HOW-TO

How-to Tune the GDI Engine in EMU PRO

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Contents

1. Introduction....3

2. Before you start....4

3. GDI Tuning Workflow....6

4. Wiring....7

5. Injector configuration....8

5.1. Electric injector characterization....9

5.2. Flow characteristic....11

6. Pressure sensor configuration....14

7. Pump configuration....15

7.1. Pump control basics....15

7.2. Pump configuration in Light Client....24

7.3. Pump configuration in EMU PRO - parameters to measure....26

7.4. Pump configuration in EMU PRO - parameters to tune....34

8. GDI performance tuning basics....36

9. Troubleshooting....42

10. Sources....42

11. Document history....43

1. Introduction

Gasoline Direct Injection (GDI) systems are an advanced fuel injection technology that offers significant benefits over traditional port injection systems. This introduction will help you understand why direct injection exists, its advantages in motorsport, and the main differences compared to port injection. While GDI provides notable benefits, it also introduces higher engine complexity.

Why Direct Injection Exists

Direct injection technology was developed to address several key needs in modern engines:

1. **Lower Emissions:** Direct injectors have better precision in providing the exact amount of fuel needed. High fuel pressure and injection geometry can provide better fuel atomization and mixing, which creates more complete combustion. Injecting into a cylinder doesn't create fuel film effects in the intake, removing the transient fuel issues.
2. **Better Fuel Economy:** The higher efficiency of direct injection engines lowers the fuel needed at the same power level. Direct injectors have better precision in providing the exact amount of fuel needed. Injecting directly into the cylinder offers better cooling of the combustion chamber, which allows for a higher compression ratio and increases the overall engine efficiency. Stratified mixtures significantly lower the amount of used fuel and reduce the amount of unwanted byproducts.
3. **Higher Knock Resistance:** Injecting directly into the cylinder offers better cooling of the combustion chamber, which lowers the probability of knocking.

Why Use Direct Injection in Motorsport?

In the competitive world of motorsport, every advantage counts. GDI systems offer several benefits that are particularly valuable for racing:

1. **More Engines to Choose From:** As more manufacturers adopt GDI technology, there are more engine options available for racing applications.
2. **Higher Knock Resistance for More Power:** The ability to resist knock enables engines to produce more power, giving race cars a competitive edge.
3. **Better Fuel Economy for Endurance Racing:** GDI's improved fuel efficiency means race cars can go longer between refueling stops, which is crucial in endurance racing.
4. **Modern Engine Technology:** Using GDI aligns with the latest advancements in engine technology, ensuring that race teams stay at the cutting edge of performance.

Main Differences Compared to Port Injection

GDI systems differ from traditional port injection in several key ways:

1. **Injector Placement:** In GDI, injectors are located in the cylinder head, injecting fuel directly into the combustion chamber rather than the intake manifold.
2. **Injection Timing:** GDI requires for injection to occur within less than two engine strokes (intake and compression), leading to a very short period for mixture preparation.
3. **Fuel Pressure:** GDI systems use variable and much higher fuel pressure, controlled by a mechanical fuel pump, to ensure optimal fuel atomization and delivery.
4. **Injector Characteristics:** GDI injectors are low-impedance and operate at high voltage during the opening phase, allowing for rapid and precise fuel injection.

2. Before you start

Warning:

Tuning a GDI engine requires precise measurement of multiple parameters due to the complex interactions between various elements. This process is challenging and should be conducted by a professional with a thorough understanding of the operating principles and experience. Incorrect tuning can lead to catastrophic engine failure, making expert handling essential for optimal performance and engine reliability.

There are multiple challenges related to tuning the GDI engine. Some of them are:

1. **Multiple OEM Designs with Significant Differences, No Standards:**
   - Each original equipment manufacturer (OEM) uses different designs for their DI systems, leading to significant variations and a lack of standardization across the industry. This makes it difficult to apply a one-size-fits-all approach to tuning.
2. **No Public Datasheets Available for Pumps or Injectors:**
   - Unlike some other engine components, there are typically no public datasheets available for DI pumps or injectors. This lack of readily available information adds a layer of complexity to the tuning process.
3. **High Pressure Pump and Injectors Configuration:**
   - Precise measurement and parameter tuning are necessary even for basic engine operation.

4. **Injection Angle Tuning:**
    - The angle at which fuel is injected into the combustion chamber has a critical impact on engine performance. An incorrect injection angle can severely affect engine efficiency and, in extreme cases, may even cause engine damage.

Check if your system can be run with the Ecumaster setup:

- **Injector Compatibility**: Identify whether your injectors are electromagnetic or piezoelectric. The GDI Driver doesn't support piezo injectors, such as those found in the Mercedes M139 or BMW N54 engines. Piezoelectric injectors are usually taller and wider to accommodate the stack of piezo elements inside and the control voltage is usually over 100 V.
- **Pump Compatibility**: Verify if your pump is supported. EMU PRO strategy supports synchronous pumps from Bosch and Hitachi. Pumps controlled with PWM signal are not yet supported.
- **Injector and Pump Capacity**: The GDI Driver can run up to 8 direct injectors and 2 pumps. If you want to run port and direct injection simultaneously, calculate the number of injection outputs you need. The EMU PRO 16 supports up to 16 injectors, allowing you to run a maximum of 8 direct and 8 port injectors.

Check if you have and know how to use the necessary tools:

- Oscilloscope
- Current probe
- Direct-Injector Flow Bench (if you don't have access to the injector datasheets)
- Dial Gauge
- Degree Wheel

Full characterization of the direct injection system is a complex and tedious process, so keep that in mind. Despite these challenges, this guide will cover the methods to perform all necessary measurements and tune parameters. It aims to provide a comprehensive understanding of the process, ensuring that even complex aspects of direct injection tuning can be managed effectively.

3. GDI Tuning Workflow

This list highlights the general workflow for setting up GDI, with detailed descriptions of all parameters provided in the following chapters.

Wiring

- Connect EMU PRO to GDI Driver (including CAN bus and control wires for each injector and each pump)
- Connect GDI injectors, high pressure fuel pump valve and *SENT sensors directly to GDI Driver

Light Client

- Configure GDI injectors in the GDI Driver through Light client (boost, peak, hold current; boost, peak time)
- Configure high pressure pump in the GDI Driver through Light client (peak, hold current; peak time)
- *Enable CAN frames for SENT in the GDI Driver

EMU PRO - communication and sensors

- Set *Fuel / Rail 1 / Injection type* to proper Direct Injection option
- *Configure *Communication / SENT over CAN bus* in EMU PRO Client
- *Configure SENT sensors (Pressure, temperature or TPS) connected to GDI Driver to be used with SENT over CAN. SENT message format (Single sensor, Single secure, Dual sensor) is set after choosing proper SENT channel in *Sensor input*.

EMU PRO - measured parameters

- Configure injectors in the EMU PRO Client
  - Change X-axis of *Dead time* table to *Sensors Fuel high pressure 1*
  - Change *Setup / Type* to *Boost, peak, hold - GDI Driver*
- Configure *Fuel high pressure sensor* in the EMU PRO
- Configure high pressure pump in the EMU PRO Client

EMU PRO - tuning

- Tune pump control in the EMU PRO Client
- Change *Fuel / Rail 1 / Injection angle / Control method* to *Start of Injection*
- Set proper value to *Fuel / Rail 1 / Injection angle / End min*
- Tune GDI related parameters:
  - *Fuel / Rail 1 / Injection angle / Base*
  - *Fuel / Rail 1 / High pressure target / Base*

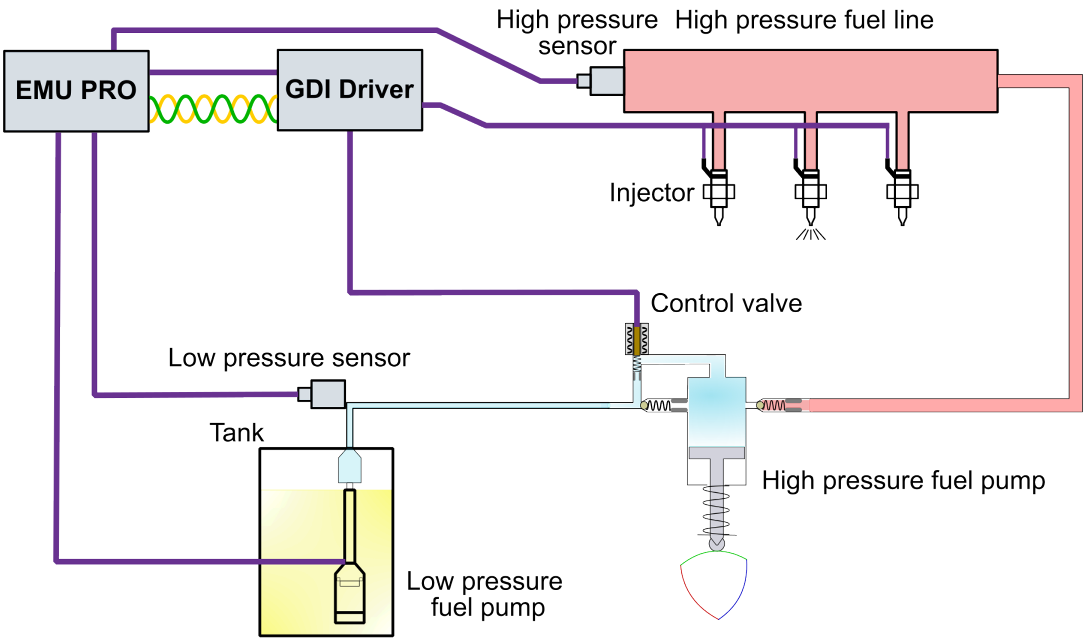
*If you're using SENT communication

4. Wiring

Note:
The EMU PRO alone cannot handle direct injection systems. A GDI Driver module is needed.

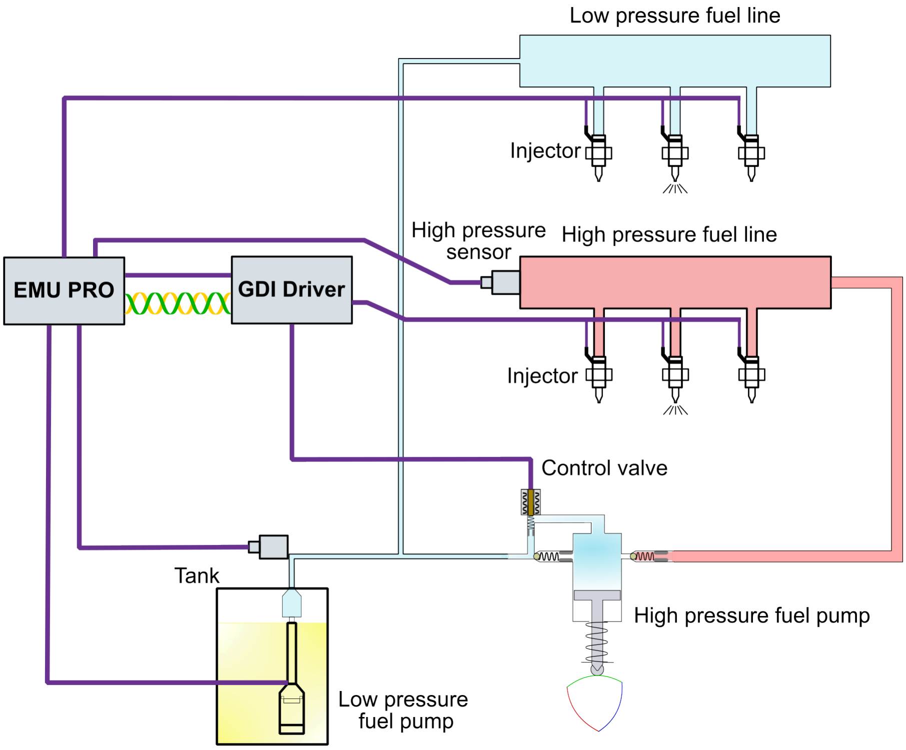
GDI System Overview - Direct injection only

The GDI Driver module controls the voltage and current for the direct injectors and pump valves, while the EMU PRO calculates timings and durations and commands the actuation.



GDI System Overview - Direct + Port injection

The GDI Driver module controls the voltage and current for the direct injectors and pump valves, while the EMU PRO calculates timings and durations and commands the actuation. Elements of port injection are connected directly to EMU PRO, like in any standard port injection setup.



For more information on wiring the GDI Driver, visit: https://www.ecumaster.com/files/devices/GDIDriver/GDIDriverManual.pdf

5. Injector configuration

Direct injection involves injecting fuel directly into the combustion chamber, with the injector tip directly exposed to the combustion event. This exposure might require a minimum fuel flow through the injectors to keep them cool, especially at higher loads. Injectors are mounted in the cylinder head, either from the top or the side.

There are no standards regarding the size, shape, mounting solutions, or pressure ranges for these injectors. Actuation can be either electromagnetic or piezoelectric, although Ecumaster does not support piezoelectric injectors. Electromagnetic injectors are low-impedance, usually below 1.5 ohms, and their short injection window requires a fast opening with a high voltage supply.

> **Note:**
> Ecumaster GDI Driver does not support piezoelectric injectors.

