative temperature coefficient sensor

BMEP: Break Mean Effective Pressure

MDA: Measure data analyzer

DGS-EC/ECP-PS: Diesel Gasoline System-Electronically Control/Engineering Customer Paris Powertrain System (Bosch service where the internship took place)

Preface

Nowadays, mankind faces global warming and acknowledges the worst effects on the environment ever seen before. Many solutions are thought to reduce these effects. One of these ways is to diminish greenhouse gases emissions that reduce the ozone layer and increase global warming. Many strategies are currently in development to find solutions to this major problem.

In order to face this issue, society needs to find alternative source of energy which will reduce greenhouse gases emissions and other particles that harm the planet but will also decrease harmful pollutants emissions which impact human health. Since the transport sector represents one of the biggest part in these emissions and is expected to rise in the future, the effort is focused on finding alternative energy sources that could replace, or decrease, fossil fuels consumption [1]. The main reasons are the emissions when an engine is running, but also the replacement of petroleum-based fuel because of the shortage that is appearing and will increase in the future.

One of those alternative energy sources is the mix of alcohol with fuel or replace the fuel by neat alcohol. Among the many alcohol, ethanol seems to be the perfect candidate due to its chemical characteristics and its production. To that extend, engines need to be adapted to work on alcohol and fuel/alcohol mixture. These types of engine are called flex-fuel engines.

Flex-fuel engines are based on a motorization process which consists in adapting materials and combustion processes to the use of alcohol/gasoline mix, and especially ethanol, in the engines. The main advantage of these engine types is that it can run both on neat ethanol and pure gasoline and the different mixtures situated between the two. Many commercialized flex-fuel vehicles already run on several mixtures of ethanol/gasoline.

These mixture ratios are classified as follow:

Exx (the number following the “E” represents the ethanol content)

- E0 = 0% of ethanol and 100% of gasoline
- E100 = 100% of ethanol and 0% of gasoline

For example in Europe, the legislation authorizes users to drive engine running on a fuel range from E0 to E85 (85% of ethanol in the mixture). The purpose of this study is a flex-fuel engine destined to the Brazilian market where the legislation allows to use mixtures going from E22 to E100, so most of the measurements made in the study will be on neat ethanol.

For this study, the flex-fuel engine studied, a mass production turbo direct-injection automotive Flex-Fuel engine, is described in Annex 1. This type of engine is capable of working from neat gasoline to neat ethanol. For that purpose, the engine needs to adapt to the fuel used and the ethanol rate contained in the mixture. The engine is directed by the ECU “Bosch MED” which modifies the different parameters in order to run at optimal set points for several parameters. These set points and strategies are previously set by engine calibration engineers.

The focus of the thesis is an experimental work targeting the optimization of the engine control unit strategies and calibrations. The aim of the thesis is to highlight the impact of different parameters (ignition timing and phasing, injection timing and phasing, throttle position…) on the several criteria imposed by the client (lambda overshoot, time of start…).

Firstly, this thesis describes flex-fuel engines and the use of ethanol in such engines. Then, it focuses on the calibration process and the tools used in order to optimize the calibration of the start of an engine. Last but not least, a description of the different parameters to calibrate will be developed. To finish, the results of the different measurements made following the test plan will be described to obtain the optimization of the calibration.

I) Flex-fuel engine

1- Ethanol

One of the major argument to use ethanol is the fact that it pollutes less than regular fuels. Flex fuel engines produce less carbon monoxide and carbon dioxide emissions hence the expansion of such technology. Moreover, the octane number of ethanol is higher than gasoline (Table 1) so mixing it with gasoline could improve its octane number and therefore, improve the engine performance, as shown on Figure 1, and its knock resistance.

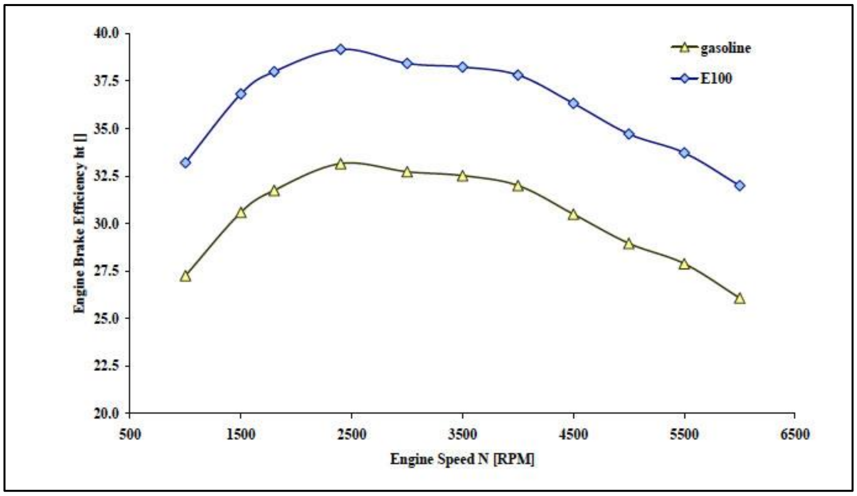


Figure 1: BMEP as a function of Engine speed for gasoline and ethanol [2]

Ethanol is more available and good for the economy because its creation is mostly based on processed corn, so there is a creation of jobs in agriculture which could improve the economy of less developed countries. Moreover, the production of this source of energy is more eco-friendly than the regular fuel production.

But the major issue is that more and more crops are grown especially for the ethanol production letting the food production aside. According to Matthew Brown [3] an energy consultant and former energy program director at the National Conference of States Legislatures: “Replacing only 5% of the nation’s diesel consumption with bio diesel would require diverting approximately 60% of today’s soy crops to biodiesel production”.

The major problem of an engine running on ethanol is the cold start. Due to the high latent heat of vaporization, the mix of ethanol has a certain advantage for the use of the engine at medium temperature but below a certain threshold, ethanol shows more drawbacks than advantages.

Table 1: Table of the characteristic values for ethanol and gasoline [4]

	Gasoline	Ethanol
Molar mass (g/mol)	102.5	46.07
C (% wt)	86.5	52.2
H (% wt)	13.5	13.1
O (% wt)	0	34.7
Density (kg/m^3)	735 – 760	794
Latent heat of vaporization (kJ/kg)	289	854
Distillation (°C)	30 – 190	78.4
Net heating value (kJ/kg)	42.690*10^3	26.805*10^3
Net heating value (kJ/L)	32.02*10^3	21.285*10^3
Stoichiometric ratio	14.7	8.95
RON	95	111
MON	85	92

Table 2: Advantages and drawbacks of ethanol [4]

Advantages	Drawbacks
Ethanol has a very good evaporation at high temperature so the mix is more homogeneous and there is less HC and NOx in the exhaust. The evaporation enthalpy of the ethanol is higher so better calorific evacuation of the combustion chamber. As a consequence, higher torque is produced for the same throttle position.	Ethanol has a bad evaporation at low temperature that's why cold start are more difficult to calibrate and there is a higher content of HC in the exhaust line. Ethanol also penetrates engine oil during cold start.
One of the most valid point to use ethanol is the knocking resistance, the engine performance isn't limited by the injection and ignition phasing but by the maximum pressure in the cylinders.	Higher presence of water in the exhaust due to carbon/hydrogen ratio.
The exhaust temperature is lower because of the decrease in the combustion chamber (see above).	The use of ethanol delay the dew point because of the –OH group of the alcohol molecule.

2- The Engine

A flex fuel engine is an engine adapted to work on both neat ethanol and pure gasoline and all the ethanol/gasoline mixtures in between. To calibrate this type of engines that adapts depending on the tank content, one solution (used on the engine of the study) is to install an ethanol sensor on the vehicle so that the ECU obtains the information of the ethanol rate present in the mix during the injection. Depending on this value, most of the parameters are adapted in order to optimize engine runs despite the fuel used in the engine.

ETHANOL SENSOR [4]

The ethanol sensor used on the vehicle is a Continental GM Ethanol Flex-fuel sensor.

This sensor gives back two information as shown on Figure 2:

- First, the frequency of the linear signal informs on the ethanol rate that is contained in the mixture (72Hz corresponds to E22 and 143Hz corresponds to E100).
- Secondly it informs on the temperature of the mixture as shown on the picture. (1ms represents -40°C and 5ms represents +125°C)

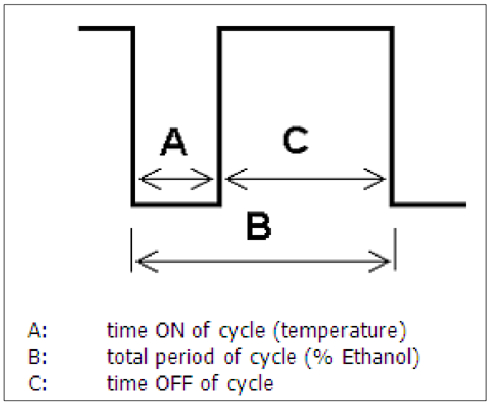


Figure 2: Flex fuel sensor output signal

Flex-fuel engines materials also need to be adapted to other fuel than regular gasoline. In fact, there is an impact of the water contained in the ethanol on materials like for instance corrosion on some engine components and on fuel system. The alcohol also as an impact on rubber and deteriorate several rubber components. Seals deterioration can also appear on some levels. That's why flex-fuel engine materials must resists to each ethanol/gasoline mixture but mostly, these materials must resist to neat ethanol.

Other strategies exist to obtain the ethanol content of the mixture used like the use of lambda deviation after a refuel of the engine.

3- Goals and objectives of the internship

The main objective of this six months internship is to find an optimization of the start of the flex-fuel engine available on site. In order to fulfill that purpose, several goals have to be validated to finally obtain the calibration of the engine start.

First, the different parameters that will have an impact on the start of the engine have to be found and analyzed in order to obtain their strategies which will allow the user to act on the vehicle and modify the start phase. Then, when those functions are deeply understood, a test plan will be elaborated and several values for the different parameters previously found will be tested to find the impact of the parameters on the engine start. After analyzing these impacts, optimized output values will be found for each parameter in order to obtain an engine start that will meet the client's expectations and validation requirements to continue the calibration process.

II) Calibration Process

1- Tools used to calibrate an engine

1) The Engine Control Unit (Bosch MED)

A specially designed ECU, called "application ECU", with an additional output CAN cable is installed on the vehicle (70-120 voices). This CAN module is not the same as the CAN network used in regular engines, it is dedicated to calibration. CCP and ETK are the two interface types for "application ECU". Most ECUs use the CCP interface.

These "application ECUs" possess two memory sections to store two different parameters sets:

- The reference page where the parameters which are currently set in the vehicle are stored.
- The working page where the parameters, modified or not by the user, are stored.

2) The modules [5]

The modules are interface modules that link your computer to the CAN network of the vehicle thanks to the CAN cable coming from the ECU. There is several types and sizes of modules adapted to deliver information at different sampling frequencies. The chosen module must be adapted to the measurement because the file size will depend on the raster chosen for each variables.

First, the interface module called ES581 is a dual-channel (CAN) module which connects the ECU to a computer over the USB port as illustrated in Figure 3. It permits the acquisition of variables with a sample rate from 10ms to 1s.

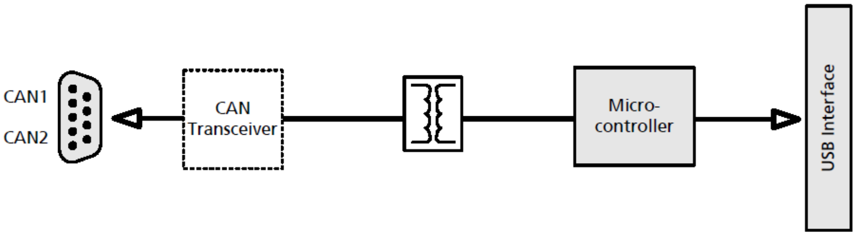


Figure 3: ES581.4 Block Diagram

Secondly, as shown on Figure 4 and Figure 5, the ES590 - ETK, CAN and K-Line module is a device that allows the use of an additional lambda meter (amongst other sensors) through the serial port. It connects your computer to the ES590 over the Ethernet port (Host). It permits the acquisition of variables with a sample rate from 10ms to 1s.

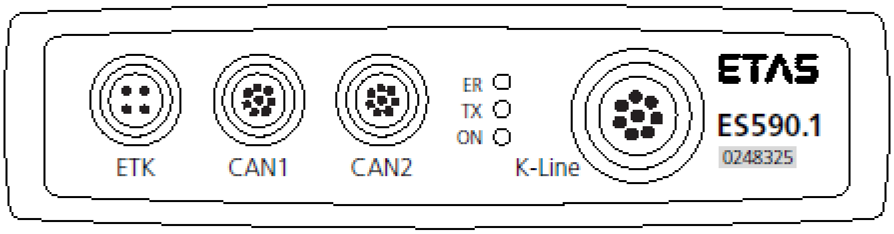


Figure 4: Front of the ES590

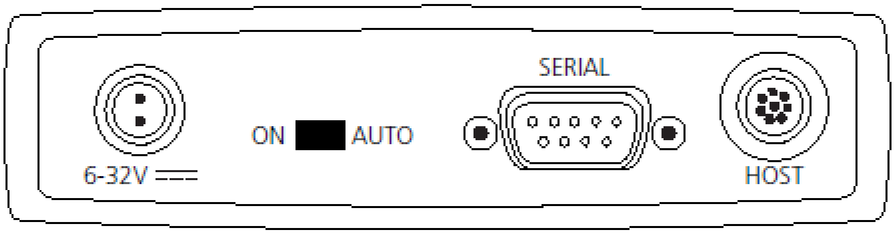


Figure 5: Back of the ES590

The ES63x is a module that measure the lambda before the catalyst. This module is necessarily used during measurements of the start of an engine because the standard lambda probe can't be used before the engine reaches the dew point temperature of the engine due to water presence in the exhaust that could damage the lambda sensor. Thanks to the sensor heater and additional protections, the additional lambda sensor is able to measure the lambda at each stage of an engine run. It is linked to the computer through modules over the serial port situated at the back of the ES590 for instance. The Figure 6 shows the connections of the lambda sensor with other devices in order to measure the air-fuel ratio at all time.

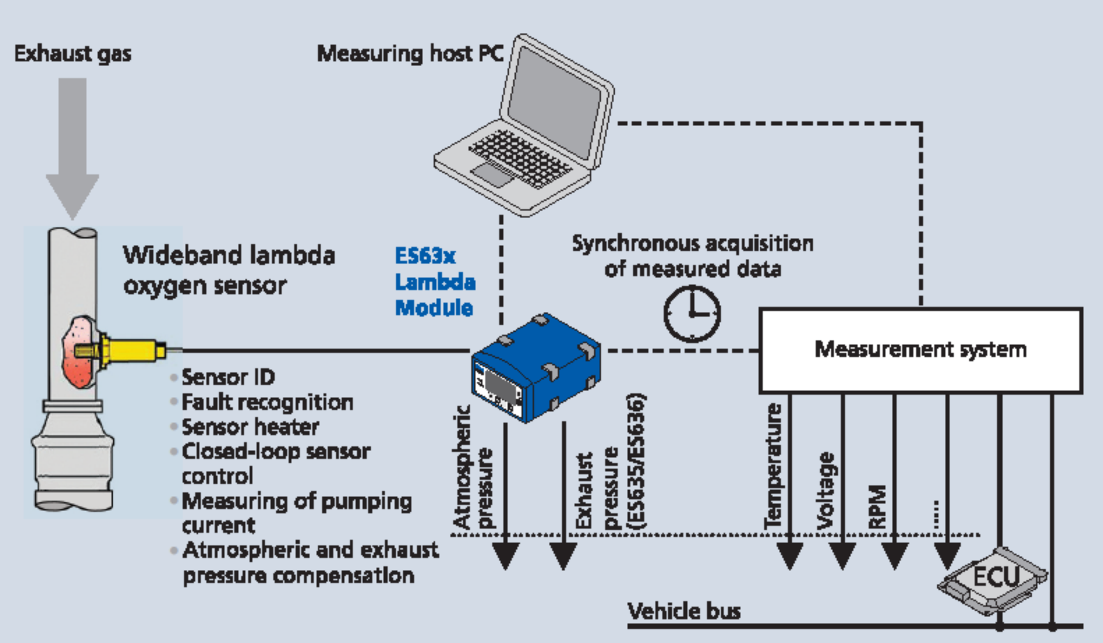


Figure 6: Schemes Lambda module ES63x connections

The interface module ES1000 (Figure 7) is the module that permits the acquisition of variables with a sample rate from 0.01ms to 1s. This module can be used with a breakout box which allows to measure specific variables such as injection and ignition signals thanks to the high sample rate. The major issue with this type of precise module is the file' size it produces.

Figure 7: Picture of an ES1000 Module

These devices are connected to the ECU on the vehicle with an additional lambda sensor as shown on Figure 8.

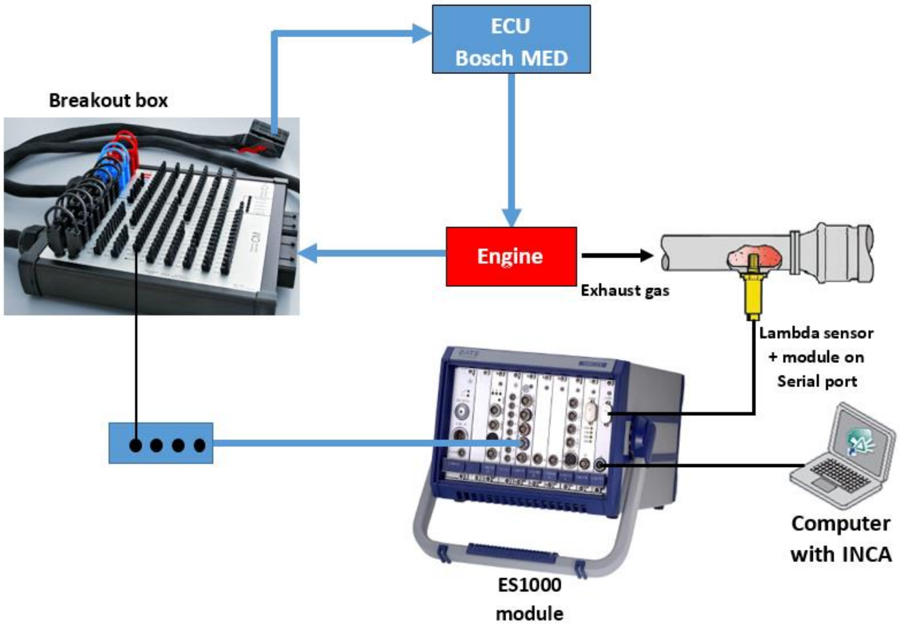
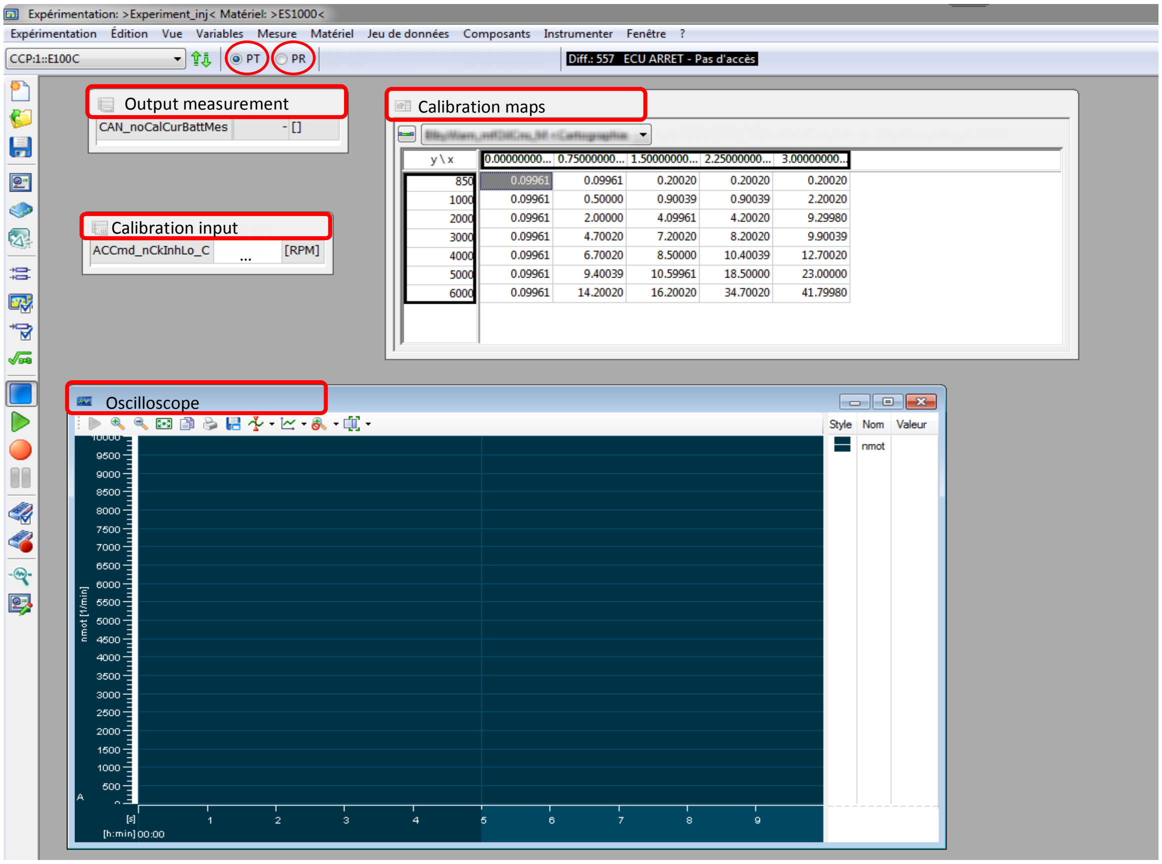


Figure 8: Breakout box connections on an engine [5], [6]

3) The software INCA [5]

When the computer is connected to the module (connected to the ECU), the software INCA allows the user to dialog with the vehicle. This software is composed of three components which allow the user to dialog with the vehicle.

First, the dataset is the file which lists every variables, parameters and maps and their addresses which enable the computer to dialog with the ECU even when the engine is running. Then, the experiment page is the software page where the user selects the variables and maps to calibrate but also the variables needed for the measurement. It receives the data selected from the workspace and displays them. The workspace is the part of the software which receives, sends and memorizes the data during a measurement. It is the part of the software which stores and sends the information from the experiment page and use the dataset to dialog with the ECU and the experiment page.



Expérimentation: >Experiment_inj< Matériel: >ES1000<

CCP:1::E100C ● PT ○ PR Diff.: 557 ECU ARRET - Pas d'accès

CAN_noCalCurBattMes - []

ACCmd_nCkInhLo_C ... [RPM]

[redacted]

y \ x	0.00000000...	0.75000000...	1.50000000...	2.25000000...	3.00000000...
850	0.09961	0.09961	0.20020	0.20020	0.20020
1000	0.09961	0.50000	0.90039	0.90039	2.20020
2000	0.09961	2.00000	4.09961	4.20020	9.29980
3000	0.09961	4.70020	7.20020	8.20020	9.90039
4000	0.09961	6.70020	8.50000	10.40039	12.70020
5000	0.09961	9.40039	10.59961	18.50000	23.00000
6000	0.09961	14.20020	16.20020	34.70020	41.79980

Style	Nom	Valeur
▬	nmot	

Figure 9: Picture of an Experiment page

As shown on Figure 9, the software INCA is divided in two different pages corresponding two the two memory sections of the "application ECU". The page entitled "PR" is the working page corresponding to the reference page of the vehicle. The reference calibration is situated in this page and the user can't modify it. The second page entitled "PT" is the working page on which the user can modify parameters before or during the calibration process.

Several types of data can be displayed: “output measurements” give the value of the variables measured, the “calibration inputs” give a value that the user can modify, “calibration maps” are tables of values which depend on the two inputs (corresponding to “output measurements”) of the map and the “oscilloscope” displays in real time the value of “output measurements”.

At the end of a test, the software automatically creates a .dat file with all the variables selected by the user in the experiment page.

4) Calibration Maps [7]

The calibration map, as shown on Figure 10, is the tool used to give an output value depending on the given input points. It consists in a table if there is two inputs, as illustrated in Table 3, or a simple vector if there is one input.

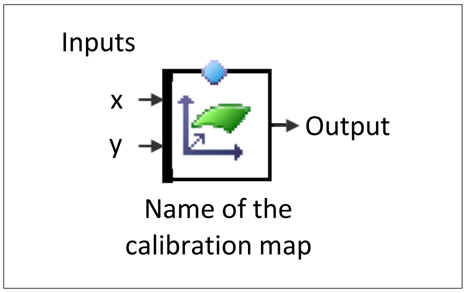


Figure 10: Calibration map representation

Table 3: Example of a calibration map

y \ x	a	b	c	d
a'	aa	ab	ac	ad
b'	ba	bb	bc	bd
c'	ca	cb	cc	cd
d'	da	db	dc	dd

<u>Calculation:</u> $c < X < d$ & $a' < Y < b'$

$$\frac{(ad - ac)}{(d - c)} * (X - c) + ac = Val1$$

$$\frac{(bd - bc)}{(d - c)} * (X - c) + bc = Val1'$$

$$\frac{(Val1' - Val1)}{(b' - a')} * (Y - a') + Val1 = Value$$

Equation 1: Linear interpolation equations

To calibrate the map, the aim is to place the engine at the input values fixed by the calibration map and to change the values given by the map. After several measurements with different values, the parameter calibration can be optimized given the impact of changing a parameter and the evolution that will follow this change which have to meet the different criteria expected by the client. Afterward, when the engine is running, the Equation 1 permits to the ECU to transmit the different values for any situation the engine will be facing.

5) MDA Analyzer [5]

MDA Analyzer is a tool which reads the .dat files and displays the measurement previously made by INCA. This software is used to analyze measurements and the impact of the calibration on an engine run. MDA analyzer also allows the user to export data in .ascii, format that can be used on excel for further calculation.

6) The software and calibration documentation [7]

The “software and calibration documentation” is the main document which explains the strategies and the different functions used in an engine.

This documentation illustrates and explains the path used as strategy between all of the functions and the link between each one of them. The different functions are presented with several bloc schemes and descriptions, very similar to the Simulink page from the software Matlab. It also defines every parameters and variables that can be encountered in the ECU program.

2- System overview [4]

In order to make a flex fuel engine running, many variables are taken into account to regulate the injection time, some of them are represented in Figure 11. The difference with a regular engine is the ethanol sensor which allows the ECU to adapt the injection time to the ethanol content of the mixture used.

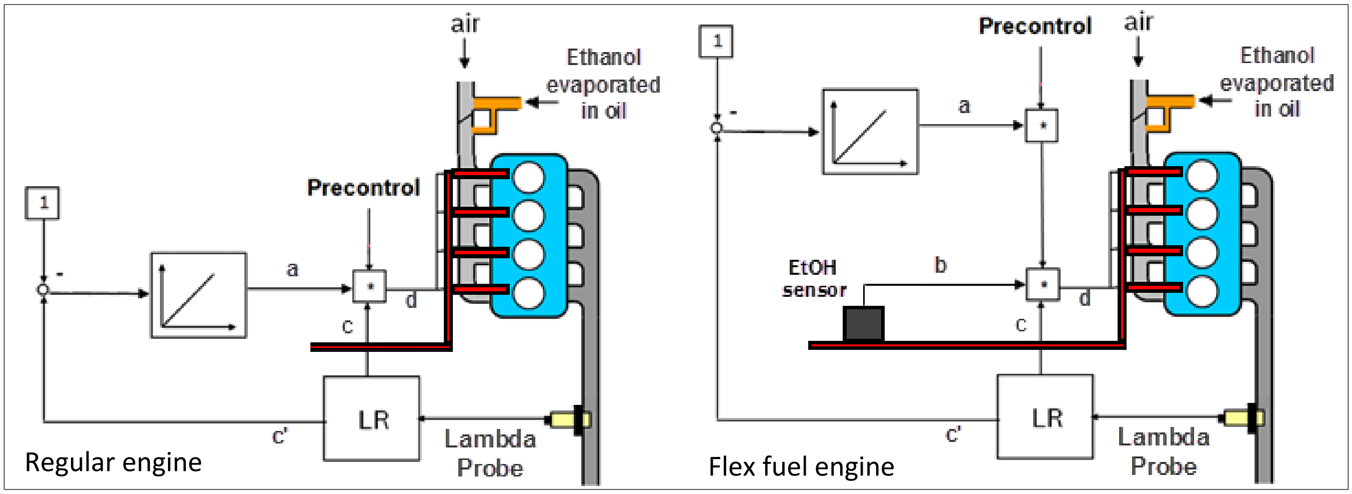


Figure 11: System overview of a flex-fuel engine compare to a regular engine [4]

“d” represents the injection time. This value depends on the injection mode and several parameters which enable engine runs.

“c and c’ ” represent lambda control factors. This measurement provides a factor given by the lambda sensor to maintain the lambda at the lambda set points.

“a” represents the mixture adaptation factor. This factor is used to take into account the deviation of the components during the closed loop control.

“b” represents the stoichiometric correction. It’s given by the ethanol sensor to adapt the strategy and the parameters to maintain an optimal injection time. It is also used as an interpolation factor.

The global strategy used by the system is an interpolation based on the factor “b” given by the ethanol sensor.

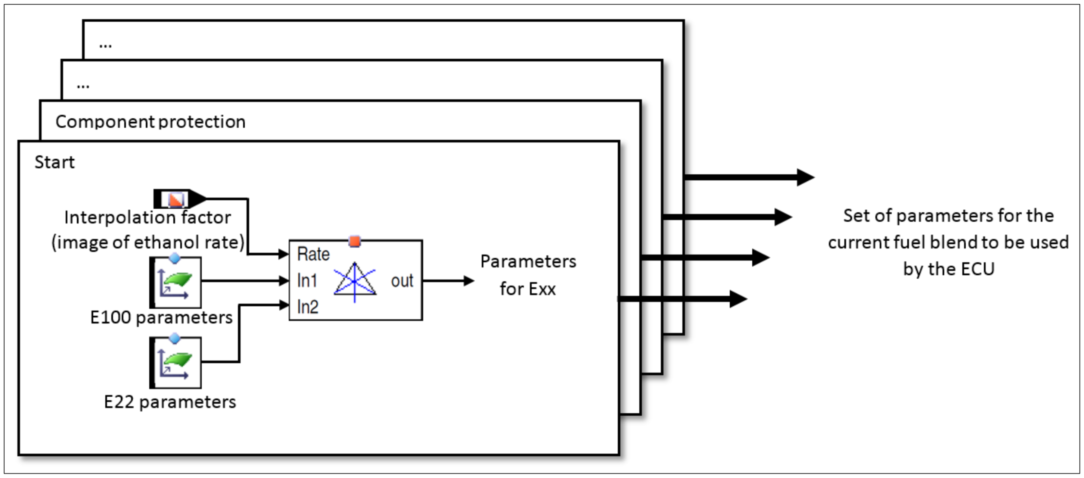


Figure 12: Interpolation principle [4]

The Figure 12 shows the global strategy of the interpolation principle used to calibrate most of the parameters. The first map is calibrated for neat ethanol E100, the second for E22/gasoline. Then depending on input values, the two calibration maps set two different values that are interpolated thanks to the “b” factor. Some parameters are not calibrated by an interpolation but by a baric center between the two calibration maps but it is the same principle as interpolation calibration.