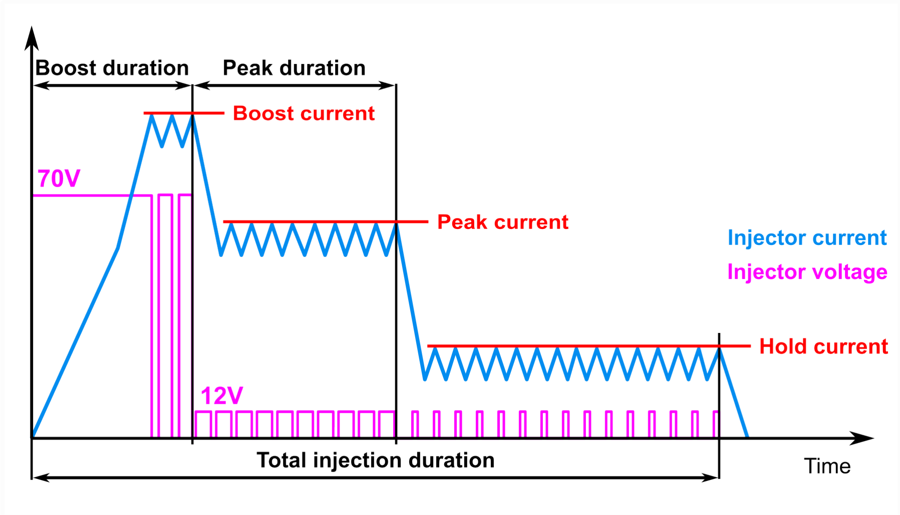
Due to the lack of standardized data, parameters for these injectors often have to be measured manually.

5.1. Electric injector characterization

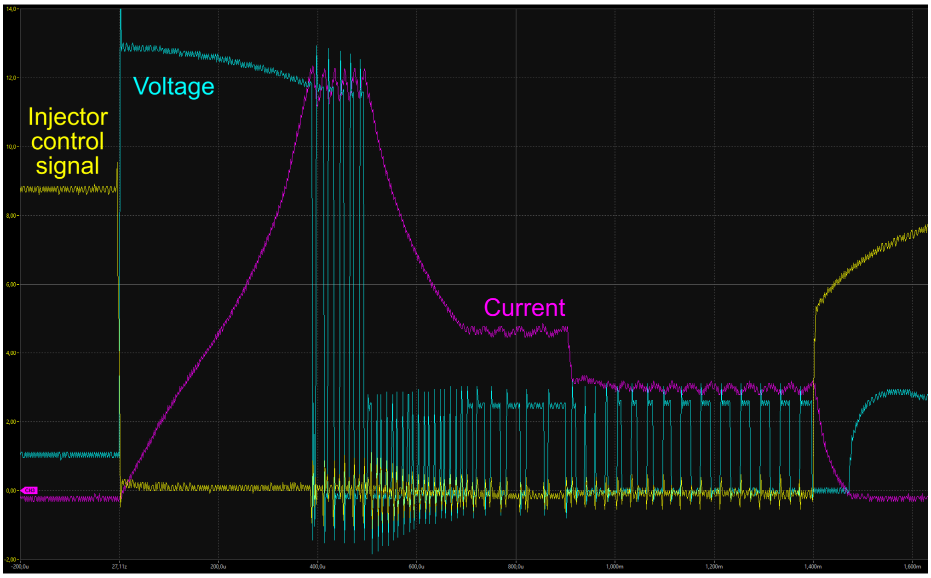
Injector configuration parameters

Injector control in the GDI Driver utilizes a boost peak and hold current strategy. This method involves initially applying a high voltage (around 70 V) and current to quickly open the injector. The higher the *Boost voltage*, the quicker the current will reach the desired *Boost current*.

After the set *Boost duration*, when the injector is fully open, the current is reduced to a lower *Peak current* to stabilize the injector, followed by a minimal *Hold current* to keep the injector open for the desired duration. This approach allows for rapid injector actuation, essential for the short injection windows typical in high-performance engines, while minimizing heat buildup and ensuring reliable operation.



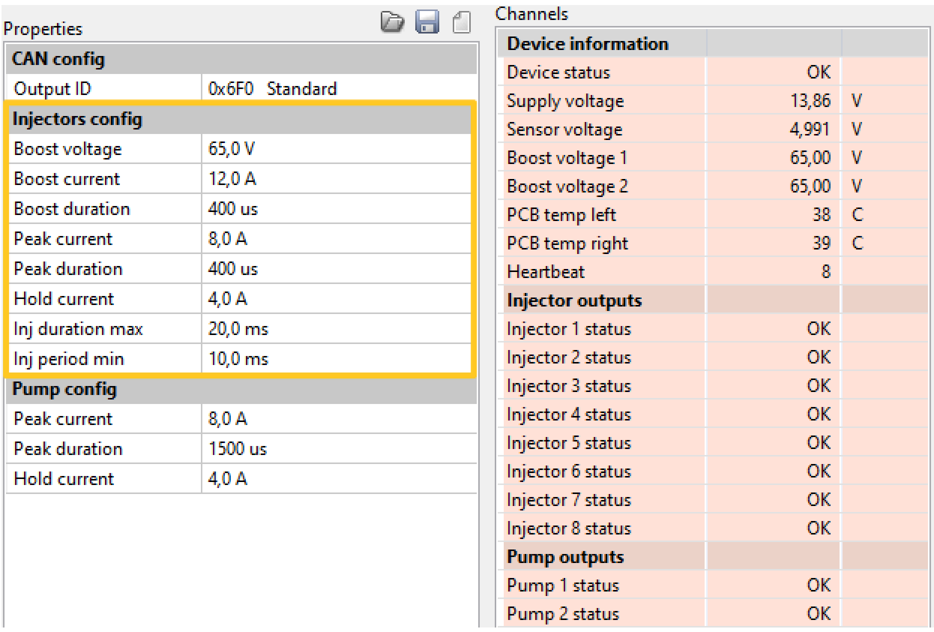
Real-life example of the previous plot, obtained with a an oscilloscope plot:



To ensure optimal performance of the injector, you need to configure the following six key parameters in the Light Client application:

Parameter	Description
Boost voltage	The voltage applied to the injector during the boost phase
Boost current	The current provided to the injector during the boost phase
Boost duration	The time period for which the boost voltage and current are applied
Peak current	The maximum current applied during the peak phase
Peak duration	The time period for which the peak current is applied
Hold current	The current maintained to keep the injector open after the peak phase

Injector parameters in Light Client



Configuration methods

There are two primary methods to configure these parameters:

Method 1: **Measuring the OEM setup**

- Measure High-side voltage:
  Use an oscilloscope to measure the high-side voltage of the injector.
- Measure Phase durations:
  Use an oscilloscope to determine the duration of each phase of the injector operation.
- Measure Injector current:
  Use an oscilloscope and a current probe to measure the injector current during operation.

Method 2: **Trial and error with a working engine**

- Start with high settings:
  Start with high values for voltage, current, and duration parameters.
- Achieve stable engine operation:
  Stable engine operation allows for the evaluation of injector performance. The engine should have stable speed and lambda readings. If the behavior of the injector opening or closing changes, it will affect the delivered fuel amount.
- Optimize parameters:
  Lower the parameters gradually while monitoring the injector's performance. Reducing the parameters too much at will degrade injector functionality. Optimal parameters depend on target pressure. A single optimization process should be performed for the highest pressure.

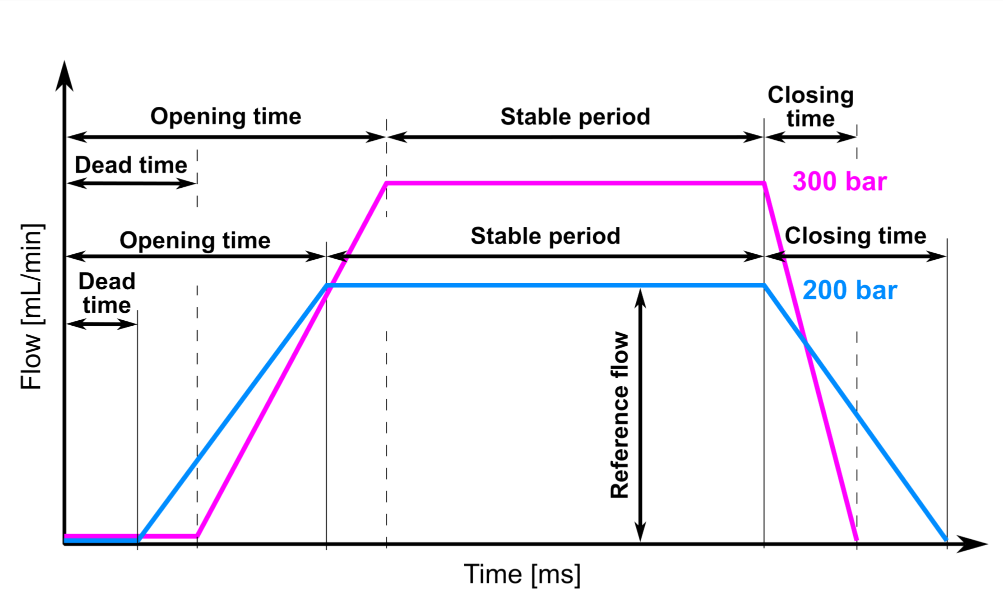
Effects of incorrect parameter settings

- Values too high:
  Overheating can occur, potentially leading to injector damage or failure.
- Values too low:
  The injector may not open or close properly, leading to poor engine performance and potential mechanical issues.

5.2. Flow characteristic

The flow parameters are configured in the **EMU PRO.** Direct injection settings are only available for *Rail 1.*

The diagram below shows a simplified flow pattern over time for different rail pressures. After applying the injector control signal, there is a delay known as the *Dead time* before fuel starts flowing. This delay is longer with higher fuel pressure due to increased mechanical resistance. Once the injector begins to open, the flow increases during the *Opening time*, which is also extended with higher fuel pressure. Following this, the injector reaches the *Stable period*, where the fuel flow is at its maximum rate—the higher the pressure, the higher the flow. Finally, the injector closes, and the flow decreases during the *Closing time*. Interestingly, the higher the pressure, the faster the injector closes.



The flow characteristics of an injector are heavily dependent on the fuel pressure. Key parameters such as dead time, opening time, and maximum flow rate all vary with pressure levels.

- **Dead time:** The interval between the application of the electrical signal and the start of fuel flow.
- **Opening time:** The duration required for the injector to fully open.
- **Reference flow rate:** The highest volume of fuel the injector can deliver within a given time.
- **Opening and closing flow:** The flow rate is non-linear during the injector's opening and closing phases. When the injector closes, it may output additional fuel depending on the closing time and conditions.
- **Short pulse adder:** A correction factor used to compensate for non-linear fuel delivery during injector opening and closing.

*Fuel / Rail 1 / Injectors / Setup / **Reference flow***

Reference flow is the flow measured in ml per minute with the injector fully open.
Flow data is either available from manufacturer or has to be measured.

Testing requirements:

- Flow for a single pressure point is enough
- Flow for any other pressure is calculated in the ECU
- Pressure for the measurement must be inside the operating range (30-200 bar)
- Testing with low pressure can introduce errors from different interactions between peak & hold control, opening/closing, and atomization
- Dedicated Direct-Injector Flow Bench should be used.

Fuel / Rail 1 / Injectors / Setup / ***Dead time***

Time between applying power to the injector and the moment when the first drops of fuel are visible out of the injector nozzle

- If pulse width is equal or lower than dead time, the injector provides zero fuel
- Unlike in port injection, dead time is not dependent on supply voltage in the vehicle because we use regulated, high voltage to open the injector
- Dead time is dependent on the injector differential pressure
- Dead time can be easily measured on the flow tester by using a piece of paper under the injector nozzle, starting with very short pulse width and increasing it while observing the paper for the first signs of fuel droplets

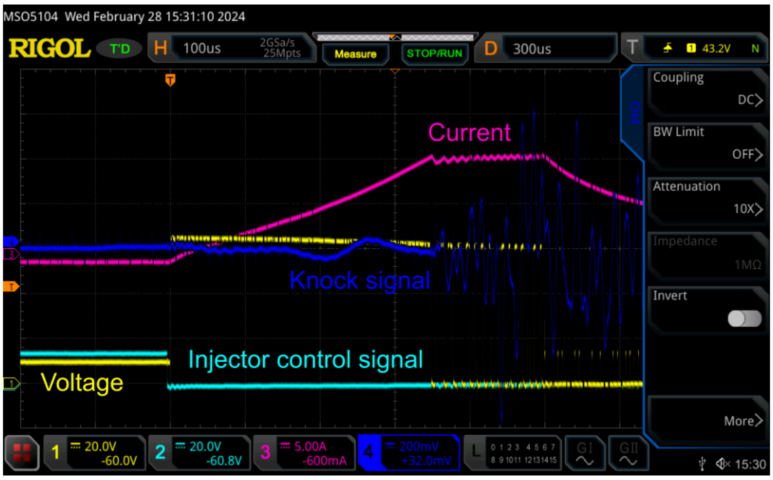
It's important to notice, that by default, *Fuel / Rail 1 / Injectors / Setup /* ***Dead time*** table in EMU PRO software has *Battery voltage* as X axis. For the GDI purposes change the X axis to *Sensors /* ***Fuel high pressure***.