3- The Start

According to Bosch definition, the start phase is characterized by the cranking phase and the beginning of the engine run until it reaches 800 rpm. In this start phase, the system strategy works in “open loop” because the lambda probe could be damaged if it is used due to the water contained in the exhaust. So, in this phase, the different parameters will have to be set manually in order to have a good start of the engine. When the engine speed is above 800 rpm, the engine is considered in the after-start and warm-up phase where the torque structure is used. The torque structure works in “closed loop” and enable a correction for some torque parameters (throttle position, ignition angles…). Then, when the dew point temperature of the engine is reached, the system strategy works in another “closed loop” for the parameter lambda which leads to produce a lambda controlled enrichment. So the parameters to calibrate during the after dew point temperature in the exhaust phase are the lambda set points.

The requirements for a well optimized start for the client are the start time and the engine speed overshoot. The aim is to obtain the fastest start time possible and the engine speed overshoot needs to be situated in between a certain percentage over the idle speed defined in the torque structure and set by the engine temperature. The aim is to choose parameters which lead to an engine speed overshoot situated between 1500rpm and 2000rpm and for which the start time is the minimum.

An additional criteria is the lambda undershoot and its oscillation around the lambda set points given by the calibration. The best start will happen when the lambda undershoot is the highest possible, because of the harmful pollutant emissions if there is a too rich combustion, and the oscillations deviations from the calibrated lambda set points are really low or don't exist.

The Figure 13 represents an example of a start at 21°C with an E95 fuel mixture:

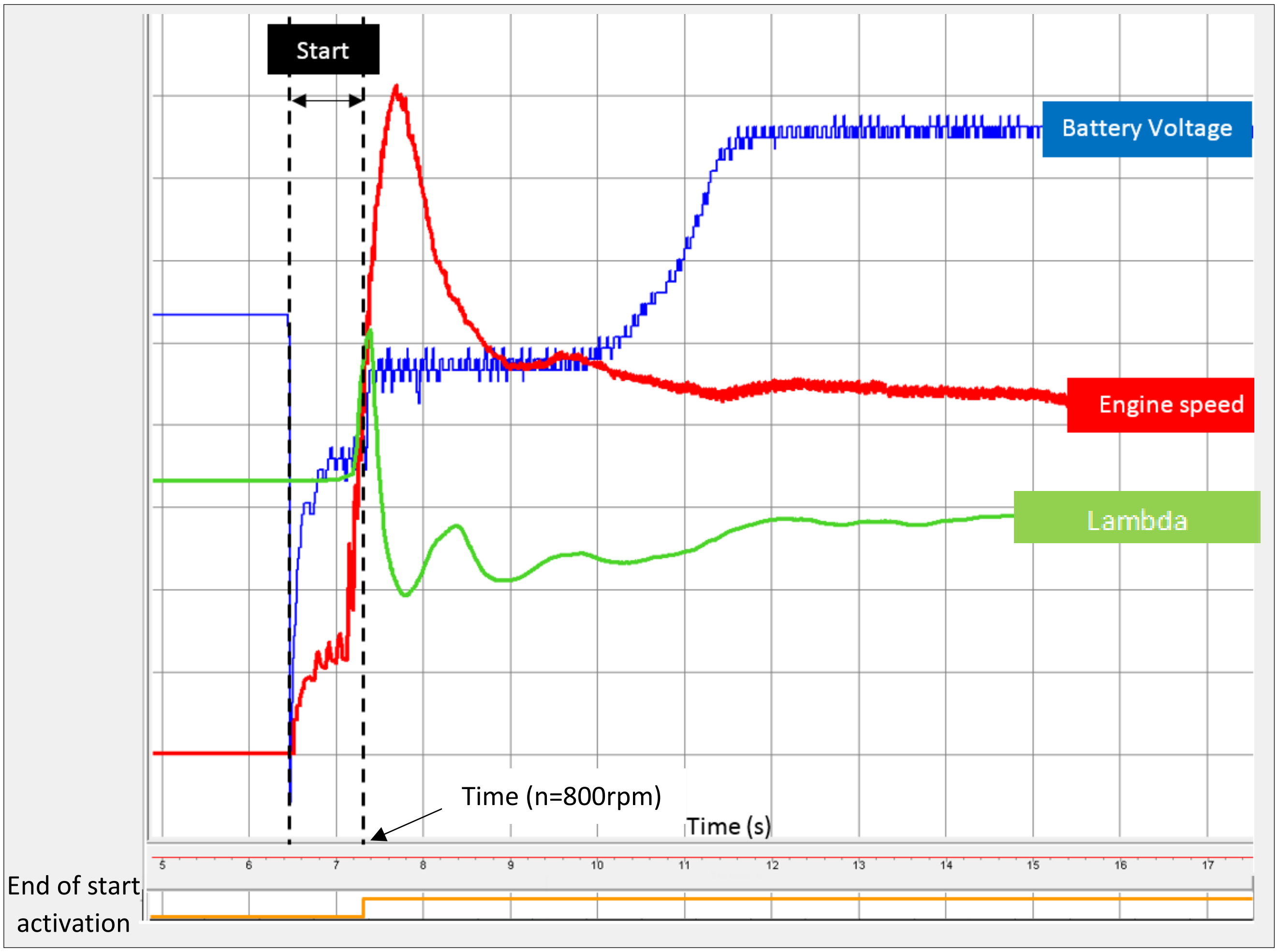


Figure 13: Start phase Measurement

The start phase begins when battery voltage falls down. Then, when engine speed reaches 800 rpm, a Boolean is activated and informs the entire system that the start phase is ended.

III) Description of the functions

In order to optimize the engine start, understanding the strategies used for each function and the impact of different inputs on the resulting value is necessary. So for each selected function, the user needs to make measurements, where most of the variables contained in the function are used, and follows the path toward the output value.

Since Bosch software is a mix of Bosch functions and functions coming from the customer, one of the issues is that some of the strategies are hidden due to confidential rules of companies. So the aim is to guess, according to the name of the variables and the similarities with the calibration maps, the strategies used for these "hidden" functions.

The functions listed below are the functions which need to be calibrated during the start phase (manual settings) and their transitions toward the after-start and warm-up phases:

- Throttle position during start
- Main ignition angle during start
- Injection mode and phasing during start
- Start injection factor
- After-start and Warm-up injection factor
- Lambda set points

Each function will be described in the following parts according to the "software and calibration documentation" and an example will illustrate the results made after a measurement on the vehicle.

1- List of the variables and parameters used in the different strategies

• Parameters

Throttle position: The throttle position is measured with a potentiometric sensor. The throttle is a valve which controls the amount of air that will enter in the engine.

Ignition: In a spark-ignition engine, the combustion is started by an electric spark coming from the spark plug which ignites the mixture in the combustion chamber. This main spark appears when the crankshaft position corresponds to the position calculated or set by the ECU.

Injection: The engine is a direct injection spark ignition engine. The mixture is highly pressurized and injected directly into the combustion chamber of each cylinder based on the crankshaft position.

Injection factors: These factors are enrichment factors used during start, after-start and warm-up phases in order to obtain richer combustions necessary to start an engine.

Lambda set points: The lambda set points are a list of air fuel ratio expected during combustions that appear after the dew point temperature of the engine is reached in the exhaust.

- Input variables:

Engine temperature: This temperature is the water coolant temperature of the engine at all time. It is measured with a NTC temperature sensor called ECT.

Engine start temperature: This temperature is the water coolant temperature when the engine starts. It is measured with the same sensor as the engine temperature (ECT) and it keeps in memory the value of the engine when it starts.

Engine speed: The engine speed is measured with a hall speed sensor. The oscillations shown on the engine speed signal are the individual combustions impacting engine speed. As shown on Figure 14, it is easier to notice misfire with the measured engine speed than with the filtered one.

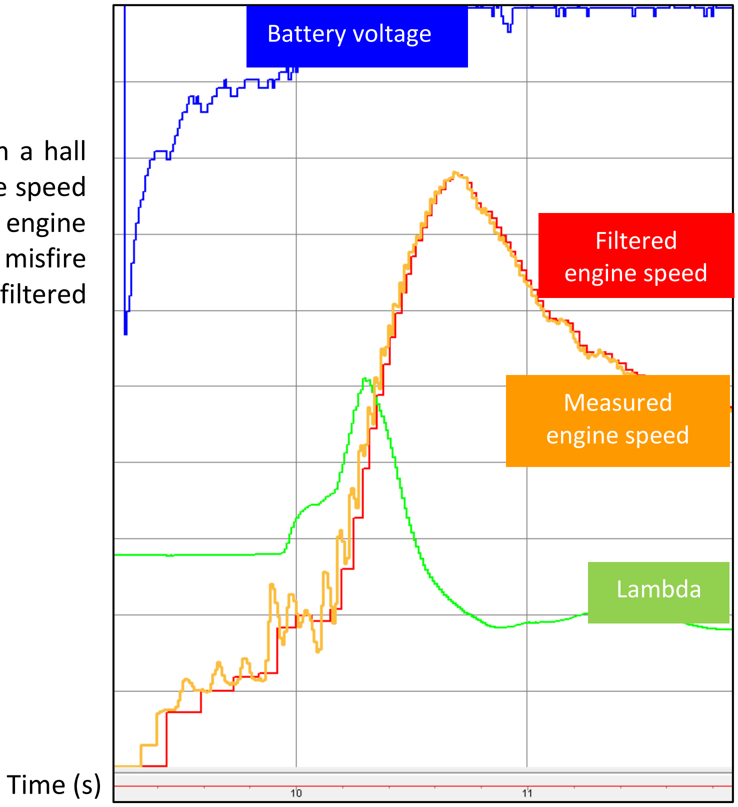


Figure 14: Example of start to compare engine speeds

Time during cranking phase: It is the time since the beginning of the engine start. The timing counter begins when battery voltage falls down.

Time during after start: It is the time since the end of the start phase which is when the engine speed reaches 800 rpm. This timing counter begin when the Boolean of end of start is activated.

Ambient air temperature: The ambient air temperature is the temperature of the environment in which the vehicle is situated. It is measured with a NTC temperature sensor.

2- Throttle position during start

The throttle position at start is defined by a calibration map based on engine speed and engine start temperature as shown on Figure 15. The value given by this main map can then be altered by other additional maps depending on the conditions of the vehicle start (driver influence, air intake temperature…). The position is automatically set when the driver uses the key to start the vehicle.

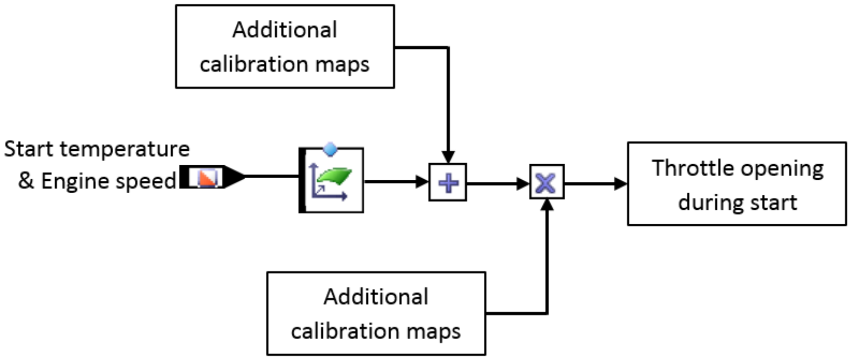


Figure 15: Strategy to obtain throttle opening during start [7]

When the end of the start phase is reached (approximately 800rpm), a transition ramp is activated to make the link between the start throttle position and the throttle position needed in the after-start and warm-up phases driven by the torque structure. This ramp can increase or decrease depending on the value of the throttle position at the beginning of the torque structure. A system constant can modify the slope of the ramp to obtain a fast or slow transition between the two phases. There is no influence of the ethanol rate of the mixture on the output value in this function.

The Figure 16 represents an example of a start temperature at 21°C with E95:

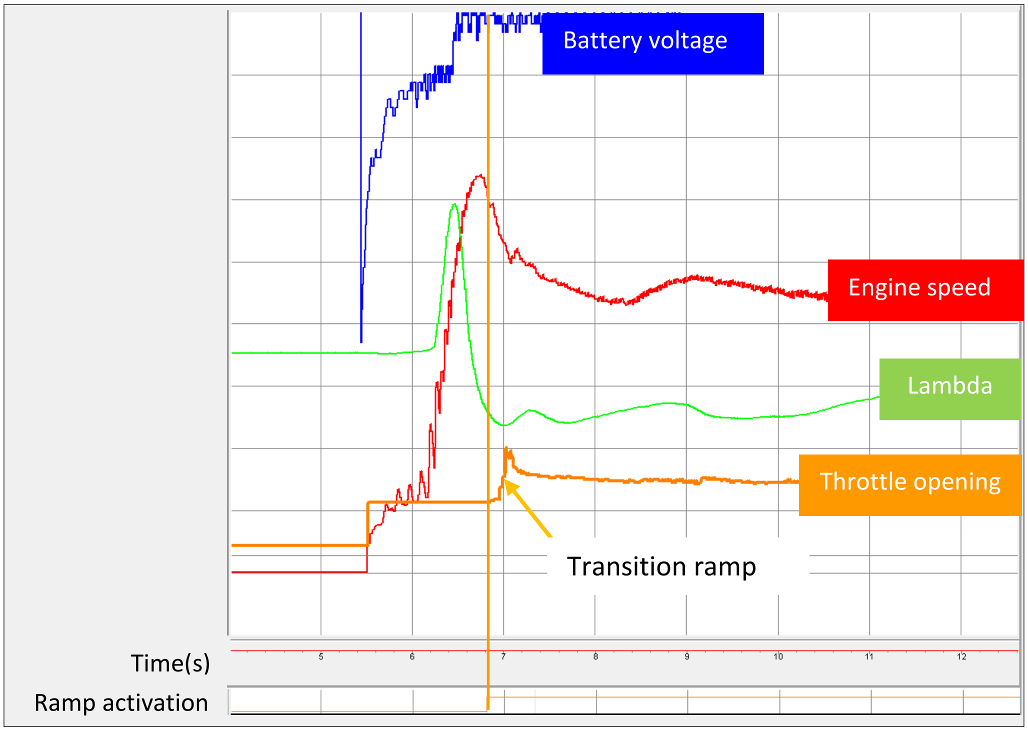


Figure 16: Start measurement of throttle opening

3- Main ignition angle during start

All the ignition function is based on an interpolation between 2 maps with an interpolation factor which is a coefficient image of the ethanol content in the fuel as shown on Figure 18. These 2 maps depend on engine speed and start temperature. As in the previous function, additional maps can modify the main value depending on different input parameters but to see the real impact of the calibration, these additional maps are usually calibrated to 0 (or 1 if it's a factor). Some additional maps set an offset to the ignition angle (for instance the altitude) but this type of offset isn't used for high pressure direct injection engines.

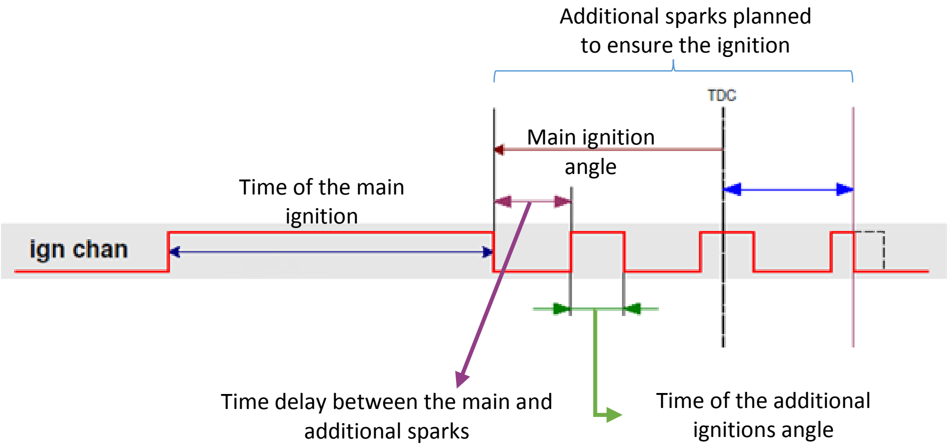


Figure 17: Scheme explaining the ignition angles setting during start [7]

As shown on Figure 17, the ignition system enables the option of additional sparks in case the first spark doesn't fire. But this option is only available for low engine speed and if the temperature of the ignition coil isn't above the threshold previously fixed. The low engine speed can be explained by the time of coil charging which can take milliseconds during start phase.