Opening time

Time between applying power to the injector and the moment when the injector is fully opened

- Flow change is non-linear while the injector is in the process of opening
- Opening time is the minimum duration for which the boost current should be applied to the injector to open the injector fully as fast as possible
- Opening time can be measured with the use of knock sensor connected to the oscilloscope
- Knock sensor that is physically touching the injector will generate a signal at the moment of injector fully opening (internal part hits mechanical stop)
- The time can be measured by looking at the injector control signal and the knock sensor signal at the same time

Opening time - knock signal example



Opening and closing flow

- While the injector is opening, the flow is not linear in relation to the pulse width
- While the injector is closing, it will output additional amount of fuel that depends on the closing time (hold current, fuel pressure) and injector flow (fuel pressure)
- Short pulse adder table should be used to compensate for those irregularities
- It is possible to measure those characteristics on a flow tester, but it is complicated and very time consuming
- Practical way of finding short pulse adder values is to tune them on a working engine, after measuring the dead time and maximum flow
- *Short pulse adder* is dependent on the effective pulse width and fuel pressure

*Fuel / Rail 1 / Injectors / Setup / **Short pulse adder*** tuning procedure:

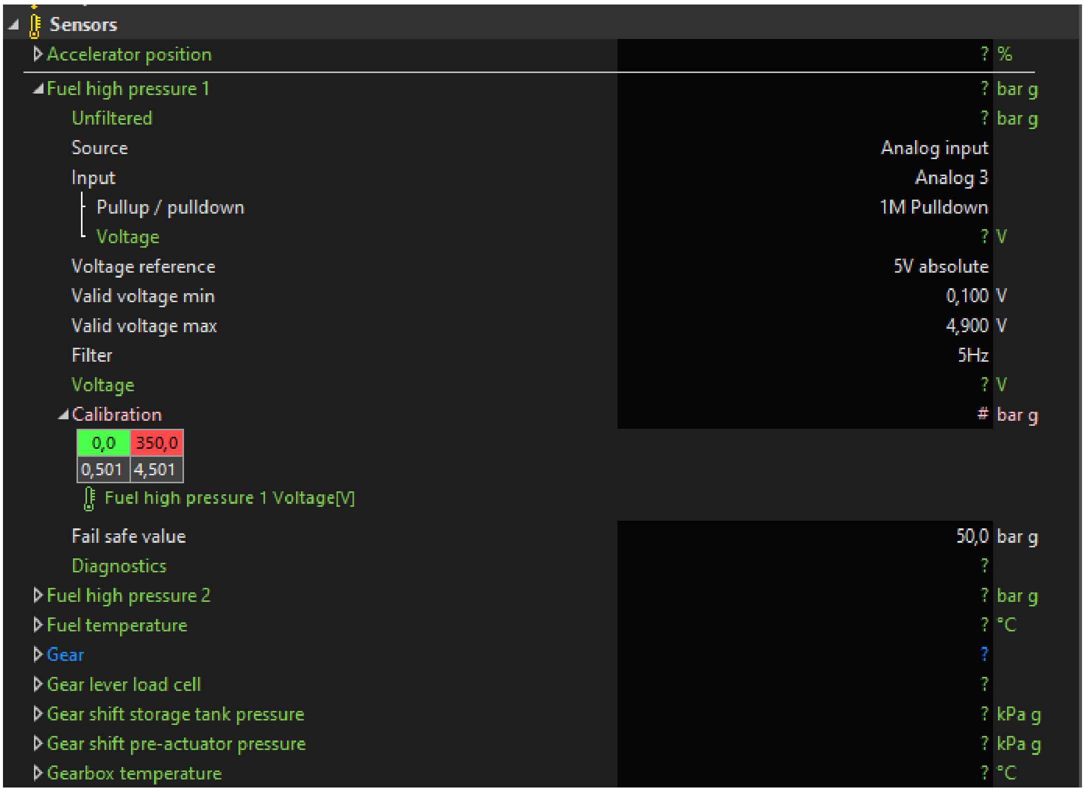
- Engine running in open loop fueling, lambda on target
- Making a change in lambda target, fuel pressure or number of injections
- Lambda should be on target after the change
- If the lambda is not on the target, adjust short pulse adder
- Repeat for different pulse width and fuel pressure values

6. Pressure sensor configuration

The configuration of the high-pressure fuel sensor is similar to any other sensor in the EMU PRO. If your setup uses the SENT protocol for this sensor, refer to the GDI Driver manual for detailed information on SENT communication.

> **Note:**
> Ensure to select proper direct injection setup in ***Fuel / Rail 1 / Injection type*** before configuring the sensor. See Pump configuration in EMU PRO - parameters to measure *(on page 26)*.

Pressure sensor configuration



7. Pump configuration

The GDI Driver uses a peak and hold current method to control the pump. First, a high current (using a 12V supply) is applied to quickly open the valve. Once the valve is open, the current is reduced to a lower level to prevent overheating, while keeping the valve open for the required time.

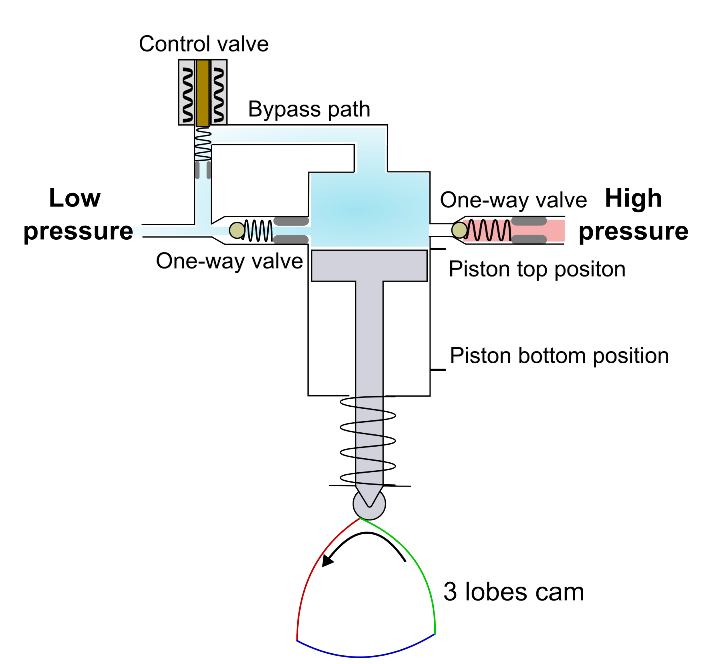
You can operate up to two pumps with this system. The pumps parameters are set up using both the Light Client and EMU PRO software.

7.1. Pump control basics

High pressure pump - Operation principle

To maintain pressure in the fuel line and properly tune an engine with Direct Injection (DI), you should understand the basics of how the high-pressure pump operates. Below is a simplified explanation of the process, focusing on a pump that works in the ***Delivery when powered*** mode. (Different types of pumps will be explained later.)

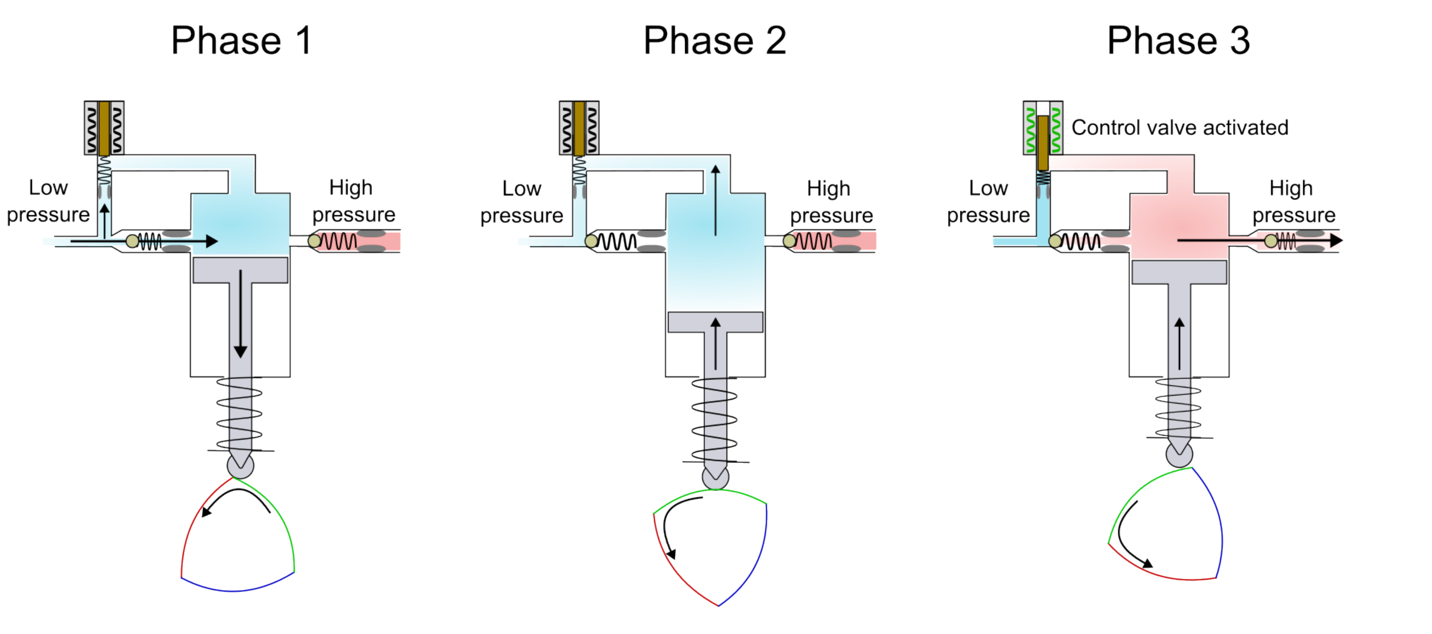
The control valve plays a crucial role in managing the pump, and it is the only way of controlling the pump and keeping the target pressure in the fuel line. It acts as a bypass valve, redirecting fuel back to low-pressure line when open (inactive). When the valve is closed (activated), fuel is compressed into the fuel line. It is important to note that once the valve is activated, it stays closed (compressing the fuel into the fuel line) until the pressure in the pump drops (after TDC of the pump). In other words, we can control when to start compressing the fuel but not when it ends.



1. Control valve:
   - The only way to control the pump.
   - Driven electrically by the GDI Driver.
   - On/off timing controlled by the EMU PRO
2. Bypass path:
   - Path for returning low-pressure fuel.
   - Connected to the control valve and the low-pressure system.
3. Low pressure:
   - Inlet for low-pressure fuel entering the pump.
   - Located at the left side of the diagram.
4. One-way valve (left):
   - Ensures fuel flows in one direction only, from the low-pressure inlet into the pump chamber.
5. One-way valve (right):
   - Prevents backflow of high-pressure fuel.
   - Ensures fuel moves towards the high-pressure outlet.

6. High pressure:
    - Outlet for high-pressure fuel line.
    - Located at the right side of the diagram.
7. Camshaft lobes:
    - Camshaft with multiple lobes that push the piston.
    - Converts rotational motion into reciprocating motion, pushing the piston up and down.

Three Phases of Operation:



1. **Suction Phase:**
    - Action: The piston moves down.
    - Effect: Fuel is drawn from the low-pressure line into the pump cylinder.
    - Mechanism: The fuel passes through a one-way check valve because the pressure in the cylinder is lower than in the low-pressure line, allowing fuel to flow in.
    - Note: The low-pressure return path is open allowing the fuel to flow into the pump. The high-pressure line valve remains closed due to lower pressure in the cylinder compared to the high-pressure line.
2. **Bypass Phase:**
    - Action: The piston moves up with valve not active.
    - Effect: Fuel is pushed out of the cylinder through the low-pressure return path since both check valves are closed and control valve inactive.
    - Mechanism: The pressure in the cylinder is slightly higher than in the low-pressure line but still lower than in the high-pressure line.

3. **Delivery Phase:**
    - Action: The control valve is activated, increasing pressure in the cylinder. Once the valve is activated (closed), the bypass line stays closed until the pressure in the pump drops.
    - Effect: Fuel cannot return through the low-pressure return line or exit through the low-pressure check valve because the pressure in the cylinder is now higher than in the low-pressure line.
    - Mechanism: When the pressure in the pump exceeds the pressure in the high-pressure line, the high-pressure check valve opens automatically, and fuel is pushed into the high-pressure line.

EMU PRO pump control strategy overview

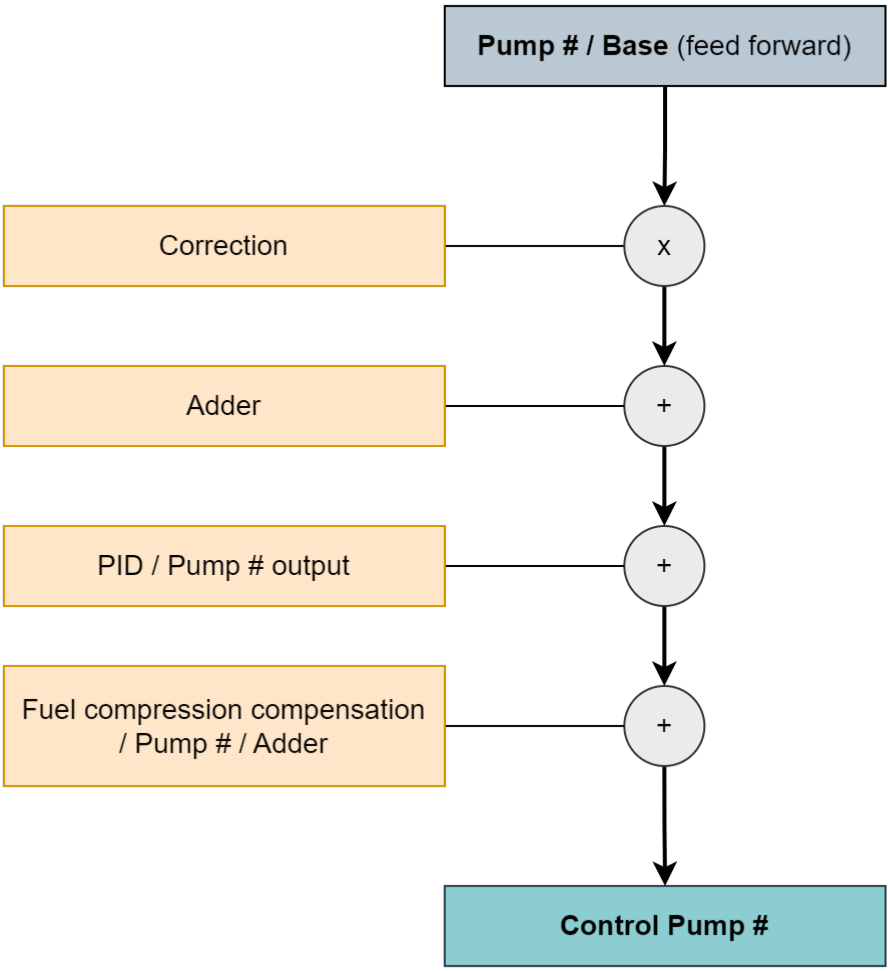
The goal of the pump control strategy is to calculate when to engage the pump control valve to compress enough fuel to reach the fuel pressure target in the high-pressure fuel line. This calculation considers several factors, which will be detailed later. The main steps are:

1. **Determine how much fuel needs to be compressed**:
   Consider the target pressure, fuel used by injectors from lines and other factors described in the further part
2. **Calculate when to activate the valve**:
   Use the relation between the pump displacement and cam angle to calculate the *Delivery Angle*
3. **Timing the valve engagement**:
   Calculate when to activate the valve, based on pump characteristics, such as the valve dead time

It is important to note that this simple description skips multiple factors, but it should give you a good understanding of the parameters needed by the strategy.