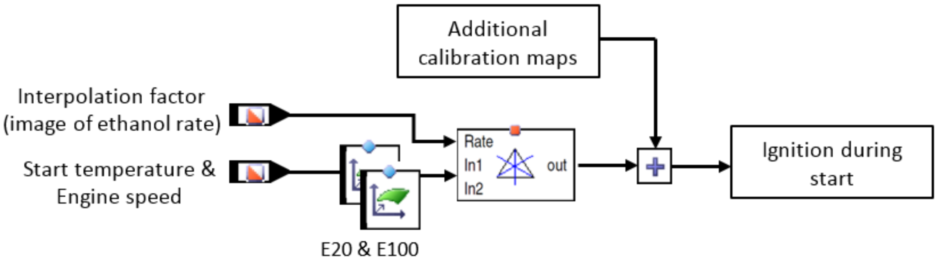


Figure 18: Strategy to obtain the main ignition angle during start [7]

The Figure 19 represents an example of a start at 20°C with E95:

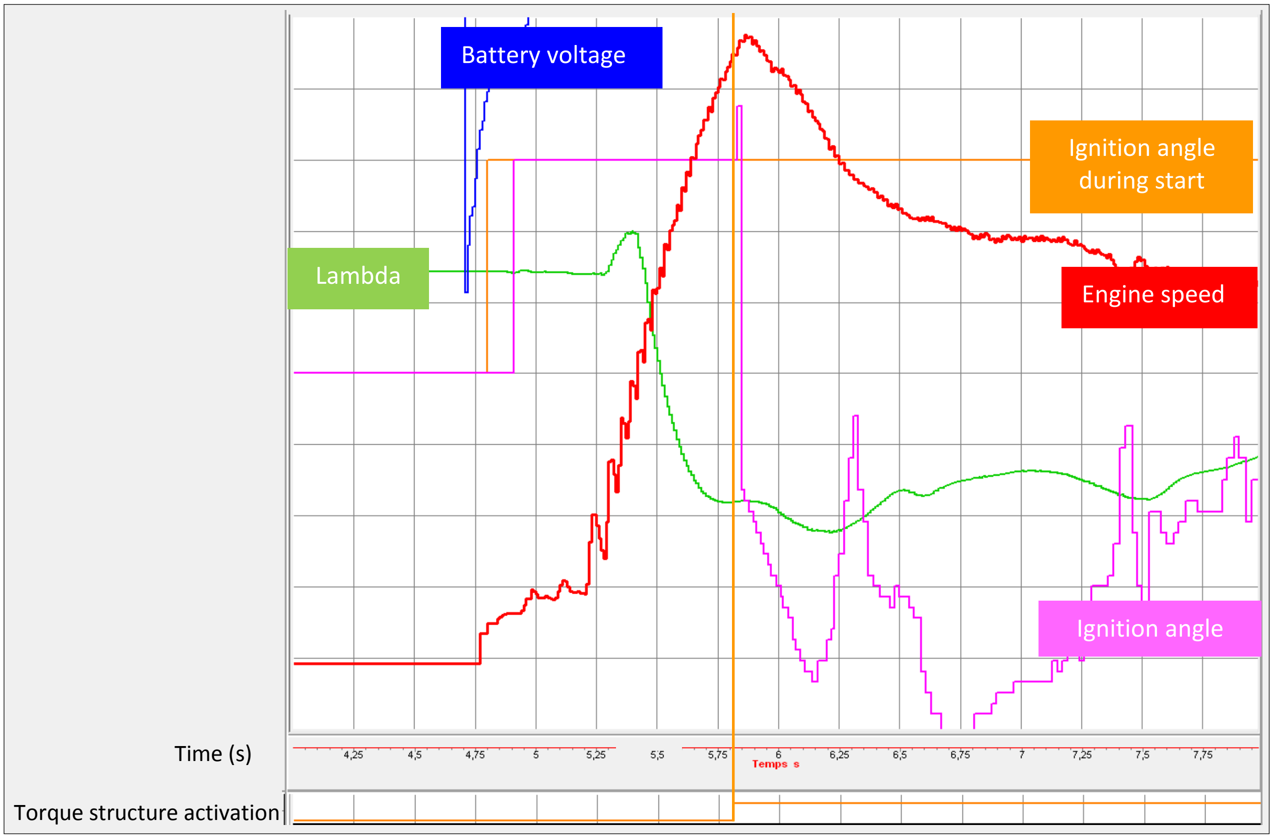


Figure 19: Start measurement of ignition angle

4- Injection mode and phasing during start

As illustrated in Figure 20, there are 5 different injection modes available in the ECU of the vehicle studied depending on the number of injections and when these injections occurs (during intake, compression or both).

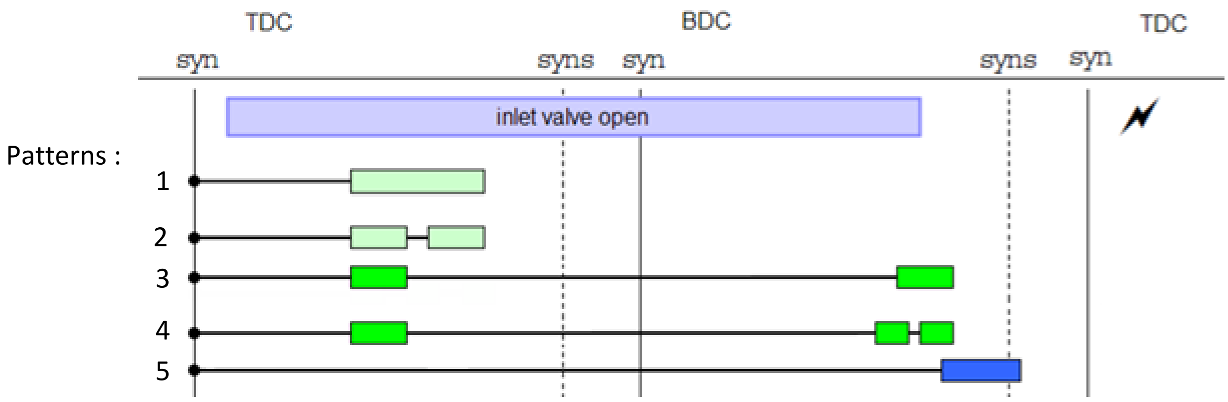


Figure 20: Schemes representing the different injection modes available on the engine studied [7]

Depending on the injection mode selected, the strategy to determine the injection angles is different. The Figure 21 illustrates the injection signal used to define the injection mode 2. The main angle is set in a calibration map as the first begin injection angle. Then, the begin injection angle of the second injection is calculated thanks to Equation 2 and the parameters needed for the calculation.

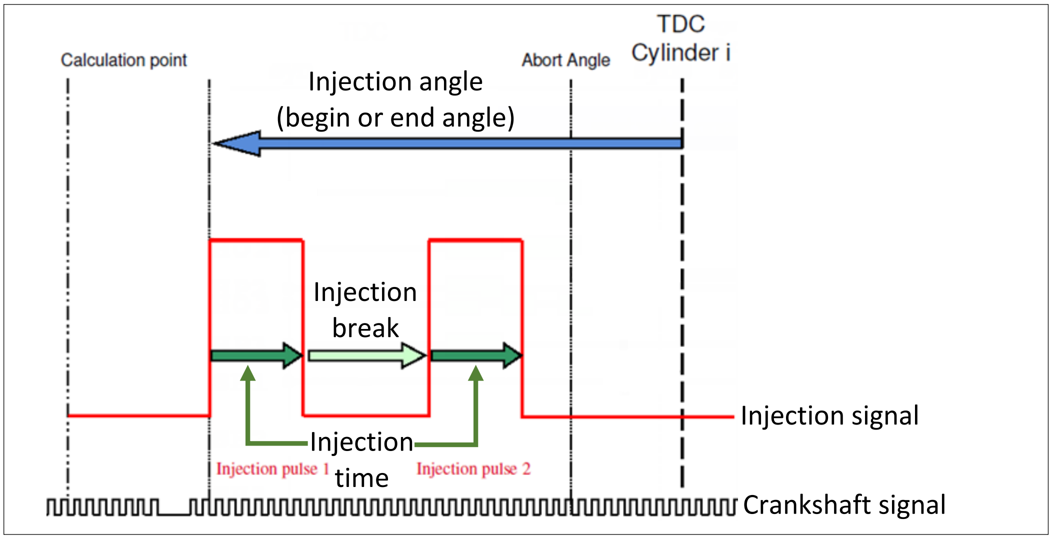


Figure 21: Scheme explaining the injection angles setting during start [7]

Figure 22 and Figure 23 represent the strategy used for the 4th injection mode angles calibration.

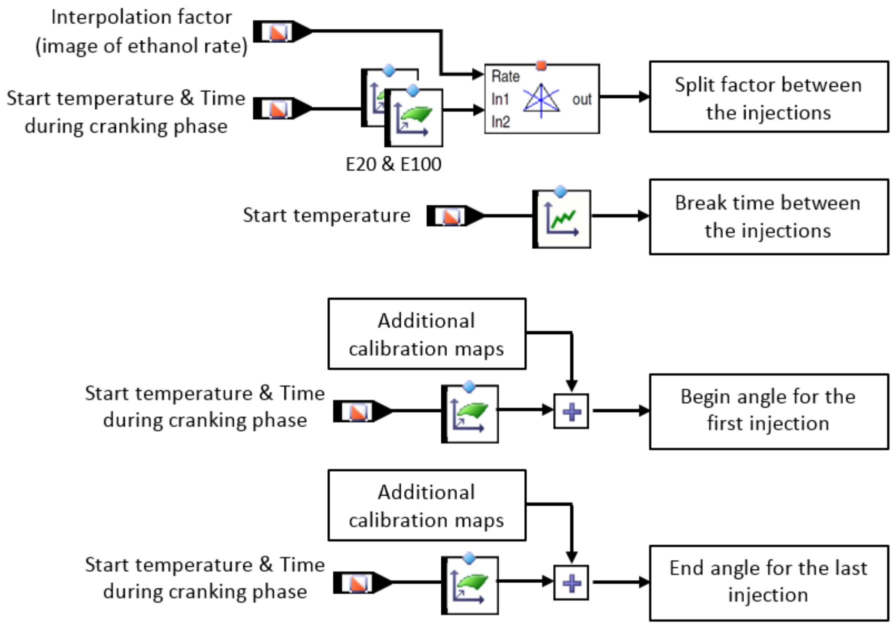


Figure 22: Strategy to obtain injection angles of injection mode 4 [7]

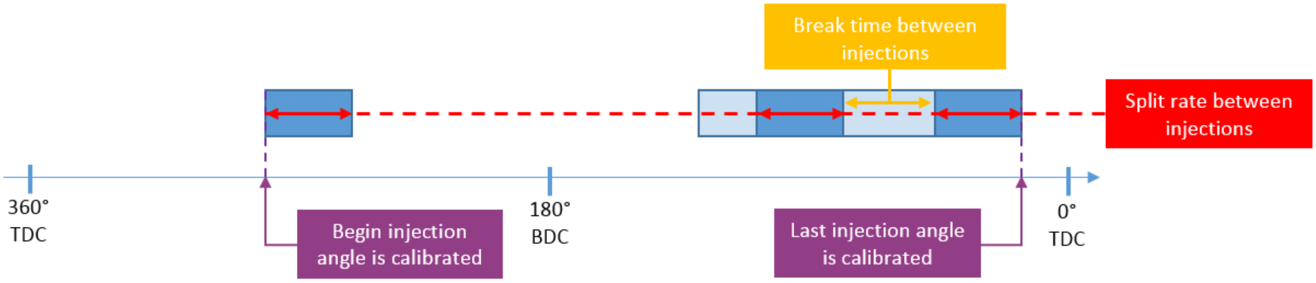


Figure 23: Schemes representing the injection mode 4

The end of the last injection angle is calibrated and then a calculation described in Equation 2 is made with the values of split factors and injection breaks given by different interpolation of calibration maps.

$$Angle\ estimation = reference\ angle \pm injection\ break * crankshaft\ speed \pm injection\ time * crankshaft\ speed$$

Equation 2: Injection angle automatic calculation [7]

The addition or subtraction signs (±) in Equation 2 appear because depending on the injection mode selected, the strategy used to calculate injection angles is based on the beginning of the first injection or on the ending angle of the last one. If the reference angle is an ending angle, the previous angles will result from the addition to the reference angle and if it's a beginning angle, the next angles will result from the subtraction.

As shown in Figure 24, an additional injection mode is composed of 3 injections during the compression phase, the ignition angle was set 0° (which corresponds to the TDC of the cylinder) and injection phasing such as the end of the last angle is calibrated. The verification of injection angles is relevant because each crankshaft signal represents 6° and since the camshaft signal represents a repeated sequence, the two signals allow the user to verify the calibration.

During high pressure start, an additional option of the ECU allows the user to change of injection mode in the case the first one doesn't fire. So if there is no combustion after the two first combustions, a second injection is selected among the list of the different patterns to start an engine. The strategy is that after the two first combustions, the injection mode can be switched depending on the condition of the engine environment. After the end of the start phase, the injection mode is automatically selected depending on the fuel quantity needed to be injected in the combustion chamber. This choice of injection mode is very significant because it could reduce a lot the start time if the different parameters describing the injection are well chosen.