Determining how much fuel needs to be compressed

First, the EMU PRO has to calculate how much fuel is needed. Those calculations lead to *Control* value. **This value is the percentage of total pump cylinder displacement.**



Pump # / Base (feed forward)

This is the starting value of the strategy. The channel indicates the percentage of displacement per lobe that needs to be pressurised into the line, based on the summed amount of fuel injected. **Therefore, accurate calibration of injector flow, dead time, and short pulse adder for each fuel pressure is crucial.**

$$Control[\%] = \frac{Fuel\,volume}{Pump\ displacement} \cdot 100\,\%$$

Example:

- amount of fuel injected: 50 uL
- displacement of the fuel pump: 250 uL

$$Control = \frac{50[uL]}{250[uL]} \cdot 100\,\% = 20\,\%$$

In theory, to keep the pressure in the rail constant, the rail would need to be only topped up with this value. In reality there are other factors that need to be included.

Correction

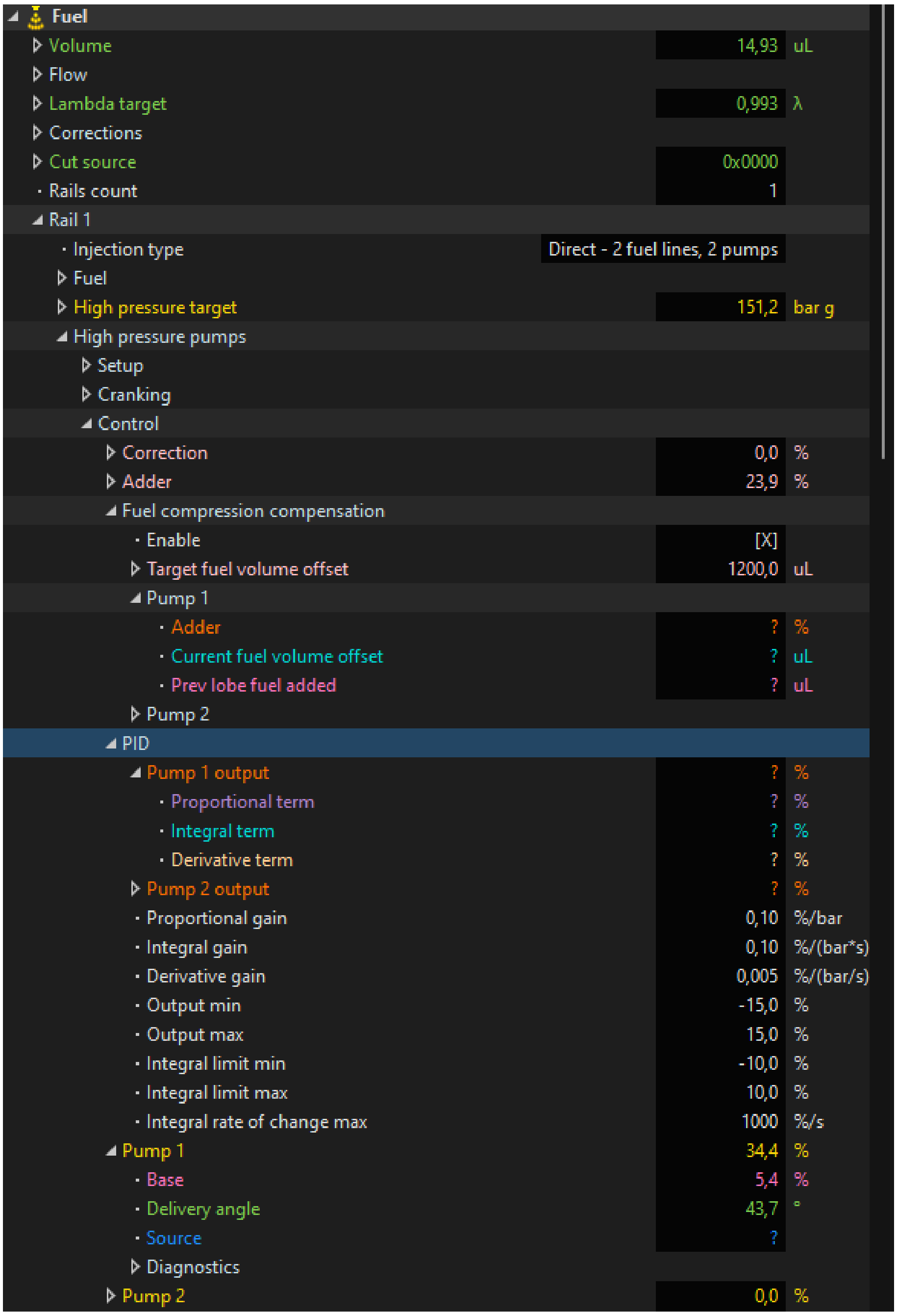
User-defined percentage correction of the *Base* (feed forward) value.

Adder

The value added to the *Base* (feed forward) value. Proper calibration of the table is crucial for the stability of the *Fuel high pressure #*.

PID / Pump # output

PID controller that increases or decreases the control value to achieve the pressure target in the high-pressure fuel rail.



Fuel compression compensation

This correction compensates for the change in the fuel volume due to compression in the high pressure rail.

The exact capacity of the fuel system is not required for correct strategy tuning. Empirically tuned values are used.

Fuel compression compensation / Pump # / Adder

The channel indicating the value added to compensate for fuel compression when the pressure target changes. The value in this channel is the last one added to the control value on the previous lobe.

Example:

$$\Delta V = -\beta \cdot V_0 \cdot \Delta p$$

$$\beta = \text{Gasoline compressibility} \left(5.0 \times 10^{-7} \frac{1}{\text{kPa}}\right)$$

$$V_0 = \text{Rail volume}$$

$$\Delta p = \text{pressure change}$$

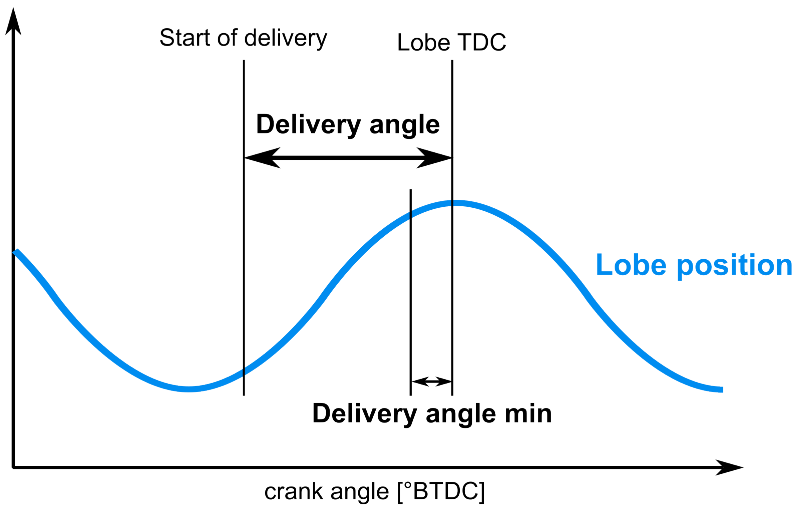
Fuel capacity in ambient pressure [ml]	Rail pressure [bar g]	Capacity after compression [ml]	Capacity change [ml]
52	0	**52**	**-**
52	50	**51,87**	**-0,130**
52	100	**51,61**	**-0,260**
52	200	**51,48**	**-0,520**

<u>**Calculating when to activate the valve**</u>:

The *Control* value calculated in the previous step is now translated to *Delivery angle*.

To increase the pressure on the high-pressure rail, the control valve is closed at a certain angle before the TDC position of the driving lobe. After closing the control valve, it is not possible to open the valve until TDC of the lobe.

Delivery angle - The angle from closing the control valve to Lobe TDC.

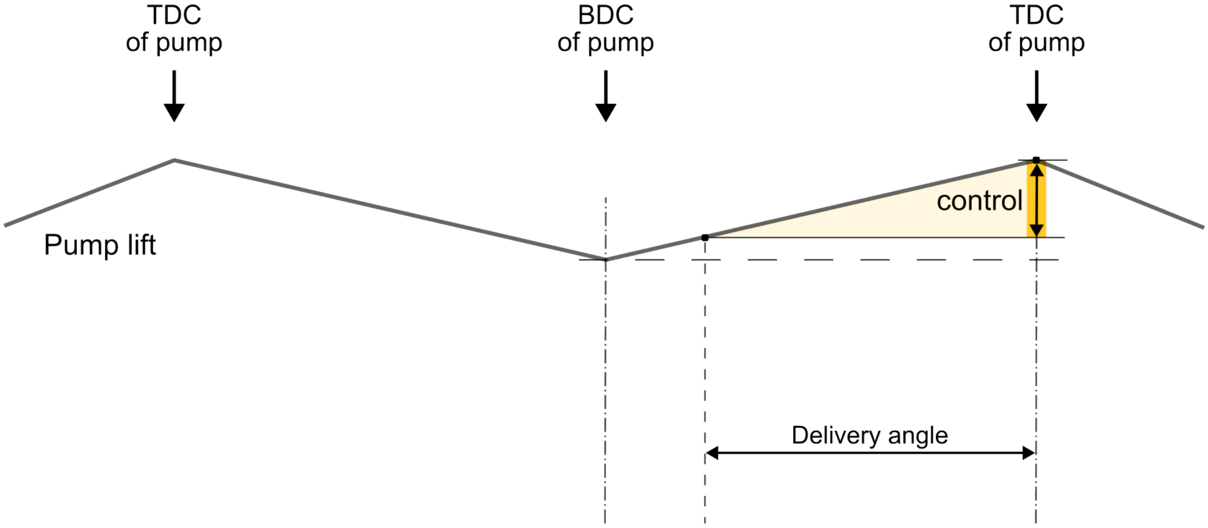


- Top dead center of the lobe is the position that will not deliver any fuel. This point corresponds to 0% fuel pump demand and a delivery angle of 0°
- Bottom dead center of the lobe is the position that will deliver highest possible amount of fuel. This point corresponds to 120° delivery angle (for 3-lobes camshaft)

The *Delivery angle characteristics* table has to be measured by the user. More details will be provided in the next chapter.

Timing the valve engagement:

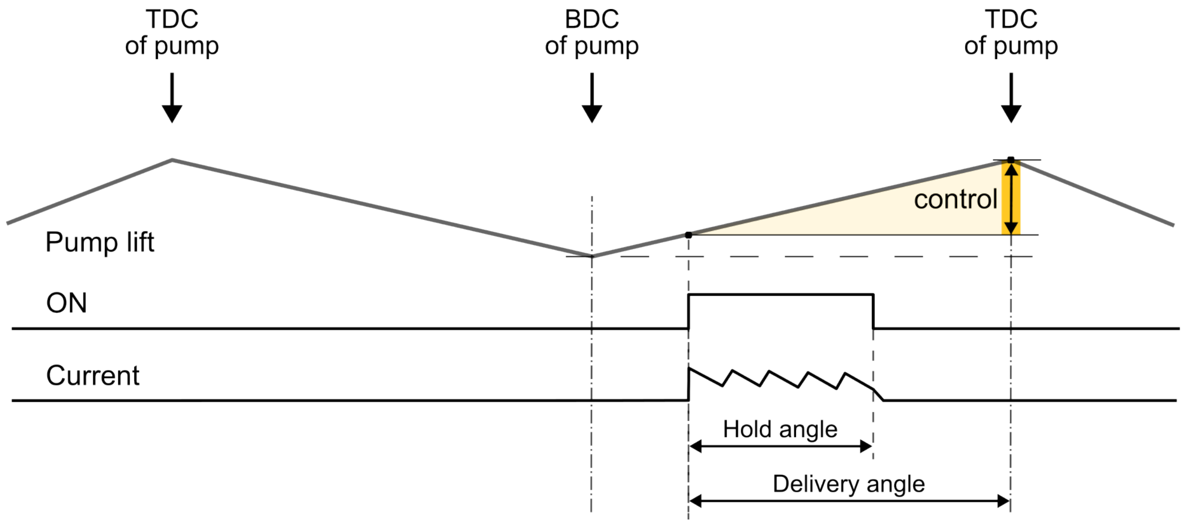
In the basic approach, once the *Delivery angle* is calculated from the *Control* value, you have to enable the valve at *Delivery angle* before the TDC of pump.



Hold angle

After switching on the valve, the hold current must be maintained for enough time to guarantee the pump will deliver fuel to the high-pressure rail.

After this angle, fuel is delivered to the rail whether or not current is supplied to the valve, so the current should be stopped to avoid overheating the coil.

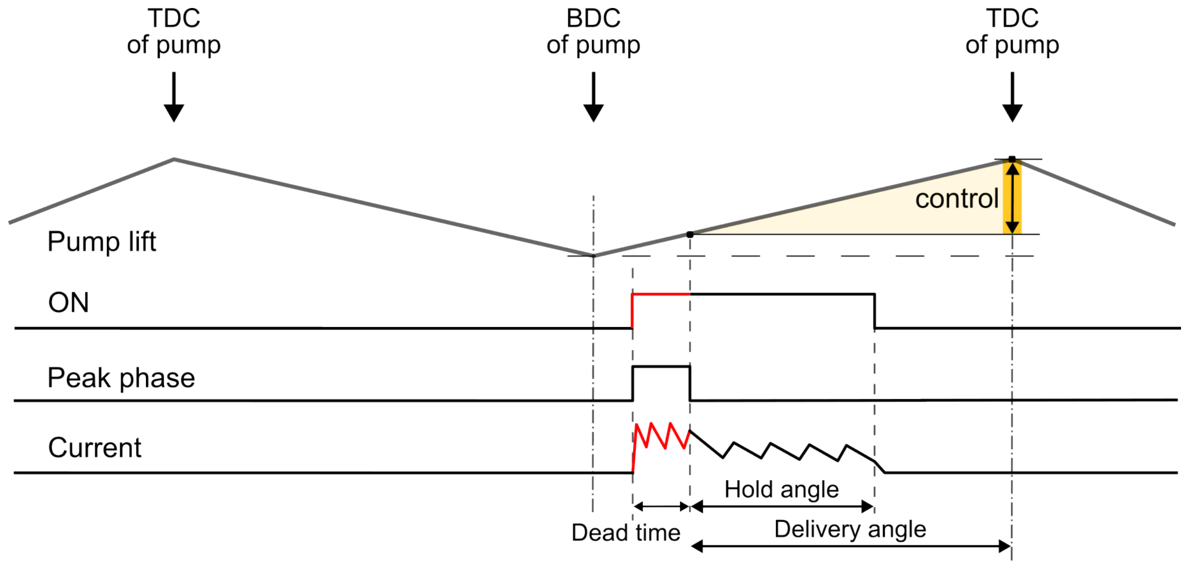


Dead time

This parameter is used for pumps that deliver fuel when powered.

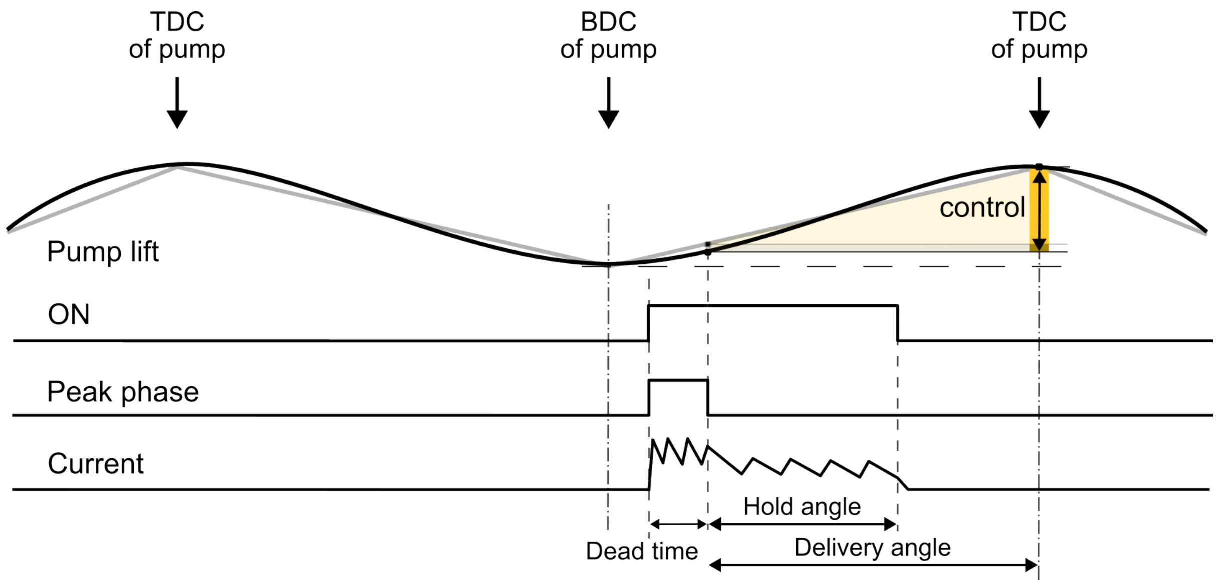
It represents the time after the high-pressure pump valve output is switched on during which the control valve remains open and the pump does not deliver fuel to the high-pressure rail.

This time is accounted for by powering the pump valve in advance to achieve the desired *Delivery angle*. *Dead time* is dependent on fuel pressure in the high pressure fuel rail.



Actual lobe lift

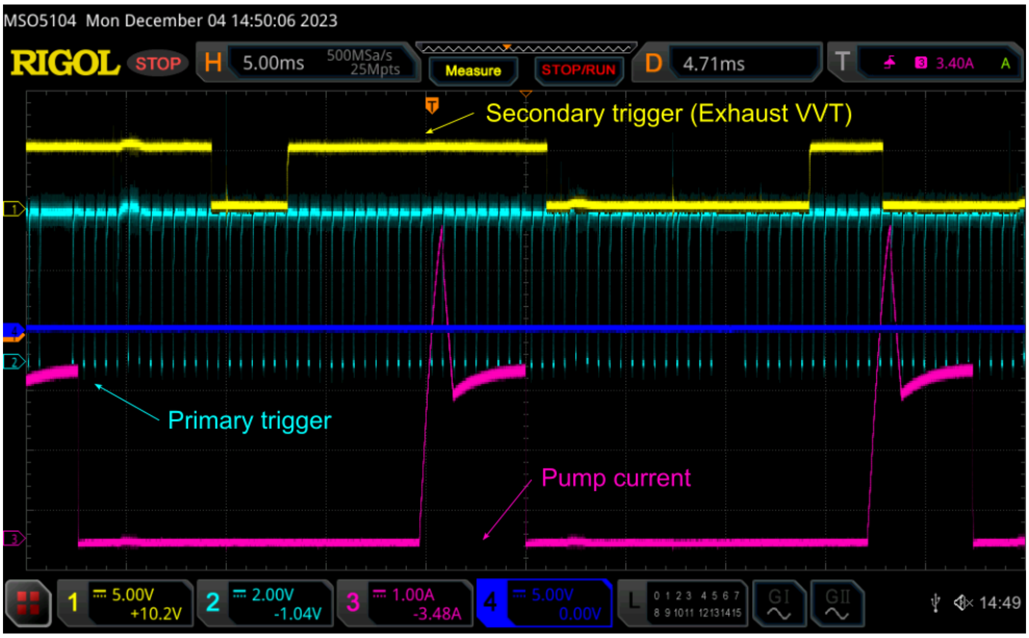
In the previous images, the lobe lift was marked as straight lines. In practice, it is a curve.



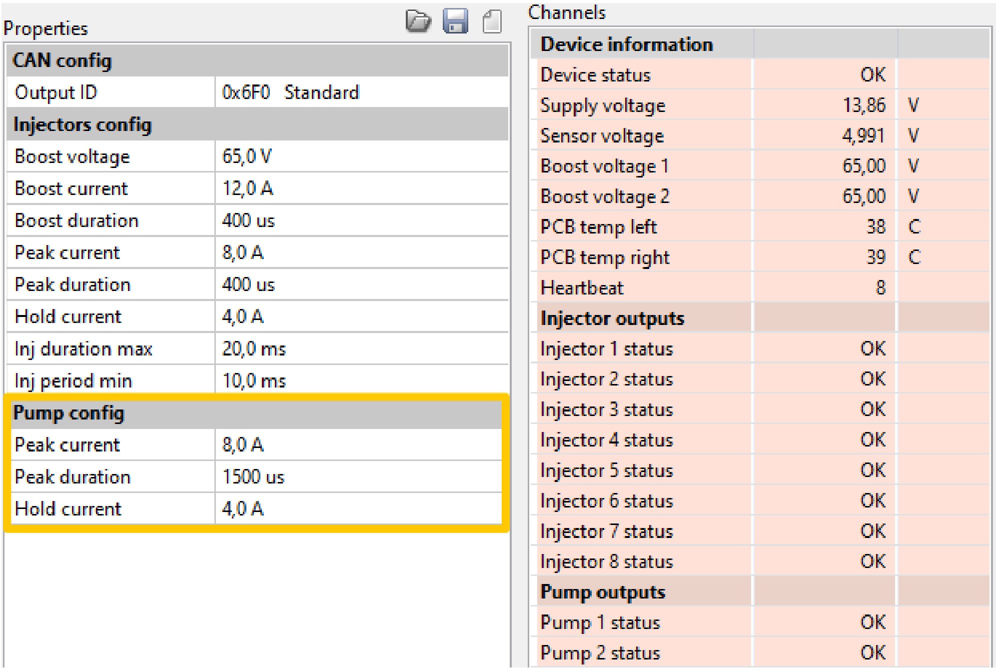
7.2. Pump configuration in Light Client

Pump current

The image below depicts a real-life example of pump control, captured with an oscilloscope. It illustrates the rise of pump current to its peak level followed by a drop to a lower hold level.



Pump configuration - Light Client



Parameter	Description
Peak current	The peak current is a high level of electric current used to quickly open a valve. It is the initial surge of current that provides enough power to move the valve from a closed to an open position.
Peak duration	The peak duration is the time period during which the peak current is applied. It lasts just long enough to ensure that the valve fully opens.
Hold Current	The hold current is a lower level of electric current used to keep the valve open after it has been activated. This lower current helps to keep the valve from overheating and allows it to close more quickly. This current is maintained for as long as the valve needs to stay open.

Configuration methods

There are two methods to configure these parameters:

Method 1: **Measuring the OEM setup**

- Measure Phase durations:
  Use an oscilloscope to determine the duration of the peak phase of the pump operation.
- Measure Pump current:
  Use an oscilloscope and a current probe to measure the pump current during operation.

Method 2: **Trial and error with a working engine**

- Start with high settings:
  Begin with high values for peak current and duration parameters.

> **Warning:**
> Values that are too high may damage the valve.

- Check Pump Functionality:
  Observe if the pump works correctly. If it does, the parameters are likely within a functional range.
- Optimize Parameters:
  Gradually lower the parameters while monitoring the pump's performance. If the performance decreases too much and the pump stops working properly, slightly increase the parameters to restore proper function.

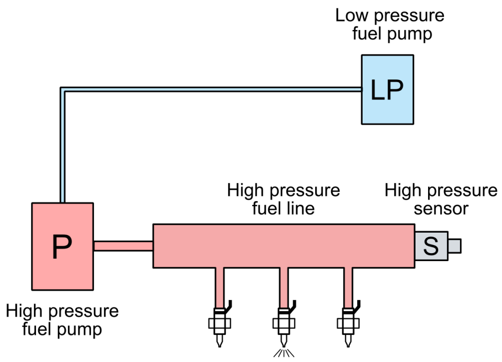
7.3. Pump configuration in EMU PRO - parameters to measure

To ensure the strategy works correctly, some parameters need to be measured or set beforehand in the EMU PRO.

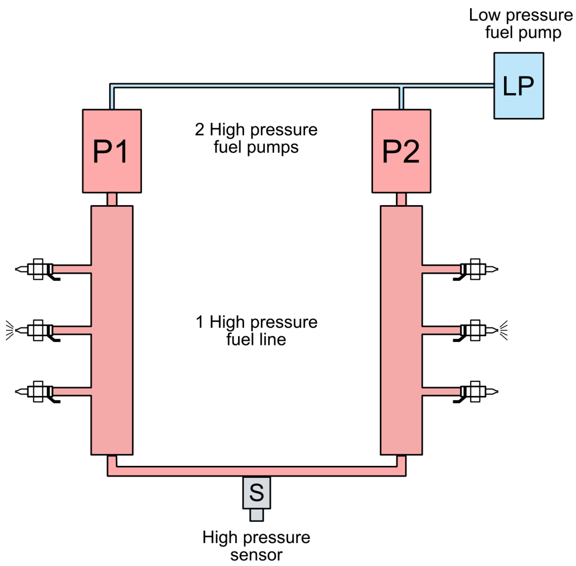
Before these parameters can be accessed or configured, you must first select the appropriate ***Fuel / Rail 1 / Injection type***.

Determining the correct *Injection type* requires verifying the fuel system configuration in your vehicle. Check the vehicle's user guide or physically inspect the system to identify whether your setup includes:

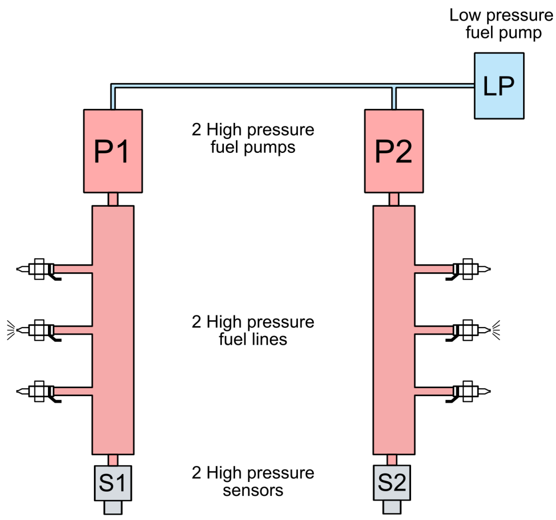
- 1 fuel line and 1 pump,



- 1 fuel line and 2 pumps,



- 2 fuel lines and 2 pumps.