The Figure 24 represents an example of a start at 21°C with E95:

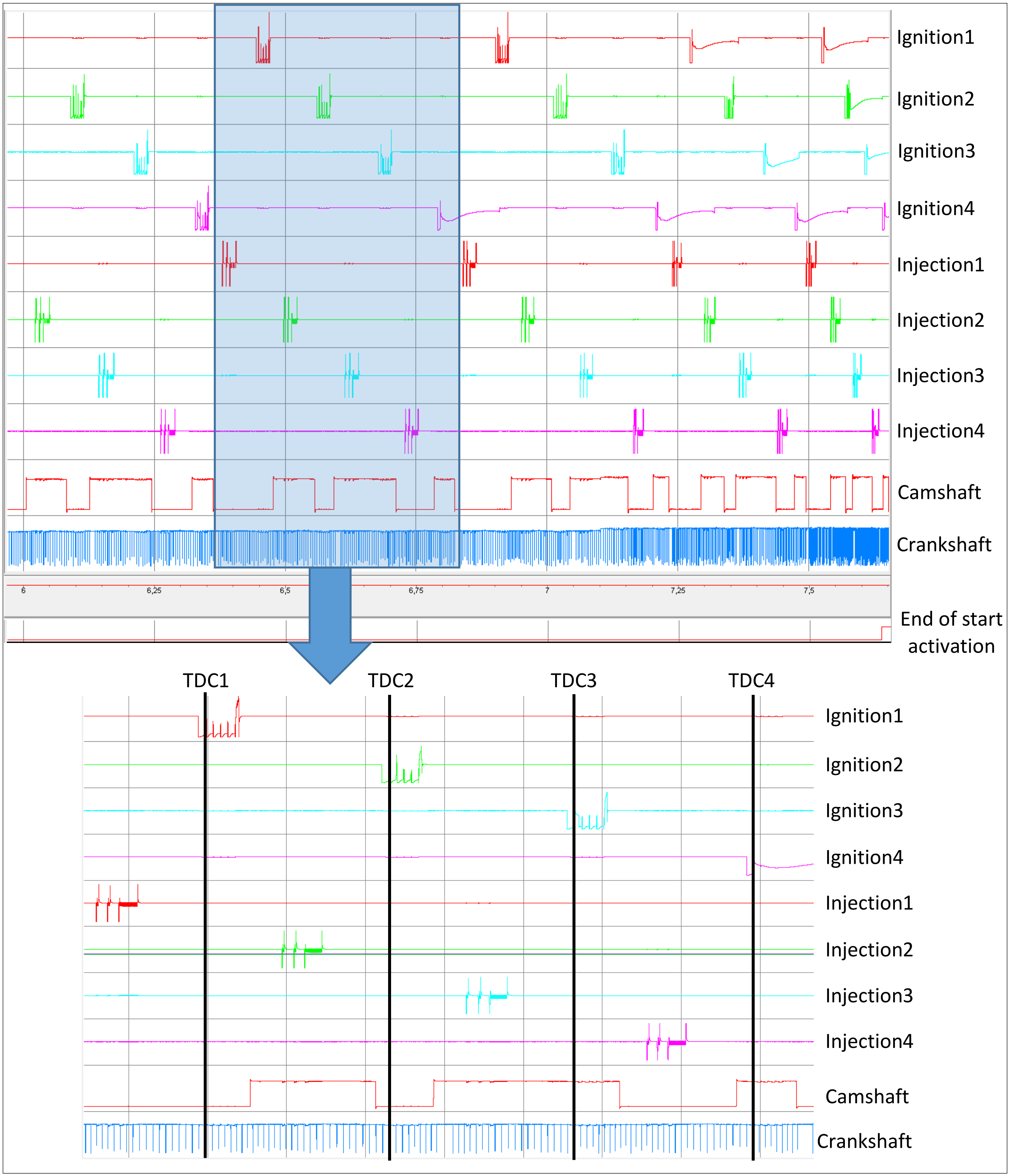


Figure 24: Start measurement of injection and ignition signal with an ES1000 module

5- Start injection factor

The start injection factor increases the value of the fuel quantity injected during the start phase of an engine run in order to compensate the injection loss on the wall of the combustion chamber. It means that if the start injection factor equals 2, there will be twice as much fuel injected than what is needed for stoichiometric ratio (maximum value of 64) during the start phase. As shown on Figure 25, basic maps for the quantity injected depend on start temperature and time during the cranking phase and the aim is to modify the factor to obtain the cleanest start possible. Some additional maps depend on the injection mode selected because there is a possibility of having two combustion modes during a start and this fact has to be taken into account in the fuel quantity to inject.

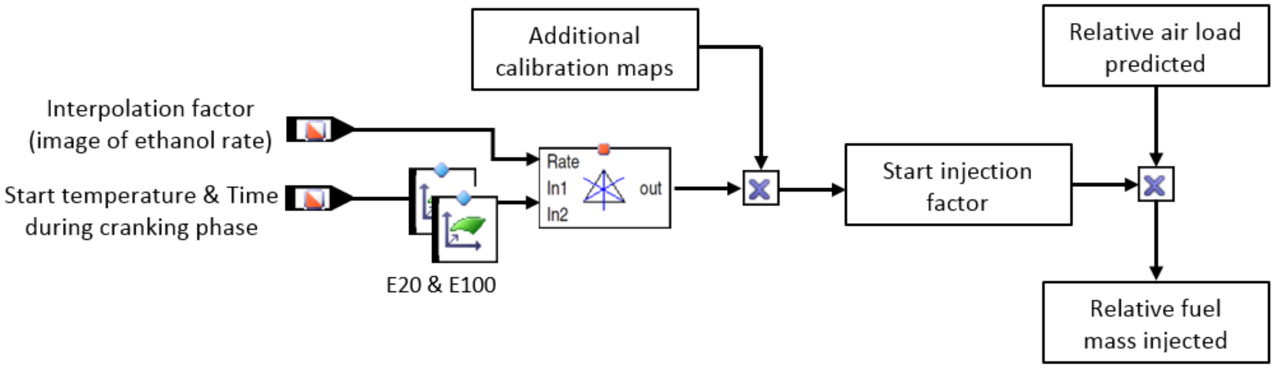


Figure 25: Strategy to obtain the start injection factor [7]

The value of the conversion factor "k" from relative fuel mass into injection time is described by Equation 3:

$$k = \frac{a * d}{100 * r * 1{,}05 * Q * 1.667 * 10^{-5}} = 50.2624 * \frac{d}{Q}$$

Equation 3: Calculation of the conversion factor from relative mass fuel into injection timing [7]

Where

a= 1.293 g/dm^3 (0°C and 1013hPa)
d = Piston displacement (dm^3)
Q = Valve constant for n-heptane (flow rate of the injection valve)
1.05 = Valve correction for gasoline
r = 14.7 (Air/Fuel constant at λ=1)
1.667*10^{-5} = Adaptation of units

The Figure 26 represents an example of a start at 21°C with E95:

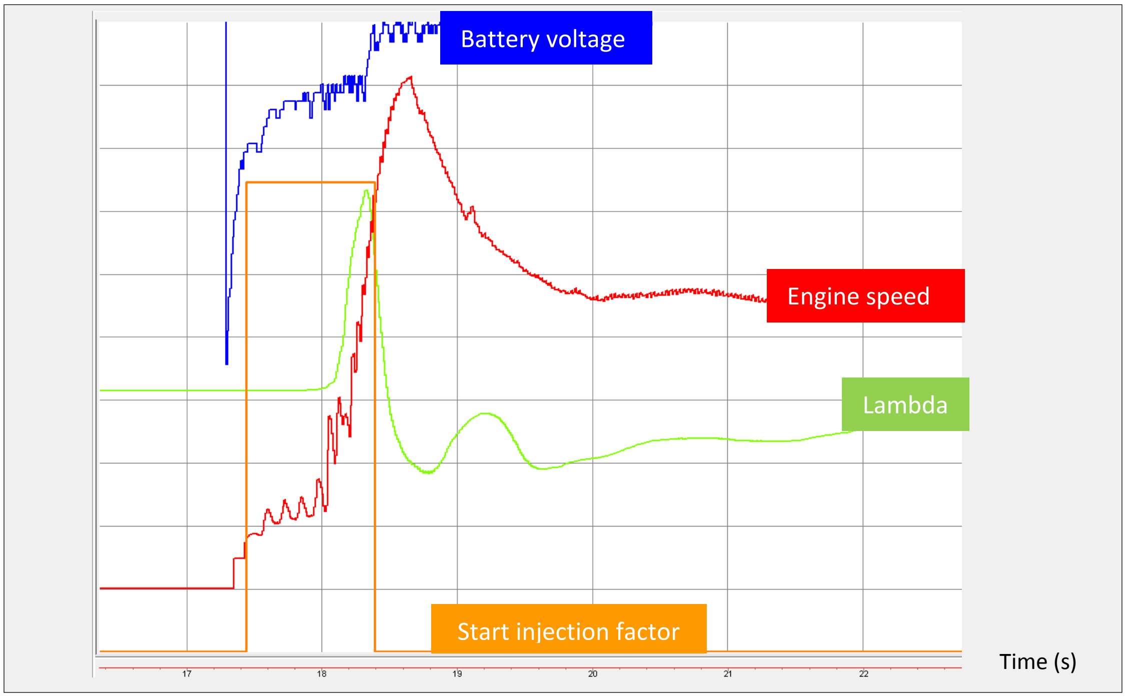


Figure 26: Start measurement of the start injection factor

6- After-start and Warm-up injection factor

The after-start and warm-up factor is an enrichment factor which will compensates losses during the two different phases in order to obtain the lambda set points defined in the next part:

- The after-start enrichment factor takes into account the vapor loss until the combustion chamber attain the engine operating temperature.
- The warm-up enrichment factor takes into account the vapor loss until the engine and particularly the intake area attain the engine operating temperature.

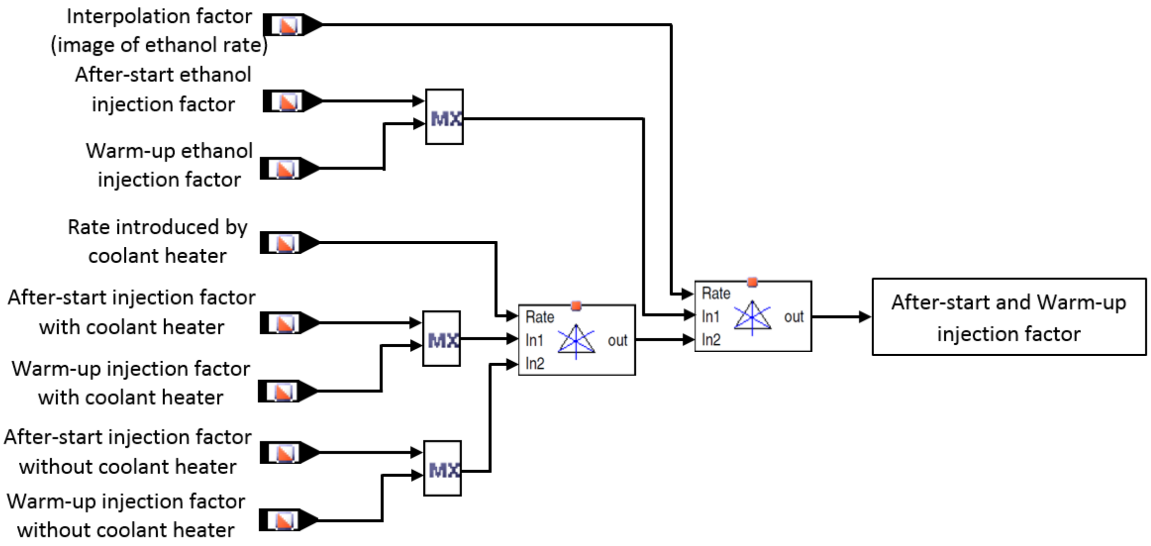


Figure 27: Strategy to obtain the after-start and warm-up injection factor [7]

The after-start and warm-up injection factor is defined by two interpolation functions as shown on Figure 27. The first one for E22 or gasoline, interpolation between the use of coolant heater and not, with a rate fixed by the use of this device. Then another interpolation is made due to the fuel choice and the ethanol rate present in the mixture.

Each factor used as an input factor on Figure 27, mainly depends on engine temperature, engine start temperature and time during after-start and warm-up phases. Additional dependencies of the factor can be calibrated depending on the environment of the vehicle.

The Figure 28 represents an example of a start at 21°C with E95:

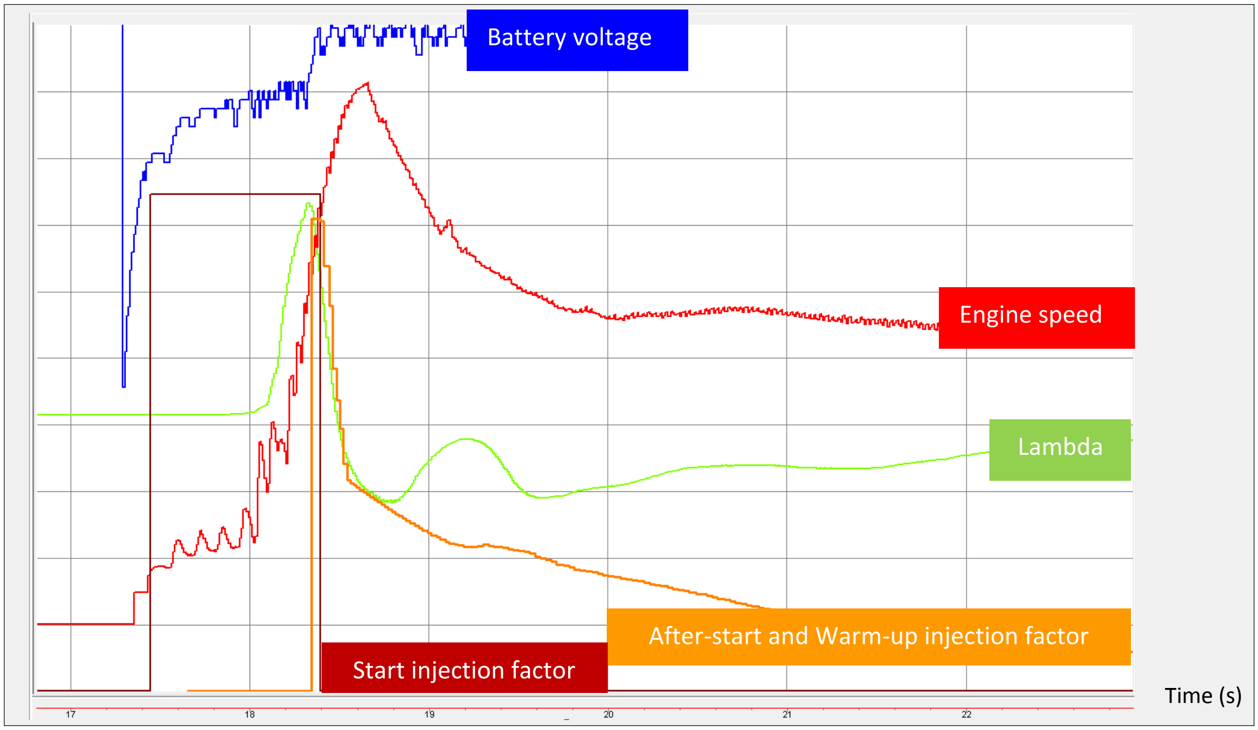


Figure 28: Measurement of After-start and Warm-up injection factor

7- Lambda set points

During the after-start and warm-up phases, the engine run is based on calibrated lambda set points. These set points are calculated after interpolations between several maps depending on the engine temperature as shown on Figure 29. The aim is to calculate the different parameters automatically in order to obtain the actual value given by the maps.

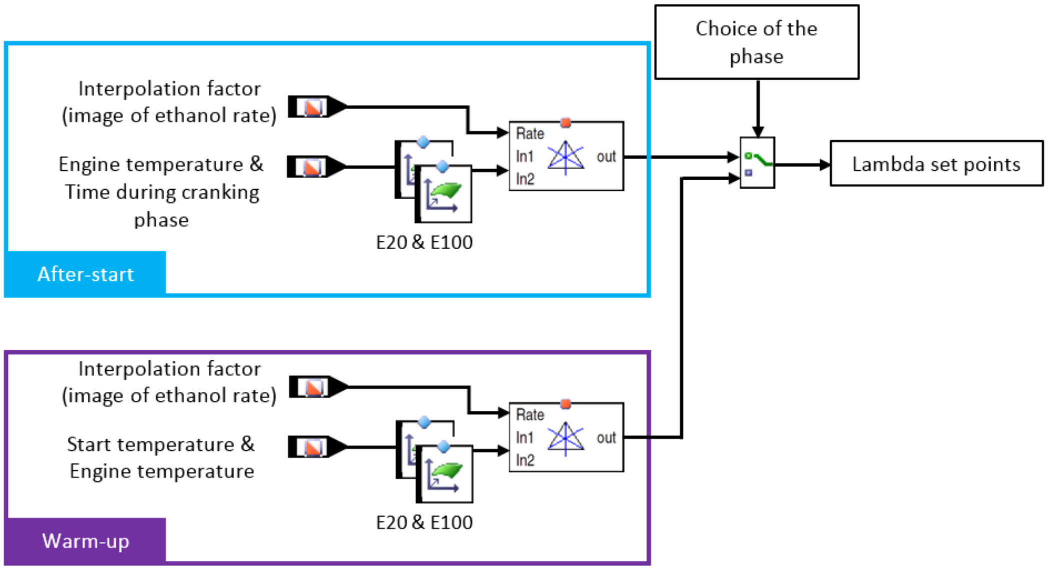


Figure 29: Strategy to obtain lambda set points [7]

The Figure 30 represents an example of a start at 21°C with E95:

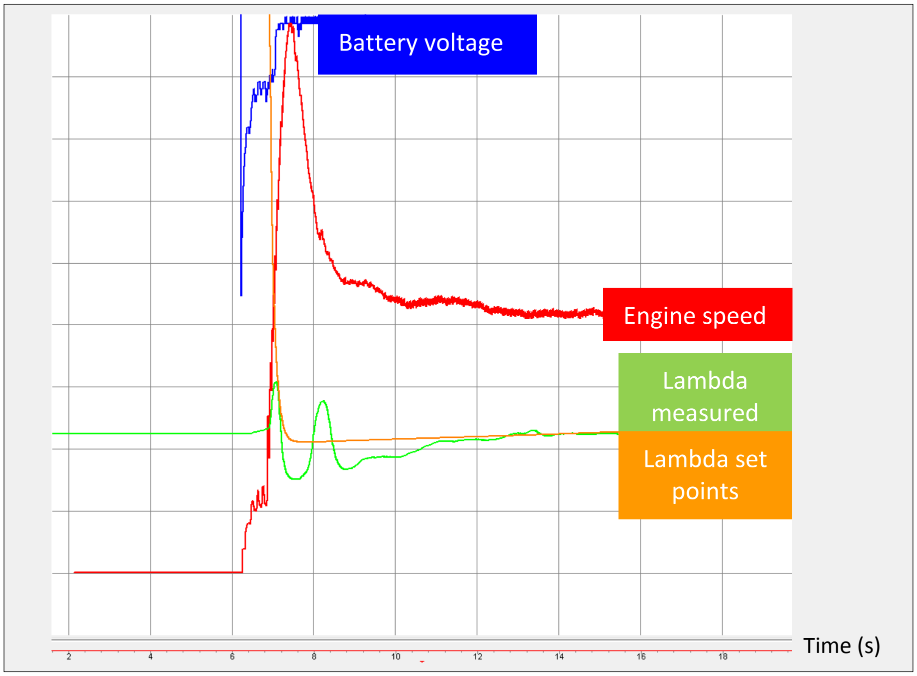


Figure 30: Measurement of lambda set points

8- Additional functions

1) After-start fuel adaptation

Operation condition to activate the start or after-start fuel injection adaptation:

In this function (Figure 31), the conditions to activate the adaptation factor of the fuel injection are listed in order to obtain satisfactory start and after-start phases. This function only leads to the activation of a Boolean that will enable the use of the fuel adaptation function explained after.

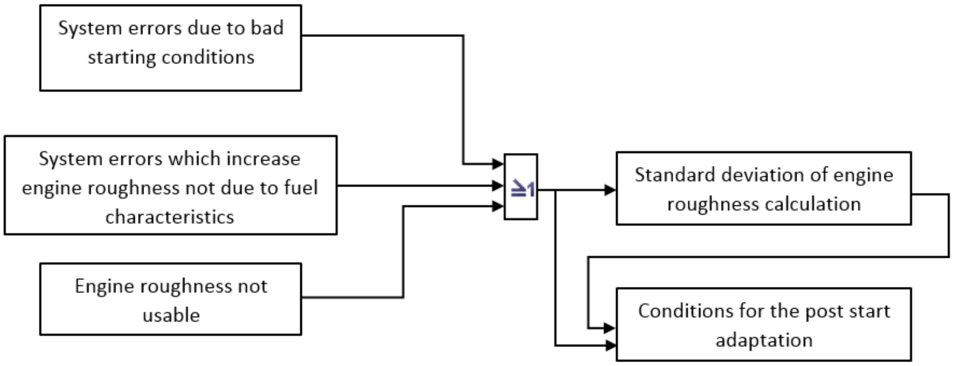


Figure 31: Strategy for conditions of start and after-start adaptation

- Conditions that can lead to a bad start are :
  - A too low battery voltage
  - Ambient pressure validity (measured ambient pressure is different from the modeled pressure)
  - Empty tank detection
  - A start with an engaged gear (moving vehicle)
  - No adaptation if one injection is aborted

- Conditions that can lead to an increase in the engine roughness apart from the mixture characteristics:
  - No information about camshaft or crankshaft position (sensors fault)
  - Injection fault due to error in electric control circuit of the injection valve
  - Error of difference between measured engine temperature and modeled engine temperature

- Engine roughness not usable :
  - Lambda control is activated against the fuel adaptation
  - Engine roughness signal not available (sensors fault)

- After-start adaptation:
  - Too high misfire rate

Determination of standard deviation in engine roughness:

This function determines a difference of deviation in engine roughness during after-start phase. This means that if the actual value increases too far apart from the nominal value, a Boolean is activated and an injection adaptation factor will modify injection timing.

Two filters with calibrated time-constants are used to determine the actual mean value of the engine roughness, based on misfire detection signal, for the first filter and the second filter determines the measured value of standard deviation in engine roughness.

The desired value for standard deviation of engine roughness is calculated with several calibration maps depending on input variables such as engine temperature and time during cranking phase.

Then, as shown on Figure 32, the difference between these two parameters is used as an input value for the after-start fuel adaptation.

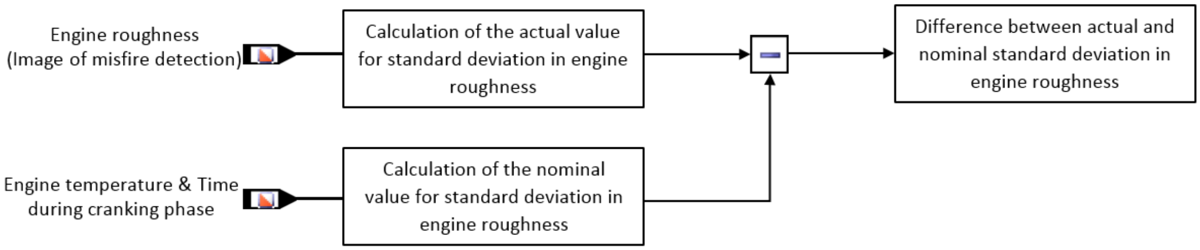


Figure 32: Strategy to obtain the delta standard deviation in engine roughness

After-start fuel adaptation:

The aim of this function is to detect a “poor fuel” with the analysis of the engine roughness signal, image of misfire detection, and to adapt the fuel injection with an additional factor to the after-start and warm-up injection factor. A “poor fuel” is characterized as a fuel with high boiling temperature or low vapor pressure. The leaner the combustion will be, the higher the misfire detection rate will appear.

This function is activated by the operating conditions of post-start adaptation. After the calculation of standard deviations of engine roughness, the after-start fuel adaptation factor is activated if a high deviation in engine roughness rate is detected. Therefore, the function will give back a value that will adapt the injection period depending on the deviations appearing. Moreover, depending on the lambda set points previously calibrated and the engine temperature as shown on Figure 33, a factor limitation is set not to obtain to rich combustions (lean combustions are limited by the value 1).

If the condition for after-start fuel adaptation is deactivated, a ramp with a calibrated time constant will decrease the factor to the neutral value of 1.

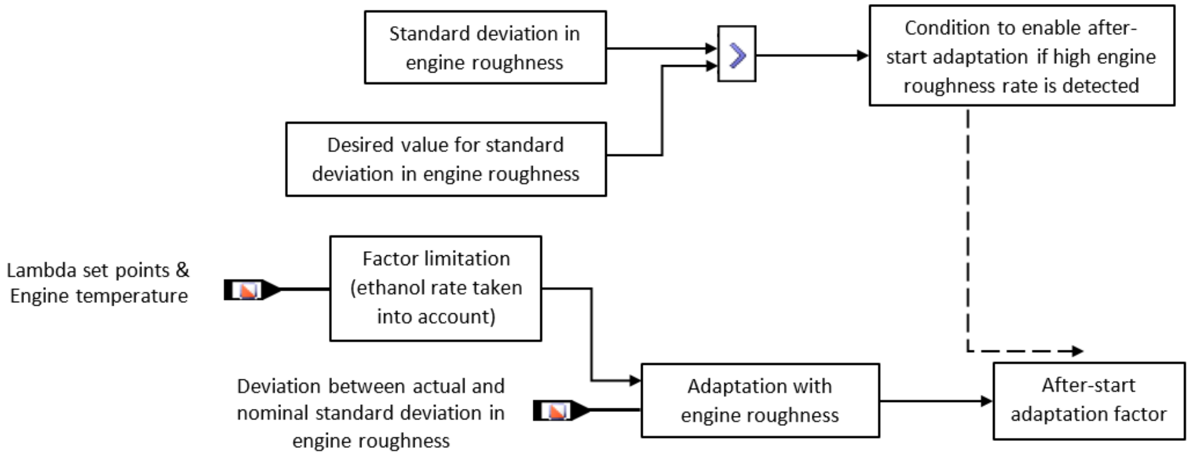


Figure 33: Strategy used to calibrate the engine adaptation factor

2) Fuel evaporated from engine oil prediction

<u>Hypothesis:</u> Only liquid fuel (which didn't vaporize or didn't take part in the previous combustions) is washed into the engine oil.

As shown on Figure 34, the strategy used to define the evaporation and dilution of fuel in lubricating oil has two main purposes:

- The first is to evaluate the maximum evaporated fuel from engine oil which permit to inhibit other functions using Air/Fuel ratio deviation. This inhibition will appear if the amount of evaporated fuel is above a threshold.
- The other is to estimate the fuel quantity evaporated in oil that could be used in the next combustions.

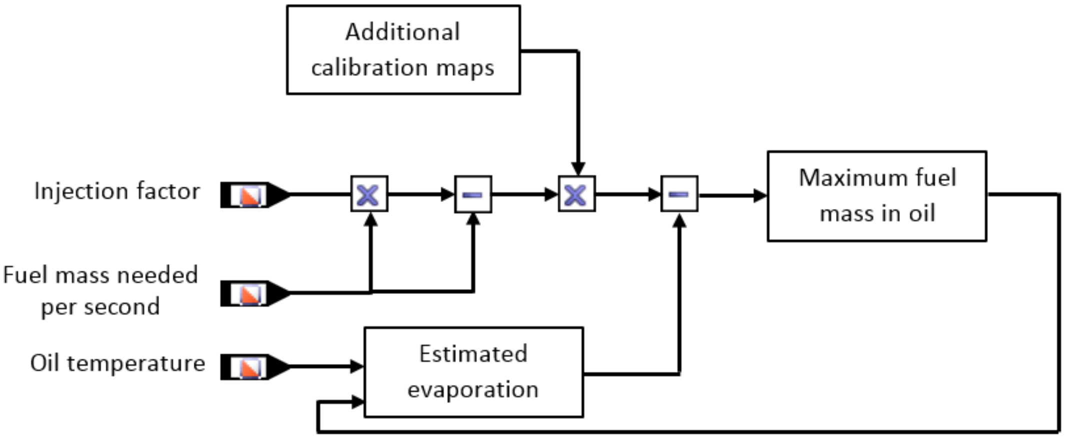


Figure 34: Strategy to obtain the amount of fuel evaporated from oil

The amount of fuel that didn't take part in the combustions is represented by the excess amount of fuel injected due to the injection factors. Even if all of the excess fuel doesn't flow in engine oil through loose piston rings (some move into the exhaust system), the aim of the function is to estimate a maximum of evaporated fuel at all time. The calculation of the amount of fuel mixing with oil is approximately the amount of fuel which didn't take part in the combustions. This amount is calculated by removing from the fuel quantity injected the burned fuel. It represents the fuel excess.

The estimated amount of evaporated fuel in engine oil during the start or after-start and warm-up phases isn't used because the parameters are set manually in these phases, but the calculation is run in order to be able to give the current evaporated amount at any time to avoid too rich or too lean mixture in the following cycles. In operating conditions with strong fuel evaporation, an adaptation functionality is activated to define the amount of fuel evaporating from oil that will take part in the combustions. Therefore, a large amount of fuel evaporated will reduce a lot the injection timing.

If the function of adaptation of the fuel injected with the fuel evaporated from oil is activated, this adaptation is always used with the results of the lambda control in the exhaust.

IV) Measurements settings

1- Test plan

The strategy used to find optimal points for the different parameters is:

- Use the current calibration of the vehicle as a reference for the tests.
- Fix as much as possible the comportment of the engine to obtain the same conditions from one measurement to the other. Indeed, two measurements can only be compared if the engine is in the same conditions.
- Deactivation of canister purge.
- Deactivation of closed loop with the dew point threshold set to the maximum value.
- Deactivation of catalyst heating.

For instance: to work on ignition settings, the injection mode and injection angles (among other parameters) need to be fixed to obtain the same conditions for each measurement.

- Place the vehicle in a box with a temperature regulation to obtain stable temperatures which will not be different from one start to the other. Moreover, the start temperature is the most used input variable for the calibration maps used for the start of the engine so the temperature regulation was compulsory. The problem is that the climatic chambers are too expensive to use but a box regulated at 20°C (±2°C) was available and free so the start calibration was only done at 20°C.
- The time to wait between two measurements is approximately 3 hours because the engine needs to cool down. Unfortunately, only 2 or 3 measurements per day were done so the measurement rate of engine starts wasn't efficient.

2- Experimental setup

In order to obtain the same conditions between the different measurements, the vehicle was placed in a box regulated at 20°C (±2°C). In this box were available a battery charger and a fan to accelerate engine cooling. For each measurement, an ES590 with an additional lambda probe were used with INCA to measure the calibrated variables except for injection and ignition calibrations where an ES1000 was used with an additional lambda probe and a breakout box to obtain the ignition and injection signals. Moreover, a different experiment page on INCA was created for each measurement to obtain more information about how is defined the output value of the parameters. Once the measurements were done, the software MDA Analyzer was used to analyze the results with for each calibrated parameter different settings in order to obtain graphical representations of what happen during the measurement.

During the measurements, the vehicle was stopped with the hand brake and there was no electrical applications used such as the radio or the car ventilation. Moreover the vehicle pressure environment was approximately 1 bar.

V) Results

1- Throttle position during start

The different parameters fixed for this calibration part are:

Injection: an injection mode is chosen and the calibrated angle is fixed in order to separate the injection and the ignition.
Ignition: the main ignition angle is fixed at the engine reference value.
Start injection factor: the start injection factor is fixed at the engine reference value.
After-start and warm-up injection factor: this factor is fixed at the engine reference value.

<u>Results of the measurements:</u>

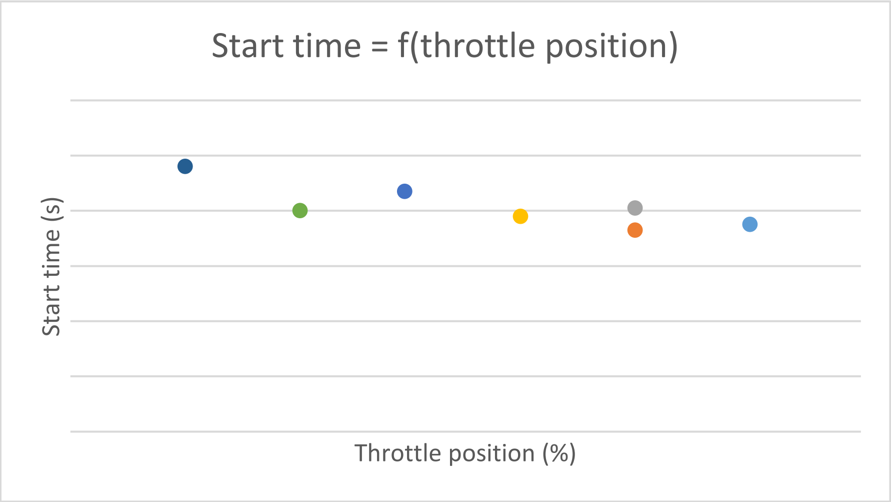


Figure 35 : Start time dependency on throttle position

As shown on Figure 35, the wider the throttle is open, the less time the start takes.