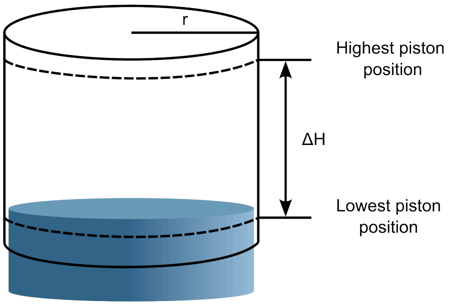


Pump configuration - Direct measurement / set parameters

- *Displacement per lobe*
- *Delivery angle characteristics*
- *Delivery angle min*
- *Lobes count*
- *Reference camshaft*
- *First lobe TDC angle offset*
- *Pressure max*
- *Control type*

• *Hold angle / Margin angle* (if datasheet available)
• *Dead time / Delay time* (if datasheet available)

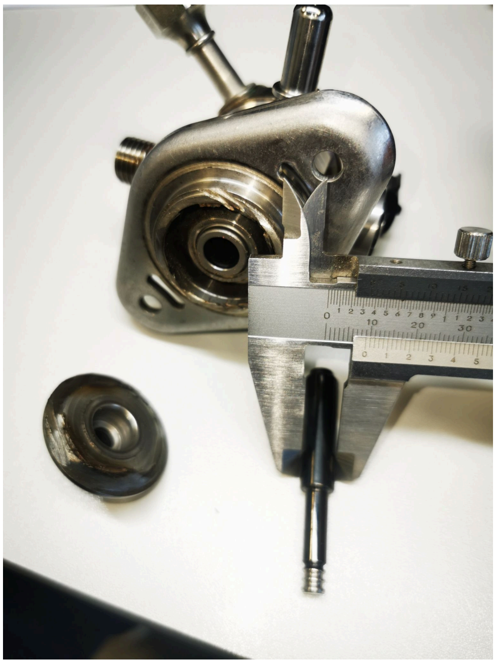
Fuel / Rail 1 / High pressure pumps / Setup / ***Displacement per lobe***
The displacement of the fuel pump during one stroke indicates how much fuel can be injected into the high-pressure line in a single stroke. This is a crucial value because all fuel calculations for the high-pressure fuel pump are done as a percentage of this value – see *Control*.



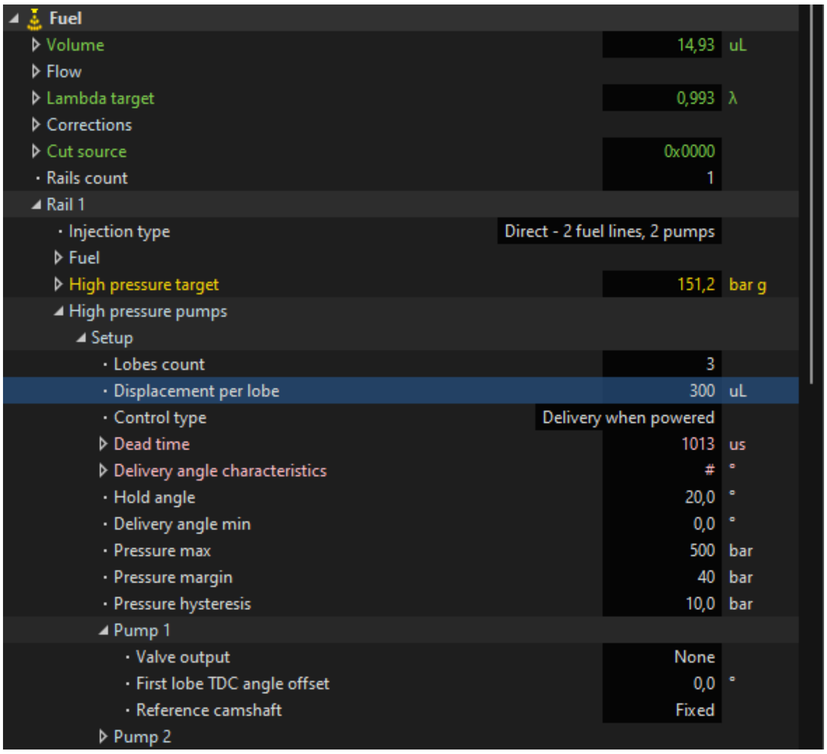
Displacement per lobe = $\pi * r^2 * \Delta H$

***Displacement per lobe* measurement**
The diameter of the piston needs to be measured. The Extreme cam movement positions measurement involves recording the difference between the dial gauge readings at the TDC and BDC of the pump.

Piston diameter measurement

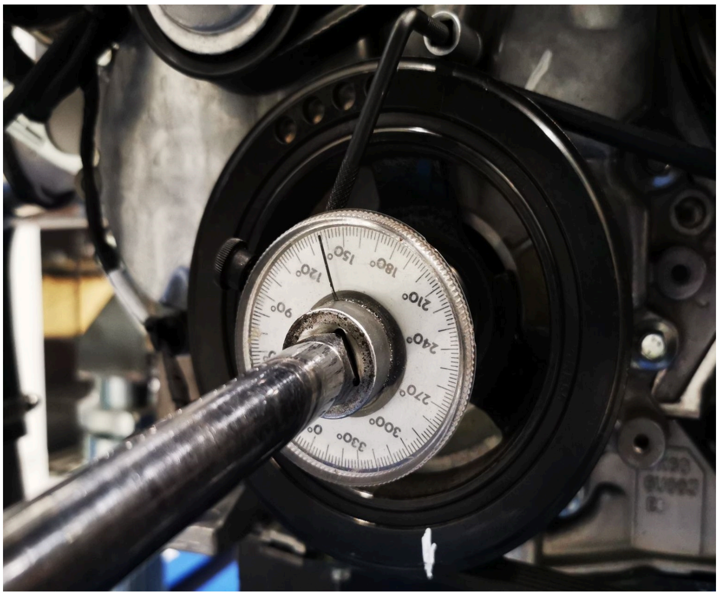


Extreme cam movement positions measurement



Fuel / Rail 1 / High pressure pumps / Setup / ***Delivery angle characteristics***

Values in the *Delivery angle characteristics* table can be measured using a dial indicator to determine high-pressure pump lobe travel versus crankshaft rotation angle measurement.



Delivery angle characteristics **- measurement**

To measure the delivery angle and fill in the table, follow these steps using two instruments (shown in the pictures): a degree wheel on the crankshaft and a dial indicator inserted into the pump's position.

1. Starting Point (TDC of Pump)
   - Begin at the top dead center (TDC) of the pump.
   - Record the initial reading of the dial indicator (e.g., 3.64 mm).
2. Rotate the Shaft and Record Readings
   - Rotate the shaft by 5 degrees increments.
   - At each 5-degree position, record the dial indicator reading as the piston moves down.
   - Continue this until reaching the bottom dead center (BDC) of the pump, where the dial indicator shows the maximum reading (e.g., 7.01 mm).
3. Calculate the Percentage of Total Pump Movement
   - For each position measured, calculate the percentage of the total pump movement.
   - Use the formula:
     Percentage = (Reading at the position - TDC Reading) / (BDC Reading - TDC Reading)
   - For example, if at a certain position, the dial indicator reads 6.16 mm:
     Percentage = (6.16−3.64) / (7.01−3.64) = 2.52 / 3.37 = 74.8 %
4. Fill in the Table in EMU PRO
   - First, modify the axis by entering the calculated percentages from the measured values.
   - Next, enter the angle values in the top row of the table (every 5 degrees close to the BDC and TDC of the lobe and every 10 degrees in between).

Delivery angle characteristics - measured values:

Delivery angle characteristics

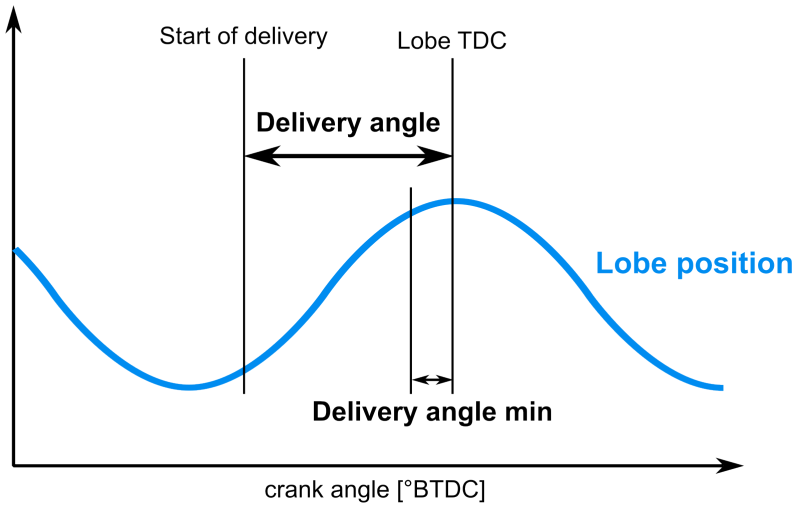
0,0	10,0	20,0	30,0	40,0	50,0	60,0	70,0	80,0	90,0	100,0	110,0	120,0
0,0	1,1	5,8	12,8	20,5	31,5	45,3	61,1	76,0	87,3	95,8	98,9	100,0

Rail 1 High pressure pump Control [%]

Fuel / Rail 1 / High pressure pumps / Setup / ***Delivery angle min***

The minimum angle below which the valve is not activated.

If the delivery angle is too small, activating the valve is unnecessary because the amount of fuel added to the rail is very small, and the resulting inaccuracies are too significant. It's better not to activate it at all.



This value is usually around 5-10 degrees depending on how flat is the top of the lobe position.

Fuel / Rail 1 / High pressure pumps / Setup / ***Lobes count***

The number of lobes or cams on the shaft powering the high-pressure pump.

In other words, the number of strokes performed by the high-pressure pump per engine cycle.

Fuel / Rail 1 / High pressure pumps / Setup / Pump 1 / ***Reference camshaft***

The camshaft on which the lobes powering the high-pressure fuel pump are installed.

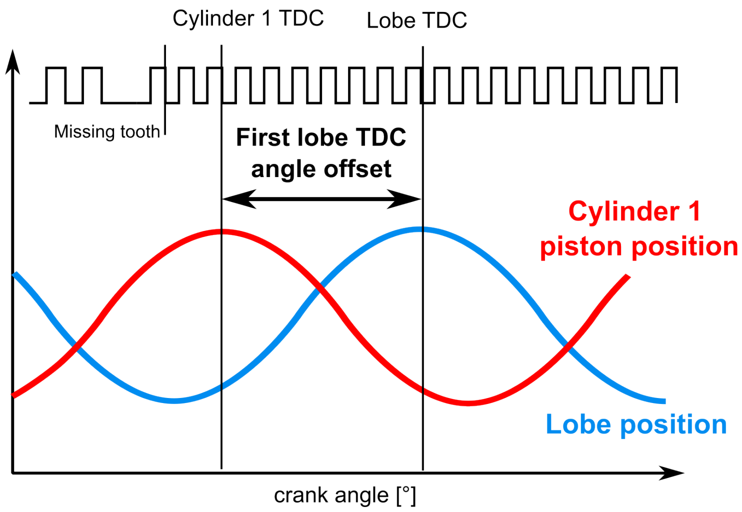
- Fixed
- Intake 1
- Intake 2
- Exhaust 1
- Exhaust 2

Fuel / Rail 1 / High pressure pumps / Setup / Pump 1 / ***First lobe TDC angle offset***

The angle offset from the Top Dead Center (TDC) of Cylinder 1 specifies the number of degrees after the TDC of the first cylinder where the first high-pressure pump lobe is located.

Note:

This is not related to the missing tooth!



Fuel / Rail 1 / High pressure pumps / Setup / ***Pressure max***

The maximum absolute pressure allowed on high pressure fuel line.

If the pressure exceeds this value, control of the pump(s) is set to 0%.

For ***Delivery when Powered***, the pump output is set to off. Regular control is restored once the pressure drops below *Pressure margin* minus *Pressure hysteresis*.

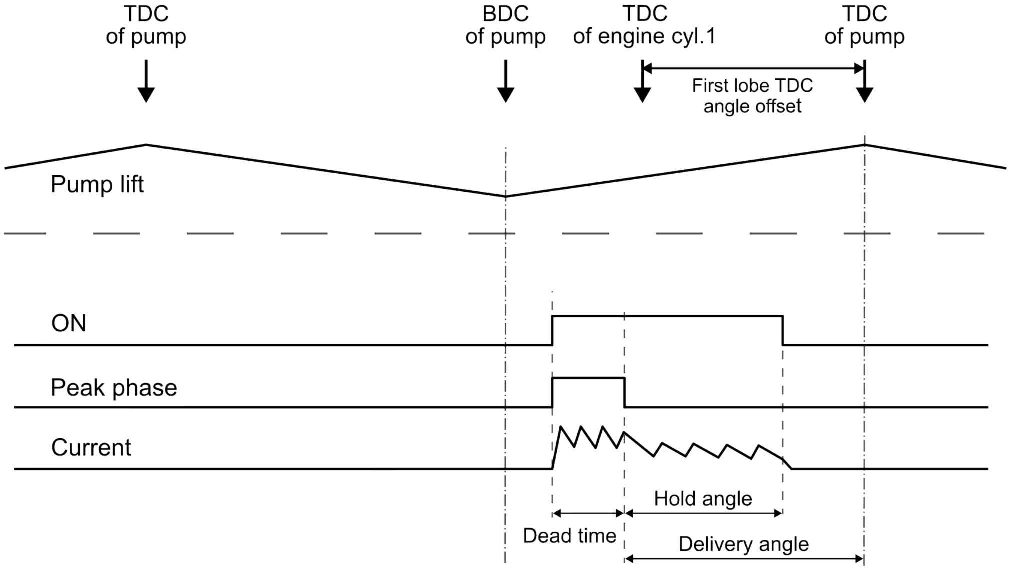
The maximum pressure should be set 10–20 bar below the pressure value of the mechanical safety valve of the pump.

*Fuel / Rail 1 / High pressure pumps / Setup / **Control type***

- *Delivery when powered*

  The control valve is closed (fuel starts to be delivered into the fuel rail) when the valve is powered. The valve must not be powered at Top Dead Center (TDC) of the high-pressure pump lobe.