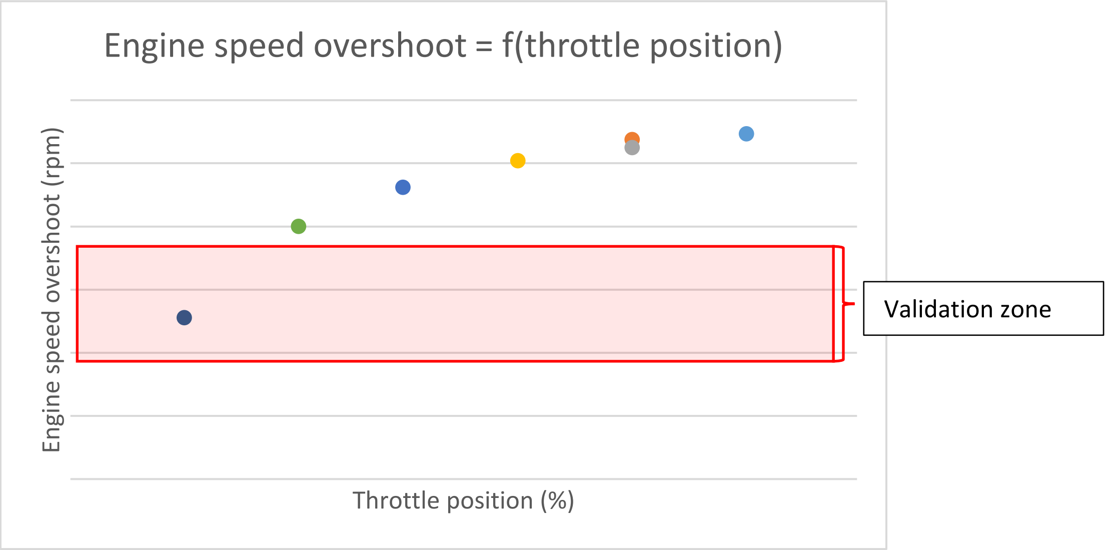


Figure 36: Engine speed overshoot dependency on throttle position

Figure 36 emphasizes the fact that the more the throttle position is open, the higher the engine speed overshoot is.

<u>Analysis:</u>

To obtain the best value for the throttle position during the start, both values showed in Figure 35 and Figure 36 need to be taken into account.

The value for the throttle position chosen is the widest throttle opening that is still situated in the validation zone for the engine speed overshoot.

2- Main ignition angle during start

The different parameters fixed for this calibration part are:

Throttle position during start: the throttle position is set at the value resulting from the previous part.
Injection: an injection mode is chosen and the calibrated angle is fixed in order to separate the injection and the ignition.
Start injection factor: the start injection factor is fixed at the engine reference value.
After-start and warm-up injection factor: this factor is fixed at the engine reference value.

Results of the measurements:

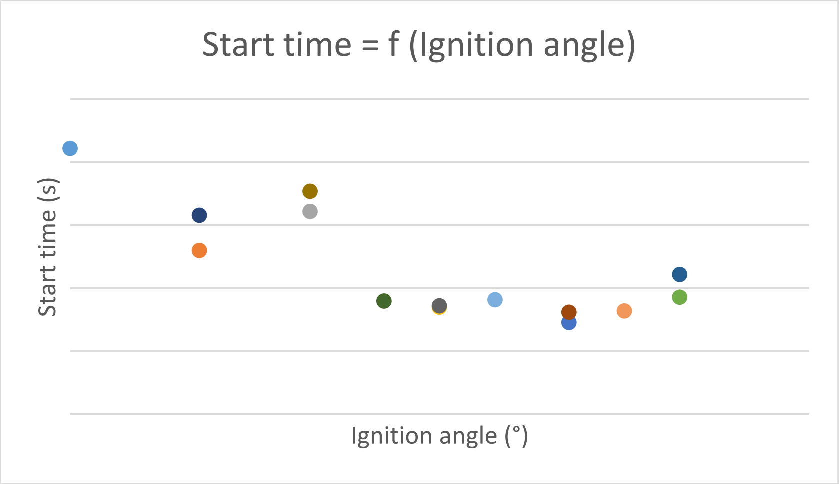


Figure 37: Start time dependency on the main ignition angle

The optimal main ignition angle appears, according to Figure 37, to be situated at the lowest start time point.

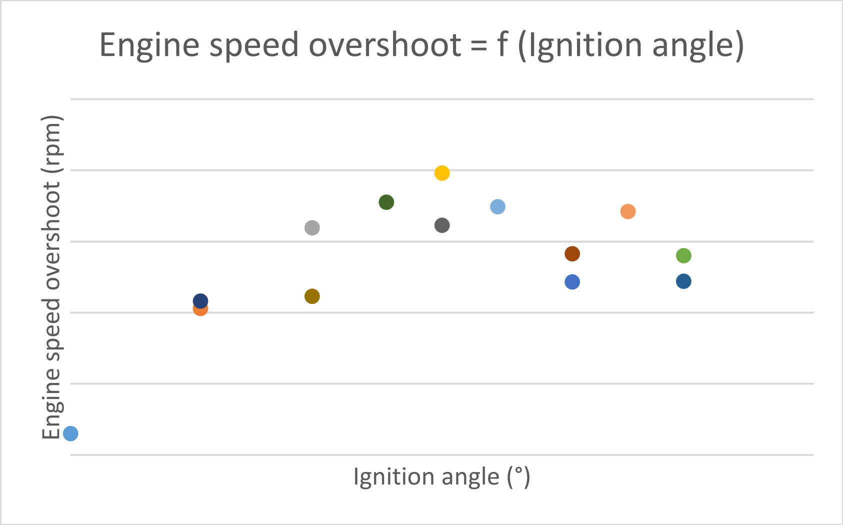


Figure 38: Engine speed overshoot dependency on the main ignition angle

As shown on Figure 38, all of the engine speed overshoots measured appear to be situated between the valid thresholds fixed by the client.

Analysis:

Since all of the engine speed overshoots are situated between the two thresholds, the optimal main ignition angle is situated at the point where the start time is the lowest. These results emphasize the important impact of the setting of ignition angles on the start time.

3- Injection mode and phasing during start

The different parameters fixed for this calibration part are:

Ignition: the ignition is set at the value resulting from the previous part.
Throttle position during start: the throttle position is set at the value resulting from part 1.
Start injection factor: the start injection factor is fixed at the engine reference value.
After-start and warm-up injection factor: this factor is fixed at the engine reference value.

Injection mode 1 and 2:

The engine didn't start for the two homogeneous injection modes where the injection happened during the intake phase. One way to solve the start in homogeneous injection mode would be to change the fixed parameters for this calibration part (for instance increasing the start injection factor and the throttle position).

Injection mode 3:

The injection mode 3 consists in one injection during the intake phase and one during the compression phase. First, the begin angle of the first injection is fixed and measurements are made when the end angle of the last injection is changed.

Results of the measurements:

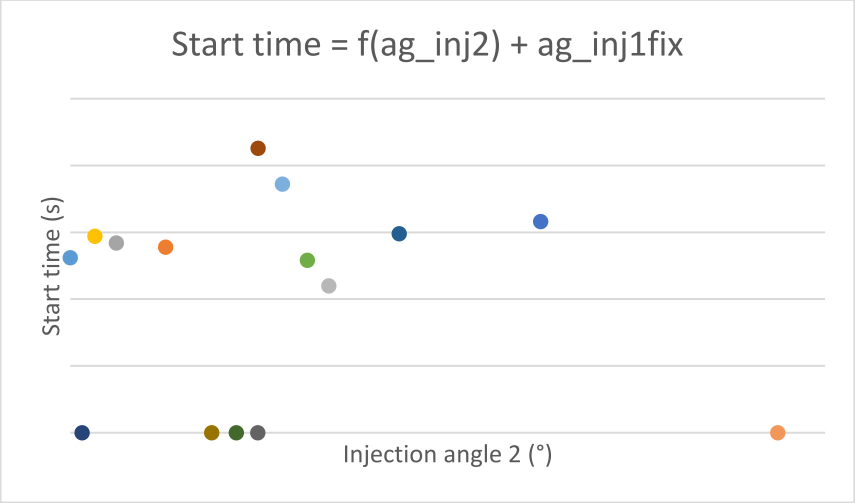


Figure 39: Start time dependency on the end angle of the last injection

It appears that the best injection angle for the last injection angle is situated at the grey point on Figure 39. One interesting point is the gap of no start that appear. This may be explained by the fact that the ignition angle set appears just after the end of the last injection and the mixture flows far from the spark plug.

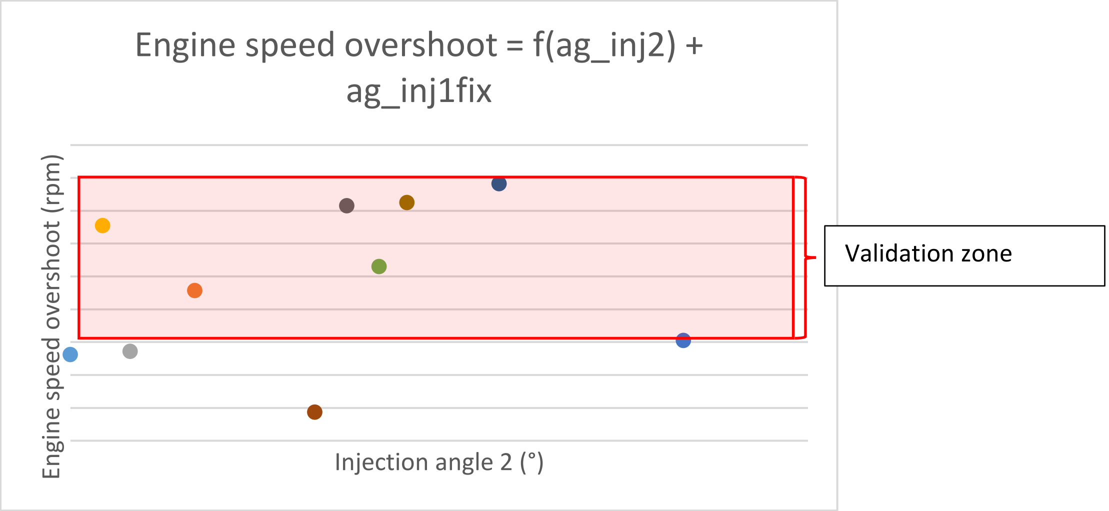


Figure 40: Engine speed overshoot dependency on the end angle of the last injection

The main injection angle with the lowest start time is situated in the validation zone, as shown on Figure 40, so the value can be fixed.

Once the second injection angle is set, the last injection angle is tested on different injection angles during the intake phase based on the begin angle of the first injection found previously.

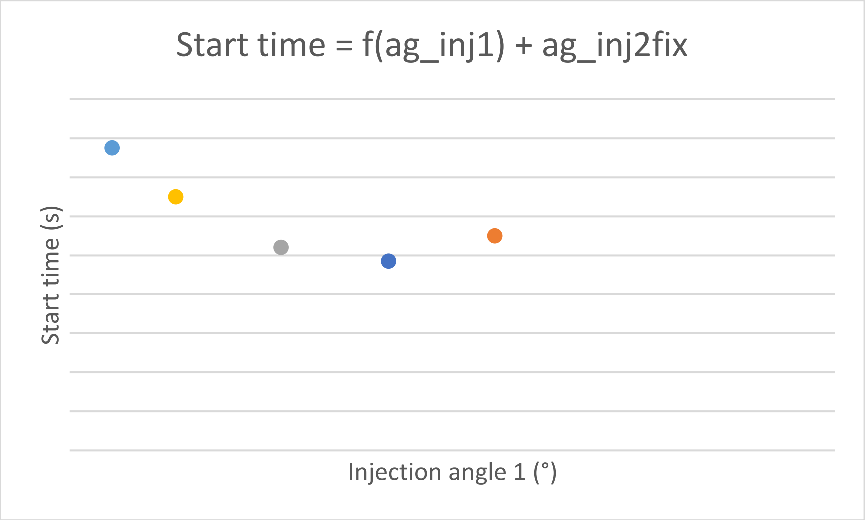


Figure 41: Start time dependency on the begin angle of the first injection

The optimal end angle of the last injection appears to be the lowest point of the curve on Figure 41.

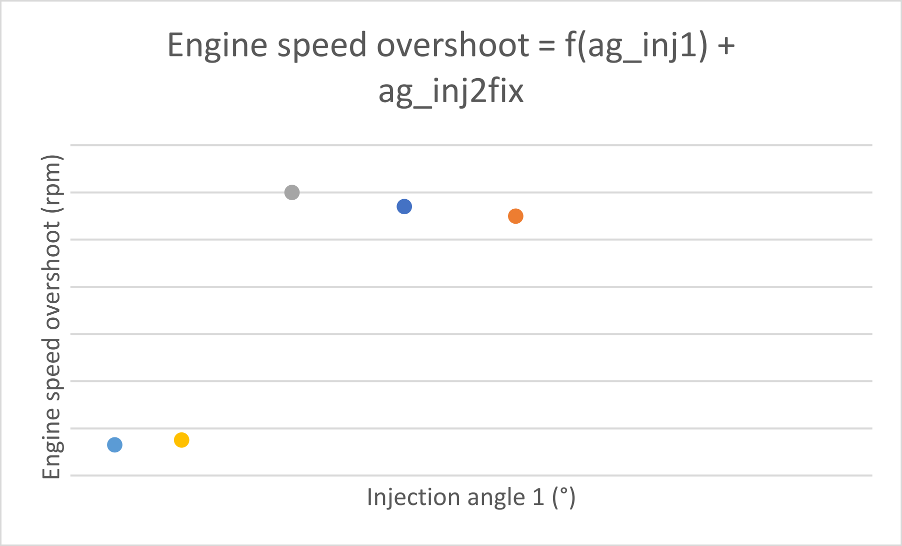


Figure 42: Engine speed overshoot dependency on the begin angle of the first injection

Based on Figure 42, every engine speed overshoots are situated in the validation zone.

Analysis:

For the injection mode 3, according to the figures from Figure 39 to Figure 42, the best injection angles appear to be the angles found previously.

Injection mode 4:

The fourth injection mode will not be calibrated because the only difference with the third injection mode is that a third injection is added and calculated automatically during the compression phase based on the last injection angle of the third injection mode. So this injection mode will only be an improvement of the third injection mode with the same input parameters. One way to improve this injection mode would be to modify the split factors and the injection break between the two last injections.

Injection mode 5:

The injection mode 5 consists in one injection during the compression phase.