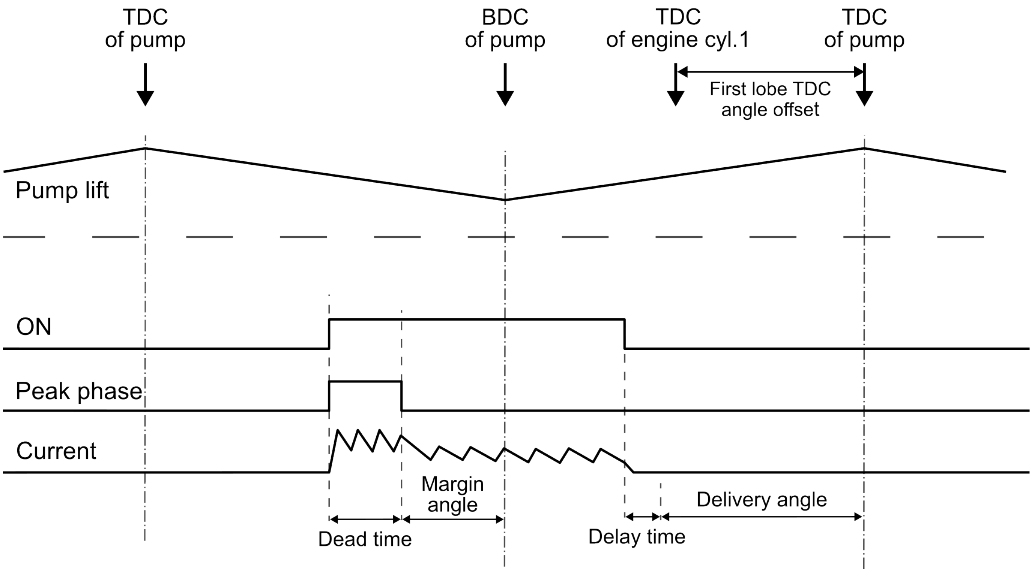
Control of Delivery When Powered Pump



- *Delivery when unpowered*

  The control valve is closed (fuel starts to be delivered into the fuel rail) when the valve stops being powered. At BDC of the high-pressure pump lobe, the valve must be powered.

Control of Delivery When Unpowered Pump



7.4. Pump configuration in EMU PRO - parameters to tune

After configuring all the necessary parameters that must be measured before starting the engine, you should be ready to initiate engine startup. The pressure target should ideally be set around 60 bar. It's technically possible to idle the engine at as low as 5-10 bar. If the configuration outlined in the Pump configuration in EMU PRO - parameters to measure *(on page 26)* section was performed correctly, the pressure in the high-pressure fuel rail should remain relatively stable. If it does, you can proceed to the next steps.

1. *Fuel / Rail 1 / High pressure pumps / Control /* ***PID***
Tuning the *PID* system doesn't differ significantly from tuning other PID systems. The setpoint for the PID controller is the rail pressure target, and the process variable is the rail pressure sensor readout.

2. *Fuel / Rail 1 / High pressure pumps / Setup /* ***Dead time*** (for *Delivery when powered*),
Fuel / Rail 1 / High pressure pumps / Setup / ***Delay time*** (for *Delivery when unpowered*)
If it is not possible to obtain dead/delay time characteristics from the manufacturer of the fuel pump or the OEM ECU, the dead time can be estimated using the experiment described below.

1. Start with too short *Dead time* (e.g., 400 us).
2. Run the engine at approximately 2000 RPM with stable fuel rail pressure.
3. Activate *Zero delivery angle and fuel cut* parameter:
   - Setting the *Delivery angle* to zero should prevent fuel from being pumped into the rail.
   - Setting Fuel cut prevents fuel from escaping the fuel rail.
   - With proper or too short *Dead time* setting the pressure in the rail should remain constant.
   - If the *Dead time* is set too long, the pump will open too early (just after the actual *Dead time*), causing fuel to be pumped and the rail pressure to rise.
4. Adjust *Dead time* and monitor rail pressure
   - Gradually increase the *Dead time* (by 100-200 us) until you observe the rail pressure starting to rise.
5. Find the correct point
   - Identify the correct *Dead time* setting by observing the point just before rail pressure begins to rise.

Perform the described experiment at different battery voltages.

3. *Fuel / Rail 1 / High pressure pumps / Control /* ***Adder***

To populate this table, observe the PID correction (*PID / Pump # output*) values and enter them at specific operating points (RPM vs. pressure target) to ensure the PID output value is near zero after the value is set. Repeat this process for each point in the table.

4. *Fuel / Rail 1 / High pressure pumps / Control /* ***Fuel compression compensation***

Start by setting the *High pressure target / Rate max* to 0 (the *Rate max* parameter is disabled then). Begin by increasing the pressure from 20 to 50 bar. The pressure should rapidly reach the target of 50 bar and closely follow the target value. If the pressure does not reach the target of 50 bar, it means the value in the table for 50 bar is too low, causing the pressure to change too slowly. If the value is too high, the pressure will overshoot the target.
Repeat this procedure for increasing the pressure from 50 to 100 bar, then from 100 to 150 bar, and so on.

5. *Fuel / Rail 1 / High pressure pumps / Setup /* ***Hold angle*** (for *Delivery when powered*),
Fuel / Rail 1 / High pressure pumps / Setup / ***Margin angle*** (for *Delivery when unpowered*)

The *Hold angle / Margin angle* should be initially set to a relatively high value, such as 20 degrees. Then, gradually decrease the angle until the pump no longer operates properly. Once you notice the pump's performance declining, increase the *Hold angle / Margin angle* back up by 5 degrees. The value of this parameter should not be lower than 10 degrees (for *Hold angle*) and 5 degrees (for *Margin angle*).

6. *Fuel / Rail 1 / High pressure pumps / Setup /* ***Pressure margin***

The pressure margin above the *High pressure target* allowed on high pressure fuel line.
If the pressure exceeds the value equal to *Pressure max* + *Pressure margin*, control of the pump is set to 0%.
For ***Delivery when Powered***, the pump output is turned off. Regular control is restored once the pressure drops below *Pressure max - Pressure hysteresis*.
The *Pressure margin* should be determined experimentally. A typical value is approximately 1.5–2 times the pressure overshoot that occurs in the worst-case scenario during control algorithm operation.

7.*Fuel / Rail 1 / High pressure pumps / Setup /* ***Pressure hysteresis***

The *Pressure hysteresis* defined for protection strategies against exceeding the maximum pressure set in the *Pressure max* and *Pressure margin* parameters.
The *Pressure hysteresis* should be determined experimentally. Typical values range from 5 to 30 bar.

8. GDI performance tuning basics

Engine mapping in DI compared to port injection

The engine mapping doesn't differ much compared to port injection engine. There are two new parameters that can be modified to optimise engine performance - fuel pressure and injection angle start.

Check for signs of incorrect fuel pump or injectors calibration

- Issues with the precise fuel pressure control.
- Issues with correct mixture control. (lean/rich spots, weird VE table shape)

Homogeneous charge

- In OEM applications the DI engines use different mixture preparation methods depending on conditions.
- High-performance applications use only one fuel mixture preparation mode - *Homogenous Charge*.
- The *Homogeneous Charge* (uniform air-fuel mixture) is achieved by injecting fuel at the beginning of the intake phase. This early injection allows for maximum mixing of air and fuel, resulting in a uniform mixture.
- While the efficiency gains are slight compared to port-injected engines at full throttle, GDI engines benefit from higher compression ratios due to the cooling effect of fuel evaporating inside the cylinders. This cooling effect improves resistance to knocking, allowing for higher compression ratios and better efficiency.

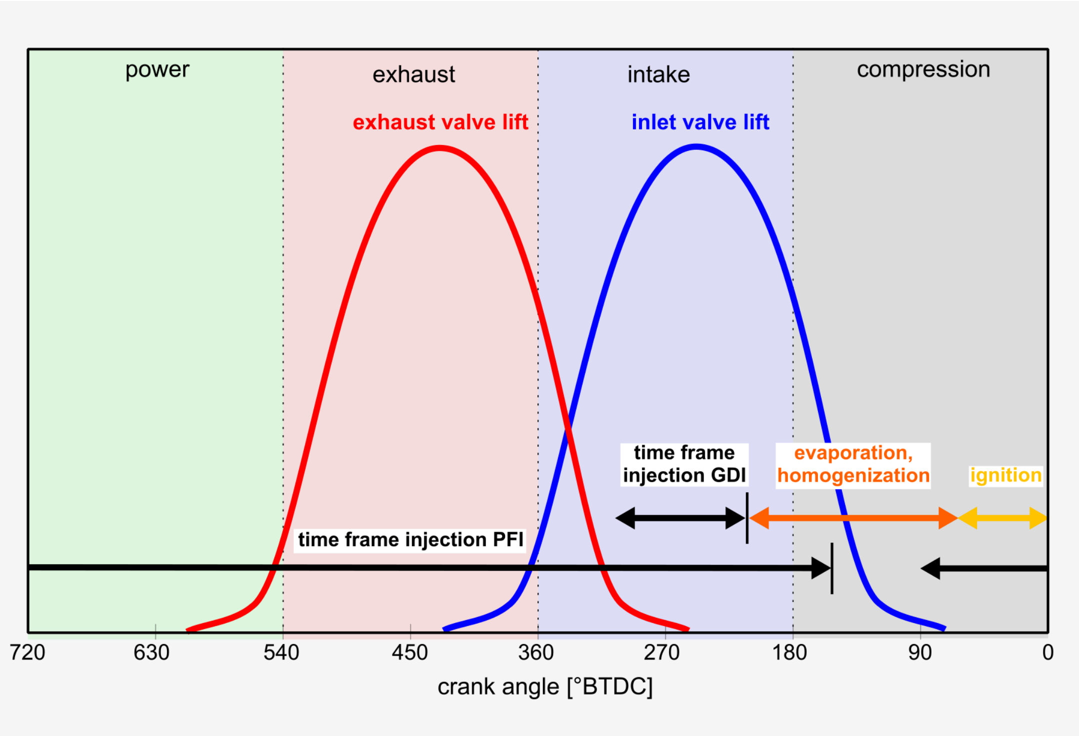
Note:
The Direct Injection strategy in EMU PRO does not support modes with stratified charges. It uses only the Homogeneous Charge mode because our goal is high performance, not high efficiency at low RPM.

Fuel / Rail 1 / ***Injection angle***

The injection angle in direct injection engines is critical for optimizing combustion efficiency and engine performance.

Incorrect injection angles can lead to poor fuel atomization, incomplete combustion, and potential engine damage.

DI mixture preparation



The time frame for injection in GDI engines is much shorter compared to PFI (Port Fuel Injection) engines. Therefore, GDI engines require higher fuel rail pressure and precise control of the injection angle, which has a greater impact than in PFI engines.

Finding an optimal angle

Injection angle is crucial and varies depending on engine load and RPM. It determines when fuel is injected during the engine cycle.

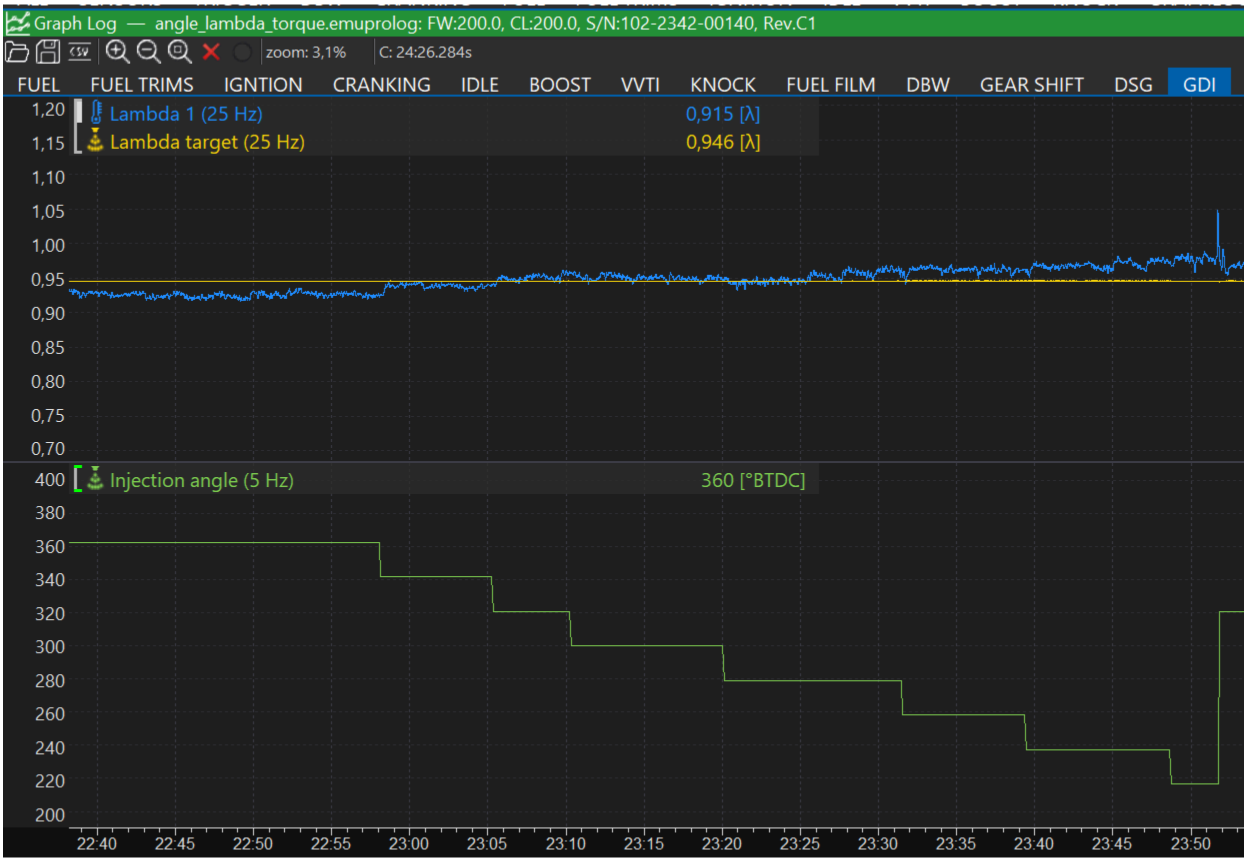
- Injection angle is highly dependent on engine load and RPM conditions.
- The optimal injection angle varies according to the engine's design and characteristics.
- Injecting the fuel too early can result in fuel being expelled through the exhaust valve.
- Injecting fuel too late may lead to inadequate fuel vaporization and a lean mixture.
- In theory, the optimal time to start the injection is at the beginning of the intake stroke, 360 °BTDC.
- In most engines, the exhaust and intake valves overlap, causing part of the fuel mixture to be expelled directly into the exhaust.
- There is a fuel injection angle window during which fuel delivery does not significantly affect the fuel mixture or engine torque.
- This window depends on the specific engine and should be set using a steady-state engine load.