Results of the measurements:

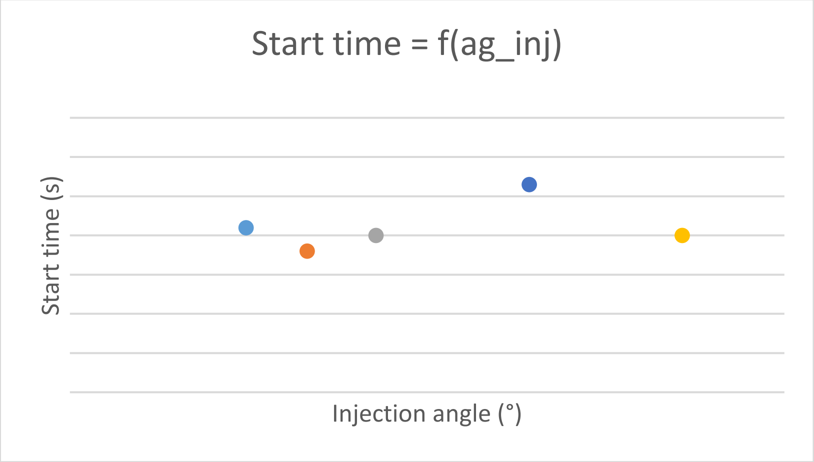


Figure 43: Start time dependency on the end angle of the injection

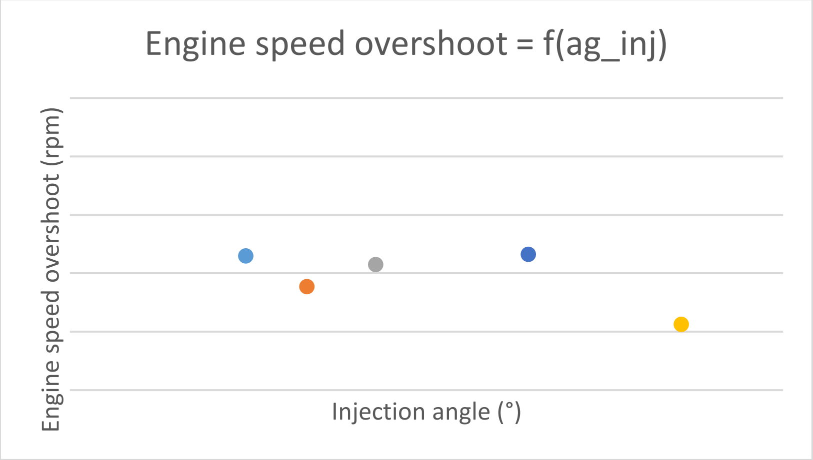


Figure 44: Engine speed dependency on the end angle of the injection

Based on Figure 44, every engine speed overshoots are situated in the validation zone.

Analysis:

According to Figure 43 and Figure 44, the end angle of the last injection is at the fastest start time.

Additional injection mode:

This additional injection mode consists in three injections during the compression phase.

Results of the measurements:

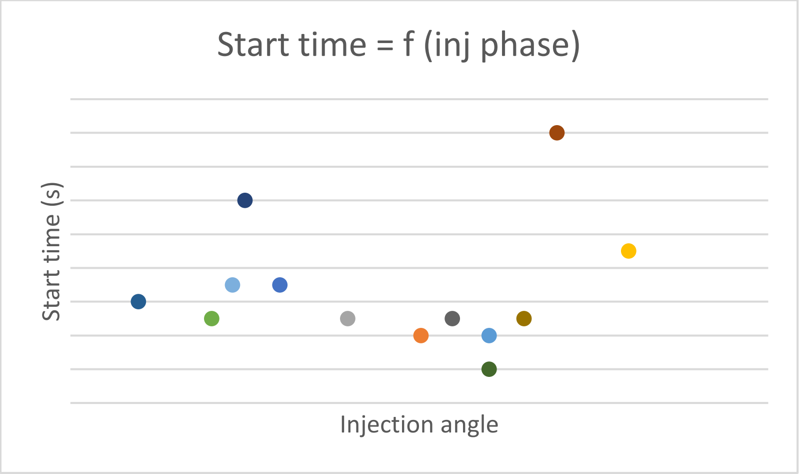


Figure 45: Start time dependency on the end angle of the last injection

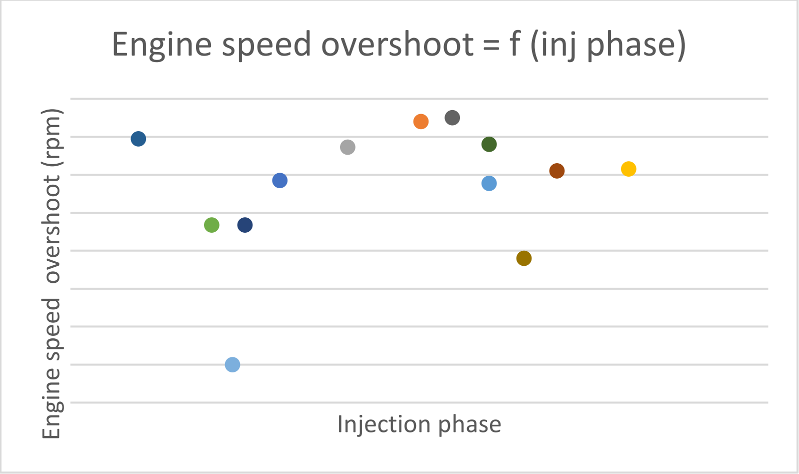


Figure 46: Engine speed overshoot dependency on the end angle of the last injection

Based on Figure 46, every engine speed overshoots are situated in the validation zone.

Analysis:

According to Figure 45 and Figure 46, since every engine speed overshoots are situated in the validation zone, the best end angle of the last injection corresponds to the lowest start time.

Conclusion:

Among all the injection modes listed before, the fastest start time obtained after calibration is the one calibrated with injection mode 5. So injection mode 5 will be used for the next calibration step.

4- Start injection factor

The start injection factor is calibrated by decreasing the reference value until the engine doesn't start because of a too low enrichment. Depending on the results of the measurement, a percentage of this value is set as the start injection factor.

The main aim of this calibration measurement is to see the impact of enrichment during start on the air fuel ratio in the exhaust and to see which start injection factor is the most convenient to follow the lambda set points calibrated by the user during the start phase. The different criteria to take into account are the start time and the lambda undershoot, but mostly the number of misfire that appear during the start.

The different parameters fixed for this calibration part are:

Throttle position during start: the throttle position is set at the value resulting from part 1.
Ignition: the main ignition angle is set at the value resulting from part 2.
Injection: the injection mode and phasing are set at the value resulting from part 3.
After-start and warm-up injection factor: this factor is fixed at the engine reference value.

<u>Results of the measurements:</u>

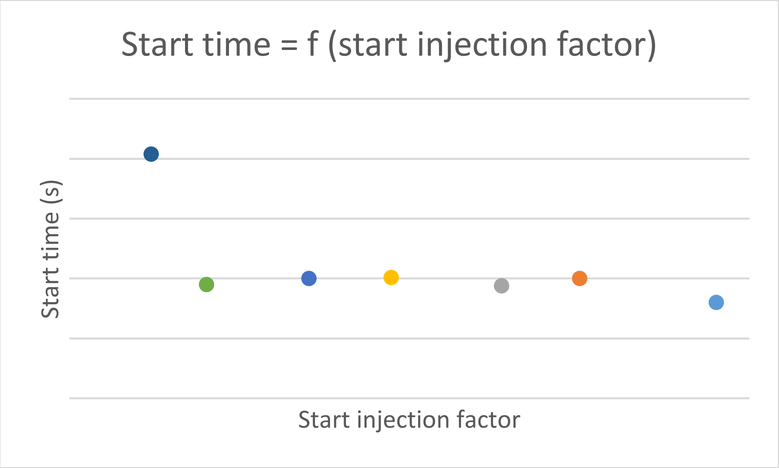


Figure 47: Start time dependency on the start injection factor

The other criteria for this start injection factor is the misfire counter during the start phase. Indeed, the lower the injection factor will be, the leaner the combustion will result and so the higher the chance of misfire will appear.

<u>Analysis:</u>

The highest point on Figure 47 is the limit start injection factor which will be taken as the reference for the calculation of the start injection factor that will be set on the vehicle.

5- Lambda set points

The process used for lambda set points calibration is quite different from regular starts. The aim is to study the engine roughness when the engine is started on specific ordered lambda set points. To that extent, the calibration map which enable the use of lambda probe is activated as soon as the engine is started in order to force the engine to work in closed loop since the start. The major issue with these measurements are damages caused to the lambda sensor in the exhaust.

The different parameters fixed for this calibration part are:

Throttle position during start: the throttle position is set at the value resulting from part 1.
Ignition: the main ignition angle is set at the value resulting from part 2.
Injection: the injection mode and phasing are set at the value resulting from part 3.
Start injection factor: the start injection factor is set at the value resulting from part 4.
After-start and warm-up injection factor: this factor is fixed at the engine reference value.

Results:

Unfortunately after two measurements, one at lambda 1 and one at lambda 0.8, the engine roughness variable which is studied wasn't precise enough. In fact, this type of calibration is supposed to be done on climatic test bench with additional sensors not present on the vehicle. Usually the engine on the test bench with pressure sensors installed on each cylinder and the aim of this calibration process is to study the engine stability with these pressure sensor signals.

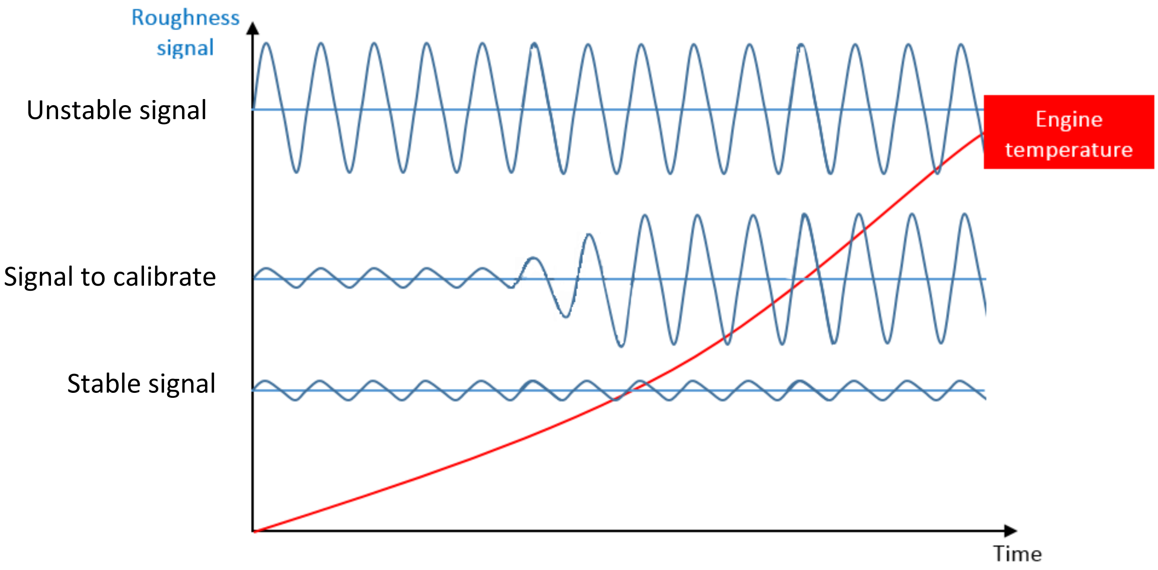


Figure 48: Scheme of lambda set points calibration principle

For example on Figure 48, at a constant lambda set, the signal to calibrate shows that the roughness appears to become unstable at an engine temperature so the lambda set points calibration map needs to be adapted at this temperature.

6- After-start and warm-up injection factor

This calibration process is based on the lambda set points ordered by the ECU so it wasn't calibrated on the vehicle due to the reasons cited in the 5th part.

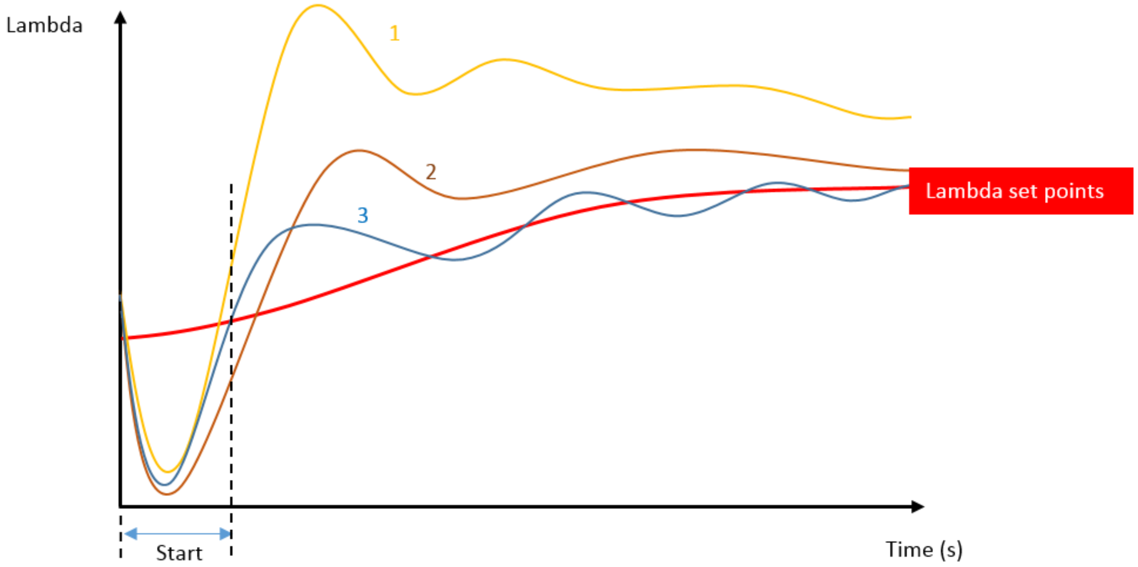


Figure 49: Scheme of after-start and warm-up injection factor calibration principle

The aim of this factor is to follow as closely as possible the lambda set points calibrated before.

For example on Figure 49, if the first curve is obtained after measurements, this factor needs to be increased to enrich the combustion and obtain the third curve which is what would be expected after calibration. Since the factor calibration function mostly depends on the engine temperature, the deviation between the lambda measured and the lambda set points can be approximately adapted after one measurement.

VII) Conclusion

During this six months internship, several goals were achieved in order to obtain the optimization of the start for a mass production flex-fuel direct injection engine. First the selection and analysis of the main parameters and functions destined to the start phase were done and as a result, five parameters were found compulsory to be calibrated (throttle position, injection mode and angles, ignition angles, injection factors and lambda set points). After explaining the different functions and listing the calibration maps that could be modified to obtain a desired output value, several tests were done to see the impact of each function or parameter on the start requirements (start time, engine speed overshoot and lambda signal). Step by step, every parameters were calibrated based on the results of the previous calibration.

To conclude, the main aim of the internship was fulfilled because calibration values that improve the start of the engine at 20° (± 2°) were found. In order to continue the process, other tests like emission analysis should be made with the start calibration found. Moreover, additional times and funds for the project would have permitted additional tests such as tests on different temperatures and ethanol rate to calibrate several points of calibration maps. In addition, the next step in the usual calibration process would be to test the start calibration with a less volatile mixture in order to make sure that the calibration will work every time.

Some improvement in the work organization could have been done if the order of the calibrated parameters had been changed. Indeed, the most important parameters are the calibration of both injection and ignition. The angle difference between the two is the parameter which impacts the most the start phase and once the two parameters are optimized, then the calibration would have been improved with the throttle position and other start parameters.

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3. Article from the website Thoughtco.com entitled “*What are the benefits of using ethanol?”* by Larry West (2016) available at: https://www.thoughtco.com/the-pros-and-cons-of-ethanol-fuel-1203777

4. Bosch Internal Documentation

5. Etas documentations available at: https://www.etas.com/fr/

6. Image of the breakout box: https://www.smart-testsolutions.de/mobile-breakout-boxes.html

7. Software and calibration documentation Bosch MED_FLEX

Annex 1

General characteristics of the motor studied

Fuel	Petrol-E22-E100
Displacement	1,6 L
Bore	80 mm
Stroke	86 mm
Engine architecture	4 cylinders in-line
Number of camshafts	2
Balance shaft	No
Compression ratio	9/1
Piston rod centerline distance	140 mm
Maximum rotation	6500 rpm
Idle rotation	700 rpm
Injector	Bosch T1504
Turbocharger	FGT
EGR valve	No
Intercooler	Yes
Variable valve lift	No
Variable valve timing	Intake
Throttle valve	Continental
Engine Control Unit	Bosch MED
Vacuum pump	Yes
Catalyst	3-way catalyst with 2 lambda sensors
Oil capacity	5.0 L
Standard installation	E/W and 0°