Case study

1. Conditions:
   - Fuel pressure 40 bar
   - Steady load and RPM
   - Constant ignition timing
   - Short term fuel trim disabled
2. Variable:
   - Injection timing was varied from 380 °BTDC to 220 °BTDC

You can observe how the lambda value changes with the injection angle. Between 320 and 280 °BTDC, the lambda remained constant.

However, outside this range — above 340 °BTDC and below 260 °BTDC — injection timing influenced the mixture and engine torque.

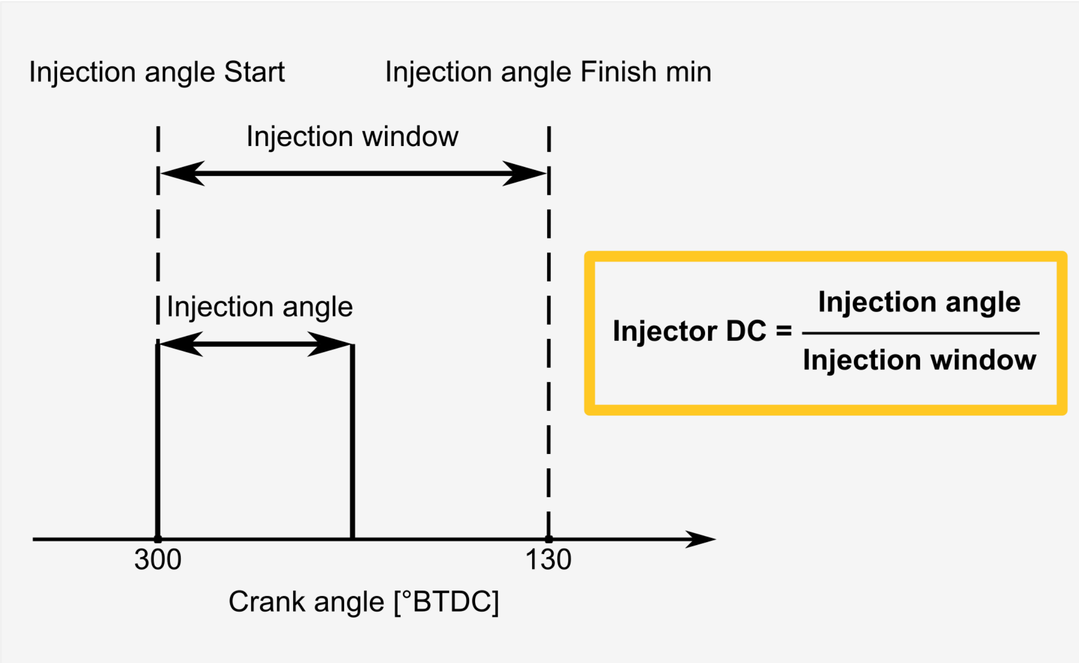


Results:

- Too early injection angle 380 - 340 °BTDC - Lambda sensor indicates a richer mixture than the lambda target - this is due to fuel escaping through the exhaust valve
- Too late injection angle 280 - 220 °BTDC - Lambda sensor indicates a leaner mixture than the lambda target - this is due to inconsistent mixture preparation
- Optimal injection angle 340 - 280 °BTDC

Fuel / Rail 1 / Injectors / Duty cycle / ***Average***

The injection window, defined by the start and finish of the injection angle, directly affects the injector duty cycle. This window is the time between the *Injector angle Finish min* and the *Injector angle Start*, representing the entire available injection period. The injection angle within this window is expressed as a percentage, known as the *Injector Duty cycle*, which is different from Port Fuel Injection (PFI).



If the *Injector Duty cycle* is too high (close to 100%), it means the injectors are nearly fully open during the available window. To correct this, the fuel rail pressure should be increased.

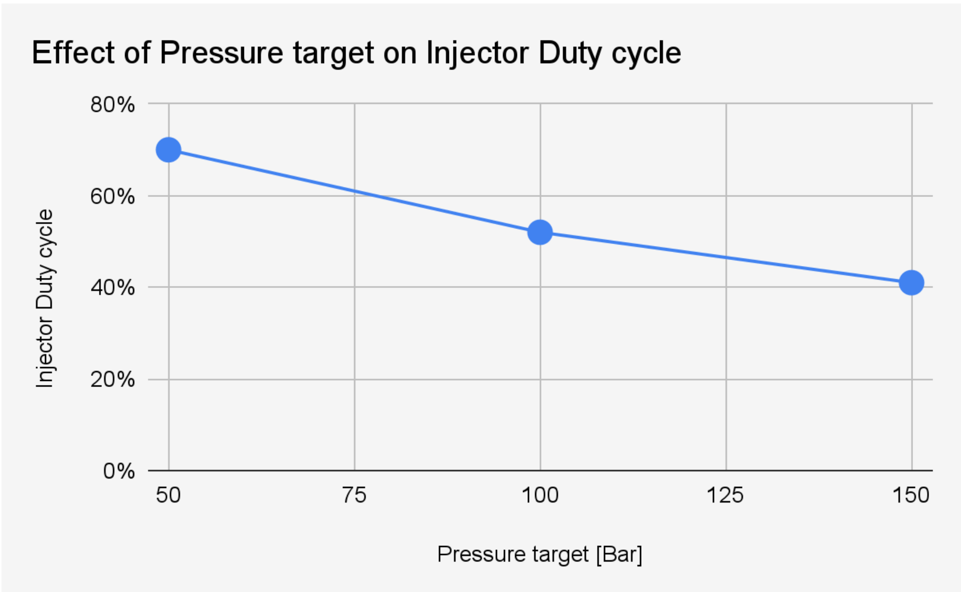
Relation to *Start of injection*

In opposition to the port injection, the start of injection affects the injectors duty cycle. This happens because it makes the injection window shorter.

Pressure target - Effect on injector duty cycle

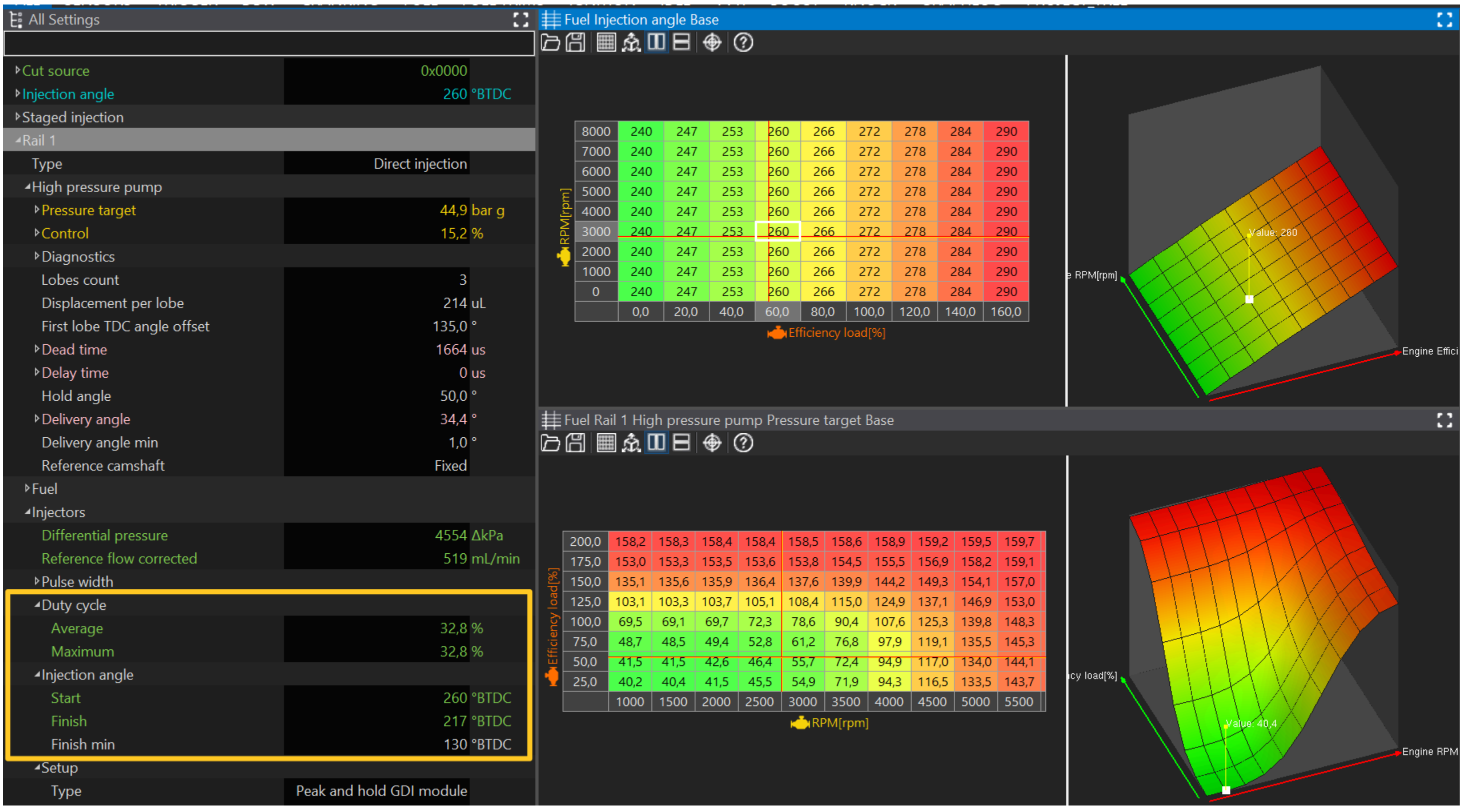
Under high load conditions, the fuel demand is greater and the time between each stroke is shorter.

The injector starting angle and injector finish angle describe the injector cycle when the injector is open. These "borders" allow the ECU to calculate the current injector duty cycle.
Based on this parameter, the user can make decisions about the fuel pressure. If the injector duty cycle is close too 100%, increasing the pressure will decrease the injection time.

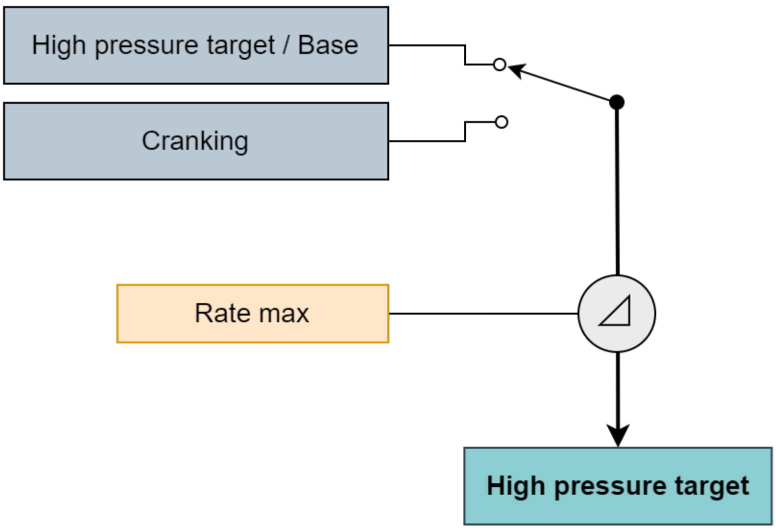


Injection angle - Case study

- Injection angle start - 260 °BTDC
- Injection angle finish - 217 °BTDC
- Pressure target - 44,9 bar
- Injectors duty cycle - 32,8%



*Fuel / Rail 1 / **High pressure target***



The channel indicating the final value of the pressure target on the high-pressure fuel rail. The final value consists of *Base*, limited by the *Rate max* parameter. This value may differ during cranking.

*Fuel / Rail 1 / High pressure target / **Base***

- The base value of the pressure target on the high-pressure fuel rail.
- For low RPM and low load, the typical value is around 30-60 bar.
- For high RPM and high load, the typical value depends on the high-pressure pump construction and may vary between 120 and 300 bar.

Efficiency load[%] \ RPM[rpm]	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000
200,0	160,0	160,0	160,0	160,0	160,0	160,0	160,0	160,0	160,0	160,0	160,0
175,0	160,0	160,0	160,0	160,0	160,0	160,0	160,0	160,0	160,0	160,0	160,0
150,0	160,0	160,0	160,0	160,0	160,0	160,0	160,0	160,0	160,0	160,0	160,0
125,0	110,0	110,0	110,0	110,0	110,6	113,1	118,8	138,8	150,0	160,0	160,0
100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	122,5	140,0	150,0	150,0
75,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	120,0	140,0	150,0	150,0
50,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	120,0	140,0	150,0	150,0
25,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	120,0	140,0	150,0	150,0

9. Troubleshooting

We will expand this section in the future.

10. Sources

These sources have been instrumental in providing accurate and reliable information for our analysis and conclusions.

1. https://stillrunningstrong.com/car-technology/gasoline-direct-injection/
2. http://speed.academy/direct-fuel-injection-how-it-works/2/
3. https://www.underhoodservice.com/high-pressure-gdi-fuel-pumps/
4. http://ipumps.eu/scisliwosc-cieczy/

11. Document history

Version	Date	Changes
0.1	2024.08.14	Initial release
1.0	2024.12.20	Public release
1.1	2025.01.15	Added parameters introduced in software version 215.0 Updated paths to parameters